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The record-breaking rainstorm in Hong Kong on 8 May 1992

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Summary
The 109.9 mm of rain recorded at the Royal Observatory, Hong Kong between 6 a.m. and 7 a.m. Hong Kong Time on 8 May 1992 was the highest 1-hour rainfall record since observations began in 1884. Heavy rain on that day was concentrated in a small area. The synoptic background and the mesoscale aspects of the event are described.

1. Introduction

Heavy rain hit Hong Kong on 8 May 1992, giving more than 300 mm of rain to the urban areas. Rain was heaviest around daybreak and 109.9 mm of rainfall was recorded at the Royal Observatory, Hong Kong between 6 a.m. and 7 a.m. (Hong Kong Time = UTC + 8 hours; used throughout unless otherwise indicated.) This figure broke all previous records of one-hour rainfall since observations began in 1884. Flash floods caused major traffic disruptions and the normally vibrant city was virtually brought to a standstill at the climax of the rainstorm. Several lives were lost, arising from lightning, landslides and fast-flowing water down steep slopes. The insurance industry is looking forward to receiving claims totalling more than 100 million Hong Kong dollars (7–8 million pounds).

Heavy rain in Hong Kong is usually attributed to two types of weather systems, namely tropical cyclones and slow-moving troughs of low pressure. June is normally the wettest month when an east–west oriented trough crosses over Hong Kong on its seasonal march northwards into China (Tao and Chen 1987). Indeed, the worst rainstorms in recent memory occurred in June 1966 (Chen 1969) and June 1972 (Cheng and Yerg 1979). That we should have a rainstorm of such a magnitude in early May was most extraordinary. The rainfall event and its meteorological aspects are described below.

2. Rainfall

Altogether, 324.1 mm of rain was recorded at the Royal Observatory on 8 May 1992. Broadly speaking, the rain came in two spells, one around daybreak and one in the afternoon (Fig. 1). The first spell was more intense and was the one responsible for most of the havoc. The second spell, though of lesser intensity, added more water to the soil and brought further landslides. Rainfall was rather uneven over Hong Kong. Based on the information from some 60 automatic-reporting rain-gauges, it was found that the daily rainfall amount at various places in Hong Kong varied by a factor of three to four (Fig. 2). Only the northern part of Hong Kong Island and the Kowloon Peninsula, where most of the population was concentrated, got more than 300 millimetres of rain. The area involved was roughly 5 km × 15 km in dimension.

Looking further afield, the rainfall distribution in southern China over the 18-hour period 2 a.m–8 p.m. on 8 May 1992, derived from GTS data, is given in Fig. 3. The very localized nature of the heavy rain in Hong Kong is strikingly illustrated.

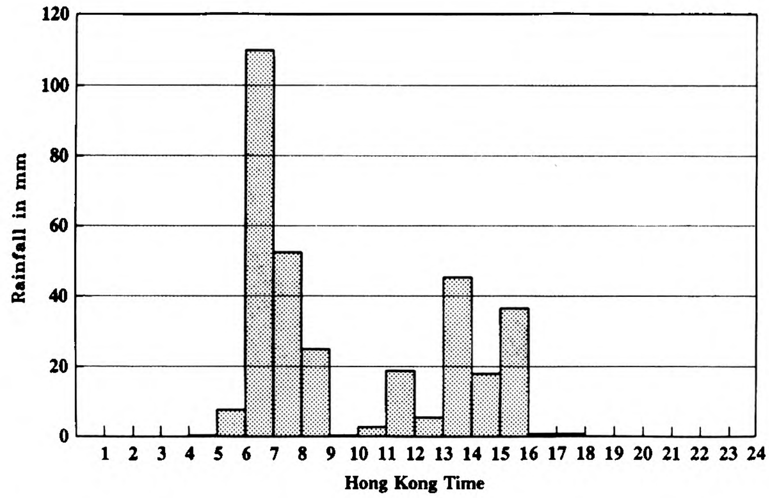

Figure 1. Hourly rainfall recorded at Royal Observatory, Hong Kong, on 8 May 1992

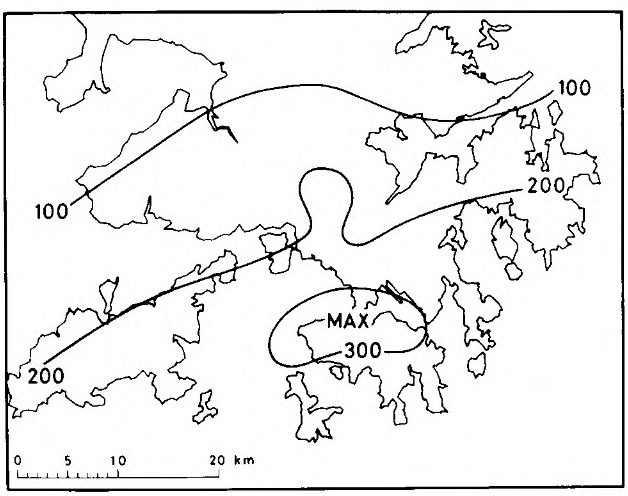

Figure 2. Rainfall (mm) in Hong Kong on 8 May 1992

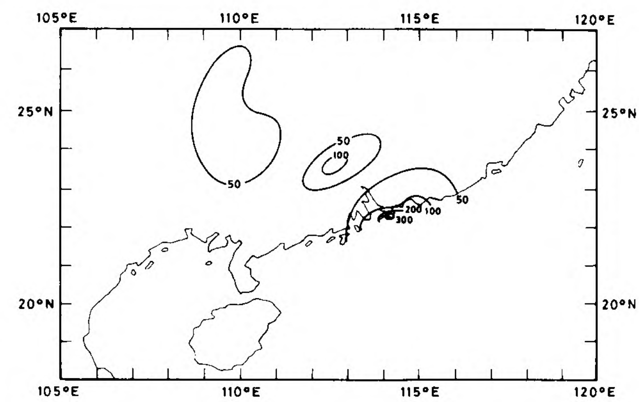

Figure 3. Rainfall (mm) in southern China, 2 a.m.–8 p.m. on 8 May 1992

3. Synoptic background

May is a transition season during which cool air intrusions reaching Hong Kong from the north become weak and infrequent. An east–west oriented trough, occasionally with frontal characteristics, is a common sight in southern China, with maritime air feeding into the trough from the south. Warm moist air, the origin of which might be traced back to the Indian Ocean, constitutes the prevailing south-westerly flow at the 850 hPa level. At higher levels, the background flow is basically westerly up to 200 hPa. In a general way, the synoptic background of the rainstorm on 8 May 1992 conforms to this pattern.

An east–west oriented trough formed over central China around 30° N on 6 May 1992. It moved southwards slowly in response to a passing mid-latitude trough in the upper-level westerlies. By 8 p.m. (12 UTC) on 7 May, the surface trough was located around 25° N, about 300 km north of Hong Kong. The upper-air conditions over Hong Kong at this time are shown in Fig. 4(a). Air in the lowest half-kilometre had wet-bulb potential temperature around 23 °C and could rise up to 250–300 hPa, provided a lifting mechanism could be found to get it above the lowest three kilometres or so. The nearly saturated layer between 400 hPa and 600 hPa and the well-mixed layer between about 600 hPa and 700 hPa are also worth noting. This profile more or less prescribed the environment for subsequent convective developments in the Hong Kong area. Fig. 4(b) shows the tephigram at 11 a.m. (03 UTC) the following day after the severe rainstorm earlier in the morning.

Reference to streamline charts (not shown) indicated that Hong Kong was then located slightly to the rear of a shallow eastward moving trough at 500/700 hPa, with appreciable amplitude confined to between approximately 20–30° N. That trough had earlier in the day brought some 60 mm of rain to Hong Kong. Cloud and rain associated with the trough were found, by 8 p.m. (12 UTC) on 7 May, off the coast of China, mostly between 120–125° E but also partly in the coastal waters north of 20° N (Fig. 5(a)).

By 2 a.m. on 8 May (18 UTC on 7 May), winds at 500/700 hPa over Hong Kong backed and became south-

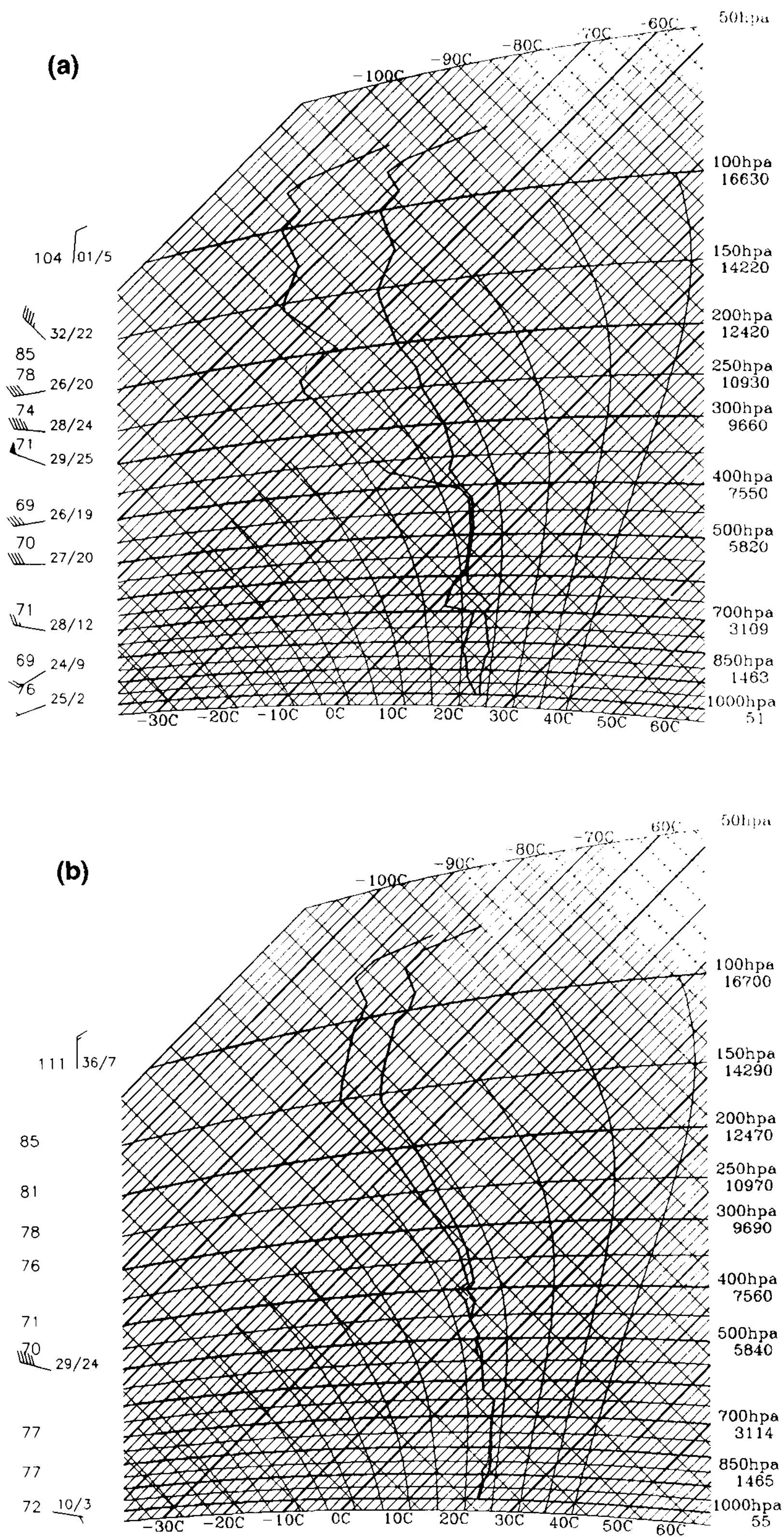

Figure 4. Upper-air conditions over Hong Kong (a) 8 p.m. (12 UTC) on 7 May 1992 and (b) 11 a.m. (03 UTC) on 8 May 1992. The equivalent potential temperature (°C) is shown to the left of the wind arrows.

westerlies (230° at 700 hPa and 250° at 500 hPa), indicating the approach of another trough at those levels. The 700 hPa streamline chart at 8 a.m. (00 UTC) on 8 May, when heavy rain was occurring in Hong Kong, confirmed the presence of a very shallow but nevertheless noticeable trough west of Hong Kong, with its axis just west of 110° E (Fig 6(b)). A similar shallow trough is found at the 500 hPa level with its axis 5° further west

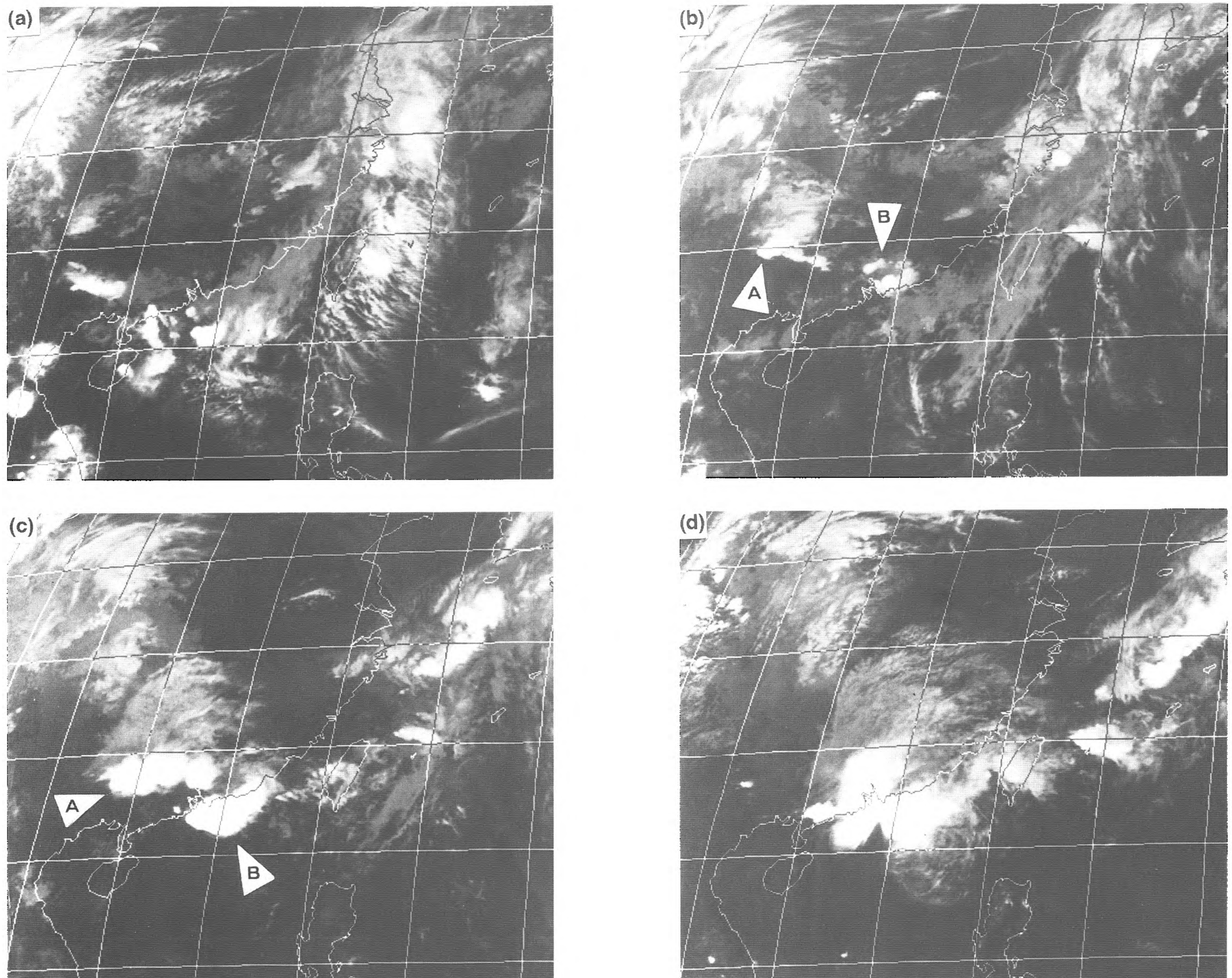

Figure 5. Infrared images from the Japanese Geostationary Meteorological Satellite for (a) 8 p.m. on 7 May, (b) 2 a.m. on 8 May, (c) 8 a.m. on 8 May, and (d) 2 p.m. on 8 May. White triangles 'A', 'B' identify cloud forms which might be associated with waves in the westerlies at the 500/700 hPa levels.

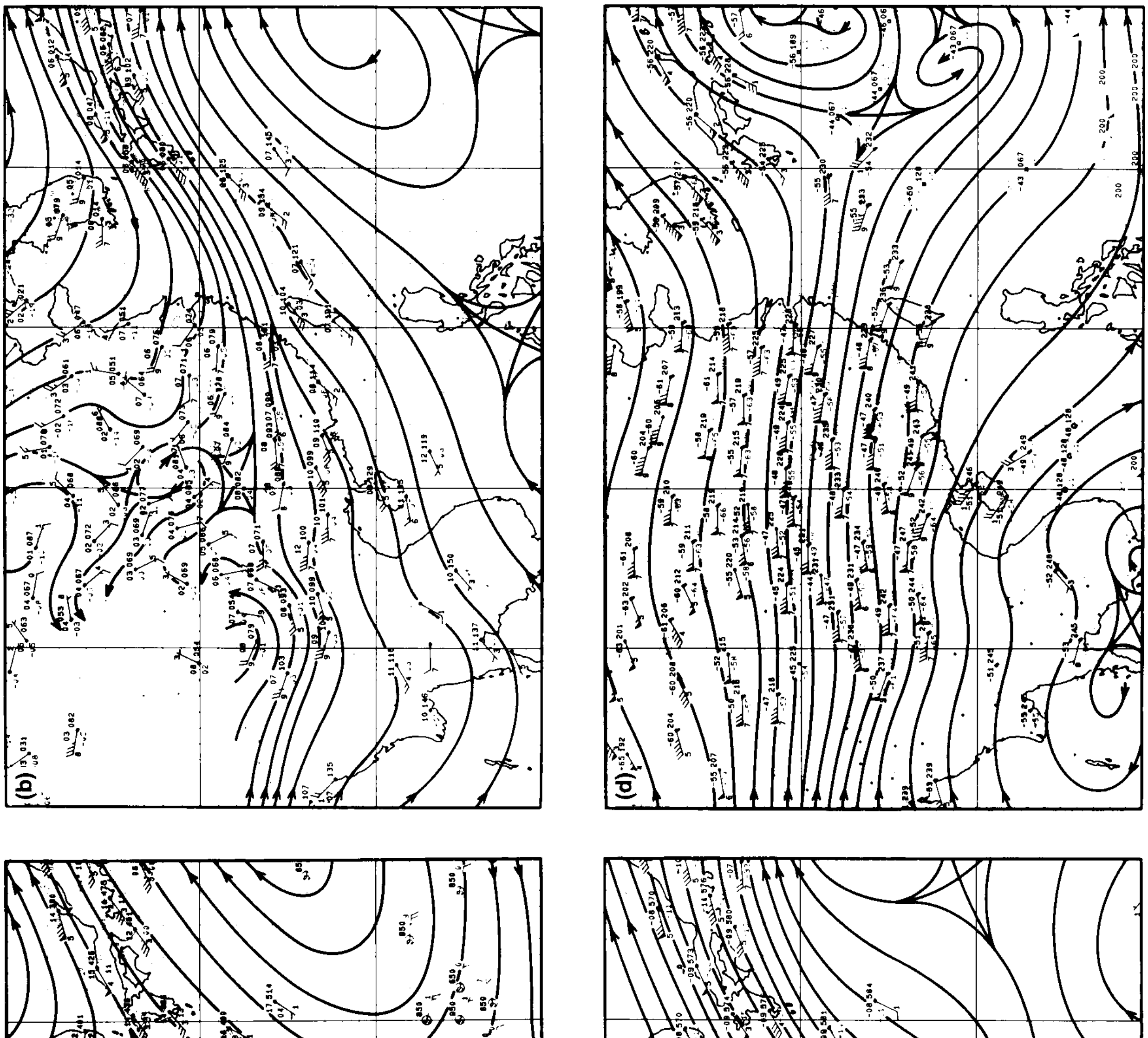

Figure 6. Upper-air streamline charts at 8 a.m. on 8 May 1992 for (a) 850 hPa, (b) 700 hPa, (c) 500 hPa, and (d) 200 hPa.

(Fig. 6(c)). By referring to satellite imageries, it would seem that this shallow trough had strong association with the intense convection near 25° N, 108° E at 2 a.m. (Fig. 5(b)) which later drifted east-south-eastward to 24° N, 112° E at 8 a.m. (Fig. 5(c)). This cloud cluster will be referred to as cluster 'A' later. It was not responsible for the record-breaking rain episode in the morning but was rather related to the second rain event in the afternoon (Fig. 5(d)). There was considerable directional divergence near Hong Kong at the 200 hPa level (Fig. 6(d)).

4. Mesoscale features

Another cloud cluster (labelled 'B' in Fig. 5) developed about 120 km to the north-north-west of Hong Kong shortly before midnight. By 2 a.m. (Fig. 5(b)), it had drifted east-south-eastward, coming to within 30 km of the northern limit of Hong Kong. If there were no new developments, the rain echoes as observed by radar would have missed Hong Kong. But a small echo was first picked up over the estuary to the west of Hong Kong around 3.30 a.m. In half an hour it grew into a significant feature with maximum estimated rainfall rates of around 20 mm h^{-1} (Fig. 7(a)). By 5 a.m. the echo took on the look of a north-east to south-west oriented band and there were higher rainfall rates (Fig. 7(b)). In a cell over the western coast of the territory, one picture element (2 km × 2 km) had an estimated rate in excess of 50 mm h^{-1}. By 6 a.m. the rain band had crossed a substantial part of the territory and was dumping rain over the urban area (Fig. 7(c)). Several picture elements had rainfall rates in the 50–100 mm h^{-1} bracket. Another cell was moving in

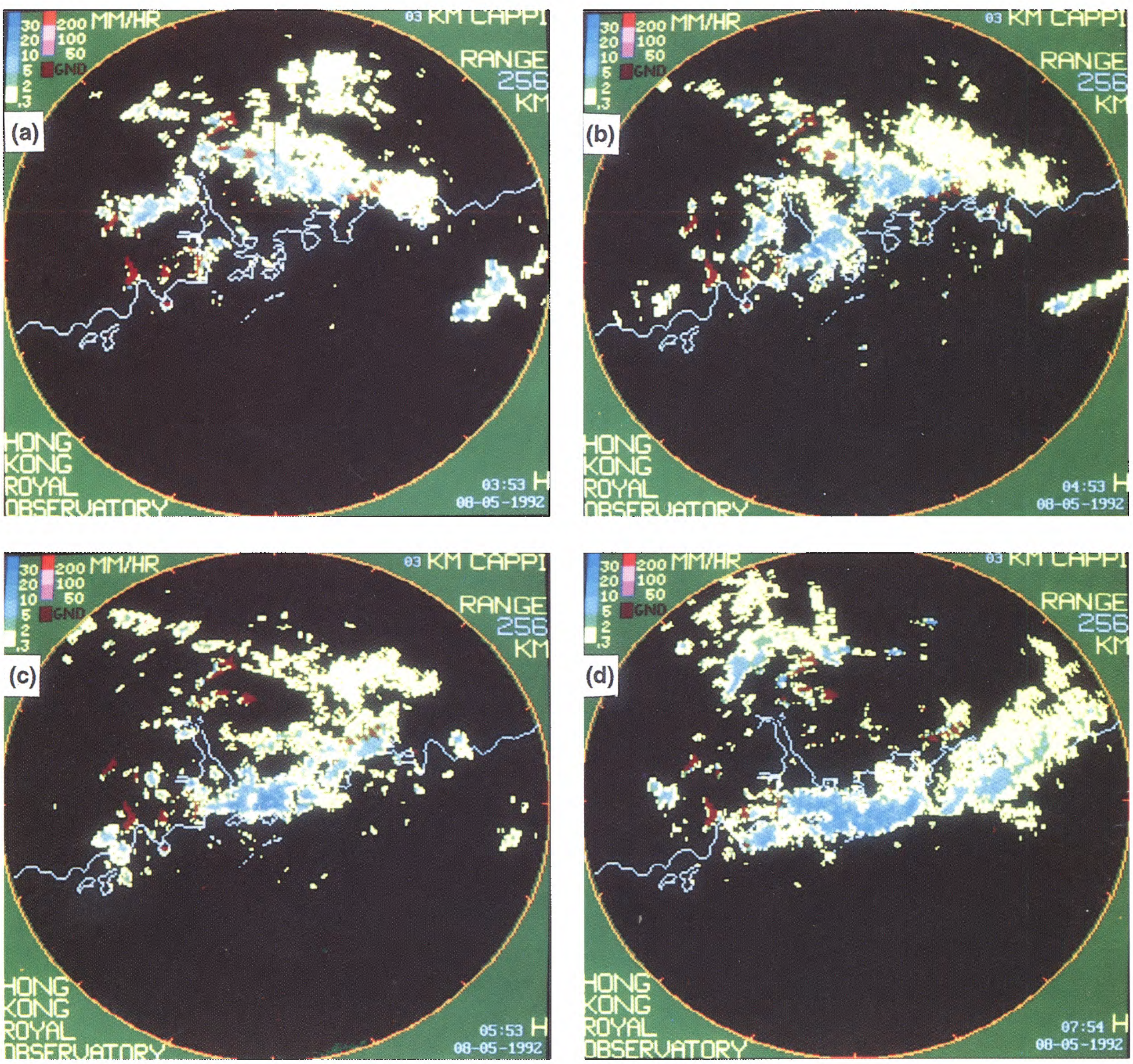

Figure 7. Three-kilometre CAPPI radar images for (a) 4 a.m., (b) 5 a.m., (c) 6 a.m., and (d) 8 a.m. on 8 May 1992. The colour-coded rainfall rate is estimated from the Z–R relationship: $Z = 200 R^{1.6}$. Brown colour represents a mask on ground returns.

from the west. The radar was inoperative at 7 a.m. By 8 a.m. the situation had evolved into one with a relatively broader east–west oriented rain band over the southern limit of Hong Kong (Fig. 7(d)). This was also the time when the rain began to subside in the urban area. The rain band eventually drifted southwards away from Hong Kong.

The existence of a number of automatic weather stations allowed us to follow the evolution of the surface flow pattern in Hong Kong during the passage of the rain band (Fig. 8). But note that it is quite hilly in Hong Kong so that some of the reports might suffer from local effects. For example, in Fig. 8(a) the anemometers at the two hill-top sites TMS and TC are respectively 969 m and 588 m in altitude. The prevailing flow before the rain band hit Hong Kong came from the south-east quadrant. A convergence line with cyclonic shear in places could be analysed over the north-western part of Hong Kong at 5 a.m. (Fig. 8(b)) when the rain band began affecting Hong Kong. No squalls, however, were reported by the stations on the passage of the shear line. C_1 marked the possible position of an incipient vortex which might be inferred from detailed examination of the time series of wind observations at the various stations. It apparently moved east-south-eastward and by 6 a.m. had moved to Hong Kong Island (Fig. 8(c)). Heavy rain commenced abruptly about five minutes later at the Royal Observatory (marked 'RO' in Fig. 8(a)). The maximum instantaneous rate of rainfall reached 312 mm h^{-1} around 6.10 a.m.

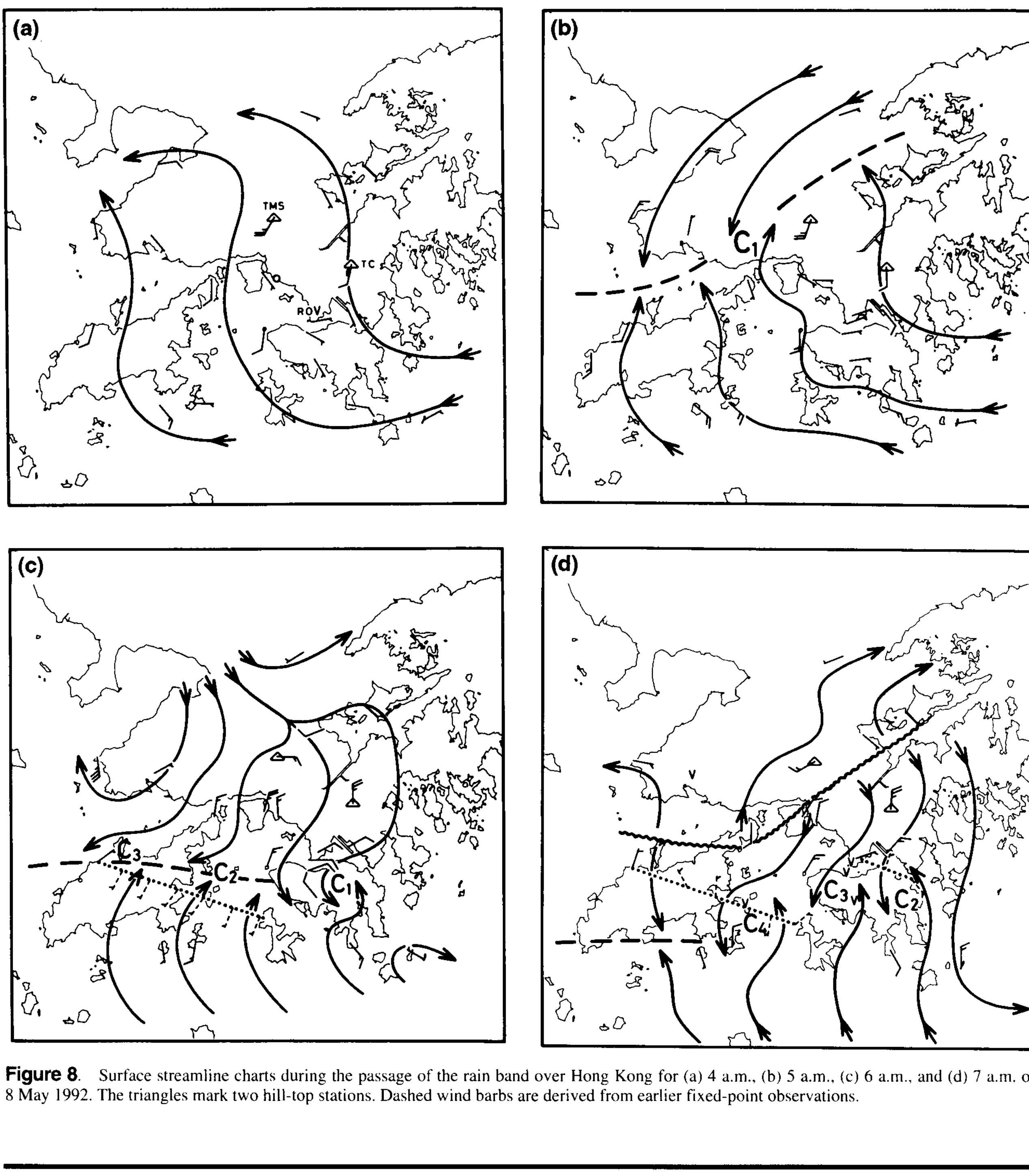

Figure 8. Surface streamline charts during the passage of the rain band over Hong Kong for (a) 4 a.m., (b) 5 a.m., (c) 6 a.m., and (d) 7 a.m. on 8 May 1992. The triangles mark two hill-top stations. Dashed wind barbs are derived from earlier fixed-point observations.

In Figs 8(c) and 8(d), some observations before the specified times have been included but displaced in the 'downstream' direction to account for propagation at a speed similar to that of the inferred vortex C_1. They are intended to help bring out certain fine details in the convergence zone between the northerlies and the south-easterlies. In both figures, inferred centres of cyclonic shear (not necessarily closed vortices) are marked. Detailed comparison of the figures with rate-of-rainfall records at the Royal Observatory (not shown) suggested that the passage of the centres C_1, C_2 and C_3 brought three separately identifiable downpours at about half-hour intervals between 6.00 a.m. and 7.30 a.m. These three downpours accounted for most of the rainfall in the morning rain spell.

The afternoon spell of rain was not so intense. Meteorologically, it was also less eventful — the surface flow over Hong Kong remained basically easterly to south-easterly throughout the period. The perturbation of the rain on the flow was much less apparent compared with the morning episode.

5. Forecasting aspects

The evolution of the synoptic situation leading to the heavy rain on 8 May 1992 was well anticipated by forecasters with the aid of prognostic charts derived from ECMWF and UK Meteorological Office data transmitted over the Global Telecommunication System. Satellite imageries also enabled forecasters to follow the development and movement of cloud and rain over southern China in response to the eastward-propagating waves in the mid troposphere. The afternoon rain spell on 8 May 1992 associated with cluster 'A' did not pose a problem to forecasters. The development of cluster 'B' was however a different matter, the only hint of a change in the synoptic situation to the forecaster being the backing of winds to south of west at 700 and 500 hPa over Hong Kong at 2 a.m. after cluster 'B' had already appeared on satellite and on radar. The explosive development from an inconspicuous radar echo over the estuary to a record-breaking rainstorm over the urban areas in Hong Kong around daybreak was virtually impossible to forecast. Indeed, even up to 5.35 a.m. the radar was forecasting only some 20–30 mm of rainfall in the next one to two hours, based on objective extrapolation. In the final stages, it was a nowcasting situation in which forecasters monitored the fast-changing situation with the help of data from automatic weather stations and rain-gauges in the territory and, in response, issued warnings of floods and landslips through the electronic media. Detailed examination of the usefulness of the various forecasting tools, such as numerical model outputs (including those of the Royal Observatory's own limited-area model) is under way and will be reported elsewhere in due course.

6. Conclusions

The rainstorm on 8 May 1992 was a very localized event, rainfall over 300 mm being confined to an area about 5 km × 15 km. It occurred in a conditionally unstable atmosphere with south-easterlies near the surface and south-westerlies at mid-tropospheric level. Rain which occurred in Hong Kong in the afternoons of 7 and 8 May could be attributed to eastward-propagating waves over southern China. However, the cluster which was responsible for the heaviest rain in the morning of 8 May had less obvious association with synoptic-scale features. The concentration of extreme rainfall in the urban areas of Hong Kong was the consequence of successive downpours coming in from the west, travelling along the convergence line between north-easterlies and south-easterlies. Had the convergence line travelled southward faster, it would have been a totally different picture. The near-stagnation of convergence lines over Hong Kong has been observed occasionally in similar situations in the month of May, such as the rainstorm of 2 May 1989 (104.8 mm in one hour at the Royal Observatory). It will be worthwhile to investigate further into this phenomenon.

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The weather during Admiral Duncan's North Sea campaign: January–October 1797

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Summary

Lawson and Rowley (1992) have shown how the tactics of modern military warfare can be partly determined by weather. If, with the formidable technology that present-day armies possess, weather can still be a factor, how much more of a consideration must it have been in more distant times? This paper looks at one, probably typical, example for its date.

1. Introduction

The battle of Camperdown was fought on 11 October 1797 between the English North Sea and the Dutch fleets, the latter then under the direction of the newly founded French Republic. The fleets were commanded by Admirals Adam Duncan and John de Winter respectively. Although comparable with Trafalgar, Camperdown has failed to exercise the same grip on the public mind. Like Trafalgar it must be viewed as the culmination of a protracted campaign during which the English fleet sought battle with a reluctant enemy (Fig. 1 shows the general area of activity). When it was finally engaged, the battle was conducted using tactics which, whether by design or accident, were strikingly similar to those used 8 years later by Nelson. That is to say, bearing down in two groups on a following wind towards an enemy fleet in traditional line ahead and not far from their own coast.

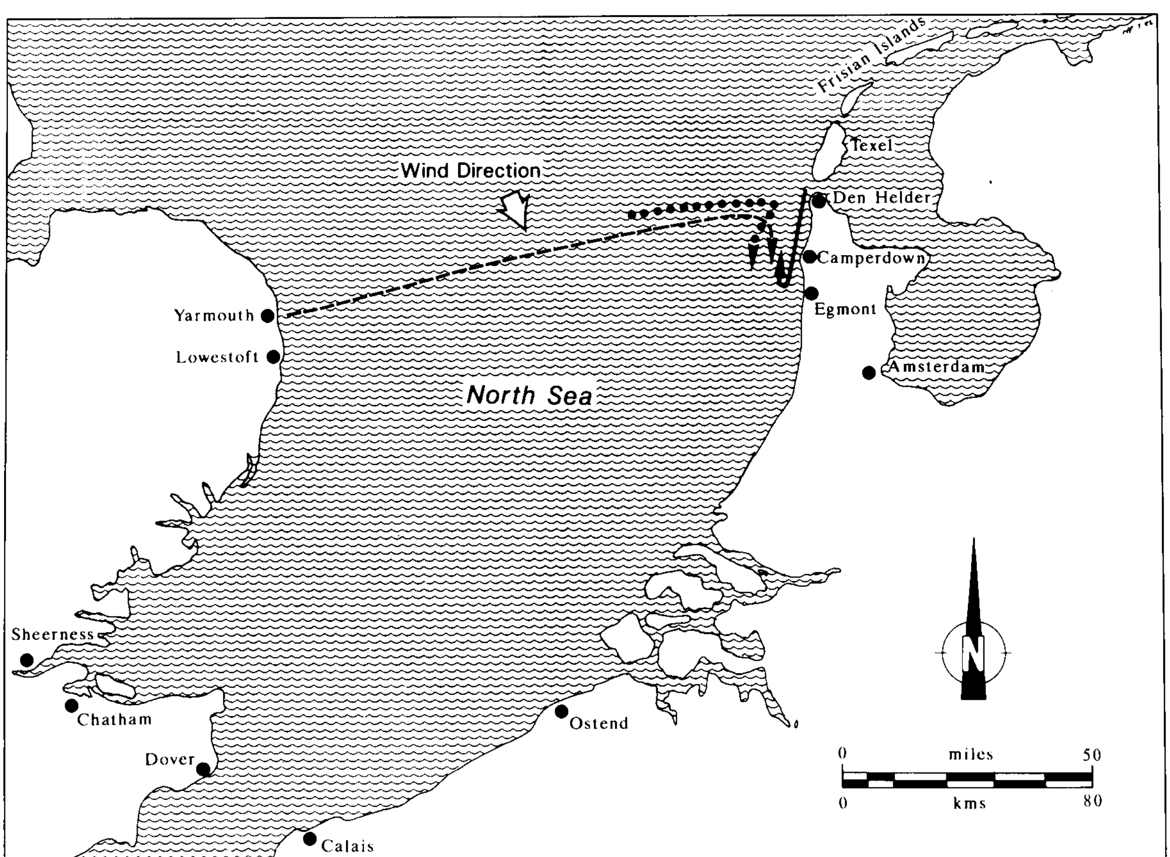


Figure 1. Map of the North Sea showing the principal locations and the routes of the fleets in the hours immediately preceding battle. The solid line denotes the Dutch fleet after having left the shelter of the Texel on 7 October 1797. The route taken by Duncan's fleet after leaving Yarmouth on the 8th is shown by the broken line. The same time-span covers the approximate route of the British observational squadron (dotted line). Battle was engaged on the 11th, offshore from the village of Camperdown.

The battleships of these times were designed to be the most powerful concentration of artillery then available. As two- or three-deck gun platforms they sacrificed the sailing qualities of speed and manoeuvrability for stability. These square-rigged leviathans could sail within only six points (about 66°) of the wind and, with a few notable exceptions, engage in battle only in light to moderate winds. Their every move and action was circumscribed by the weather.

2. The campaign

In 1795 the armies of the French Republic had subdued Holland converting it to the state of the client 'Batavian Republic', and with that action acquired a substantial, and skilfully manned, fleet. Austria and Russia had withdrawn from conflict with France and left Britain to stand alone against a powerful land-force, the potency of which was stemmed only by 21 miles of sea separating Britain from the European mainland. The fact that the distance was a mere 21 miles was immaterial, that it was sea, the successful navigation and control of which was so dependent on the weather, was crucial. As Fisher (1936) so aptly described the situation '....behind her tutelary waves and winds Britain stood impregnable. Nature was her friend.'

Adam Duncan had taken control of the North Sea fleet, based at Yarmouth, in 1795. His principal aim was to bring to battle and destroy the Dutch fleet which preferred to remain in the fastness of the Texel, protected by shallow seas and sand banks and posing a constant threat of support to an invading army launched towards the Thames Estuary and London. In the complex balance of forces the weather was critical. Westerly winds would prevent the Dutch from leaving port in any kind of order and minimized the need for anything other than an observational squadron. Easterly winds would allow the enemy to sail but would at the same time make it hard for the English fleet to break out from their base at Yarmouth Roads. In the open waters of the North Sea northerly and southerly winds offered equal advantage to ships that could make headway on port and starboard tacks. Gales, unless particularly severe, were not necessarily a danger in themselves, but they did hinder communications between vessels, hastened the general deterioration of wood, rope and canvas, and made battle all but impossible.

Of the detailed weather of those distant times there is a remarkable amount of evidence. Sources, which are described at the conclusion of the paper, are based largely on the captains' and masters' logs of Royal Navy vessels, the utility of which have been demonstrated by Oliver and Kington (1970) and Wheeler (1987, 1988). Landsmens' weather diaries were also a fruitful source of information.

3. Winter weather in 1797

By January of 1797 Duncan's fleet had established a blockade of the Texel. The general tendency to storminess, cold conditions and short hours of daylight that characterize the winter season normally combined to limit the opportunity for battle-line confrontations. As if to forewarn the French Directory of the inherent dangers of the season, the previous Christmas Eve had seen a French invasion force irretrievably scattered in Bantry Bay by a fierce storm (Lloyd 1963). Otherwise, the winter of 1796 into 1797 was unusually tranquil. The diary of William Bent, a London apothecary, indicates a mild New Year. His January entry reads:

> 'The month in general was mild; for though cold prevailed from 6th to the 16th, the thermometer was only twice so low as 29, and the medium was nearly 41.'

The February entry presents a similar picture:

> 'This month is remarkable for little rain and wind, and for the latter being scarcely ever to the northward of the east or west. Fogs and haziness prevailed very much; but whenever they cleared a while, the atmosphere appeared almost free from clouds. The barometer was high, in general.....'

A document in the care of the Institut Royal Météorologique de Belgique confirms similar weather on that side of the North Sea; '...the winter of 1796–1797 was very moderate. January was little cold, it froze for only seven days and passed without snow. Likewise February which was fine and dry.'

The impression is one of settled anticyclonic conditions with depressions being forced northwards leaving most of Britain dry, often cloud-free and spared the normal disruptions brought by winter gales. Such conditions aided Duncan's blockade of the Texel. Nevertheless, the protracted exposure to the North Sea waters took a heavy toll on the fabric of the fleet, which by March had returned to Yarmouth for repairs and revictualling. Duncan meanwhile sailed for the Nore, leaving his fleet under the command of Vice-admiral Richard Onslow.

4. Spring weather in 1797

The weather, previously so benign, was now to put Duncan at a disadvantage as a run of strong easterlies kept him in port. These easterlies continued until 16 March when a fall in wind speed and a backing to north-east allowed the fleet to put to sea. During that time the log of the *Venerable* (Duncan's flagship) records winds of force 5 and 6 rising to force 9 on the 10–12th. It is interesting to note that even headwinds of as little as force 5 were sufficient to prevent the English fleet from sailing. Duncan's sense of frustration is conveyed in his correspondence with the Admiralty. His letter of 4 March observes '.....from the wind continuing to blow strong at SE and the ebb tide done I have been under the necessity of anchoring the squadron'. On the same day his Vice-admiral, Richard Onslow, then on board HMS *Nassau*, wrote '...it now blows a gale of wind from the SE'. Duncan's letter of the following day includes '...the wind blew strong all last night and this morning from the eastward which prevented my getting under weigh...' Conditions continued bad on the 5th and deteriorated sufficiently to drive even the observational squadron away from the Dutch coast and back to port. Captain Hargood of HMS *Leopard*, a more manoeuvrable fourth-rater of 50 guns, reported '...drove off my station by a heavy Gale of Wind at SE and SSE...' by the 8th conditions had not improved and Duncan wrote '...I have used every effort in my power to get to Yarmouth, but all Saturday night and Sunday morning it blew very strong at ESE...'.

A brief spell of southerlies on the 8th and 9th allowed Duncan to excape from the Nore and rejoin his fleet but strong gales returned on the 10th to hinder further activity. On the 14th Duncan wrote again, '...from the wind continuing to the eastwards with a swell from the sea... I thought it right not to put to sea...'. But on the 18th Duncan could report that winds had moderated, veered to the west and his fleet were some 24 miles off the Dutch coast.

March's spell of dry, easterly weather was widespread. William Bent observed, '...this month has been very cold and dry for the season, which has greatly retarded the progress of vegetation... the dryness was such that the public roads, round the metropolis, were watered to lay the dust, as in summer...'. He notes winds almost continuously from the east until the 21st; thereafter becoming more south-westerly. In Edinburgh, Professor John Playfair observed '...in March the east wind began to prevail; a pretty smart frost was felt in the beginning of the month and some snow fell on the 6th and 7th; the weather was cold for the season until April.' The Belgian diary notes '...March was very cold and dry, but the weather became milder towards the end.' Although conditions in early March were favourable for an easy sailing from the Texel, the invasion forces were not prepared and the French, wishing to retain the naval forces to protect the invasion barges at a later stage, avoided any risk of engaging the English.

Information from further afield helps to recreate a picture of the wind circulations at the time. Far to the south-west, in what today is sea area Finisterre, Captain Beaufort, who a few years later was the codify his wind scale, also experienced poor weather. His log records 'heavy swell from the SW' on the 3rd, 'fresh gales' on 4 March and again on the 5th, all with winds, significantly, from between west and north-west. On the 6th more settled conditions allowed him to pursue and capture a French corsair, *L'active,* which he took back to England. Beaufort arrived off Falmouth on the 10th where he encountered easterlies.

Table I shows the relative abundance of easterlies during a month which was also one of relatively high pressure in Britain. Even as far afield as Trondheim (Birkeland 1949) the mean was 6 hPa above the average. In Britain temperatures remained cool, with sleet and snow showers, until the 23rd.

Table I. Percentage frequency of winds from the eight directions for the months March–October 1797. The data are averaged over observations from weather diaries and Royal Navy logs.

Month	N	NE	E	SE	S	SW	W	NW
March	3	31	28	10	9	11	6	2
April	14	19	23	3	12	9	15	5
May	3	14	11	5	16	30	15	7
June	19	10	10	5	7	20	18	11
July	1	2	3	3	16	29	39	7
August	0	1	2	6	30	27	24	10
September	6	8	8	3	23	16	30	6
October (to 11th)	13	29	11	0	13	11	11	12

The evidence suggests an anticyclone over northern Europe and Scandinavia extending its influence over Britain. The strength of easterly winds along its southern flanks and Beaufort's supplementary evidence of westerly weather to the far south indicates that depressions were tracking to the south of Britain, steepening the pressure gradients as they do so and bringing the occasional sleet flurries to the immediate north of their associated fronts. Fig. 2 is a reconstruction of one such situation which, though not uncommon, is more likely to occur in March than in any other month (Lamb 1950).

This particular spell of weather ended on the 23rd with a marked pressure drop noted at all English barometric stations of around 20 hPa and a simultaneous increase in temperature from an average of about 2 °C to over 6 °C; a clear indication of the arrival of milder, south-westerly weather.

Easterlies continued to be dominant, but were less persistent in April (Table I). Duncan enjoyed sufficient steerage way to remain at station off the Texel despite the frequent gales noted in the log of the *Venerable* as 'strong' (force 9) on five days between the 5th and the 11th, and fresh on two further occasions. The unsettled weather is also reflected in the low average air pressure for the month (Table II). Duncan's task was probably made easier by the easterly character of some of the gales; the short fetch off the Dutch coast at least minimizing the risk of heavy seas.

The easterlies of early April were associated with a deep depression and widespread rain and snow over England. On 10 April *Venerable*'s log recorded strong easterly gales.The mid-month period was marked by steady air pressure and variable weather with a good deal of cloud and rain over the North Sea. Winds rarely exceeded force 5 until 21 April when force 7 easterlies were noted in many ships' logs. It was, however, very cold and William Bent's April entry includes; '...the month has, in general, been rainy, and very cold for the season ...smallpox, which was becoming frequent at the beginning of the month, was checked by the cold winds...'. The frequency of easterlies suggests that a pattern established in March of high pressure to the north had not altogether disappeared.

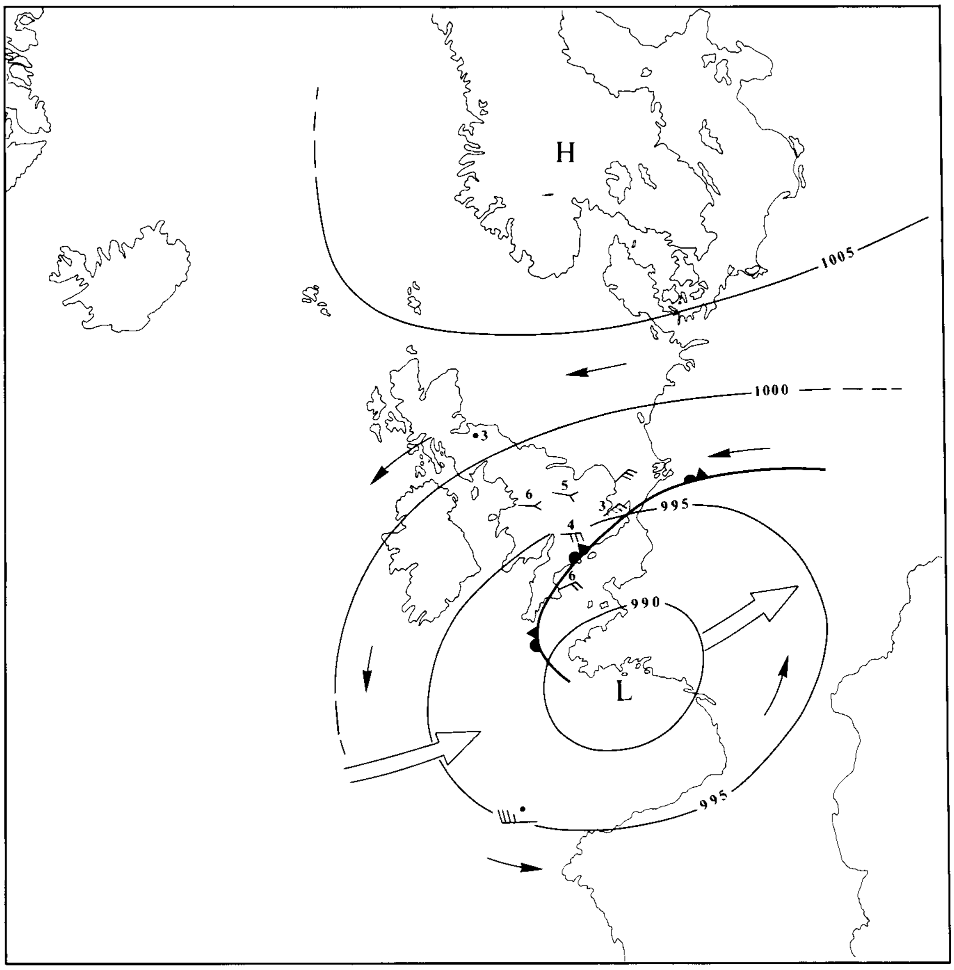


Figure 2. Generalized weather map for 4 March 1797 showing a situation which occurred commonly during the late winter and spring of that year. The symbols employed in this and the following figures are in most respects conventional. Wind arrows with 'feathers' are used where the force was known otherwise direction only is indicated by open-fork arrows. Temperatures, where known, are expressed in degrees Celsius. The isobars are interpreted from barometric readings and wind data and plotted in hectopascals. All such data were abstracted from ships' logs and other documents cited at the conclusion of the paper. To emphasize the wind circulations solid black arrows are used, while open arrows indicate the interpreted directions of movement of the principal weather systems. All such reconstructions must, of course, be regarded as approximate

Table II. Average monthly rainfall for 1797 estimated from various station records and average air pressure (from Royal Society records). For general comparison, the Central England Temperatures and their deviations from the 1784–1813 (30-year) means are also given.

	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
Rainfall (mm)	28.7	47.6	61.5	90.9	64.9	89.3	114.1	69.2
Air pressure (hPa)	1016	1010	1013	1013	1016	1013	1015	1013
Central England Temperatures (°C)	4.3 −0.4	7.4 −0.5	11.3 −0.2	13.6 −0.8	17.3 +1.5	15.8 −0.1	12.5 −0.7	8.2 −1.2

The inclemency of the gale of the 21st forced Duncan's fleet to seek refuge at Yarmouth. The winds, however, were not exceptional and the motive for the fleet's return lay in its general state rather than the weather. The North Sea Fleet, it should be noted, was infamous for containing some of the oldest and least reliable vessels in the English Navy at the time. It must also be acknowledged that revictualling of the fleet by small vessels working, heavily laden, against a constant headwind would carry its own risks and delays.

May was a month of trauma for the nation, and remembered above all for the Great Mutiny by the poorly paid, often pressed, crews of the Royal Navy. Duncan's fleet 'refused orders' on 12 May, only two ships of the line remaining loyal to him; his own *Venerable* and Captain William Hotham's *Adament.* Fortunately, nature was indeed to be England's friend at this perilous moment.

Long runs of 'westerly' weather (Table I) combined, it must be recognized, with a lack of preparedness on the part of the invading forces, gave little opportunity for the Franco-Dutch fleet to leave port in order and safety. May was a wetter month than those immediately preceding it (Table II). The rain was especially heavy in western districts of England, less so in eastern areas. The log books' frequent references to westerly gales and the barometric data from land stations suggest the weather to have been determined by the passage of a number of depressions not far to the north.

If the air pressure data are averaged for each day (Fig. 3), the more important pressure variations are clearly identified with major systems on the 5th, 12th, 20th and 29th. The log of the *Venerable* notes strong south-westerly gales at Yarmouth around the first of those dates, and strong north-easterlies on the second of them. The 1st to 6th was unsettled with rain recorded widely over land and sea. Hail fell in London on the 3rd and 6th and in Edinburgh and Stroud (Glos.) on the 5th. Baker's *Record of the Seasons* quotes hailstones in London on the 6th of up to half-inch diameter and in Lewes of one inch; indicative perhaps of cold-front activity.

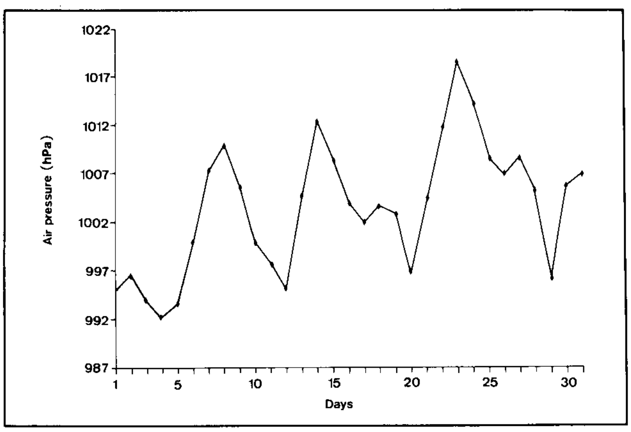


Figure 3. Trace of mean air pressure over Britain during May 1797. The daily figures are based on observations taken at various locations around Britain, all of which are listed in Fig. 5.

The latter system moved slowly eastwards and northerlies prevailed between the 7th and 11th. Snow was recorded in such disparate locations as Stroud on the 8th and Modbury and Derby on the 9th. Stormy weather continued until the 14th. Thereafter westerlies were again dominant, and while they failed to achieve gale force they would have been sufficient to deter any attempt at invasion using flat-bottomed, unstable, barges of the type then in service for the transport of infantry and cavalry.

5. Summer weather in 1797

Leaving the mutinous fleet at Yarmouth, Duncan had set out to the Dutch coast on 29 May, his flagship *Venerable* accompanied only by HMS *Adament*. He then engaged in an elaborate charade whereby his two ships, in turn, sailed within sight of the enemy, making signals to an imaginary fleet just over the horizon. The two changed stations frequently, flying various pennants and flags in order to pass as a succession of different ships. The ruse was a well-known one but appears to have served its purpose.

The weather during those weeks of frantic activity on board *Venerable* and *Adament* was, not for the last time, helpful. The barometer data indicates the passage of at least four depressions, but accompanied by little more than moderate winds. No gales were recorded until as late as 23 June when *Venerable*'s log notes them as strong. There was, however, a good deal of rain. William Bent's diary observes '...there has been only nine fair days, which for the most part were hazy and cloudy; the wind was trifling and in all points, continually varying...rain 4 inches 64 hundredths'.

Most of the month's depressions brought westerly winds, but that of the 18th was accompanied by strong easterlies, with heavy rain on the east coast. Edinburgh recorded 0.46 inches on the 19th and George Waterston's diary noted '...heavy rain and cold weather'. Thunder seems to have been widespread overland during the final week of the month. The *Gentleman's Magazine* reported a whirlwind at Chichester on the 22nd. Winds were light south-westerlies, the instability being assisted by heating over southern districts. The cooler surface of the North Sea, as it does today, minimized such activity and spared Duncan any consequent danger from this source.

July and August were dominated by westerlies (Table I). Air pressure was steady and fell away only at the close of August. Such 'lows' as were active appear to have passed well to the north, southern areas being more firmly in the grip of anticyclonic conditions. Gales were rare. They were recorded between 3 and 6 July in the logs of *Venerable* (still off the Texel) and *Director* (mutiny-bound at Yarmouth).

No log registers further gales until as late as 9 August and again on 30 August. Fig. 4 is a reconstruction using data from 20 July, but it is probably representative of much of these two months. An outbreak of peculiarly severe thunder in a southerly airstream on 16 and 17 July has already been described in the pages of this publication (Wheeler 1989).

It was during July that the invasion forces were finally prepared and embarked. However, the conclusion of the Mutiny in mid June had availed Duncan of his full complement of ships. The persistent, if light, westerlies left the Dutch fleet unable, possibly unwilling, to venture forth.

The Irish patriot Wolfe Tone was at that time seconded to the Dutch Republic as a 'political adviser'. His diary allows us to see matters from another point of view, with Tone, at one time elevated by the prospect of war, only then to be thrown into despair by the weather.

July 14th: '...the report today is that we shall get under way tomorrow... the men are in the highest spirits and singing national songs and cheering the general as they pass; it is a noble sight and I found it inexpressedly affecting.'

July 18th: '...the wind is as foul as possible this morning; it cannot be worse. Hell! Hell! Allah! Allah! I am in a most devouring rage.'

July 19th: '...it is impossible to conceive anything more irksome than waiting, as we now are, on the wind; what is still worse, the same wind that locks us up here is

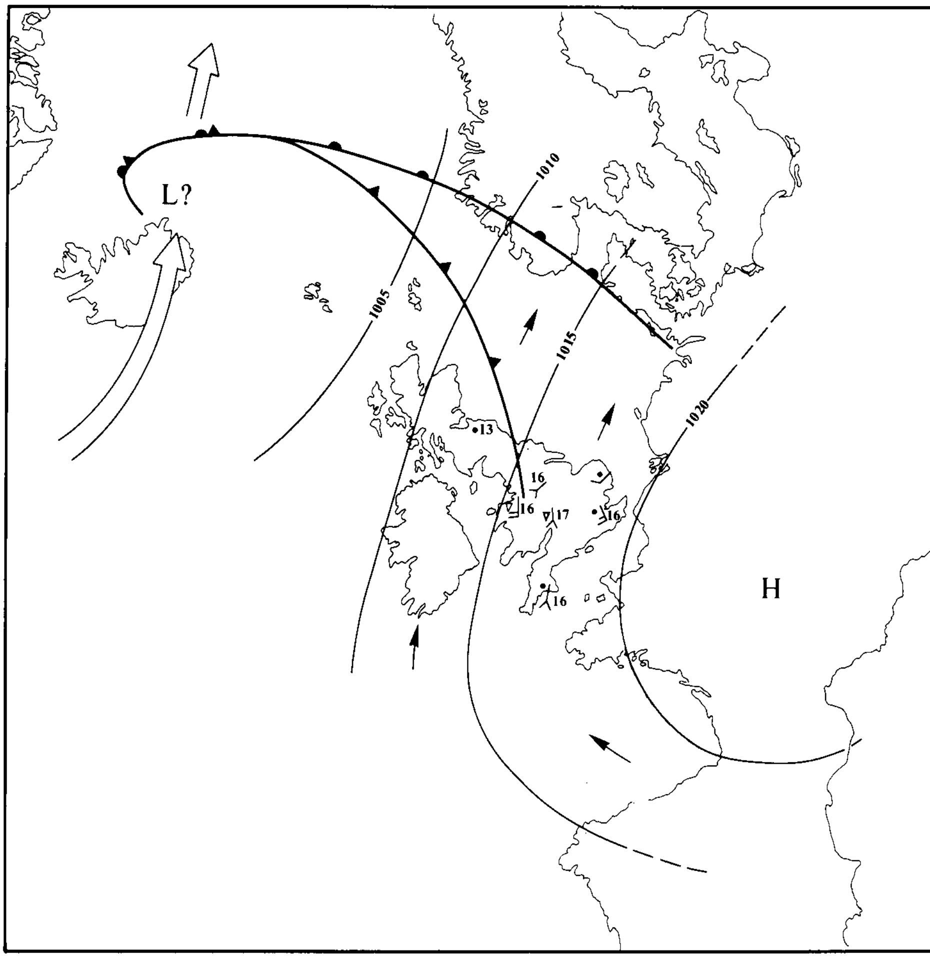


Figure 4. Generalized weather map for 20 July 1797. Unlike the situation in March (see Fig. 2 for explanation of symbols), the sequence of 'lows' and their attendant circulations are now following their more usual routes eastwards to the north of Britain. In this situation, a common one during the month, a generally mild but wet south-westerly airstream is sustained over Britain. The location of the fronts have been interpreted from the weather descriptions in diaries and logs.

exactly favourable for the arrival of reinforcements for Duncan...'

July 26th: '...I am today eighteen days on board and we have not had eighteen minutes of fair wind...'

His entry for 2 August deserves more lengthy quotation: 'Everything goes on here from bad to worse and I am tormented and unhappy more than I can express. On the 30th in the morning early the wind was fair, the signal given to prepare to get under way and everything ready, when, at the very instant we were about to weigh anchor and put to sea, the wind chopped about and left us.... there seems to be some fate in this business. Five weeks, I believe six weeks the English fleet lay paralysed by mutinies... and now that we are ready here, the wind is against us... the destiny of Europe might have been changed.'

By mid August the army had been disembarked and the invasion plan abandoned. The vigilance of Duncan and the timely intervention of the weather had confounded yet another attempt on England. But the Dutch fleet still required attention and the blockade could not be lifted.

The infrequency of gales was a welcome aid, but constant manoeuvring off a shallow lee shore took its toll on ships large and small. On 8 August Captain Henry Wray of the sloop *Seagull* observed '...we have not a rope or a sail to be depended upon. The hull is likewise much out of repair'. Even in fresh winds of force 5 or 6, keeping station for long periods was no easy task, as Duncan's letter of 7 August indicates: '...the wind has blown strong from the northward and westward for these five days past which has put the fleet to the northward and eastward. It is more moderate at present and I am endeavouring to regain my rendezvous.. '

The advance of the year was to bring its inevitable difficulties for Duncan as the weather showed signs of deterioration from what appears to have been a largely benign summer.

6. The weather of autumn 1797 and of the battle

Westerly winds continued to dominate, though less so than during the preceding summer (Table I). The approach of autumn was marked by an increase in the frequency of gales, all of which were from between south-west and north-west; they were registered by most of the fleet on 3, 6, 8–10, 12–14, 17 and 20 September. The gale of the 10th prompted the following dispatch from Duncan to the Admiralty: 'September 11 — *Venerable*, at sea. On Friday last a strong gale came on at WNW and for sixteen hours it blew a mere hurricane, during which period the *Agincourt* and *Warrior* made the signal of distress.'

And on 14 September '...Very constant and stormy since 11th from West to WSW. Yesterday *Naiad* made signal of inability...' The change in weather exposed again the fleet's vulnerability and one-by-one the ships sought the safety of Yarmouth. At the end of the month only an observational squadron, under Captain Henry Trollope in HMS *Russell*, a 74-gun two-decker, was on station off the Texel.

In October brisk westerlies gradually subsided veering within a few days of the month's start to equally moderate northerlies. Fig. 5 summarizes the situation during the first 15 days of October 1797. The air pressure traces give no indication of deep depressions and winds were generally light to moderate. Rain was recorded on a number of days but it was not prolonged. The south-westerly airflow over the period from 1st to 3rd, accompanied by a slow rise in pressure and followed by a wind veer to north-west suggests a 'low' to the north of Britain. A modest high pressure ridge with drier conditions then prevailed on the 5th but was, in turn, followed by a second 'low' on the 6th to 8th. The prevailing easterly winds point to an approach from the south-west (Fig. 5). This system may then have moved into the North Sea (possibly on the 7th) to give the variable, then north-westerly airflow that marked the following days.

The subsequent rise in pressure but persistence of north-westerlies was, most probably, due to high pressure advancing from the west against the slow-moving 'low' and consequently steepening the pressure gradient across the North Sea (Fig. 6). The prevailing north-westerlies brought unstable, typically showery, weather noted in all ships' logs. The Modbury observer noted unseasonal, by today's standards, snow showers in the highest parts of Dartmoor.

No gales were experienced before mid month and the respite gave the opportunity for the English fleet to revictual and repair. But the weather also allowed the Dutch to escape from the Texel, though why they should choose to do so, their strategic importance now nullified and no advantage to be gained by risking battle, is not clear. Such historical uncertainties notwithstanding, on 7 October Henry Trollope could write to his Admiral: '*Russell*, at sea. Sir, I have but moments of time to acquaint you I have learnt by the *Speculator* lugger the Dutch Fleet are now out and the *Circe* [the English frigate] who is hull down from us bearing NE is in sight of them — it is at present almost calm and very uncertain which way the wind may come, but whether they go north or south you may depend on seeing the *Russell* and *Adament* in sight of them...'

Duncan received this welcome news later that day and on the 9th set sail with such ships as were ready. Within 24 hours moderate westerlies had carried him to within a few miles of his target. The Dutch fleet, consisting of 15 ship-of-the-line and a screen of frigates, were on a south-westerly course having taken advantage of the light easterlies on the evening of the 7th. At daylight the winds veered to west-south-west allowing the Dutch to tack and stand to the southwards. For the next two days the sedate

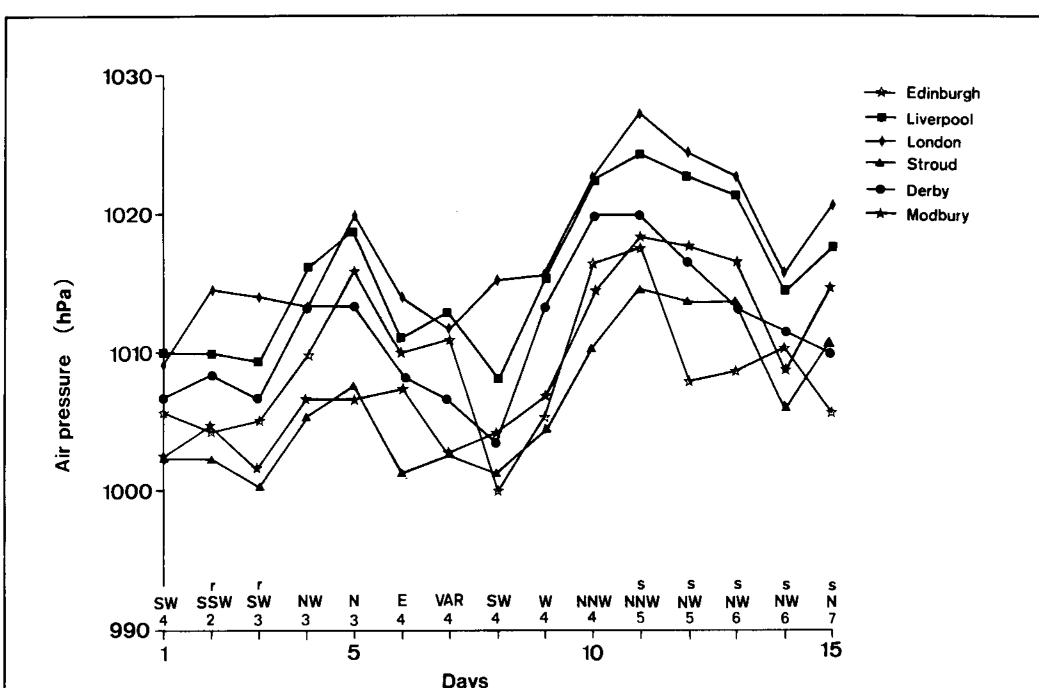


Figure 5. Composite graph showing the air pressure and associated wind and weather over Britain and the North Sea during early October 1797. Air pressure is plotted for six stations and shows the degree of agreement between them. Wind forces and direction are averages derived from the ships' logs. Where rain (r) or showers (s) are widely recorded the fact is indicated on the graph.

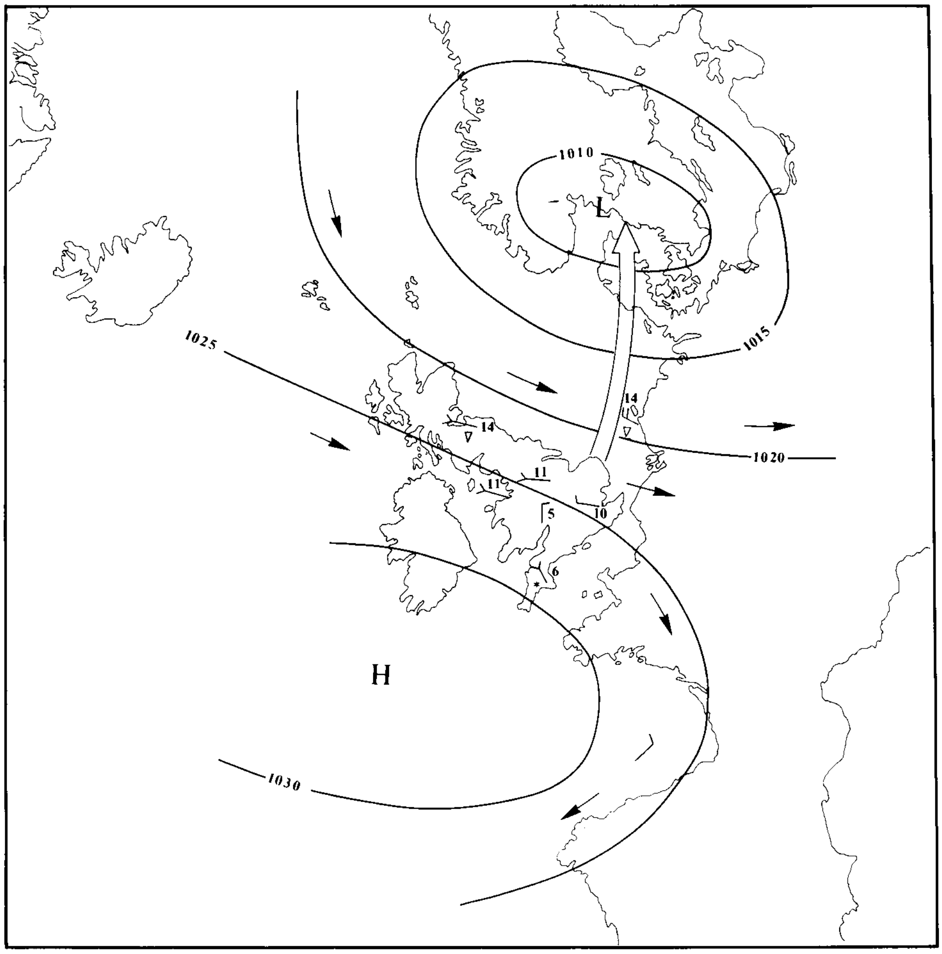


Figure 6 Reconstructed weather map for 11 October 1797 showing the disposition of pressure systems on the day of battle (see Fig. 2 for explanation of symbols). Low pressure to the north-east and high pressure to the west were responsible for the cool, showery north-westerly airstream that dominated the weather at that time. The 'low' then over Scandinavia had crossed Britain on the 8th (see Fig. 5) bringing cold showery weather in its wake.

progress of the Dutch was observed by Trollope's squadron. What appears to have been a sudden shift of wind to north-westerly on the morning of the 9th nearly drew the observational squadron on to the enemy. Lieutenant White on the cutter *Vestel* wrote in his diary: '...the *Adament* being so close from the change of wind that they might have cut her off had they made the attempt...'. During the day the wind slowly veered further to north-north-west. The north-westerly airstream now registered in all logs and land-based stations was to persist until the 12th.

Duncan sighted the Dutch coast at 11 a.m. on the 10th. The winds were moderate from the north-north-west rising to force 5 and the weather clear, but later cloudy. The English frigate *Circe* quickly found the enemy fleet 11 miles to the south-east and off shore of Dutch village of Camperdown.

Under the prevailing conditions the coast was a lee shore. The Dutch were familiar with these waters which, to their shallow-draughted vessels, represented a manageable hazard.

Matters were more critical for the deeper-draughted English ships. De Winter's tactic was to encourage the English into the shore where grounding was a serious risk. On the morning of the 11th he put his fleet about in line ahead on a port tack offering a tacit challenge to the English. Considerations of time imposed upon Duncan the need for swift action. He lay to windward of the Dutch and the following north-westerly allowed him to move quickly down upon the enemy. The principal requirement was to 'break the enemy line' to prevent them falling off with the wind and forcing Duncan to follow towards the shore. The risk was apparent to Duncan but, like Nelson at Trafalgar, he was resolved to engage and destroy the enemy. Duncan reminded his reluctant pilot to '...go on at your peril, for I am determined to fight the ships on land if I cannot by sea!' Indeed the whole battle was witnessed by a large crowd gathered on the shore.

Debate surrounds planning of the final approach which was in the manner of two loosely-knit groups, one under Duncan attacking the centre, the other, under Onslow, attacked the rear. If this tactic had been deliberate, then it represents a significant precursor to those used by Nelson at Trafalgar. But it is by no means certain that the move was not brought about by accident and under the hurried circumstances in which the engagement was approached. The battle was particularly bloody and its details are well-discussed in both Lloyd (1963) and Taylor (1937). The winds remained north-north-west at force 4 to 5 during the battle, giving enough manoeuvrability to Duncan whose close engagement prevented the enemy from escaping shorewards.

The outcome was a notable and, by the standards of the times, more than convincing victory to Duncan who captured 11 of the enemy vessels including the flagship with Admiral John de Winter on board. Hellier's representation of the battle (Fig. 7) with its choppy seas, brisk winds and cumulus clouds is probably very close to the conditions at the time.

The conclusion of battle did not signal the end of the Duncan's problems. The winds backed to north-west late on the 12th and detained his fleet, now encumbered by their valuable prizes, close to the Dutch coast. On the 15th Duncan wrote to his superiors: '...from the wind continuing to blow on the Dutch coast, the ships have had great difficulty in keeping off the shore and that we have unavoidably been separated. On Friday last [13th] the wind blew strong from WSW to WNW and continued to do so until Saturday morning, it then shifted to the north when I made the signal to wear, and fortunately anchored here [Yarmouth] last evening.'

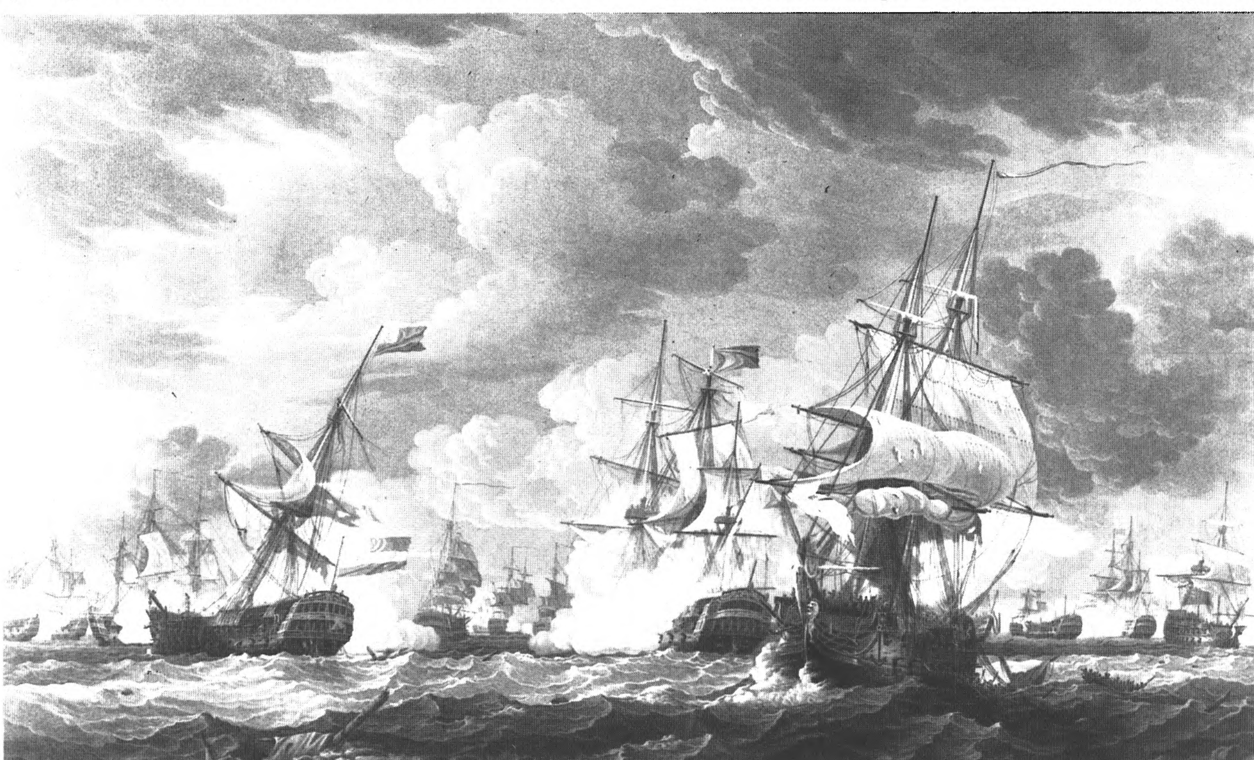
On the 14th and 15th, as the fleet struggled across the North Sea, the wind freshened to gale force and delayed yet further the safe arrival of several of its members. The master's log of HMS *Veteran* contains the following (abridged) entry for 14 October; '...strong gales and squally. At 1 p.m. came to the wind ...the ship not keeping to the wind, the prize lying like a log on our starboard quarter...Captain took counsel of all officers what was best to be done...it blowing so hard and the sea so high.'

In the event their prize, the *Delft*, had to abandoned and sank. As late as the 23rd Captain Williams of the frigate *Endymion* wrote from sea to express his hope of bringing the Dutch 74-gun *Jupiter* safely into port.

7. A supplementary note on data sources

The National Meteorological Archive of the Meteorological Office has care of the weather diaries of William Bent of London, Thomas Hughes of Stroud, Thomas Stanwick of Derby, the anonymous diary written at Modbury in Devon and the contemporary records of the Royal Society. The archives of the Royal Society of Edinburgh hold the diary of George Waterston of Edinburgh while the annual reports of city's weather prepared by Professor John Playfair of the University appear in the Society's *Transactions*. All the above mentioned items contain, or are based on, daily instrumental observations which include some or all of rainfall, air pressure and temperature. Wind direction is also commonly recorded together with brief descriptions of the weather.

Further valuable information is contained in the Captains' and Masters' logs of Royal Navy vessels. These logs, with the exception of that for Beaufort's *Pheaton* (which is kept at the National Meteorological Archive), are held at the Public Records Office, Kew. The log's, either Master's or Captain's, of the following ships were



By courtesy of the National Maritime Museum.

Figure 7. The Battle of Camperdown. This aquatint by T. Hellyer (after an original by T. Whitcombe) shows the Dutch flagship *Vrijheid* on the left and *Venerable* and the Dutch ship *Hercules* in the centre. The cumulus clouds, choppy seas and shortened sail of the vessels are all indicative of fresh, showery north-westerly winds.

examined: *Venerable*, *Director*, *Beaulieu*, *Lancaster*, *Russell*, *Veteran*, *Belliqueux* and *Powerful*. The Public Records Office also hold the Admiralty In-letters which were consulted for correspondence by Duncan and Onslow.

The Duncan Papers, in the care of the National Maritime Museum at Greenwich, were also a valuable source of incidental observations on the weather and its general influence on activities at the time. The Earl of Camperdown's (1898) biography of his grandfather also contains some illuminating correspondence. The contemporary publications *Gentleman's Magazine* and *Edinburgh Magazine* are valuable supplementary sources with monthly weather reports and tabulated daily statistics. A final useful item was Wolfe Tone's *Life and Writings*, Vol. 3 (Paris 1838).

Acknowledgements

The author acknowledges with thanks the help of Michael Wood and his staff at the National Meteorological Archive, and the staff of the Public Records Office and in the Reading Room of the National Maritime Museum.

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Thunderstorms and a gust front — 9 August 1992

The Figures relate to one of the severest thundery outbreaks to affect England during the summer of 1992. The northernmost region of activity (labelled storm area 1 on Fig. 1) originated over north Hampshire around 2100 UTC on the 8th; whilst the second area (labelled 2) developed over western France on the afternoon of the 8th. The most noteworthy features of these storms were probably the frequency of lightning, and localized sudden wind gusts. Although rainfall totals were larger they were not exceptional. One of the highest was 42 mm, recorded at Skegness in Lincolnshire in the 24 hours to 0900 on the 9th.

Synoptic background

During the night of the 8th/9th England and northern France were covered by a broad, slack area of low pressure containing very warm, moist, unstable air (850 hPa θ_w around 18 °C). The airflow above about 850 hPa was predominantly southerly, increasing with height to around 90 knots at tropopause level (about 200 hPa).

Ambient surface pressure over England fell from about 1012 hPa to 1006 hPa in the 12 hours to 0600 UTC on the 9th.

Mesoscale structure

Analysis of SFERIC data for storm area 2 suggests there was intensification of one particular cell over the English Channel very early on the 9th. From observations over southern England it appears that when north-

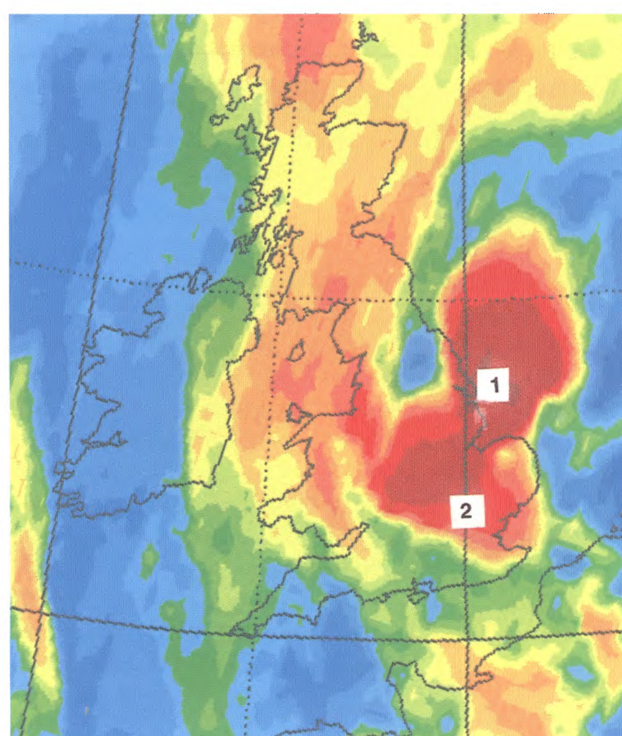


Figure 1. False-colour Meteosat infrared image for 0300 UTC on 9 August 1992. Coldest cloud tops are coloured brown (just east of the Humber). The boundary between brown and dark red corresponds to an estimated cloud-top temperature of −60 °C; each colour band covers a 6 °C temperature range. Two storm areas are labelled as indicated in the text.

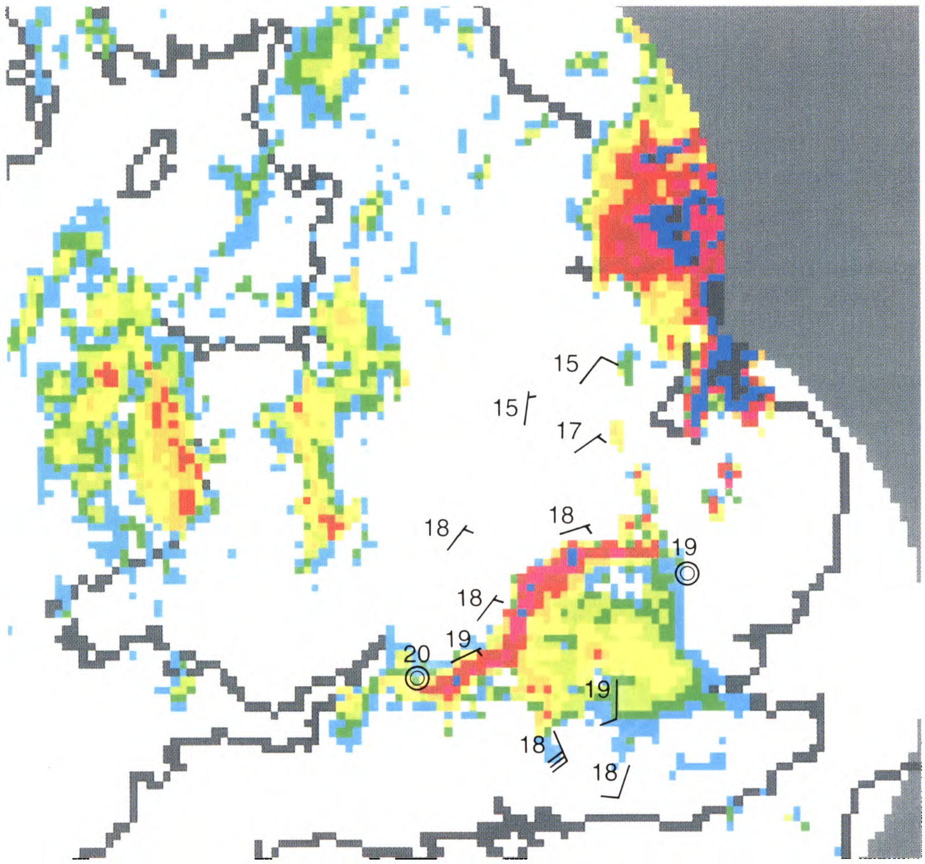


Figure 2. Raw radar data for 0230 UTC on 9 August 1992, with selected surface observations (wind and temperature) for 0200 UTC. Estimated rainfall rates, in mm h^{-1}, are as follows: cyan 0.1–0.5, dark green 0.5–1.0, light green 1–2, yellow 2–4, orange 4-8, red 8–16, dark red 16–32, pink 32–64, blue 64–128, black >128.

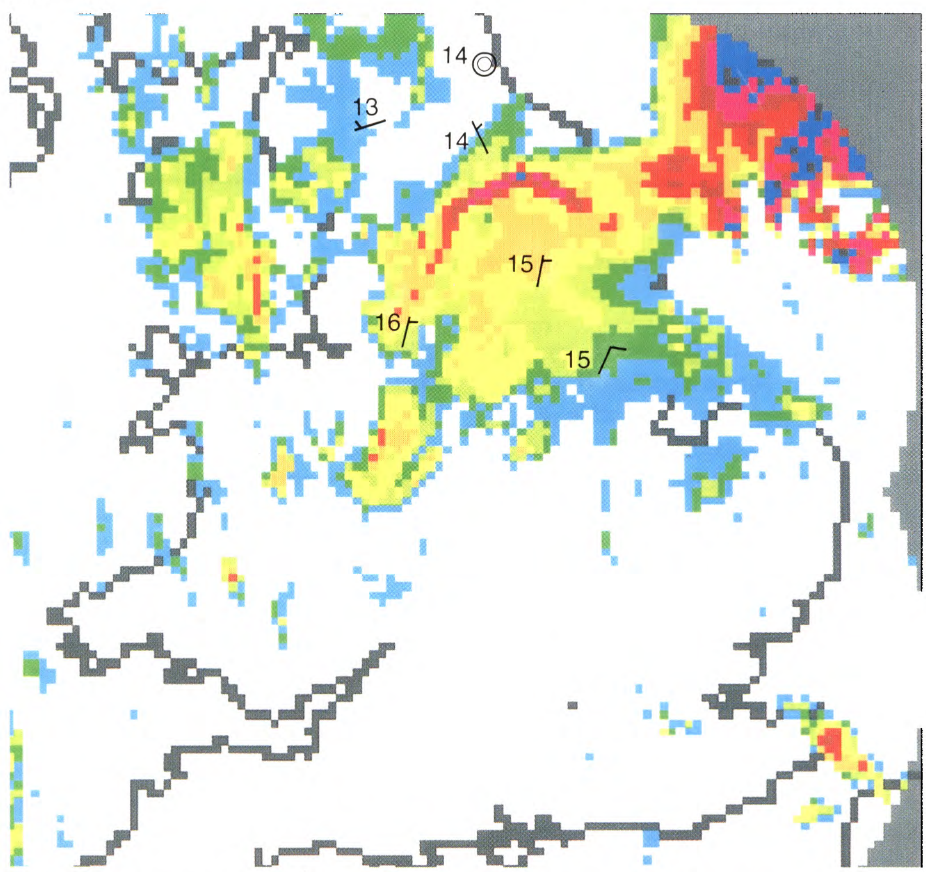


Figure 3. As Fig. 2 but for 0500 UTC on 9 August 1992; radar data and surface observations are both for this time.

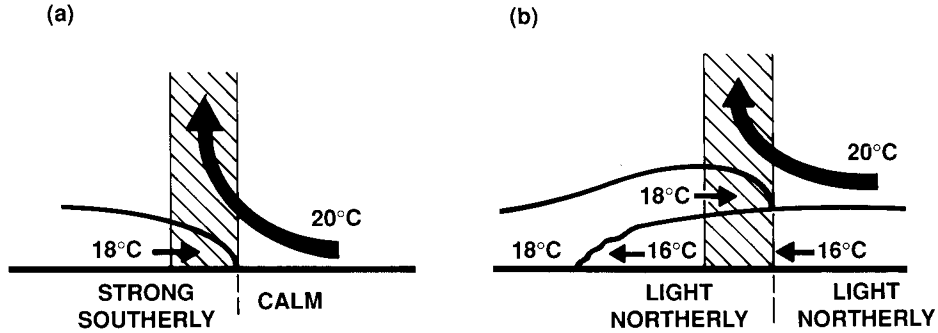


Figure 4. Schematic cross-sections of the boundary layer close to the gust front over (a) southern England at about 0200 UTC, and (b) northern England at about 0500 UTC on 9 August 1992. The cross-sections are aligned longitudinally, with north to the right. Thick solid lines show air-mass boundaries, arrows airflow, figures potential temperature, and text approximate surface winds. The gust front (dashed line) triggered rapid ascent (thick arrows), giving rise to the band of heavy precipitation (shaded). Evaporative cooling from this precipitation sustained the gust front.

ward-bound outflow from this cell (having a surface temperature 18–19 °C) came up against stagnant, warmer air (20–21 °C) over Hampshire, Dorset, Surrey and Sussex a narrow band of intense precipitation was generated. This appeared first on radar imagery at 0130 UTC. The band then moved north, as a readily identifiable feature, at a constant 55–60 knots, eventually developing into a large, intense storm over north Yorkshire around 0600 UTC. Figs 2 and 3 clearly show the arc of intense precipitation. Remnants of the cell which intensified over the English Channel are also evident on Fig. 2, as the area of yellow echoes over north London.

Many places in southern England experienced a sudden increase in wind speed as the precipitation band passed overhead, suggesting that it could be termed a 'gust front'. For example at Odiham (Hampshire) winds were reported calm at 0100 UTC, and south-easterly 29 knots, gusting 48 knots at 0200 UTC. By 0300 UTC, however, this front was moving into a region of light north to north-easterly winds (perhaps outflow from storm area 1) where surface temperatures were around 16 °C (note the surface observations on Fig. 2). In this region the surface winds appear not to have changed as the front passed overhead. This is probably because air behind the front had ridden over the now cooler surface air, instead of forcing it to rise, as illustrated on Fig. 4. Browning and Hill noted a similar effect associated with a thunderstorm system over south-west England. (Browning, K.A. and Hill, F.F.: Structure and evolution of a mesoscale convective system near the British Isles. *Q J R Meteorol Soc.*, **110**, 1984, 897–913.)

T.D. Hewson

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Advances in bioclimatology — 1, by R.L. Desjardins, R.M. Gifford, T. Nilson and E.A.N. Greenwood (Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1992. DM 118.00) emphasizes the mechanisms linking biological processes with their physical environments. It is the first book in a series aiming to provide a common forum for the many separate strands to be found in the vast bioclimatological field. ISBN 3 540 53843 7, 0 387 53843 7.

Advances in bioclimatology — 2: The bioclimatology of frost, by J.D. Kalma, G.P. Laughlin, J.M. Caprio and P.J.C. Hamer (Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1992. DM 118.00) aims to provide a comprehensive worldwide review of recent advances in frost research. It is the second in an ongoing series on bioclimatology. ISBN 3 540 53855 0, 0 387 53855 0.

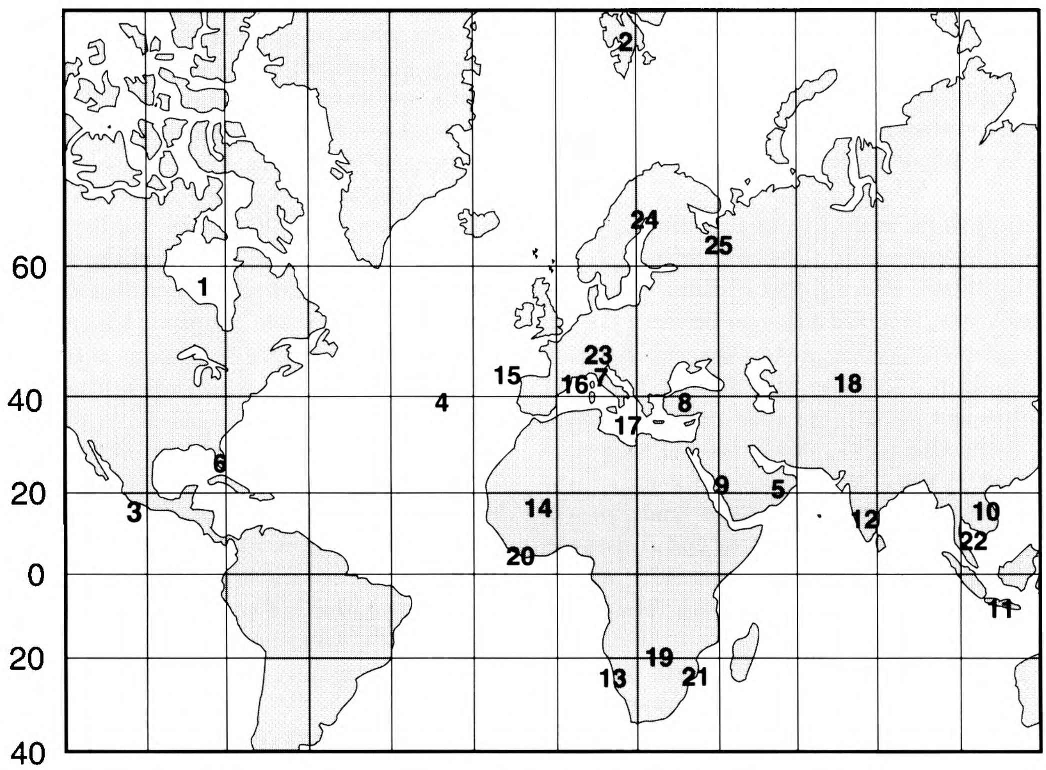
Exploration of the solar system by infrared remote sensing, by R.A. Hanel, B.J. Conrath, D.E. Jennings and R.E. Samuelson (Cambridge University Press, 1992. £75.00, $125.00) describes all aspects of the theory, instrumentation and observation concerned with the subject. The presentation should appeal to advanced students and planetary-science researchers. ISBN 0 521 32699 0.

Diffraction effects in semiclassical light scattering, by H.M. Nussenzveig (Cambridge University Press, 1992. £35.00, $59.95), based on the Elliott Montroll Lectures, considers critical effects in the subject, and presents new physical insights. The book should interest graduate students and researchers in many areas of physics. ISBN 0 521 38318 8.

World weather news — October 1992

This is the first of what I hope will be a monthly round-up of some of the more outstanding weather events each month, three preceding the cover month. If any of you, our readers, has first-hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and in the 'Casualty Reports' pages of Lloyd's List. *Naturally they are heavily biased towards areas with a good cover of reliable surface observations. It is not yet clear whether these are best compiled chronologically, by WMO Region or by phenomenon. The first method has been chosen for this month.*



Locations of places mentioned in text

1	Hudson Bay	10	Vietnam	18	Alma Ata
2	Spitzbergen	11	Jawa	19	Zimbabwe
3	Mexico	12	India	20	Ivory Coast
4	Azores	13	Walvis Bay	21	Mozambique
5	Masirah and Muscat	14	Mali	22	Gulf of Thailand
6	Florida	15	Asturias	23	Munich
7	Northern Italy	16	Gulf of Genoa	24	Gulf of Bothnia
8	Turkey	17	Crete	25	Arkhanglsk
9	Jeddah				

At the start of the month two sea-surface-temperature anomalies caught the attention. In the North Atlantic very low temperatures off north-east Canada (Hudson Bay's ice did not clear during the summer) were balanced by a warm surge near Spitzbergen. Off the Pacific coast of Mexico sea temperatures were around 29 °C providing the energy for many tropical storms.

On the 1st Tropical Storm 'Bonnie' passed through the Azores; although there was little rain, the wind reached 60 kn at times causing considerable disruption. Next day Hurricane 'Virgil' began rapid development to the west of Mexico. Meanwhile an Arabian Sea Cyclone, romantically named '06A', passed close to Masirah Island and gave Sur, in Muscat, 33 mm (previous maximum in a day, 1.6 mm in a 10-year record).

On the 3rd a trough crossed Florida and the resulting severe thunderstorms and tornadoes dropped 202 mm on Jacksonville, killed four people and did $100m worth of damage. Next day 'Virgil' crossed the Mexican coast 90 miles east-south-east of Manzanillo with winds of up to 90 kn: rainfall at Acapulco reached 125 mm (there was a *forecast* of up to 425 mm in the mountains). Despite the flooding there were no reported fatalities.

Low pressure over the western Mediterranean brought massive amounts of rain to northern Italy and a heatwave to Turkey. By the 7th twelve were reported dead in the north of Italy from the flooding chaos after three days of heavy rain with more than 100 mm in many places (156 mm in Naples on the 4th) and the Po broke its banks. The southerly winds brought föhn conditions to Turkey; 33.2 °C on the 6th set an all-time record at Bandirma on the Straits of Marmara. But the next day the 25 kn winds helped the temperature up to 37.0 °C! It was hotter in Saudi Arabia where Jeddah's October record was beaten by a whole degree when the temperature reached 43.0 °C.

It always seems worse in the Far East! In the period 5th to 7th, Da Nang in Vietnam accumulated 295 mm. If this looks like a lot of rain then the port of Dong Hoi about 100 miles north-west received 680 mm between the 5th and 9th. Not surprisingly the worst floods in 40 years resulted and at least 37 deaths with half the homes in Quang Binh Province flooded and 1000 vehicles stranded on National Route One as the floods washed away sections of the road. A few days later Jawa (formerly Java) had torrential downpours causing huge landslides in Barat Province burying 50 unfortunates and destroying vast areas of rice fields. On the 9th Cyclone '07B' moved across India killing more than 70 in flash floods and landslides in Kerala and Tamil Nadu.

Acapulco had 20 mm overnight on the 7th followed rapidly by a further 187 mm! Two days later, on the 10th, Hurricane 'Winifred' made landfall in Mexico near Manzanillo where 75 kn winds gusted to 110 kn and created 13 ft waves in the harbour (temporarily closed). The storm decayed amongst the mountains of Jalisco state without any immediate reports of casualties. Rain made an impact at Walvis Bay on the coastal fringe of the Namib Desert whose 4 mm was about 20% of the annual total. Elsewhere in Africa it was hot; Gao in Mali had a day maximum temperature of 42 °C followed by a cloudy night minimum of 31 °C.

The western Mediterranean low continued to cause disruption when on the 11th Madrid reported 70 mm, Valencia 44 mm and in Asturias Province in the north of Spain a high tide combined with the rainfall to cause flooding. Late the next day a thunderstorm moved south down the Rhône Valley into the Gulf of Genoa and dumped 70 mm on Le Luc in three hours. On the eastern flank, a scirocco raised the temperature at Souda, on the north coast of Crete, to 33.5 °C, 0.7° above the record.

During the 15th Alma Ata, in Kazakhstan, the temperature reached 25 °C under sunny skies: next day the maximum was only 3 °C with wet snow!

Over the period from 17th to 21st it continued very wet in and around the Alps with 25 mm of rain at low levels and good deal of snow over the mountains, while to the south, Italy had more flooding in its northern Regions with extensive damage in Tuscany with all the bridges in central Pisa closed for a while and at least three incautious motorists were drowned. Over in Mexico at Atizapan de Zaragoza storms damaged 200 homes, drowned two more motorists and killed one with lightning. (Climate tables suggest that the rainy season here is from June to September; this year it started in April and was clearly not over by this day.) About this time reports coming out of the worst drought-ridden areas of Zimbabwe spoke of heavy rains doing 'colossal' damage. In west Africa, Abidjan in the Ivory Coast collected 151 mm in the 24 hours up to 0600 UTC on the 23rd (about the average monthly total). To point the other extreme of African weather, it was reported that at Beira, Mozambique, the rivers have run dry so there is no drinking water for ships bringing supplies — there is also so little fuel for bunkering that some ships are having difficulty in reaching the next port.

Typhoon 'Angela' brought yet more torrential rain to Vietnam, 247 mm in 24 hours to Qui Nhon being the largest readily available total: earlier the 200 000-ton ore-carrier *Daeyang Honey* vanished with its crew of 28 near the eye of the storm. Although the storm decayed over land it was correctly forecast to rejuvenate in the Gulf of Thailand. The close proximity of 'Coleen' complicated matters for the forecasters but they got the heavy rain warnings right — 297 mm at the Thai island resort of Ko Samui in three days of downpours before she dissipated on the 29th. The Germans managed some storms of their own when on the 26th there were reports of violent storms around Munich uprooting trees, damaging buildings and blocking some higher-level roads with snow. Meanwhile the remains of 'Frances' provided the wet air to bring a lot of heavy rain to the north-west of Spain on the 27th with totals of 60–100 mm in many coastal gauges.

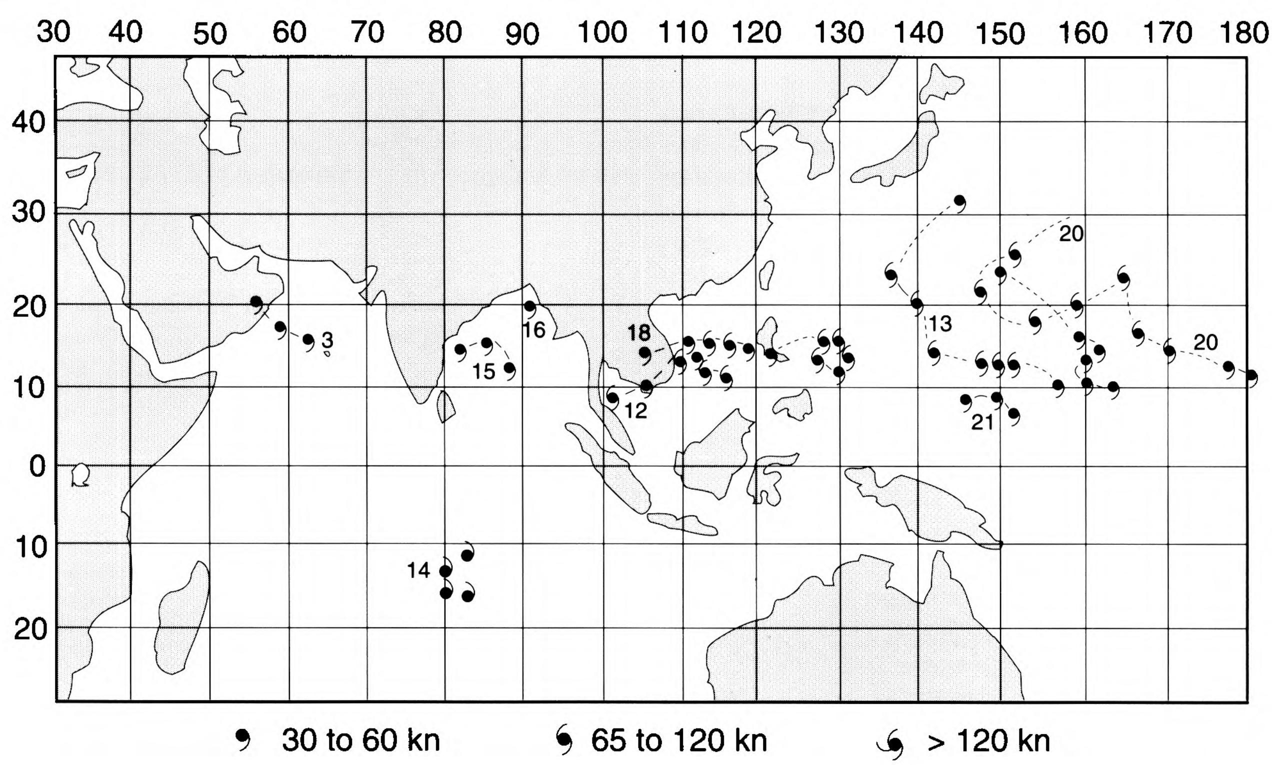
To end on a seasonal note: recent cold weather over Scandinavia has resulted in the formation of sea-ice 4 weeks earlier than usual at the northern end of the Gulf of Bothnia. Further north on the Kola peninsula near Murmansk snow had accumulated to a depth of 79 cm by the 26th. The cold weather had reduced the flow in the river Dvina at Arkhanglsk to the extent that navigation was becoming difficult.

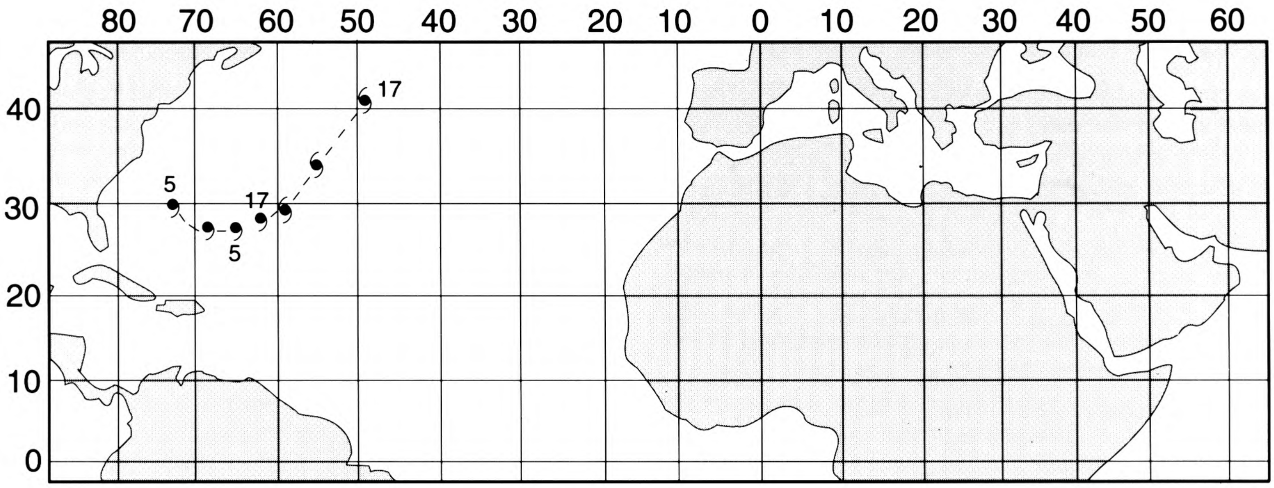
October tropical storms

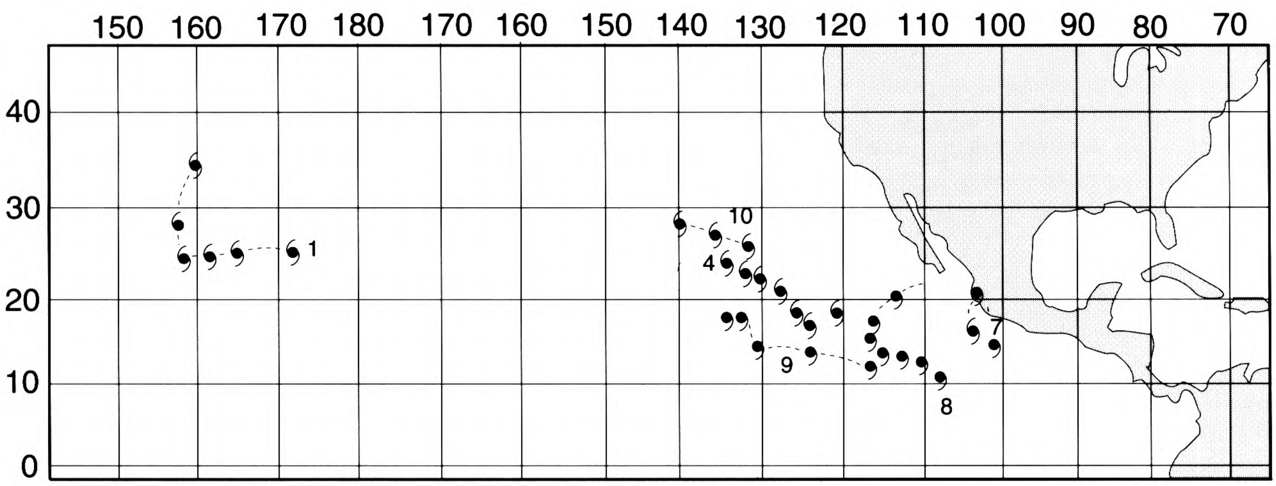
List of tropical storms, cyclones, typhoons and hurricanes active during October 1992. The number is the key on the charts shown, the dates are those of the first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during its lifetime. 'Tina', the strongest eastern Pacific storm in 1992, was also the longest lived on record.

No.	Name	Basin	Start	End	Max.
1	Ward	NWP	26 Sept.	6 Oct.	100
2	Aviona	SWI	27 Sept.	1 Oct.	65
3	06A	NI	1 Oct.	3 Oct.	55
4	Tina	NEP	24 Sept.	10 Oct.	130
5	Earl	NA	26 Sept.	3 Oct.	50
6	Virgil	NEP	1 Oct.	5 Oct.	115
7	Winifred	NEP	7 Oct.	10 Oct.	95
8	Xavier	NEP	13 Oct.	15 Oct.	45
9	Yolanda	NEP	16 Oct.	22 Oct.	50
10	Yvette	NWP	8 Oct.	17 Oct.	155
11	Zack	NWP	7 Oct.	15 Oct.	35
12	Angela	NWP	16 Oct.	29 Oct.	90
13	Brian	NWP	17 Oct.	25 Oct.	100
14	Babie	SWI	18 Oct.	21 Oct.	50
15	07B	NI	7 Oct.	9 Oct.	65
16	08B	NI	21 Oct.	21 Oct.	30
17	Francis	NA	23 Oct.	27 Oct.	75
18	Colleen	NWP	18 Oct.	28 Oct.	80
19	Zeke	NEP	25 Oct.	30 Oct.	45
20	Dan	NWP	24 Oct.	3 Nov.	115
21	Elsie	NWP	29 Oct.	7 Nov.	150

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific; I — Indian Ocean; WI — west Indian Ocean.







A new Moon?

A report in *Space News* for January 4–10 1993 tells of a Russian plan to unfurl a 20 m diameter sail at their Mir space station in early February 1993. The sail will reflect sunlight onto an area about 4 km in diameter with light equivalent to the brightness of five full moons. However, the beam will be moving so fast that any point in its path will only be illuminated for one second. The visual effect will be a single brilliant flash, visible by day as well as at night.

I believe there are distant plans for a series of large reflectors to provide illumination for high-latitude parts of the CIS during their long winter nights. The current test is of material and principle and might give rise to reports of UFOs or other unlikely phenomena.

R.M.B.

GUIDE TO AUTHORS

Content

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Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (IBM-compatible or Apple Macintosh) can be labour-saving, but only a print-out should be submitted in the first instance.

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The
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I think it was Einstein who was a asked what he would say to God when he got to heaven. The great man said he would ask the almighty to explain turbulence, but he did not really expect to understand the answer! This paper does not fully explain turbulence, but you should be able to understand it (the paper that is). So, whatever you may think of the topic you should give the following a try.

Editor

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Turbulence simulation in the Meteorological Office

S.H. Derbyshire
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R. Kershaw
Meteorological Office, Bracknell

Summary

Progress in simulating turbulence in the Meteorological Office is described. Applications of the 'large-eddy' model include boundary layers, gravity waves and clouds of various types. In each area there is some evidence of good performance. The technique has considerable potential for increasing our understanding of atmospheric processes and helping to improve forecast model parametrizations. Validation of the model using high-quality observations continues to be very important..

1. Introduction

One of the functions of the Atmospheric Processes Research (APR) Division of the Meteorological Office is to study phenomena which in forecast or climate models need to be 'parametrized', i.e. represented in a simplified way. Such processes are generally 'subgrid-scale', i.e. they occur on scales which are too small for the large-scale model to resolve. The art of parametrization is to represent in a simplified and computationally efficient way the large-scale effects of the process concerned in terms of the resolved variables of the model.

'Atmospheric Processes' include clouds, radiation, turbulence and gravity waves. The first three have been thought of as 'physics' rather than 'dynamics', a classification which is natural for radiation. But turbulence, just like weather systems, obeys laws of fluid dynamics and is not just a branch of statistical physics. Although parametrizations involve predicting turbulence statistics, and fluxes in particular, their derivation requires considerable dynamical understanding. For clouds too, the dynamical circulations can be just as important as the 'physical' processes. Of course the point is that traditional distinctions between 'dynamics' and 'physics' now seem increasingly arbitrary and outdated. There is a significant distinction, on paper at least, between reversible and irreversible processes, but in the real atmosphere the two can never be completely separated.

Turbulence is important first of all because it largely controls the profiles of wind, temperature, humidity and other variables, e.g. pollutant concentration, in the lower atmosphere. We often talk of 'turbulence in the boundary layer' but the depth of the boundary layer is quite variable, and indeed during deep convection the boundary layer may in a sense extend to fill the troposphere. Most clouds are turbulent to some extent, whilst clear-air turbulence is well known to aviators. So the applicability of atmospheric turbulence modelling is rather wide. In terms of climate models or extended-range forecasting the turbulent exchange of heat, momentum, humidity, etc. between the atmosphere and land, sea or other surfaces is particularly important, as is also the turbulent contribution to the dissipation of atmospheric disturbances which arise on much larger scales.

In the Meteorological Office we seek to understand and predict the effects of turbulence in a practical context. It is not enough to gather abstract understanding on its own, indeed making testable predictions is arguably the essence of science. However, we still need reliable and up-to-date theories to help organize our predictions and help analyse any real or apparent discrepancies between forecasts, or hindcasts, and observations. In the important area of climate change for instance, we need models based on a 'firm physical basis with a minimum of adjustable parameters' (Mitchell and Zeng 1991), and not simply on a fit to present-day climatology. This is why the climate issue has stimulated research in almost every area of 'atmospheric processes'.

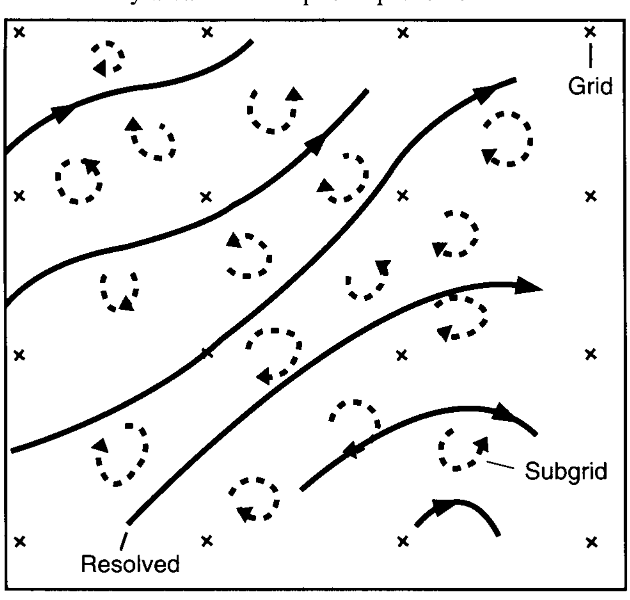

Figure 1. Sketch showing resolved (full lines) and subgrid (dotted) motions. The resolved flow can be represented explicitly in a model by storing the velocity at each grid-point (x): The subgrid motions can not; their effects must be represented statistically.

Amongst the questions we need to answer in detail are: how exactly does turbulence affect clouds? What determines the formation, persistence or break-up of stratocumulus and other layer clouds? Do convective clouds transport momentum significantly? How deep is the boundary layer under various conditions, and how fast does entrainment deepen it? How much drag is carried from topography by gravity waves, and where is it deposited? How much heat and momentum are transported during intermittent turbulence associated with stable nocturnal conditions? ...not to mention many questions relating to pollution dispersion and other practical concerns.

Last, but in some ways most important, how should all these effects be represented in forecast models? Capturing the essential behaviour of the atmosphere in a computationally economical,and therefore usually simplified manner is an art in itself, but good parametrization rests on an accurate knowledge of the true physics. So one aim of research is to provide accurate standards against which parametrizations can be tested.

A dynamical approach to the above questions is essential. Given the complexity of turbulent flows this makes computer modelling an important tool. The models used are similar in principle to forecast models, even though the dynamics of 3-D boundary layer turbulence differ considerably from those of weather systems. In boundary layers, because the time and length scales are smaller, the appropriate Rossby number* is much higher, so the Coriolis effect of the Earth's rotation is less dominant. However, a wide range of significant scales may exist within the same turbulent flow, typically from 1 km to 1 mm. Hence we cannot just compute everything by brute force, and must instead parametrize the small eddies which slip through the computational mesh, but are crucial to the dissipation of turbulent kinetic energy.

In the context of turbulence modelling this procedure is called 'large-eddy simulation' (LES). The 'large eddies' are computed explicitly ('resolved') while the small ones, including their effect on the large eddies, are parametrized ('subgrid') — see Fig. 1. The rationale is that we think we more or less understand the small eddies from 'universal' turbulence theories but the large ones vary more between particular flows, e.g. between stable and unstable conditions. The word 'simulation' implies that the resolved and subgrid motions taken together should statistically mimic atmospheric turbulence, but the timings of transient eddies cannot be taken literally. Compare a 'climate simulation' which may to some extent, depending on resolution, represent weather systems in the next century but cannot predict particular weather on, say, 24 August 2023.

The equations needed for our LES model are not very different from those used in numerical weather prediction or climate models, both being derived from equations describing the dynamics and thermodynamics of air

* See Appendix

in a rotating reference frame. The differences lie in the approximations and idealizations which are made. In synoptic-scale models the hydrostatic assumption is appropriate because vertical accelerations are relatively small when averaged over grid squares typically 100 km square. Such an assumption is clearly inappropriate in a model of horizontal resolution 1 km or less. For 3-D turbulence or convective cloud simulations, the vertical component of acceleration has to be calculated from Newton's 2nd law just like the horizontal components are. Unfortunately the full equations of motion permit sound waves. Sound waves are not thought very important in real atmospheric dynamics, but cause trouble in models, for technical numerical reasons, when their period of oscillation is comparable to or smaller than the model time-step. So steps must be taken to eliminate or control them. In a model confined to the boundary layer, the assumption of incompressibility is an acceptable approximation, but to model deep convection properly we have to allow expansion and contraction due to vertical motion, as atmospheric pressure varies with height. This is done by making the deep anelastic approximation (Lipps and Hemler 1982). Because the domain of the LES model only covers a small portion of the earth's surface we do not have to worry about curvature effects and spherical coordinates: ordinary cartesian coordinates (x, y, z) are good enough.

2. Boundary-layer modelling

In recent years the Meteorological Office, particularly P.J. Mason, has been in the forefront of developing large-eddy simulation, especially in its application to atmospheric flows. However the origins of LES were in America in the 1960s and early 1970s, when meteorologists Smagorinsky, Lilly and Deardorff developed it into a convincing method of turbulence simulation, the first application being the structure of convective boundary layers.

The basic instabilities responsible for convective turbulence are fairly robust and insensitive to subtle details of profiles, boundary conditions or numerical computation method. A superadiabatic layer will support convective instabilities unless the viscous-diffusive terms are large, which they rarely are in the atmosphere. However, detailed flow structures such as shown in Fig. 2 require quite high resolution to be computed accurately. Mason (1989) showed that various subtle but important features of the convective boundary layer, including the 'skewness' of the probability distribution of vertical velocity, were misrepresented by coarse resolutions. This skewness means physically that updraughts tend to be narrow and vigorous, but downdraughts broad and sluggish.

Here by 'convective boundary-layer' we refer to shallow convection occurring when the boundary-layer is unstable but the free troposphere fairly stable. Such convection may be marked by small cumulus. Simulations of deep convection and other clouds are discussed in section 4. There are dynamical similarities between deep and shallow convection, but to model deep convection requires more 'physics'.

Recently Mason (1992) has used LES to release and track 'particles' in a convective simulation both with and without wind-shear. This provides a means of predicting how the dispersion of pollutants changes according to boundary-layer winds and stability.

Convincing simulations of thermally neutral boundary layers, where turbulence is driven by wind-shear, have been possible only fairly recently. Mason and Callen (1986) showed that certain technical problems previously attributed to parametrization errors (laminarization occurred, i.e. turbulence died out, unless the subgrid viscosity was made rather small) were really associated with model resolution. This implies that a fair-sized computer is needed for shear flow simulations! Armed with this knowledge, Mason and Thomson (1987) successfully simulated a neutral boundary layer.

Completely neutral boundary layers are hard to find in nature, because some thermal stability or instability is usually present. Why bother modelling them then? Well, strong-wind situations, especially over the sea, are often 'nearly neutral', with small Richardson numbers*. But also, in testing our simulations initially we need to focus on certain idealized cases which approximately correspond to a reasonable quantity of reliable data. In time one obviously progresses to modelling 'complex situations', and we shall outline in section 5 some ideas for dealing with these. It is simply a matter of learning to walk before trying to run.

Mason and Thomson analyzed many features of the neutral boundary layer, such as the elongation of gust structures along the wind, which is characteristic of shear-driven turbulence. One perhaps surprising conclusion was that the computational domain needs to be very deep, up to 10 km or so, before the effect of the upper boundary becomes negligible. This slightly disquieting result underlines the somewhat unrealistic nature of the strictly neutral boundary layer, as stability effects will become important well below 10 km. Bull and Derbyshire (1990) discussed further the relation between simulations and parametrizations of the neutral boundary layer.

Stable, typically nocturnal, boundary layers remain somewhat enigmatic and inordinately sensitive to influences such as small slopes. It is therefore often hard to interpret stable boundary layer observations. Some datasets seem very complicated, unsteady and sensitive to local effects; others show simplifying features like 'local scaling' (Nieuwstadt 1984) (local scaling or local similarity implies for instance that the turbulent energy balance applies locally, and that certain energy transport terms are small). Idealized simulations are potentially a vital tool in unravelling the structure of stable boundary layers and their various sensitivities, but it had been widely thought that LES of stable boundary layers was

* See Appendix

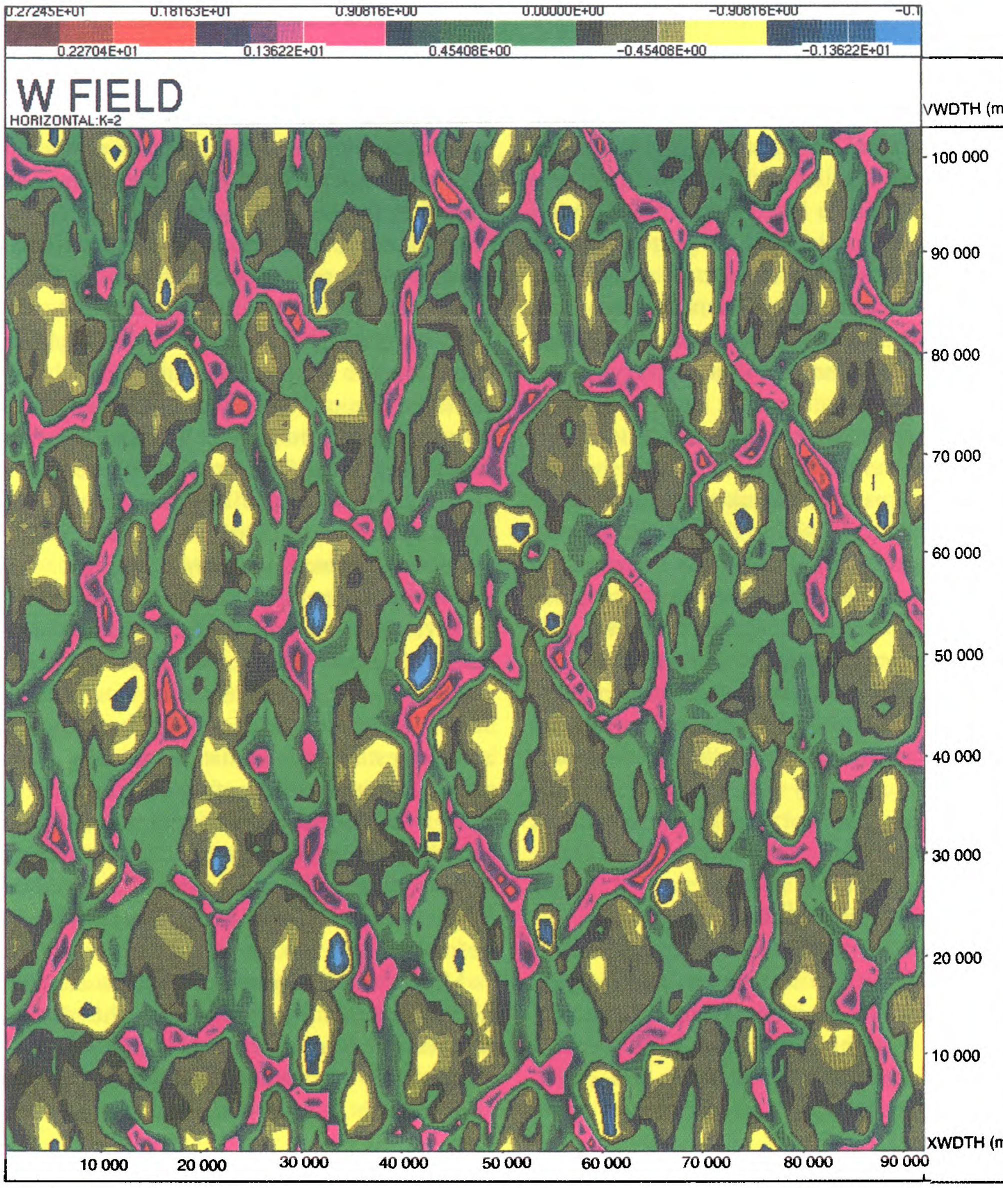

Figure 2. Vertical velocity field on a horizontal slice through a modelled convective boundary layer. Magenta/red = upward motion, yellow/blue = downward motion.

virtually impossible at present. However, Mason and Derbyshire (1990) showed that it could be done, and obtained results which fit well with Nieuwstadt's analysis of observations, and in turn with a theory (Derbyshire 1990) which predicts a limit on the surface heat-flux in terms of the geostrophic wind. There is a lot more to be written on this subject, but it is already clear that simulations can shed considerable light.

The Meteorological Office group, whilst by no means alone in performing boundary layer simulations (see, for example, Nieuwstadt and deValk (1987), Moeng (1984), Schumann (1990)) has shown above all how essentially the same model can handle all three main dry types of boundary layer. Work continues on some important aspects (e.g. Mason and Thomson (1992) show how partial randomization of subgrid parametrization can improve performance in the surface layer), but the overall success of the model and general consistency with the best observations are clear.

3. Gravity waves

Gravity waves are oscillations in which buoyancy provides the vertical restoring force. They are very common in stable regions of the atmosphere and they can transport significant amounts of energy and momentum in the vertical. Mountain lee waves are a familiar example of such oscillations .

Some may be surprised to see gravity waves mentioned in this paper, since even when they occur 'randomly' they are not a form of turbulence. In principle the differences are clear, although making the distinction from observational records is not always easy. Turbulence is chaotic, strongly non-linear and dissipative; gravity waves are predictable, often essentially linear phenomena, and do not dissipate significantly until they 'break' and become turbulent, in a way roughly similar to water waves breaking on a beach.

What then has all this to do with the large-eddy model? First of all, from a very general point of view gravity waves obey the same underlying physical and dynamical equations as turbulence. Secondly, in stably stratified conditions almost any disturbance (including turbulence) can generate gravity waves. Thirdly, various transitions can occur between waves and turbulence, e.g. by wave-breaking or collapse of turbulence. So it is quite important that our model can handle both waves and turbulence, and if it could not we might question its accuracy.

The large-eddy model's handling of both waves and turbulence has recently been demonstrated in 2-D simulations of breaking gravity waves in the lower stratosphere. The model was initialized using real wind and temperature profiles taken from field experiments in the Lake District. In these experiments orographically forced gravity waves were observed using radiosondes .

Even though the LES model contains no orography, such waves can be simulated by imposing a fixed, sinusoidal vertical velocity at the lowest grid-point, imitating the effect of the hills. The domain width (18.8 km) was chosen to satisfy a resonance condition, allowing the waves to build by constructive interference. The top of the domain was at 30 km, with a damping layer above 23 km, and 250 grid-points in each vertical column.

With imposed vertical velocities of amplitude 0.25 m s^{-1} at the surface, waves of maximum amplitude 3 m s^{-1}were simulated, similar to those observed. The vertical resolution was sufficient for wave breaking to be seen in the model (Fig. 3). The heights and some features of the breaking are in reasonable agreement with the observations.

Other results show that:

(a) The large-eddy model accurately conserves energy in long gravity-wave integrations (this is a moderately strict test which revealed imperfections in the original formulation).

(b) Gravity-wave phase speeds match predicted values both in the incompressible and anelastic cases (recall that our dynamical equations can take two slightly different forms).

(c) The model satisfies the generalized Charney–Drazin non-acceleration theorem (Andrews and McIntyre 1976), which says that momentum carried by steady gravity waves is absorbed only in regions of dissipation (this is a significant test of the model's numerics).

An illustration of gravity waves occurring naturally in the model is shown in Fig. 4 where boundary layer convection radiates waves. The momentum transport of these waves can be inferred from the sense of the phase line tilt.

4. Clouds

The simulation of clouds is a particularly important application of the LES model, because of the sensitivity of climate models to the representation of cloud processes. We seek deeper understanding of the processes themselves, with a view to improving their parametrization in larger-scale models. There are two areas of current interest. The first is the study of stratocumulus, and especially of the conditions under which break-up occurs. This is

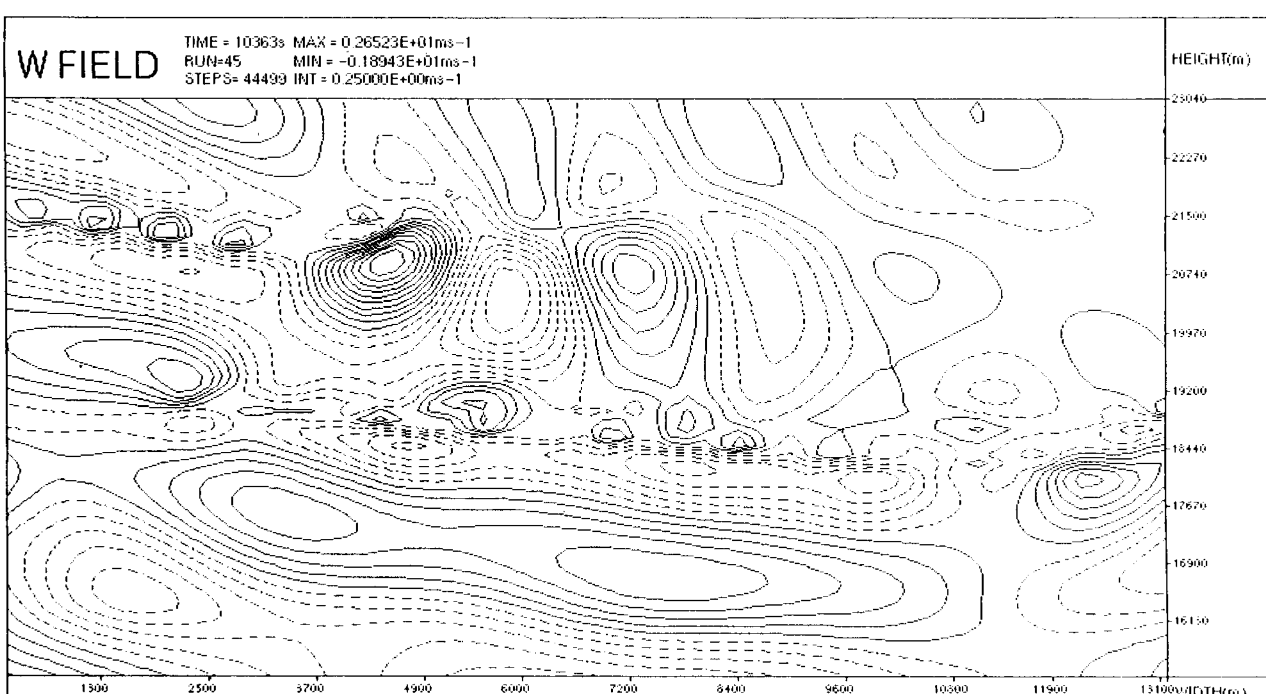

Figure 3. Vertical velocity from a 2-D simulation of gravity waves. Solid contours = upward motion and dashed contours = downward motion. The small-scale features in the centre of the figure and at top left are indications that the waves are breaking.

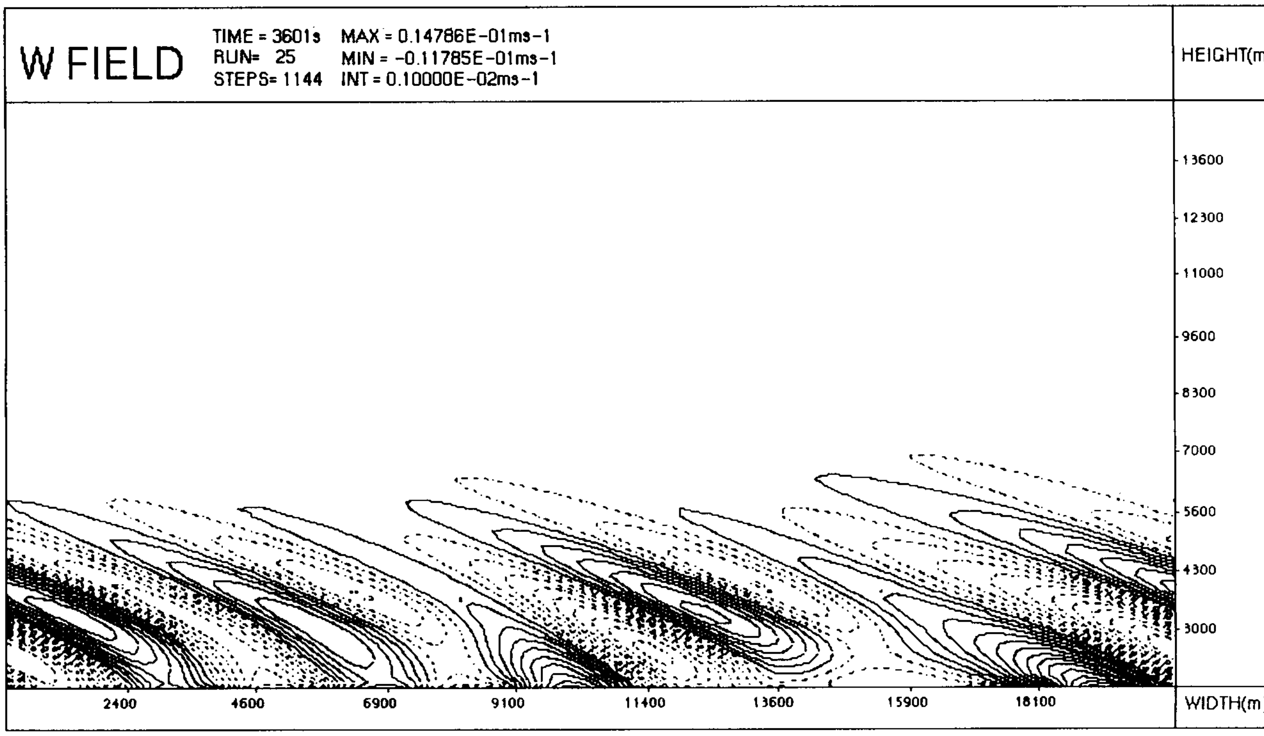

Figure 4. Vertical velocity from a 2-D simulation of an atmosphere heated from below, with strong wind shear near the surface. The shear inhibits convection and gravity waves are generated. Solid contours = upward motion and dashed contours = downward motion.

important because stratocumulus has a major impact on the radiation balance in the atmosphere. Clearance of stratocumulus is also difficult to forecast. The second area is the simulation of deep convection. This process transports substantial quantities of heat, moisture, and (possibly) momentum in the atmosphere, and latent-heat release in convective systems is a major energy source for atmospheric circulations, especially in the tropics.

In order that the LES model might be used to simulate cloud, the code has had to be extended. The minimum extension required to simulate non-precipitating cloud is the inclusion of suitable moist variables. There are various possible choices, but many cloud models use a thermodynamic variable which is conserved even when condensation occurs. Wet-bulb potential temperature (θ_w) is a familiar example of such a variable, though it is not easy to use in a model. The LES model uses liquid water temperature

$$T + gz/c_p - Lq_l/c_p$$

(Shutts 1991), because it proves to be more accurate and computationally convenient than other possible choices for the simulation of deep convection. The moisture content variable is total water mixing ratio (q_t), which comprises vapour and cloud. In the absence of precipitation, this too is a conserved variable.

Simulation of precipitating clouds requires the addition of a rain density variable, together with a parametrization of the microphysical processes of autoconversion (growth of raindrops by condensation), accretion (coalescence of rain and cloud droplets), and evaporation. In the current version of the model, two alternative parametrizations of these 'warm rain' processes have been included, based on the work of Kessler (1974) and Lee (1989). The ice phase is not currently represented, but virtual temperature and water loading effects are. Moist air is less dense than dry air at the same pressure and temperature; cloud and rain droplets exert a drag on the air: these effects modify the buoyancy of convective plumes. Indeed the evaporation and drag due to precipitation generate an important dynamical ingredient of convective storms, the downdraught. Fig. 5 shows the downdraught from our simulation of the Halifax storm (Collinge *et al.* 1990), spreading out as it reaches the ground.

The simulation of the break-up of stratocumulus is a particularly challenging problem because the model needs to resolve dynamical features near the inversion. The scale of these features is comparable with the depth of the cloud-top inversion, which might be only a few metres. However, the domain of the model must be several kilometres deep, to include the whole boundary layer, and several kilometres across, to include the largest eddies. Three-dimensional simulations are not yet feasible at sufficiently high resolution (grid length 5 m or so), but 2-D simulations are. Fig. 6 shows a chart from such a simulation. The moisture gradients are very sharp near the cloud boundaries: the model must use quite sophisticated numerical schemes to simulate accurately the advection of such gradients. To date this modelling work has helped to confirm recent developments in the

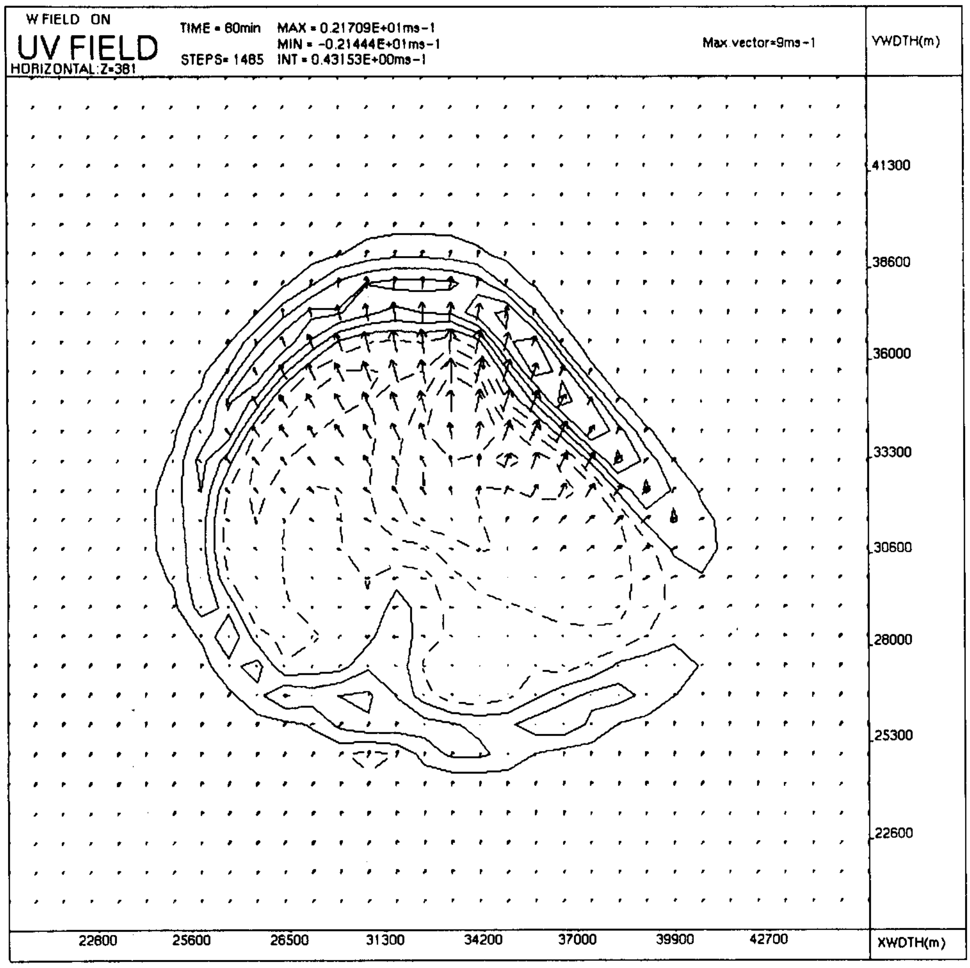

Figure 5. Horizontal slice through simulation of the Halifax storm. Height 380 m. Contours are of vertical velocity (solid = up). Arrows represent horizontal wind vectors.

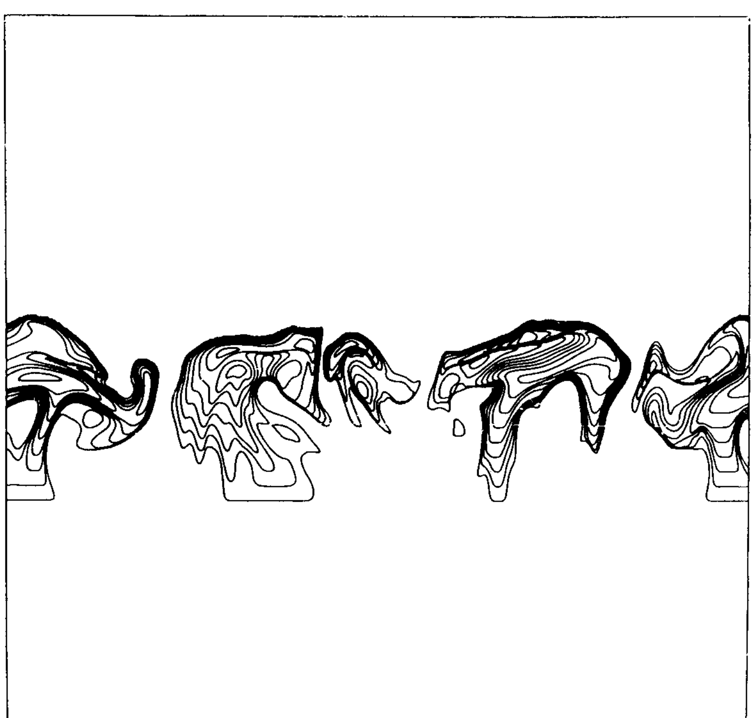

Figure 6. Liquid water content in a 2-D simulation of the break-up of a stratocumulus deck. Contour interval 0.07 g kg^{-1}.

theory of cloud-top entrainment instability. Under certain conditions, mixing and evaporative cooling near the inversion can lead to instability and rapid break-up of the cloud. The model simulations have helped to define these conditions more precisely, and shown that the instability can lead to complete break-up of the cloud deck within one hour or so. See MacVean and Mason (1990) and MacVean (1992) for further details.

The simulation of deep convection is a relatively new application of the LES model. Cumulonimbus models have been used for many years and have been reasonably successful in simulating individual storms, in mid latitudes (e.g. Miller (1978)), and in the tropics (e.g. Tao and Simpson (1989)). Given adequate resolution, and an adequate parametrization of the microphysical processes, such models can represent the dynamical structure of storms, and the vertical profile of latent heat release. This previous work has highlighted, amongst other features: the 3-D nature of convective flows, the importance of the ice phase, and the significance of long-wave cooling near cloud top. Ideally, our model would represent these dynamical, microphysical, and radiative processes accurately.

However, our goal is to simulate not one convective system but many within the model domain, because we seek to quantify the statistical effects of the convection on the large scale. This poses the fundamental difficulty that we need a large domain, to include many systems, and high resolution, to resolve the main dynamical features of the individual storms. For tropical systems, which are organized on scales of 100 km or more, a domain 1000 km square is probably needed, and horizontal and vertical resolution near 100 m would be preferable. This is clearly out of the question: it would need 1000 times more memory than we have on our CRAY-YMP and each time-step, around 1 second, would take approximately 1 day of CPU time! For the foreseeable future, integrations will have to be restricted to smaller domains and/or lower resolutions. With current computing power, integrations with 1 million points and 1 km horizontal resolution are feasible. That should allow us to simulate less-organized systems such as cold air outbreaks in mid to high latitudes, and even for tropical systems we may be able to learn something from the model. With a domain size equal to the grid-length of a climate or weather forecasting model, we can think of the LES model as a means of simulating the unresolved circulations within a single column of the large-scale model. Experiments which compare the diagnosed effects of convection, in the LES model, directly with single column versions of the parametrizations, in the large-scale model, are likely to be a useful area of research.

Available computer power also limits the complexity of the microphysical parametrization which can be used in a cloud ensemble model. A measure of that complexity is the number of cloud physics variables included. A cloud physicist would like to keep track of many different size classes of cloud and precipitation particles, ranging from small droplets to large rain drops, and from ice crystals to graupel, hail and snowflakes. A typical scheme might have 40 variables which have to be advected around, and sources and sinks have to be calculated for each one. For a 3-D model we are unlikely to be able to afford many more than 5 variables, amounts of cloud water, rain, cloud ice, snow or graupel, and hail, for example. The current version of the model only has the first two. Bearing in mind the aims of our modelling to guide parametrizations in larger-scale models, it is important to assess which variables and processes are really important, and which just add the icing on the cake.

5. A look ahead

As a research tool the LES model has many advantages. It is for example simpler in many ways than a climate model: it has no orography, the vertical coordinate is height, it has simple boundary conditions, and it has no physical parametrizations except those we choose to add. This simplicity is an advantage because it enables us to run idealized experiments to isolate, study and understand individual processes. For the simulation of deep convection, more complex physical parametrizations will be necessary; for example the ice phase must be included and so must long-wave cooling. However, it is important to proceed step by step and understand the effects of each addition to the model, since the usefulness of such a research tool rests on three characteristics:

(a) the integrity of the computer code (a 'bug-ridden' code could be worse than useless),

(b) our detailed understanding of the processes within it (a purely 'black box' model would not be much help), and

(c) the facility to redeploy computational resources, e.g. between sophisticated physics and high resolution (so that we can test out the importance of different processes).

The LES model does not attempt to be a forecast model. A forecast or climate model has to some make provision for handling nearly every process that is likely to be important, even when relatively poorly understood. It also has to handle complex terrain, which can be a significant overhead. Many of the overheads in a complex model tend to remain even when one tries to run it in a 'simple' mode, e.g. without orography. Also the overriding need for a forecast model to run fast and efficiently imposes various constraints. So whilst it is useful to be able to run a forecast model in research mode, e.g. the Meteorological Office mesoscale model is both a research and an operational model, there is also an advantage in having a research model which does not have to worry about direct forecasting applications. This is the role of the large-eddy model, for which the flexibility to run all sorts of idealized experiments is a prime consideration.

The development of simulations is at best only a partial substitute for high-quality detailed observations of boundary layers and other processes. The observational database continues to play a vital role in validating many aspects of simulations and pointing up their deficiencies. Models are useful in setting up idealized situations which may act as benchmarks to forecast models, and thus pinpoint any failings of, say, the boundary layer scheme. But comparison with observations always provides a vital check against the real atmosphere, which is far more complex than any model. So work done for example by the Meteorological Research Flight C-130 research aircraft and by the Meteorological Office Research Unit at Cardington is important to the future development and application of the model.

Observational verification of simulations of ensembles of convective clouds is likely to depend on international field experiments, especially for cases of organized convection. Measurements are needed on vastly differing scales: the microphysical scale (μm) for cloud variables, the convective scale (km) for individual up/downdraughts, and the mesoscale (100 km) or even synoptic scale (1000 km) for the large-scale organization. TOGA–COARE (the Tropical Ocean Global Atmosphere–Coupled Ocean Atmosphere Response Experiment) is an example of a forthcoming experiment which will provide useful data. Expensive experiments of this kind can only be run infrequently, and in a limited number of regimes. They are an important means of validation in a subset of the possible atmospheric conditions. One of the advantages of a computer model is that it can be run again and again under different conditions, at far less cost than a large experiment, though with much more simplistic physics than in the real world.

A new possibility which we are only beginning to exploit is to combine simulations and observations directly. It is probably not appropriate here to use the elaborate assimilation schemes developed for blending synoptic (or asynoptic!) data into forecast models. However, relatively simple techniques for nudging simulated profiles towards observed values could help us considerably in comparing real and simulated turbulence levels and fluxes. As an example Lilly and Mason (1990) showed that incorporation 'by hand' of a pronounced mesoscale influence on wind profiles measured during an experiment in eastern Colorado (the influence was presumed to relate to the nearby Rocky Mountains but not completely understood) led to good agreement with observed turbulence structure.

This raises the hope that in complex situations, which we promised earlier to consider, simulations and observations will complement each other to give a full picture from which detailed deductions may be drawn about the performance and possible improvement of forecast models. In summary, the Met. Office has a leading position in meteorological applications of large eddy simulation. The development work has taken several years, but our ability now to simulate all the main types of boundary layer represents something of a breakthrough. One of the most exciting prospects is to be able to represent various types of cloud accurately enough to help parametrization in a significant way.

Acknowledgements

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Appendix

A Rossby number *Ro* can be defined as a ratio of the Coriolis timescale f^{-1} to the characteristic flow timescale. In textbooks on dynamical meteorology one often takes $Ro = V/fR$ for a circularly symmetric synoptic system where *V* is the wind and *R* the radius. In that case *R/V* can be interpreted as the time that a parcel of air would take to circulate an angle of 1 radian around the system, if the pressure system were constant and stationary. Many different characteristic Rossby numbers can be defined for different aspects of flows in a rotating atmosphere. Basically, when *Ro* is small rotation is dominant and the flow will be nearly geostrophic, but when *Ro* is large rotation is relatively unimportant.

The gradient Richardson number *Ri* is the ratio of the static stability to the square of the wind-shear. The static stability is proportional to the rate of change with height of potential temperature, whilst the wind-shear is of course the rate of change of vector wind with height. This number is very important in determining the amount of turbulence in stably-stratified layers. Where it exceeds a certain critical value Ri_C we expect the flow to be laminar, i.e. not turbulent. Clear air turbulence is often thought of in terms of flow instabilities which occur when *Ri* falls below Ri_C.

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Quasi-operational test of a forward scatter visibility meter at Ronaldsway, Isle of Man

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Summary

Assessments of Runway Visual Range (RVR) at Ronaldsway Airport (Isle of Man) are currently made by manual observation but a proposal has been made to install an instrumented (IRVR) system. Whilst the current standard instrument is the transmissometer, in the USA the FAA have recently adopted the forward scatter meter (FSM) for future IRVR applications. An FSM was tested at Ronaldsway during 1991 and this report compares measurements by the instrument with visibility parameters used operationally at the airfield during several periods of low visibility.

1. Introduction

During conditions of low visibility at Ronaldsway (Isle of Man) Airport, assessments of runway visual range (RVR) are currently made by manual observation. A proposal has been made to install an Instrumented RVR (IRVR) system. The current standard IRVR instrument is the transmissometer, which measures the light transmittance of the atmosphere between a light source and detector over a baseline of (usually) some 10 to 200 metres. However, there are some operational problems with the instruments currently in use. The optical alignment is critical, so the bases for the transmitter and receiver must be very stable, which often leads to high installation costs. The optical surfaces must be cleaned frequently, and if maintenance is required (such as lamp replacement) during conditions of poor visibility it is not possible to recalibrate until conditions improve. The Federal Aviation Administration (FAA) of the United States has recently instigated a replacement programme for the transmissometers which have been in use at major US airfields for more than a decade with a new generation of IRVR systems employing forward scatter meters (FSMs) (S. Ammann, *ICAO Journal*, April 1990). The advantages of forward scatter meters are increased reliability and simplified maintenance, reduced overall cost, and the ability to allow calibration in moderately low visibility.

During preliminary discussions, a FSM (manufactured by HSS Inc., Massachusetts, USA) was offered on loan to the Isle of Man Meteorological Office for a practical assessment at Ronaldsway. It was installed for a period from early February to mid-April 1991, and some results from this test are presented here.

2. Principle of operation of the forward scatter meter

Horizontal visibility through the atmosphere is determined by the presence of particles which cause light to be scattered. For light in the visible (and near-visible) part of the spectrum, scattering occurs by suspended particles such as fog droplets, dust and smoke particles, and by precipitating particles such as raindrops, drizzle droplets, snowflakes and hailstones. When viewing a distant object or light-source two processes affect its visibility to the observer. Light travelling from the object or light-source towards the observer is scattered out of the line-of-sight, reducing the intensity reaching the observer directly. Also, stray light from other sources also scattered by the particles can be scattered into the line-of-sight. This added stray light (sometimes called 'air light') has the effect of reducing the apparent contrast between the distant object or light-source and its background, making it less discernible (commonly said to increase 'haziness'). Consequently, visibility is determined by the concentration and type of scattering particles and can be quantified in terms of an atmospheric scattering coefficient. When measured scientifically, this scattering coefficient is called the 'extinction coefficient' (EC). The EC is very low on clear days, but high in mist and fog. Meteorological optical range (MOR) is defined as the length of path through the atmosphere required to attenuate a beam of light to 5% of its original intensity; it approximates to meteorological visibility but it can be measured instrumentally whereas visibility cannot. Koschmieder's Law relates MOR to measurements of EC through the simple relationship:

$$MOR = 3/EC.$$

The forward scatter meter is an instrument which measures values of EC, enabling the calculation of MOR. When the instrument is situated close to the edge of a runway, the MOR determined is considered the best assessment of RVR.

Fig. 1 illustrates a plan view of the instrument, which is around 1.5 m in overall length and mounted on a pole at its mid-point, where there is a junction-box for the electrical connections (covered by a splash-guard to stop rain bouncing into the sample region). A weatherproof box containing the power control unit is also mounted on the pole near the ground. A source of light is mounted at one end of the instrument (actually an infrared source with central wavelength 0.89 μm, modulated at 2000 Hz). The detector mounted at the other end contains a hybrid Si-sensor amplifier. Unlike the transmissometer which has a direct optical path between the source and detector and measures the transmittance of the atmosphere, the FSM detects light scattered out of the source beam in the direction of the detector by particles suspended in or falling through the atmosphere. The sample region is defined by the aperture and acceptance cones of the source and detector respectively. It represents a volume of 3000 ml, covering scattering angles from 27° to 42°. The amount of scattered light received by the detector depends on the type, size and number of scattering particles in the sample volume, and the signal produced enables the EC to be measured. A photograph of the instrument is shown in Fig. 2.

3. Interpretation of data

The instrument was installed at Ronaldsway from early February to mid-April, 1991. Due to the temporary nature of the installation, the only convenient site was situated between runways 18 and 22, as shown in Fig. 3. The site was approximately equidistant from the Meteorological Office (where observations including meteorological visibility are made) and the runway 09 RVR observers' position (ROP), and a little further from the 27 ROP. Information from the sensor was fed back to a computer situated in the Meteorological Office.

During that time, a spell of frequent fog occurred during the second week of March. Fig. 4 shows the development of the synoptic situation between the 11th and 14th of March. The fogs occurred in various wind directions (from NE through E and S to SW), and wind speeds from calm to over 10 kn. A series of four 6-hour periods was selected, for which the MOR measured by the FSM instrument is indicated, together with the visibilities (MV) reported by the meteorological observer and RVR assessments for runways 09 and 27. The sea temperature around the south of the Isle of Man at that time was about 7.2 °C.

In order to interpret the data, it is important to remember the relative positions and elevations from which each visibility measurement was made and to understand something of the physics of the fogs which affect Ronaldsway. Fig. 5 shows schematic tephigram constructions of idealized fog formation.

Figs 5(a)and 5(b) illustrate the classic formation of advection fog, with warm moist air moving over a relatively cooler sea surface. Firstly, stratus forms by turbulent mixing under a low-level inversion (Fig. 5(a)). As cooling of the mixed layer proceeds, the base of the stratus lowers towards the sea surface, eventually producing fog (Fig. 5(b)). This type of fog forms in light to moderate (and occasionally strong) winds, usually from the south to south-west direction (since the Irish Sea is often exposed to warm moist Atlantic air from that direction). Turbulent mixing occurs on a range of scales (from metres to hundreds of metres), leading to large variations in visibility over the airfield. However, due to the limited number of condensation nuclei in maritime air favouring relatively large fog droplets, the lowest visibilities are usually around 200–400 m. Fog depth is often 100–400 m.

Fig. 5(c) shows how fog can develop in warm moist air in calm or very light wind situations. Cooling occurs first near the sea surface, with latent heat release providing small-scale mixing to increase the depth of the fog, usually to around 50–100 m. This type of fog often forms

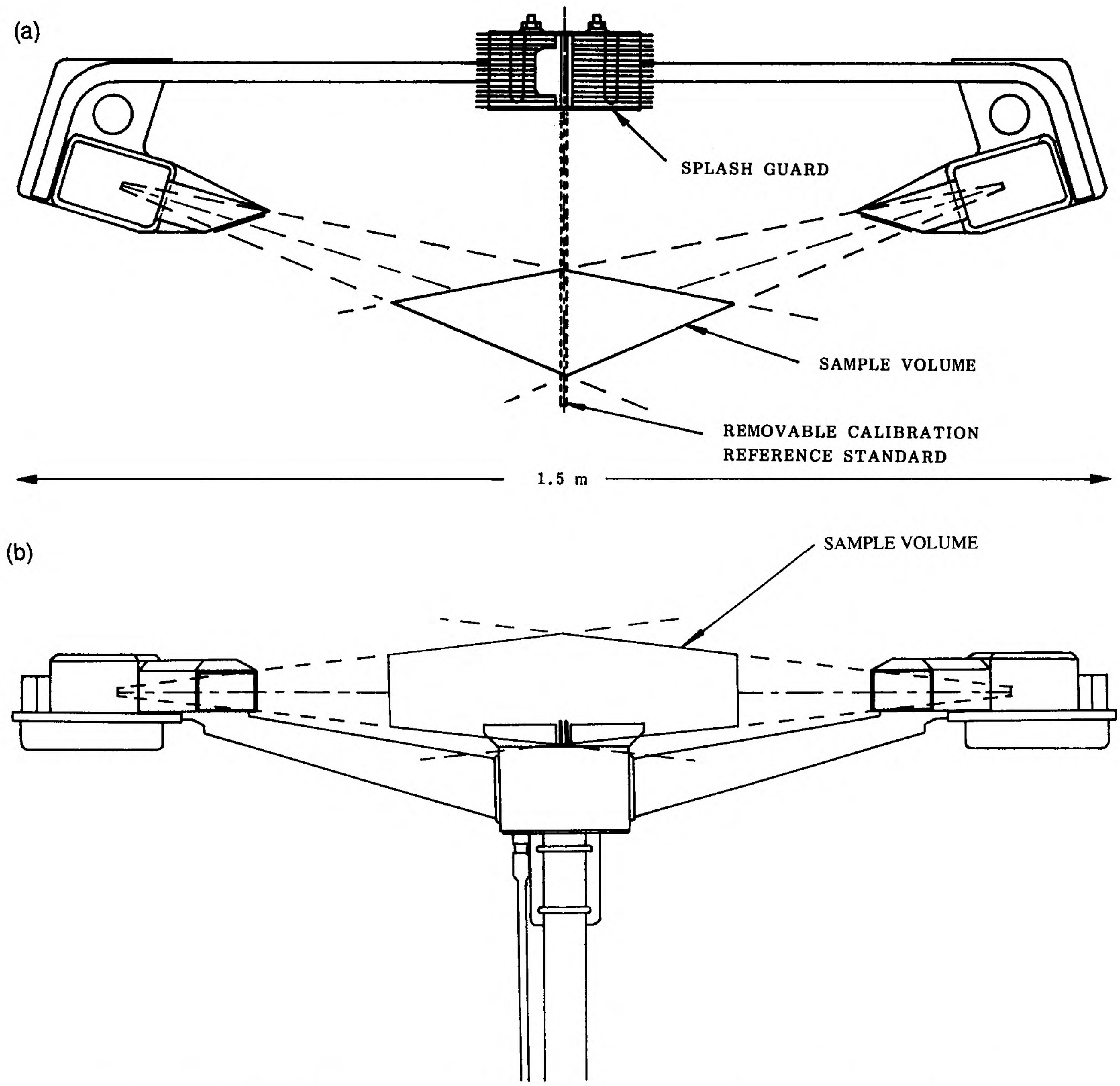


Figure 1. Views of the HSS FSM sensor head. (a) plan view, and (b) elevation. Sample volume is around 3000 ml.

Photograph by courtesy of M. Stephens-Row, BIRAL/HSS.

Figure 2. The HSS forward scatter visibility meter.

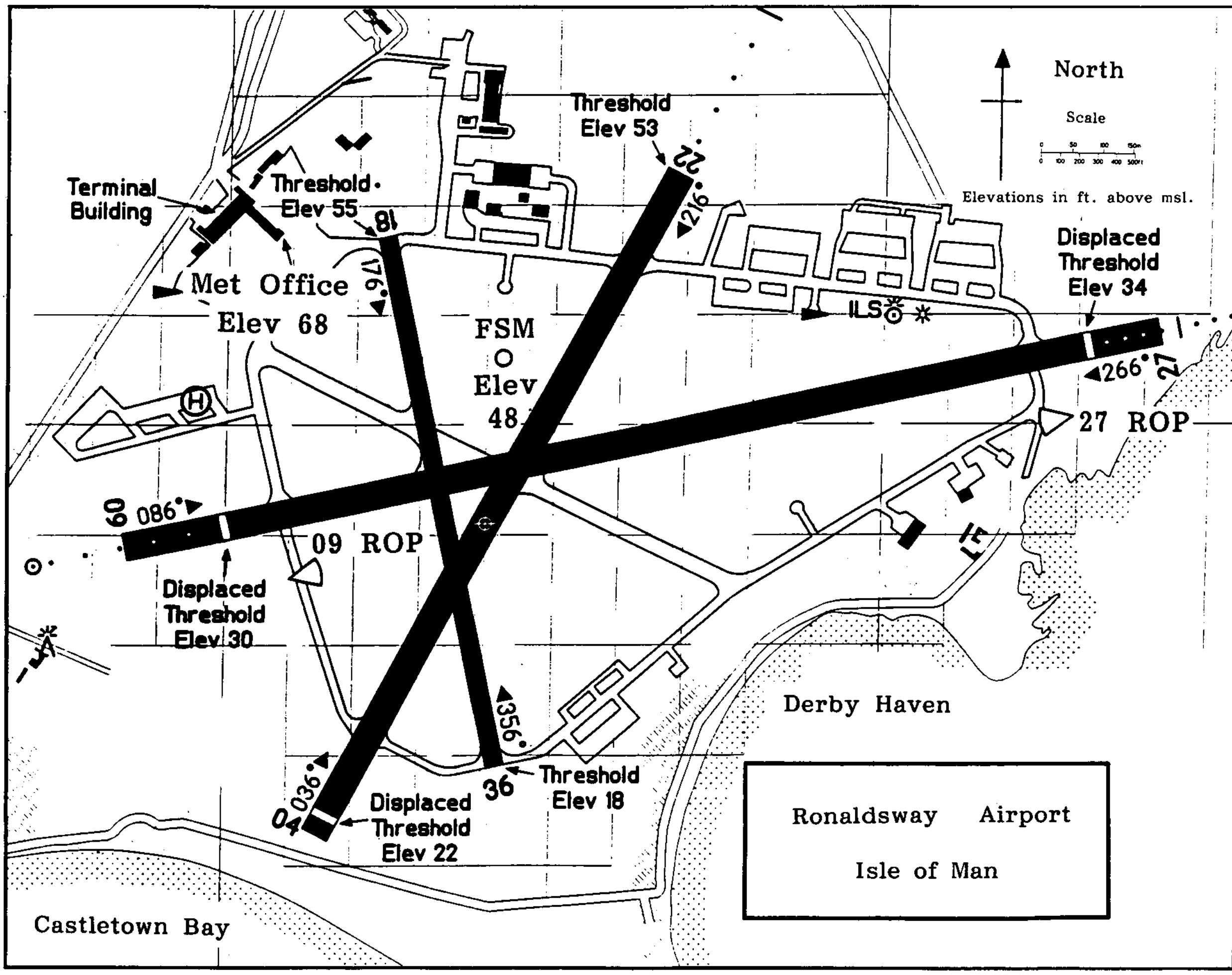


Figure 3. Plan of Ronaldsway Airport, Isle of Man.

or thickens overnight, behaving in some ways like land radiation fog. It can encroach inland as the coastal land temperature falls overnight (unless held back by katabatic drainage) and is sometimes driven inland by light onshore winds developing or by sea breeze circulations in summer. The encroaching fog then cuts off the sea breeze by cooling the land, but the heat thus absorbed can lead to the inland edge of the fog eroding and allowing the sea breeze to develop again. The balance between these competing processes is often reached at Ronaldsway close to the line of the main 09/27 runway! Due to the production of fog droplets occurring at low levels (and sometimes a partly continental history of the air mass providing an abundance of condensation nuclei) the visibility is often around 100 m or less.

Fog can also occur in slow moving cold-frontal zones, due to mixing of the two air masses producing supersaturation. It usually develops from the base of warm-sector stratus descending towards the surface (similar to the advection fog described above) but the visibility can be less than 100 metres and the fog top undefined (merging with frontal cloud above).

Radiation fog is rare and only occurs when there is sufficient synoptic pressure gradient to counteract the katabatic drainage (from high ground to the north) which normally occurs in radiation conditions. When it does occur, visibility can fall below 100 m with fog depth usually less than 50 m.

The physics of real fog is obviously more complicated (often involving a combination of formation processes) but in any case the fogs which affect Ronaldsway usually produce large temporal, spatial and directional variations in visibility.

4. Some results obtained during the period 11–14 March 1991

The graphs in Fig. 6 show data obtained during four 6-hour periods of reduced visibility at Ronaldsway during 11–14 March 1991. In each case, the meteorological visibility assessed by the duty observer is shown for

(a) routine reports completed for SYNOP reports (at 50 minutes past each hour),

(b) METAR reports (at 20 and 50 minutes past each hour during airport opening hours), and

(c) whenever special reports were issued to Air Traffic Control (due to the visibility changing through certain specified values of operational significance).

Values of MOR calculated from measurements of EC by the FSM are plotted at 1-minute intervals. Manual

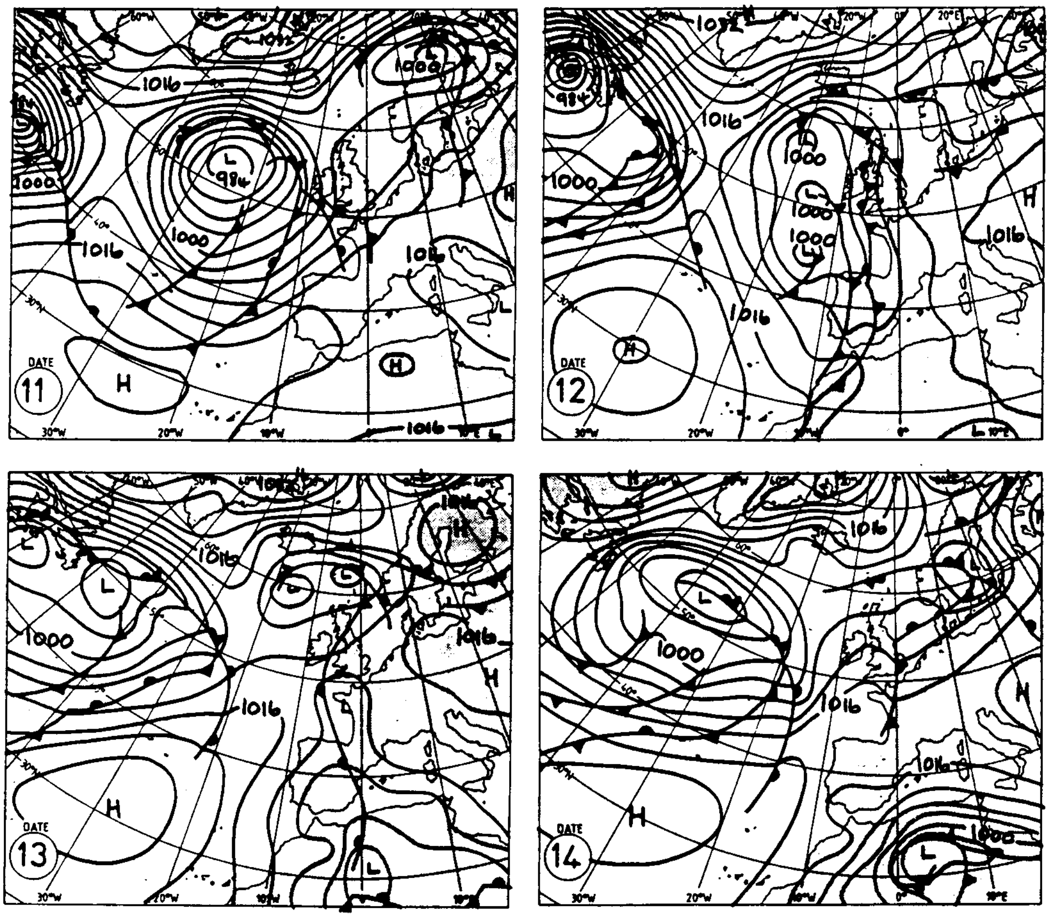


Figure 4. Surface charts for 1200 UTC on 11–14 March 1991. Dates shown in bottom left-hand corner.

assessments of RVR from the ROPs at each end of runway 09/27 are also shown.

Fig. 6(a) shows a comparison of visibility measurements for the period 1700–2300 UTC on 14 March. There was a light moist south-westerly airstream with visibility around 6 km during the afternoon. After 1700 UTC the wind decreased and both the temperature and dew-point dropped, with the relative humidity (RH) rising from 88% towards 100%. At 1748 UTC the visibility was 5000 m, with half cover of stratus developing at base 300 ft. The visibility deteriorated below 1000 m at 1812 UTC, with the cloud base touching the ground in places and generally 100 ft. By 1824 UTC the observer reported a meteorological visibility (MV) of 200 m. Initially, the MV and RVR reported from the 09 ROP were in close agreement. As the fog reached the FSM it gave good agreement with the observer, while RVR reports from the 27 ROP showed the approach of the edge of the fog. For the remainder of the duration of the fog, the FSM and MV remained in remarkably close agreement, with RVR reports around twice the MV. This effect might be due to stratification of the fog, with the ROPs (at elevations around 30 ft AMSL) remaining below the layer of lower visibility which affected the FSM and observer. Alternatively it might be due to the test instrument not having a background luminance meter (which is required for true RVR calculation in darkness) and continuing to measure MOR, thus illustrating the difference between MV (and MOR) and RVR in conditions of darkness. After 2100 UTC the wind fell calm and with little change in the temperature and RH; the visibility increased towards 8 km, with the fog lifting and breaking to patches of stratus at base 600 ft, below overcast stratocumulus with a base of 5000 ft.

Fig. 6b) shows a comparison of visibility measurements for the period 0300–0900 UTC on 13 March. There was a very slow moving frontal zone over the area, with the weak surface front crossing the airfield around 0540 UTC and veering the light easterly wind to south-south-westerly. At 0300 UTC the screen-level temperature was 9.0 °C with RH 100% and complete cover of stratus with base between 50 ft and 200 ft. The temperature fell to 7.9 °C by 0350 UTC, as the cloud lowered to form fog with MV 100 m. Between 0350 and 0450 UTC the temperature and dew-point rose a little (7.9 to 8.2 °C) and the fog became patchy on the surface below a stratus base at 400 ft. This is illustrated by the fluctuating FSM readings, whereas the observer is constrained to report the lowest MV in any direction. After 0620 UTC (with the availability of RVR assessments after airport opening) the situation appears similar to that in Fig. 6(a) with a stratification of visibility, decreasing from the

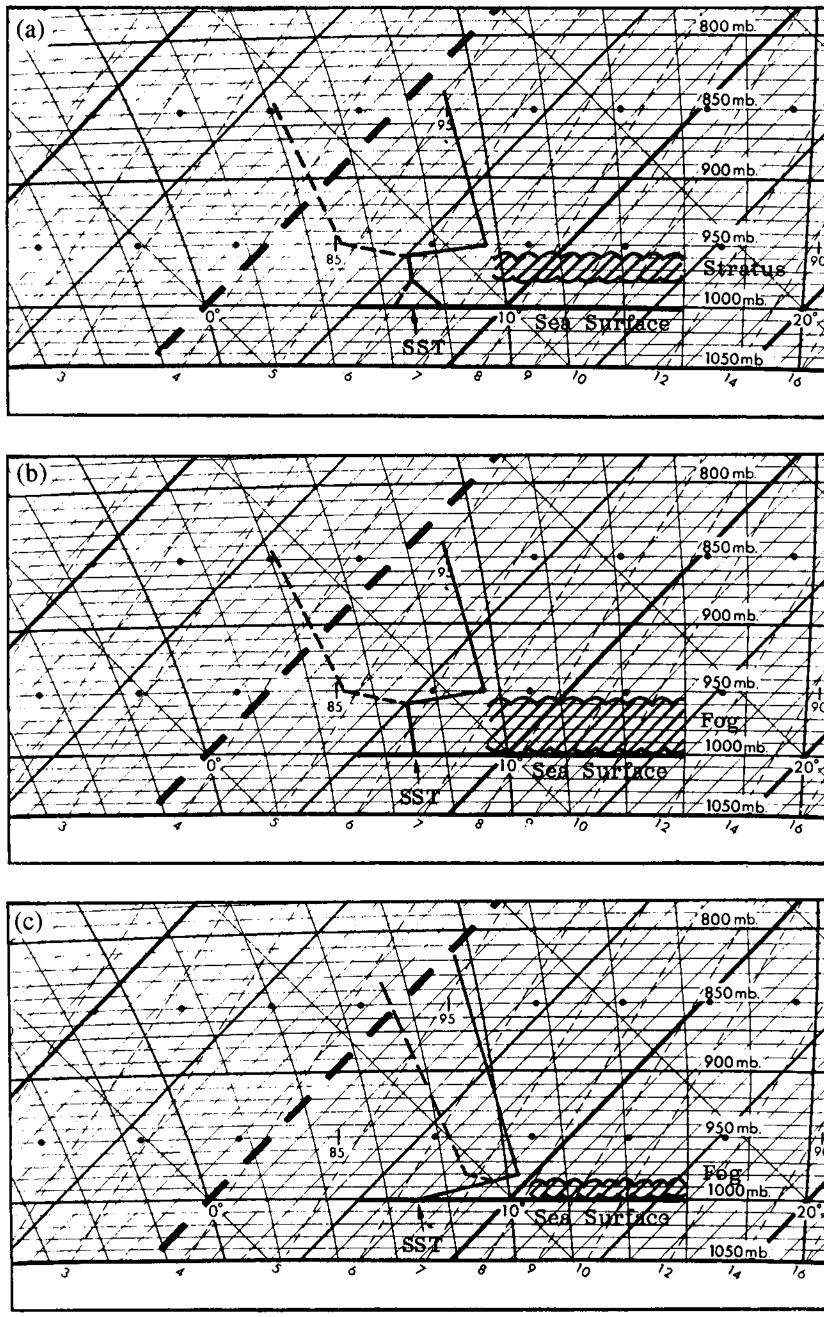


Figure 5. Idealized tephigram constructions showing processes of fog formation. For full details see text.

ROPs (30 ft AMSL) through the FSM readings (48 ft AMSL) to the observer (68 ft AMSL).

Fig. 6(c) shows a comparison of visibility measurements for the period 1200–1800 UTC on 11 March. There was a moist easterly airstream at the surface ahead of a warm front approaching from the south-south-west. The screen temperature of 7.3 °C at 1200 UTC fell abruptly to 5.7 °C (with RH around 93%) by 1220 UTC then gradually increased to 6.7 °C (with RH 100%) by 1650 UTC. Patchy fog around the coast below a stratus base at 100 ft (with inland visibility 15 km at first) became widespread over the airfield for most of the period. The scatter of the results illustrates the variability of visibility around the airfield. However, as long as the FSM could be seen from the Meteorological Office it appeared to respond rapidly to the approach of thicker patches of fog and to the clearances around 1500 and 1700 UTC.

Fig. 6(d) shows a comparison of visibility measurements for the period 0600–1200 UTC on 12 March. The synoptic situation showed a waving cold front near the east coast of Ireland, with a surface easterly wind around 10 kn at Ronaldsway. Light rain and drizzle from 0826 to 1010 UTC gave the lowest visibility, with MV down to 1000 m for a short time around 0850 UTC. The generally good agreement between the observer and FSM indicates that the instrument coped well with the precipitation. The dip in the FSM reading around 0940 UTC was reflected in the 09 RVR assessment but did not meet the criteria for a special report by the observer.

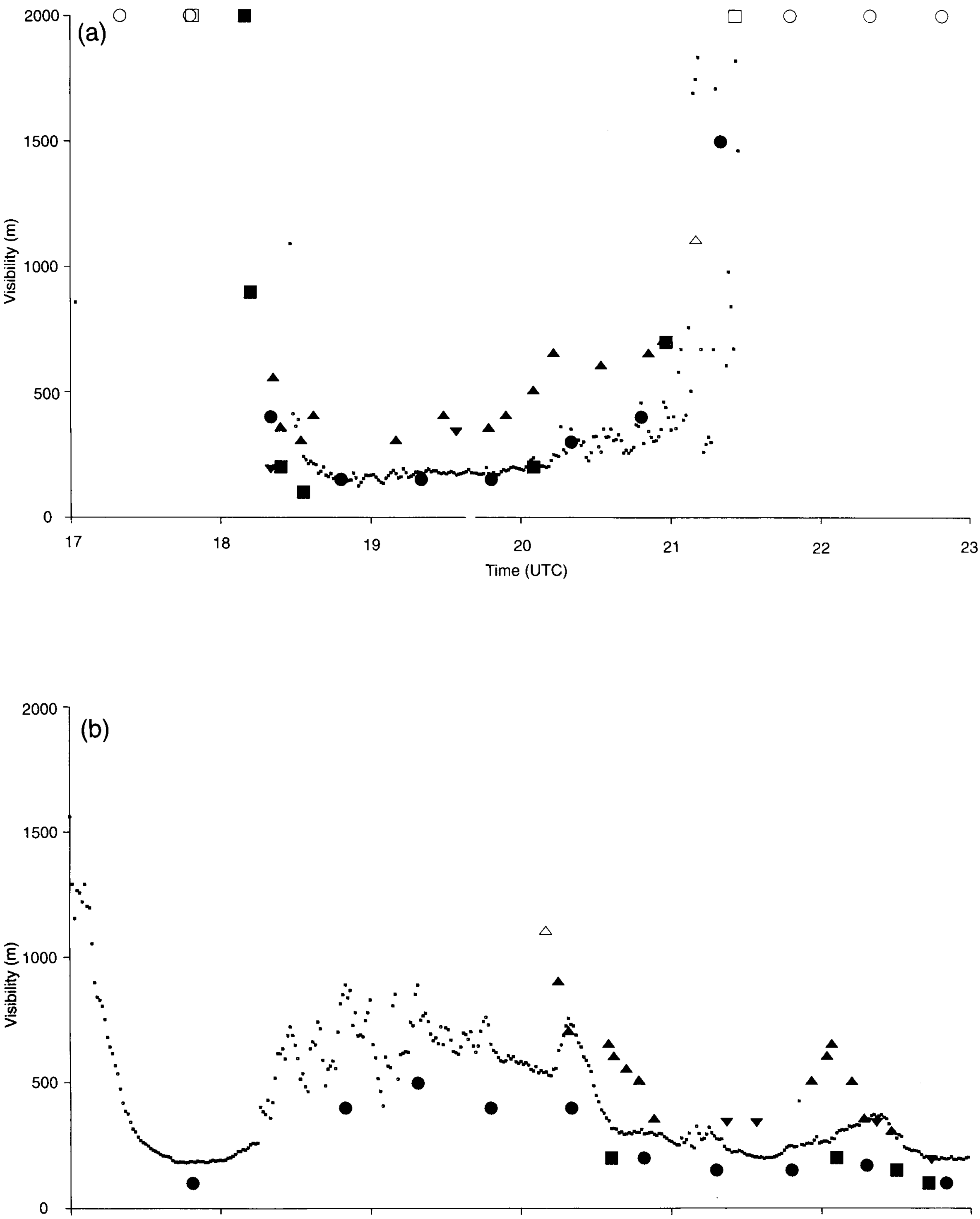
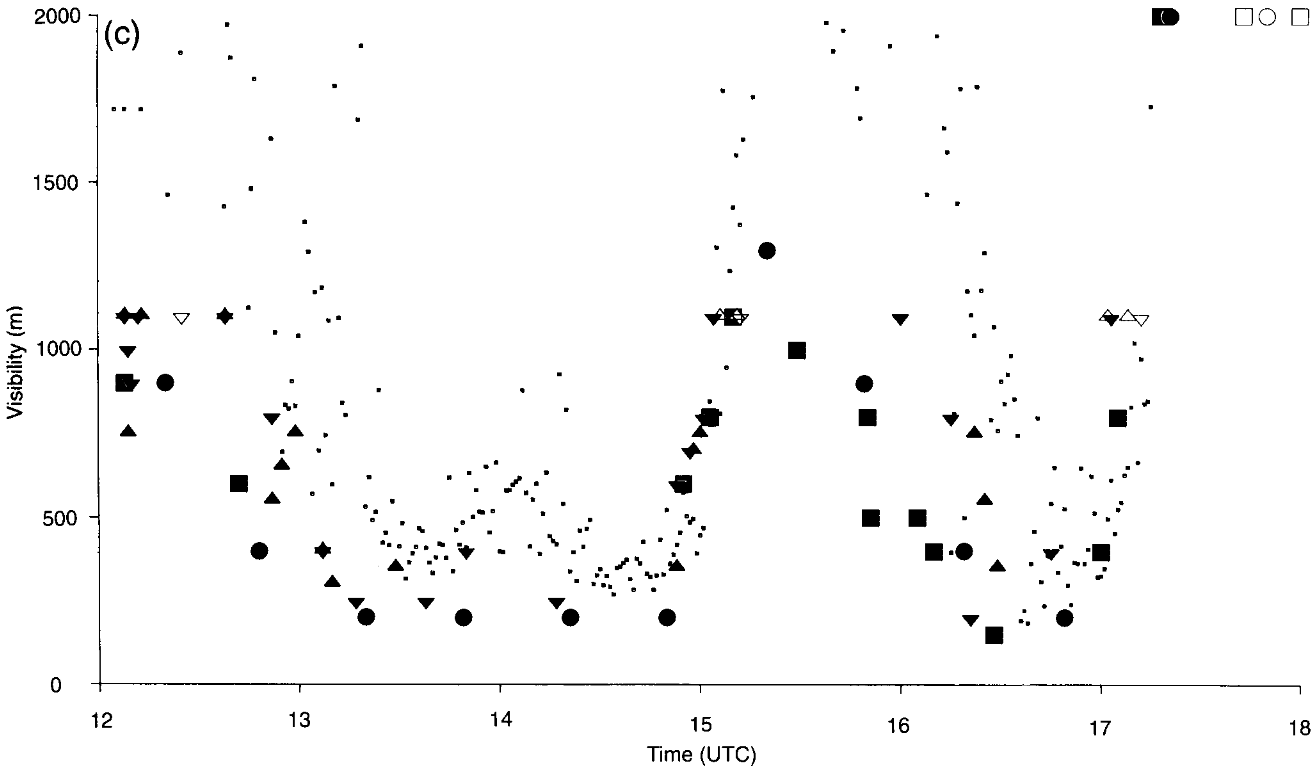


Figure 6. Comparison of visibility assessments and measurements at Ronaldsway. (a) 14 March 1991, 1700–2300 UTC, (b) 13 March 1991, 0300–0900 UTC, (c) 11 March 1991, 1200–1800 UTC, and (d) 12 March 1991, 0600–1200 UTC. Key: ▪ MOR calculated from EC measured by FSM: ● Meteorological visibility estimated by observer in routine reports: ■ meteorological visibility in special reports by the observer to ATC: ▼ manual RVR assessment from 09 ROP: ▲ manual RVR assessment from 27 ROP. Open symbols indicate FSM/observer values >2000 m and RVR values >1100 m.



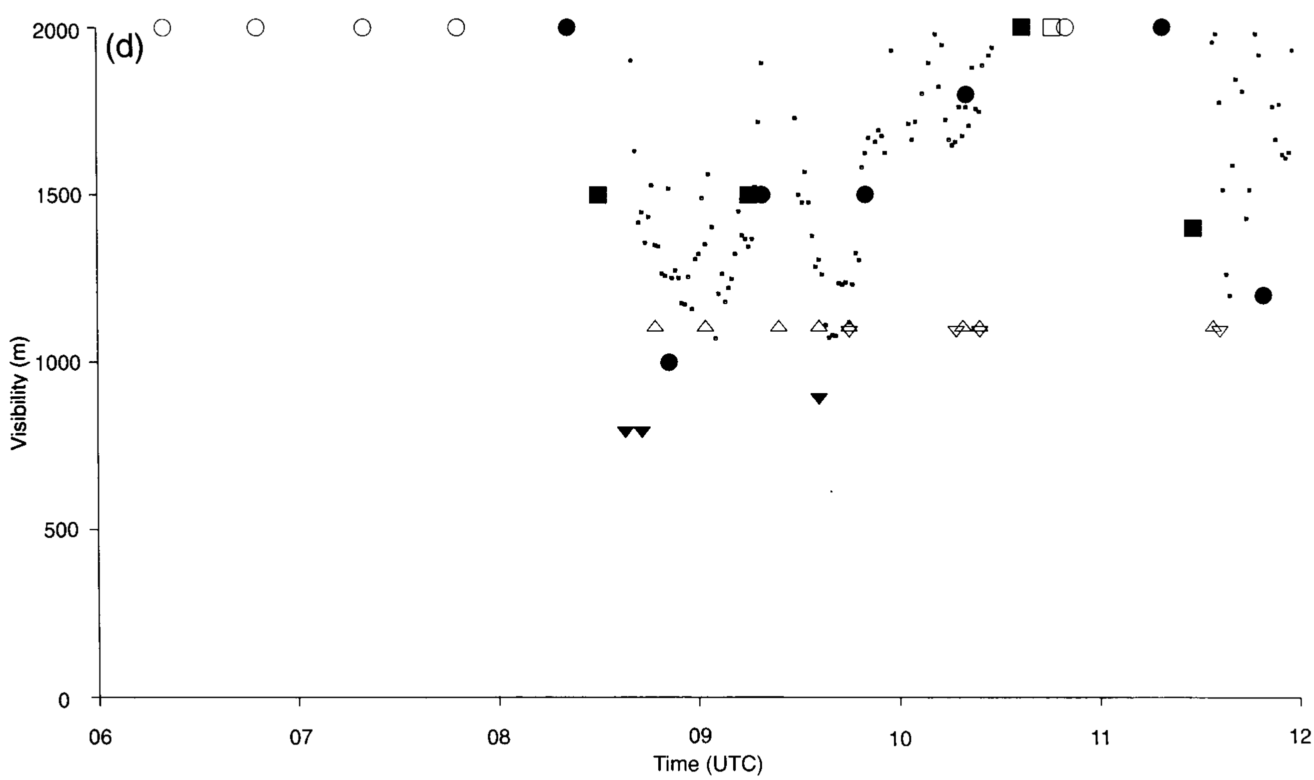


Figure 6. Continued

5. Conclusion

Overall, the variations in assessments and measurements of low visibility during the selected periods can be explained in terms of the physical behaviour of fog at Ronaldsway. Whenever possible the movement of thicker patches of fog around the airfield was observed, in particular as variations occurred in the vicinity of the FSM. Subjective assessment by experienced observers indicated that the FSM was performing very well at all times, and responding quickly to variations in visibility within its sample region. After initial calibration and cleaning of the optical surfaces, no maintenance was required for the duration of the test.

The preliminary report on the First WMO International Intercomparison of Visibility Measurements concluded that 'The useful range of most of the forward-scatter devices is clearly much greater (than transmissometers), although there is some doubt about their accuracy, particularly at low visibilities. However, their general level of serviceability and apparent lack of sensitivity to optical contamination suggest a useful role in remote operation in support of synoptic meteorology.' However, in the results presented for 10 forward-scatter devices employed in the test, the HSS version does appear to perform well at visibilities around and below 1000 m, with deviation from 'standard' generally less than that of the human observer. This would suggest that the discrepancies of some of the other forward-scatter instruments might be reduced by modifying the calibration coefficients (the prototype HSS FSM was calibrated against standard FAA approved transmissometers at the USAF Geophysical Laboratory on Cape Cod, Massachusetts, over an extremely wide range of fog and haze situations).

This test provides further evidence that FSMs can perform reliably in harsh conditions and supports their lack of sensitivity to optical contamination (which is important for a coastal station where airborne salt deposition can be a serious problem) and ease of calibration. The HSS instrument appears to measure visibility in its sample region comparable with the assessment of a human observer, both in daylight and in darkness. Due to the fact that such sensors can be frangibly mounted much closer to the runway edge (near the touchdown zone) than the existing ROPs they would more closely fulfil the aims of RVR measurement as 'the best possible assessment of the range over which the pilot of an aircraft on the centreline of a runway can see the runway surface markings or lights'. However, due to the sensitivity of such instruments to variations in visibility it might be worth considering the application of 2- and/or 10-minute digital averaging to RVR reports (in the manner that ICAO requires averaging of surface wind reports).

Acknowledgements

Thanks are due to Mark Stephens-Row of Bristol Industrial and Research Associates Ltd. for the loan of the instrument, to Andy Roberts for processing the data, to Brian Rae for helpful comments and to many Airport staff for obtaining the non-instrument data and for assistance with the installation.

Appendix

Since there are probably few remaining practising meteorologists who have been involved with manual RVR calibration, it is perhaps worth briefly explaining how RVR assessments are made (in the United Kingdom the responsibility for RVR calibrations now rests with the Civil Aviation Authority).

RVR is defined (ICAO Annex 3) as 'The range over which the pilot of an aircraft on the centreline of a runway can see the runway surface markings or the lights delineating the runway or identifying its centre line'. The Eighth Air Navigation Conference (Montreal, 1974) developed the definition, recommending that 'Since, in practice, the runway visual range cannot be measured directly on the runway and in view of other limitations imposed by observation methods, a runway visual range observation should be the best possible assessment of the range over which the pilot of an aircraft on the centreline of a runway can see the runway surface markings or the lights delineating the runway or identifying its centreline. For this assessment a height of approximately 5 metres should be regarded as corresponding to the average eye level of a pilot in an aircraft.' At Ronaldsway, this is achieved by placing the RVR observer on top of a fire tender (to approximate the 5 m eye level) at a safe distance to one side of the runway (actually around 100 m to the south side of the main east–west runway) as close as possible to the 09 and 27 touchdown points.

Calibrations are normally carried out by meteorological staff every three years, or when changes are made to the runway lighting system or RVR observers' position. The procedure is carried out in darkness in conditions of good visibility (more than 20 km). The runway edge lights (RELs) are fitted with covers and the lighting system turned on. The observer stands on top of a fire tender positioned on the centreline of the runway. Each REL to be used for RVR assessment is uncovered in turn, and the observer uses a Gold visibility meter to measure the apparent brightness of each REL from the centreline position. The readings are used to calculate an equivalent extinction visibility (EEV, the equivalent daylight visibility if the atmospheric transmittance was reduced to the value measured by the meter for the REL to be just visible) for each REL from that position. The observer then moves to the normal ROP and the procedure is repeated to obtain EEVs for each REL from that position. A graph is then plotted of the distance of each REL from the observer against corresponding EEV for both the centreline and ROP readings, from which a table is constructed relating the number of RELs visible from the ROP to the corresponding centre line RVR. In practice, complete calibrations are produced for RELs on the opposite side of the runway to the ROPs only, for intensities set at both 30% and 100%.

In operational use, whenever the visibility falls below (or is forecast to fall below) 1500 m, an observer is positioned at each ROP and counts the number of appropriate RELs visible. This information is passed by radio to Air Traffic Control, where the calibration graphs are used to estimate the corresponding RVR.

There are problems with this system at Ronaldsway due to the fitting of flush lights in the runway intersection area which are unsuitable for use in assessing RVR, leading to large increments in the values reportable, especially in the region critical for minimum operating conditions for modern aircraft. Also, undulations in the profile of the main runway make the RVR assessments available using RELs for runway 09 very limited, with a large gap around the critical take-off minima. Also, the advection fog which affects Ronaldsway is sometimes accompanied by strong cross-winds which, as well as making life difficult for pilots, makes the RVR observer's position more hazardous!

Glossary of terms

Visibility or meteorological visibility (MV): By day, the greatest distance at which a black object situated near the ground can be seen and recognized, when observed against a background of fog or sky. By night, the greatest distance at which lights of moderate intensity can be seen and identified.

Fog: Conditions of meteorological visibility less than 1000 m.

Transmittance: The relative intensity which remains in a beam of light after traversing a path of given length through the atmosphere.

Extinction coefficient (EC): The relative attenuation of a light beam due to scattering and absorption in passing through a certain distance of the atmosphere.

Meteorological optical range (MOR): The length of path through the atmosphere required to attenuate a beam of light to 5% of its initial intensity. MOR approximates visibility (MV), but it can be measured instrumentally whereas visibility cannot.

Visual range (VR): The maximum distance at which an object or light is just visible under particular conditions of transmittance and background lighting.

Runway visual range (RVR): The range over which the pilot of an aircraft on the centreline of a runway can see the runway surface markings or the lights delineating the runway or identifying its centreline.

Koschmieder's Law: An equation which relates the illumination of an object against its background when nearby, compared to the same object viewed at a distance. Used to determine visual range by day, it enables MOR to be calculated from a measured value of extinction coefficient.

Allard's Law: An equation which relates the illumination produced at some point by a distant light to the intensity of the light source and the transmittance of the intervening atmosphere. Employing the visual threshold of illumination of the eye (for a light source to be just visible), it applies to the visual range of lights.

Gold visibility meter: A simple visual photometer which measures the apparent brightness of a distant light of known intensity, and hence the transparency of the intervening atmosphere. It consists of an eyepiece sliding over a variable density filter. In use, the eyepiece is moved along the filter (from the more transparent end towards the less) until the light observed is almost extinguished, and the position of the eyepiece noted on the scale of filter density, which is calibrated in units relating to transmittance (nebules).

Equivalent extinction visibility (EEV): Used in the manual RVR calibration. The observer uses the Gold visibility meter in conditions of good atmospheric visibility to obtain the value of filter transmittance required to almost extinguish a distant light. The value is used to calculate what the equivalent daylight visibility would be if the atmospheric transmittance was reduced to that value (for example, by mist or fog).

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The winter of 1991/92 in the United Kingdom

G.P. Northcott
Meteorological Office, Bracknell

Summary

The winter of 1991/92 was generally mild and dry with about average sunshine, although quite sunny in many eastern areas and dull in the far north and west.

1. The winter as a whole

Mean temperatures were above normal nearly everywhere and ranged from 2.2 °C above normal at Kinlochewe, Highland Region to just below normal at Chivenor, Devon. Winter rainfall amounts were above normal in central and western parts of Scotland and Northern Ireland, but below normal elsewhere, ranging from more than 150% of normal along the Great Glen to less than 30% in the London area. Snowfall was less than normal generally, but particularly so in the south. Winter sunshine amounts were generally about average over England and Wales, but below average over Scotland and Northern Ireland. However, that statement fails to show the contrast between the quite sunny winter on the east coast and the very dull winter in the Western Isles.

Information about temperature, rainfall and sunshine during the period from December 1991 to February 1992 is given in Fig. 1 and Table I.

2. The individual months

December. Mean monthly temperatures were generally below normal in southern and eastern areas but above normal elsewhere, ranging from about 1.5 °C above normal in north-west Scotland to 1 °C below normal in East Sussex. Monthly rainfall amounts were below normal over the United Kingdom as a whole, and much of southern England and South Wales had less than half the normal rainfall amount, with as little as 14% of average falling at Odiham, Hampshire. In contrast, 144% of average rainfall fell at Holme Moss, West Yorkshire. The provisional rainfall value for England and Wales for the month makes it the driest December since 1988. Northern Ireland had the wettest December since 1986, ending a sequence of five dry Decembers. Monthly sunshine amounts were above average in many eastern areas, but generally dull in northern and western areas, exceeding 140% of average in the London area and around Tyneside, but with less than 40% of the average sunshine in much of the Scottish Highlands. Northern Ireland reported the dullest December, together with December 1981, since 1977.

Most parts of the United Kingdom had dry weather during the first two weeks. Over England and parts of southern and central Scotland a combination of very light winds and clear skies overnight produced some severe frosts between the 11th and 16th. The cold weather gave way gradually on the 16th and 17th to mild moist

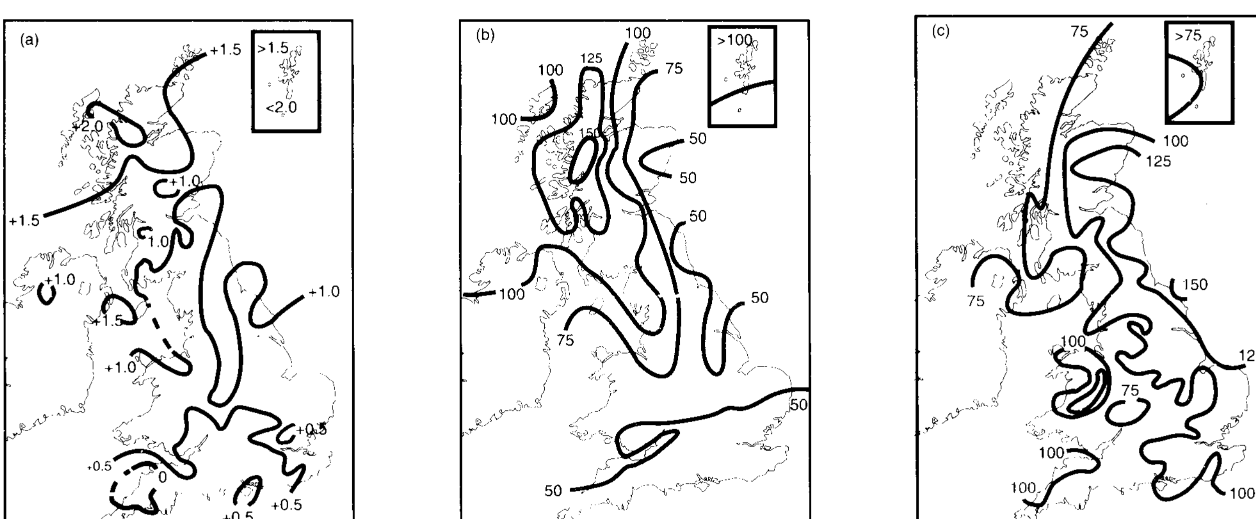


Figure 1. Values of (a) mean temperature difference (°C), (b) rainfall percentage and (c) sunshine percentage for winter, 1991/92 (December–February) relative to 1951–80 averages.

Table I. District values for the period December 1991–February 1992, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+1.6	−2	128	68
Eastern Scotland	+1.2	−6	80	107
Eastern and north-east England	+1.0	−6	66	115
East Anglia	+0.7	−7	53	105
Midland counties	0.0	−7	63	85
South-east and central southern England	+0.5	−7	37	107
Western Scotland	+1.3	−1	131	77
North-west England and North Wales	+1.0	−2	84	99
South-west England and South Wales	+0.3	−8	52	95
Northern Ireland	+1.3	−4	103	71
Scotland	+1.3	−3	119	84
England and Wales	+0.7	−6	61	101

Highest maximum: 15.1 °C in east and north-east England in December.
Lowest minimum: −11.2 °C in western Scotland in January.

Atlantic air, bringing rain to many places; a thunderstorm was reported at Prestwick, Strathclyde Region and hail showers were reported in south-west England and South Wales on the 20th. Heavy rain on the 21st accompanied by gale-force winds washed away bridges, flooded roads and blocked railways, particularly in the areas of Sheffield, Manchester, the Severn Valley and the Welsh Marches; during the following 36 hours occasional rain continued to affect many areas, often accompanied by strong winds. It continued unsettled for the next few days as very disturbed and windy weather with bands of rain advancing from the west alternated with sunshine and showers until the 24th, when settled weather returned to much of the United Kingdom. Many parts became unsettled once more on the 31st. On the 31st winds were very strong over northern parts of the United Kingdom and several places in northern Scotland recorded gusts over 60 kn: at Butt of Lewis, Western Isles a gust of 96 kn was recorded during the late evening, equalling the record for December set at Stornoway and Benbecula, Western Isles in 1956 and at St Mary's, Isles of Scilly in 1935.

January. Mean monthly temperatures were generally above normal in northern Scotland and about normal over much of England and Wales, but below normal over south-west England, ranging from 2.3 °C above normal at Baltasound, Shetland and Kinlochewe, Highland Region to 1.2 °C below normal at Chivenor, Devon. Monthly rainfall totals were below normal everywhere, except central Scotland and an area of the Midlands from Hereford and Worcester to Cambridgeshire, where rainfall was above normal, and ranged from more than 222% at Fort Augustus, Highland Region to 16% at Bexhill, East Sussex. Monthly sunshine amounts were above average over much of eastern Scotland and north-east England, the east Midlands, East Anglia and south-east England, western Wales and southern coastal counties of England and below average elsewhere, ranging from 228% at Cwmystwyth, Dyfed to 43% at Stornoway, Western Isles.

The month started unsettled, with strong winds, heavy rain and hail, mainly in northern and western areas of Scotland, the rain turning to sleet in many places and to snow over high ground. Gales, locally severe, came to northern and western areas between the 1st and 3rd. A number of stations measured gusts in excess of 70 kn on the 1st, including a gust of 93 kn at Kirkwall, Orkney, and two of 78 kn at Lynemouth, Northumberland. Outbreaks of very heavy rain in places on the 1st resulted in extensive flooding and disruption to traffic, especially in western Scotland. Over Northern Ireland it was wet until the 8th and then mostly dry. England and Wales remained generally cloudy, but dry, with some lengthy bright periods; however, rain came to many places in southern England overnight on the 7th/8th. On the 19th and 25th small amounts of rain fell in all areas overnight. On the 26th, the pressure rose, reaching 1049 hPa in North Wales, to give the highest January pressure for 30 years over England and Wales. On the 28th northern Scotland had very small amounts of rain.

February. Mean monthly temperatures were above normal everywhere, ranging from 3 °C above normal at Inverness, Highland Region and Haydon Bridge, Northumberland to 0.6 °C at Plymouth, Devon. Monthly rainfall amounts were above normal over much of Scotland apart from the eastern coastal areas and over parts of North Wales, Merseyside and Northern Ireland, but below normal elsewhere, ranging from 283% of normal at Isle of Rum, Highland Region to less than 25% of normal in parts of Cambridgeshire. Monthly sunshine amounts were above average in eastern areas and below average in western areas, ranging from 171% of average at Whitby, North Yorkshire to less than 40% of average at Poolewe, Highland Region.

The month was generally unsettled and mild, with periods of rain or showers, heavy at times, mainly in the north and west, the rain largely dying out over East Anglia and the south-east. While conditions became somewhat more settled in southern areas around the 15th, northern areas remained unsettled with snow and sleet or wintry showers. On the 17th, after a cold sunny start in most places, a band of rain, sleet and snow spread slowly eastwards, affecting most areas by evening; the precipitation was heavy in places. Heavy snow in the Midlands led to some severe road conditions for a time on the 18th. The unsettled weather continued over the next ten days, with a change to more settled weather in southern ares on the 28th. Thunder was reported at Cape Wrath, Highland Region on the 2nd, Aberporth, Dyfed on the 12th and Manchester on the 13th, while hail was reported in West Yorkshire on the 10th and over Shetland on the 24th.

Awards

Due to an administrative oversight the 1990 awards below were omitted last year. Our apologies are extended to all concerned.

L.G. Groves Memorial Prizes and Awards for 1990

Meteorology Prize — Dr M.J.P. Cullen

The citation for this award was:

'The unexpected cancellation of the contract for the ETA-10 supercomputer, and its replacement at the end of 1989 by a Cray YMP computer led to a fundamental reappraisal of the Office's plans for its new operational forecasting model. Dr Cullen took the lead in planning and managing the project. The new model, known as the Unified Model because it meets the needs of both operational forecasting and climate research, has been constructed in a versatile and flexible way that allows it to be reconfigured to suit particular requirements; it can be run as an atmosphere model, as an ocean model or as a coupled atmosphere–ocean model; it can be run as a global model or as a limited area regional model; it can be run as a forecast model or as a data assimilation model. Internationally agreed coding standards have been followed throughout; this means that, for the first time, it will be possible to exchange software between other major national weather services and to set up fruitful cooperative research and development projects. Dr Cullen's personal scientific input to the project has provided very efficient energy conserving techniques for solving the model equations; he has also developed still more accurate methods that will be tested in the near future. His tight management of a large team drawn from three Divisions in the Office and his decision to use the PRINCE methodology for project control and quality assurance (the first time it has been used for an Office project) has allowed the model to be developed and introduced more smoothly and within a shorter time-scale than has been possible for similar exercises in previous years. The model is already producing more accurate forecasts than before for many weather features, and its clearly designed and well documented structure is ideal for permitting further development and improvement in the future.'

Meteorological Observation Award — J. Gloster

The citation for this award was:

'The impact which John Gloster has had on MRF is most easily seen in the number of hours flown by the C-130. In 1988/89 this was 75; in both 1989/90 and 1990/91 it has been over 500. Much of the credit for this must go to John, who has developed closer liaison (particularly with RAE and RAF Lyneham) to give MRF a C-130 for scientific flying.

John has been extremely effective at organizing the many international detachments, so that the airborne scientists can concentrate on the research without worrying about the details of logistics which can often make or mar a detachment. In the recent Gulf detachment, he (together with OC MRF) visited a number of the Gulf states to obtain diplomatic clearance for the MRF to operate in record time.

Part of his success undoubtedly lays in his affable personality and positive attitude, but mainly it comes from hard work and application.'

L.G. Groves Memorial Prizes and Awards for 1991

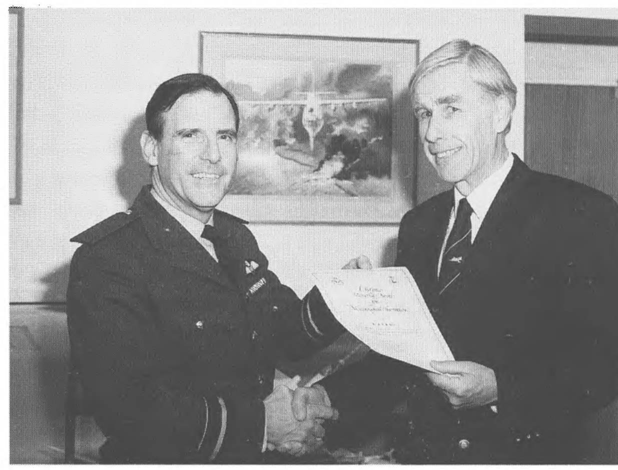
Meteorology Prize — C.K. Folland and D.E. Parker

The citation for this award was:

'Over a number of years Mr Folland and Mr Parker have led the painstaking work of assembling and analysing sea surface and air temperature data measured from ships over the period from the middle of the last century to the present day. Of particular note is their recent, unique work, on the theoretical and experimental estimation of corrections that need to be applied to sea surface temperature data collected from uninsulated (mainly canvas) buckets in widespread use prior to the 1940s, and also new corrections to air temperature data. The resulting sea surface and air temperature data sets provide the most comprehensive and consistent record currently available of changes of temperature at the global ocean surface over the last 130 years. This is particularly important for the assessment of the observational evidence for climate change (e.g. due to the greenhouse effect) and for devising methods of seasonal forecasting, especially for the semi-arid tropics.

On the basis of this work, Mr Folland and Mr Parker have made major personal contributions to the scientific assessment of observed climate variability and change, published in the 1990 Report of the Intergovernmental Panel on Climate Change, and in the Supplementary Report produced for the 'Earth Summit', held in Rio de Janeiro in June 1992. The cited work also led to the publication of a much needed and highly regarded Global Ocean Surface Temperature Atlas, in conjunction. with other scientists in the Meteorological Office and at MIT, Boston.'

Meteorological Observation Award — P.G.W. Healey



The citation for this award was:

'Mr Healey has been concerned with the measurement of the atmosphere by sondes dropped from the Meteorological Research Flight C-130 for the last 14 years, and his work has contributed directly to the success of the 1987 and 1992 campaigns for measuring the detailed structure of frontal systems. During this time he has mastered the technical difficulties of ejecting and tracking multiple sondes from an airborne platform while ensuring the quality of the measurements, by maintaining careful control of the manufacture, calibration, deployment, reception and post flight validation of the dropsondes. He routinely flies with the aircraft when sondes are being deployed and it is his skill in organizing the deployment of the sondes and in monitoring their measurements that has led to the current very high success rate in the use of this system during recent campaigns.

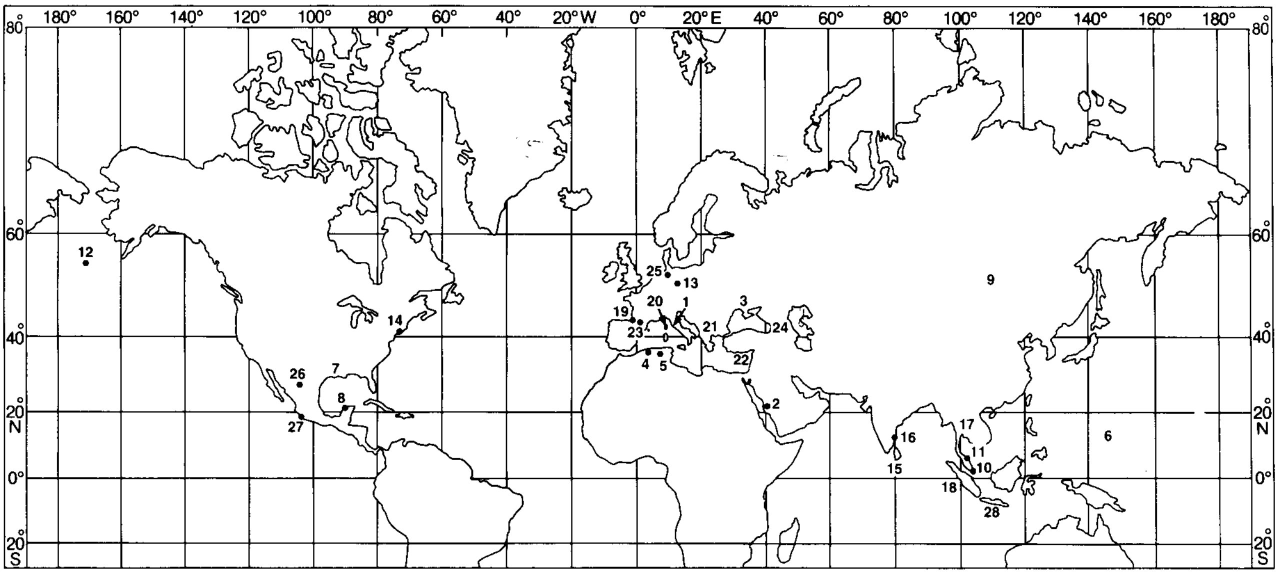
He has developed a system on the aircraft for receiving and decoding the sonde measurements in real-time and for displaying plotted profiles on request to the mission scientist. This facility has greatly increased the effectiveness of scientific research by allowing the mission scientist to optimize the flight pattern in the light of actual conditions.

He is currently working on the deployment of a highly automated, low cost, lightweight sonde, which will enable soundings to be taken routinely during scientific flights of the MRF C-130. This development will further enhance the contribution of the MRF C-130 scientific programme to improving the accuracy of weather forecasting models.'

World weather news — November 1992

This is a monthly round-up of some of the more outstanding weather events of the month, three months preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and in the 'Casualty Reports' pages of Lloyd's List. *Naturally these are heavily biased towards areas with a good cover of reliable surface observations. Places followed by bracketed numbers in the text are identified on the accompanying map. Spellings are those used in* The Times atlas of the world.



Location of places mentioned in text

1	Tuscany, Florence	11	Kota Baharu	20	Corsica
2	Jiddah, Makkah	12	St. Paul	21	Albania
3	Ukraine	13	Leipzig	22	Cyprus, Adana
4	Alger	14	New York	23	Tarbes
5	Constantine	15	Sri Lanka	24	Dagestan
6	Guam	16	Madras	25	Hamburg
7	Louisiana, Houston	17	Thailand	26	Chihuahua
8	Merida	18	Sumatra	27	Manzanillo
9	Lake Baikal	19	Biarritz	28	Jawa
10	Singapore				

The month began with a report that Florence (1) had its wettest October on record. Although the city centre escaped the floods, the river Arno did flood its northern suburbs; flooding was widespread throughout Tuscany (1) and the worst since 1966 costing an estimated \$745m. The disturbed weather continued into this November with Rome having strong winds and more than 60 mm of rain on the 2nd. A less likely candidate for heavy rain is Saudi Arabia, but on the 2nd and 3rd high winds and thunderstorms gave Jiddah (Jedda) (2) 42 mm and Makkah (Mecca) 83 mm in a few hours; their November average is about 10 mm.

Another unusually wet place at the start of November was the west of Ukraine (3) where heavy rains and snowfall created the worst floods for decades which killed eleven. A small low moving along the North African coast gave Alger (Algiers) (4) 93 mm (November average 85 mm) and to Constantine (5) 84 mm.

An unwelcome leftover from October was typhoon 'Elsie'. She passed about 30 miles south of Guam

(6) (causing the local elections to be postponed but only minor damage). By the 5th she was rated a super-typhoon with central pressure down to about 900 hPa and with winds of 150 kn gusting 180 kn. The storm was diminishing as it passed safely offshore of Japan but managed to dislodge some 4000 tree trunks from the deck of a bulk carrier 180 n mile east of Tokyo.

The USA got off to a bad start (a sign of what was to come) when a cold front entered Louisiana (7) on the 3rd bringing high winds, golf-ball size hail and at least one tornado which did about $25m damage in the Shreveport–Bossier City area. Totals of 70 to 100 mm of rain were not rare in other states and the temperature fall was about 16 °C as the front passed. Part of the trouble seems to have been persistent high temperatures (often above 30 °C) around the Gulf of Mexico which gave the air great moisture-bearing capacity: Merida (8) in the Yucatan got 106 mm in 6 hours followed by 22 mm in the next six (their November average is 34 mm).

Another long-term trouble maker was the Siberian High: its central pressure got up to nearly 1063 hPa around Lake Baikal (9) on the 6th with temperatures about −10 °C by day and −30 °C by night. This cold air spread south over the next few days, reinforcing the NE Monsoon and generating some big rainstorms. Many places in Indonesia and Malaysia were to have 100 mm or more of rain from the system which caused temperatures over China to fall from about 30 °C to near zero. Singapore's (10) heavy rain and thunderstorms produced 210 mm in the 36 hours up to 1200 UTC on the 11th; Kota Baharu (11) on the east coast of Malaya got 152 mm in 6 hours and 311 mm in 24 hours. The floods drowned five in Tregganau and Kelantan states.

A fascinating item was reported on the 9th, the island of St Paul (12) in the Bering Sea had its first thunderstorm since 21 November 1951! On the 11th and nearer home, an intense depression crossed southern England into northern Europe with gales near and to the south of the centre. Mean speeds of 40-45 kn were recorded and noteworthy gusts were 62 kn at Brüggen (NW Germany) and 89 kn on the Brocken (100 miles west of Leipzig (13)). The storm brought down trees and power lines, disrupting road and rail transport. The East Scheldt storm barrier was closed for only the twelfth time since its completion in 1986.

Disasters now struck 160° longitude apart on the 12th at 80° E and W. The first does not seem to have cost any lives but did great damage to property. This was a slow-moving cold front over central and southern states of the USA. Heavy rain and severe thunderstorms were accompanied by gusts of up to 60 kn in Kentucky, Ohio, Pennsylvania and New York (14) states. Mobile, Alabama got 76 mm in a few hours and New Orleans 46 mm (here the total for the month so far was 223 mm, twice the monthly average). The worst event of November began when cyclone '10B' appeared just east of Sri Lanka (15) on the 12th. It was soon crossing the island killing 13 with falling trees and damaging thousands of homes with floods and landslides. Emerging almost unscathed by this experience the cyclone wound up to about hurricane intensity and dawdled around the southern tip of India and up the west coast. Over the next few days many places in Tamil Nadu and Kerala had over 200 mm of rain (Madras (16) 271 mm): the massive rainfall filled dams to overflowing and caused flooding and landslides which claimed at least 250 lives and rendered some 25 000 homeless. Kochi Airport was closed on the 14th by knee-deep floodwater on the runway. Huge seas damaged the breakwaters of the port of Tuticorin and closed it pending a hydrographic survey.

Tropical storm 'Forrest' developed on the 12th, it failed to reach typhoon strength but frightened workers of the offshore natural gas fields before it went ashore on the 15th and caused a lot of flooding in southern Thailand (17). The main reported casualty was the crash of a Vietnam Airlines YA4-40 in Khanh Hoa province on the fringe of the storm, 30 died and one survived. A lighter note was struck when, heeding the warnings of 6 m waves, fishermen closed the main road by hauling their boats onto it, the safest place! 'Forrest' drifted round the Bay of Bengal as a tropical depression before making his second landfall at 0900 UTC on the 21st on the Burma/Bangladesh border. Following these storms the NE Monsoon eased off in Malaysia (Kuantan (between 10 and 11) had 464 mm between 15th and 19th with 301 mm on the 16th) and temperatures rose to record highs: Rangoon's 37.5 °C on the 20th was 2.5 °C above the November record and Padang (Sumatra (18)) 1.5 °C above. 'Gay' appeared on the Dateline near the equator on the 15th and cruised steadily west-north-west. A typhoon by the 18th and super-typhoon by the 19th with winds gusting up to 190 kn, this exceptional storm headed for the North Marshall and North Marianas Islands. One third of the former was made a disaster area (no details available). In the latter group Guam had its second strike of the month; although winds were over 100 kn there were no reports of severe damage, perhaps because there was little rain with it. (Earlier Guam had had a near miss from 'Hunt' as it strengthened to a typhoon on the 18th.)

A push of cold air into the eastern Mediterranean on the 13th and 14th gave 40 mm of precipitation over much of 'Yugoslavia' with the rain turning to snow as the temperature fell to freezing and compounding the misery of its unfortunate inhabitants. A northerly gale in the Aegean reminded locals there that winter had arrived.

Back home on the 17th, a trough from Iceland to the Strait of Dover drove cold air south-east across most of south-west Europe. The cold front was preceded by 25 mm of rain in many places which turned to snow over hills. The NW wind was very strong with gusts of 60 kn in NW France and 54 kn at Biarritz (19). The strongest winds seem to have been around the north and west coasts of Corsica (20), Cap Corse having a mean speed of 52 kn with a gust to 82 kn. As is often the case in these situations a low formed in the lee of the Alps and helped maintain the activity of the front. The eastern side of the Adriatic was doused with about 50 mm of rain and eventually the river Mali broke its banks in the north of Albania killing 11 and making 35 000 homeless. As the low had drifted round the southern end of Greece its front transferred its attentions to the eastern Mediter-ranean. On the 21st Cyprus (22) had high winds (gusts to 42 kn in Paphos) with floods in Limassol and landslides in the Troodos mountains. Adana (22) in Turkey received 108 mm in 36 hours while Antalya's 125 mm in 24 hours should be compared with their November average of 119 mm.

The return of warm, moist westerly flow to southern Europe brought avalanche threats to the Alps where on the 22nd La Dole, at about 1500 m, had 56 mm of rain. The air was further warmed by descent in the lee of mountains and Tarbes (23), on the French side of the Pyrenees, had one of its highest ever November temperatures at 27.6 °C. The boundary between the warm and cold air masses generated a low which rushed south-east and deepened rapidly as it crossed Turkey; the result was gales and widespread heavy rain in the eastern Mediterranean with 25–50 mm of rain over much of Israel, Lebanon and Syria on the 23rd. The last fling of this low was to give heavy snow and then a rapid thaw in the Caucasus, the Russian region of Dagestan (24) being badly affected by the resulting avalanches and floods.

The weekend of 21st/22nd brought the third catastrophe of the month to central USA, one of the severest tornado outbreaks for many years with some ground tracks as long as 30 miles. The tornadoes were accompanied by torrential rain (50 to 100 mm) and marble-size hail. Twenty-seven were killed and more than 400 injured. Insurance claims of $425m include damage at West Houston Airport (7) where a tornado scored a direct hit on a hangar destroying 15 private planes and severely damaging another eight.

After a series of intense Atlantic depressions had curved north to Iceland, the last, on the 26th, raced almost due east along the English Channel to the southern Baltic. Winds reached 50 kn widely over north France, the Low Countries and Germany with 66 kn at Brussels and 72 kn at Vlissingen causing considerable damage to property. There was a fair amount of excitement in the port of Hamburg (25) as tugs struggled to control larger vessels.

A renewed surge of cold air across the USA brought blizzards to the Great Plains and Lakes with ten killed as level snow depths reached 50 cm in places. The effect in Mexico was dramatic: on the 27th Chihuahua (26) had a frost followed by a daytime maximum of 9 °C, in the warm air Monzanillo (27) had a new November record of 38.8 °C.

At the end of the month, Jawa (28) and the surrounding area was starting its wettest season and daily rainfall totals included 199 mm at Semarang and 133 mm at Madium were reported on the 25th. On the other side of the world, New Orleans, Louisiana (November average 96 mm) had accumulated 387 mm by the 29th. By contrast, Riverside in California had its first completely dry November since 1956.

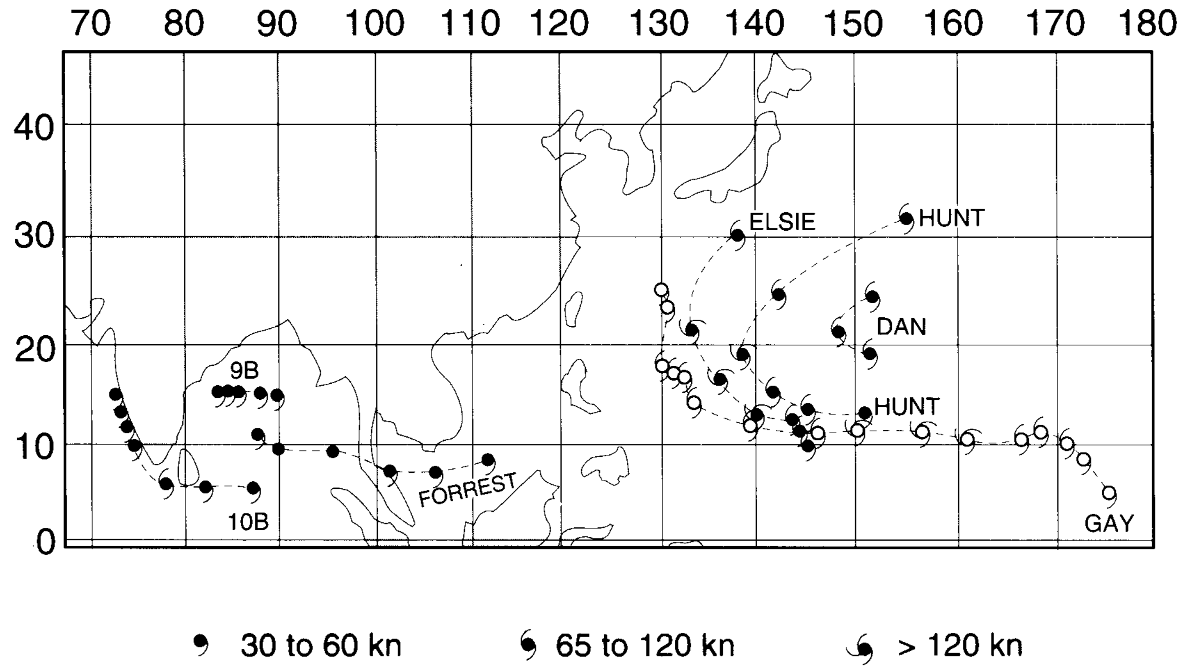
Over the United Kingdom November was mild and wet. The Central England Average Temperature was one and a half degrees higher than normal (the mildest since 1978): further north temperatures were nearer normal. Rainfall totals were above average everywhere and nearly double the average in south-east England. It was particularly wet in South Wales towards the end of the month with around 100 mm in last two days.

October tropical storms

List of tropical storms, cyclones, typhoons and hurricanes active during November 1992. The dates are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during its lifetime. The map shows 0000 UTC positions during November, the symbols for 'Gay' have been left unfilled to distinguish its track from 'Elsie's' and 'Hunt's' which it crossed.

No.	Name	Basin	Start	End	Max.
1	Dan	NWP	24 Oct.	3 Nov.	115
2	Elsie	NWP	29 Oct.	7 Nov.	150
3	Forrest	NWP	12 Nov.	18 Nov.	70
4	Gay	NWP	15 Nov.	30 Nov.	160
5	Hunt	NWP	16 Nov.	21 Nov.	125
6	9B	NI	3 Nov.	7 Nov.	55
7	10B	NI	11 Nov.	17 Nov.	70

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific: I — Indian Ocean; WI — west Indian Ocean.



Reviews

Perspectives of nonlinear dynamics

(Volumes I and II), by E.A. Jackson. 188 mm × 247 mm, pp. xix + 496 (Vol. I), *illus.*, pp. xvii + 633 (Vol. II), *illus.* Cambridge University Press, 1992. Price £19.95 (per Volume). ISBN 0 521 42632 4 (Vol. I), 0 521 42633 2 (Vol. II).

According to the author, these two books are intended to access non-mathematicians to the methods and viewpoints of the ever-growing field of non-linear dynamics. Collectively the two books certainly achieve their goal, introducing various concepts with a readable text that places emphasis on the idea and application rather than the mathematical detail. The material is presented, despite its technical nature, like a mathematical history book, providing the reader with a fascinating chronological account of many important mathematical discoveries.

Broadly speaking, the 500 or so pages of Volume I are concerned with 1st- and 2nd-order differential systems and 1st-order difference systems. Jackson begins by defining non-linear phenomena and non-linear dynamical systems and then moves on to such elementary concepts as phase and control space, phase portraits, Poincaré maps, stability, dimension and measure, bifurcations and catastrophes. He then demonstrates these ideas with specific non-linear systems, introducing further concepts such as ergodicity, period doubling and chaos, and emphasising the differences in behaviour between continuous and discrete time-systems. His exposition is elementary, and uses many well-known equations from all areas of science, including those of van der Pol and Lotka, as examples of continuous time systems, and the logistic and tent maps of discrete time systems.

Volume II continues the story moving from 2nd-order difference equations to 3rd- and higher-order differential systems, on to partial differential equations and solitons, and finally treating coupled maps and cellular automata. In a little over 600 pages, Jackson covers a vast amount of advanced material, including AM theory, lattice maps, dynamic entropies, Lorenz dynamics, integrability, FPU phenonema, solitons, chemical oscillations, cellular automata and the dynamics of living systems. This he does with constant reference to physical models and related experiments, each carefully explained with the general scientist in mind.

The two volumes have identical presentation and the references and indexing in each covers both volumes. Each chapter begins with an introduction and recap of ideas and concludes with hints and answers to the elementary exercises contained within. Many mathematical terms and concepts are left to a glossary and appendices at the back of each volume. There are plenty of clarifying illustrations, although some are perhaps unnecessary, and, since they are in text, definitions and theorems are often difficult to isolate. A large number of references are made to relevant literature and these are listed both by subject and by author at the back of each volume.

Perhaps the most refreshing aspect of Jackson's approach is the way he uses history to explain the development and refinement of each mathematical method.

This he is well-placed to do, having observed the advent of the computer and the boom of research into non-linear dynamics. He uses this experience to show us how contemporary ideas, some correct, some incorrect, led scientists towards many important mathematical discoveries. For example, in Volume I, he describes the original experiment of van der Pol and van der Mark that led to the discovery of chaos in forced oscillators, and in Volume II he relates how an uncharacteristic mistake by Fermi led to the discovery of FPU recurrence phenonema. This relaxed approach not only makes the learning process more enjoyable, but also shows how research works and therefore serves to inspire and encourage the intended audience.

Together these two books introduce an extensive range of ideas in a lucid and entertaining way and with an unusual number of references to physical models. The treatment of each topic is elementary, but many references are given for further reading. Volume II is more advanced than Volume I, but the lucid style is maintained and most of the mathematical concepts outlined in Volume I are briefly revised, making it mostly self-contained and suitable for a graduate with a basic knowledge of non-linear dynamics. Having said this, the volumes are best read in sequence as the material is arranged so that the dynamical systems are presented in increasing order of complexity.

For the researcher applying mathematics to the field of meteorology, these two volumes will provide a comprehensive introduction to this fast-growing and important field.

S. Baigent

The solar–terrestrial environment, by J.K. Hargreaves. 177 mm × 253 mm, pp. xiv + 420, *illus*, Cambridge University Press, 1992. Price (hardback) £50.00, $79.95. ISBN 0 521 32748 2.

'Almost everyone has heard about astronomy although they might not understand it, and almost everyone knows about meteorology even if they cannot spell it. This book is all about the bit in between.'

This is the latest in the Cambridge atmospheric and space science series and is, in my opinion, far and away the best. In the days when the University of Aberdeen still had an Honours Physics undergraduate class, I taught a 12-hour course on 'Aeronomy'. There is an obvious plan to such a series of lectures and I began with gas laws applied to the upper atmosphere, continuity, radiowave probing of an ionized medium with an embedded magnetic field, Chapman layer, and went on to discussion of the solar wind and magnetosphere, geomagnetic storms and aurorae, ozone layer, water vapour in the upper atmosphere, the exosphere. In assessing the value of any textbook, therefore, I match its content against this syllabus and Hargreaves' book matches up very well. It may be a case of great minds think alike although the sceptic will quote Emerson about 'the hobgoblin of little minds, adored by little statesmen and philosophers and divines.'

Hargreaves' and my paths met in the sixties when we were both employed by the US Government in the large upper atmosphere, ionosphere, magnetosphere laboratories in Boulder (Colorado). He moved to Lancaster, myself to Aberdeen; he retained his research interests in solar–terrestrial disturbances, I moved my interests from airglow to noctilucent clouds (and, yes, these are mentioned in this book). The selection of topics for this book reflects Hargreaves' interests, very much leaning towards the ionosphere and magnetosphere.

The meteorologist will find that the boundary between 'astronomy ... and ... meteorology' is not dealt with in great detail. The transition from meteorology to aeronomy, which in general terms might be placed somewhere between 30 km and 100 km in altitude, is not dealt with in the detail one might expect. The discussion could profitably have been extended to deal with the diffusion of water vapour up through the atmosphere to the exosphere, and the accompanying chemical and ionic changes in balance of hydrogen-containing compounds. This is currently relevant to discussion of the consequences at all levels of the atmosphere of an increase in methane concentration at ground level. As it is, the section on water vapour consists of three sentences and a reference to a couple of sentences later on in the section on the D-region ('... hydrates occur when the water vapour concentration exceeds about 10^{15} m^{-3}').

The book uses SI units (unlike some of the earlier books in this series) and is therefore understandable by the modern student. The print layout is clear and the illustrations are well-chosen. I would not have included 'physical aeronomy' and 'chemical aeronomy' as subsets of 'principles of the ionosphere' and I would have chosen more apposite quotations from the great, the good, and the dead, for chapter headings. These are minor carpings: the book is a good textbook for use by students at finals level, and in the first year of postgraduate work. Principles are well covered, applications described in sufficient detail, and the range of topics approaches comprehensiveness. The book is worth the price. Those who do not want a textbook but an introduction to the science will not be disappointed.

M. Gadsden

GUIDE TO AUTHORS

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Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS1991: Part 1:1976 and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

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Evolution of forecasting for the offshore industry
Rime and hoar-frost deposition
Richardson's Forecast factory
Ozone minima
World weather — December 1992

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The Meteorological Office National Severe Weather Warning Service (NSWWS)

K. Hymas
Meteorological Office, Bracknell

Summary

The NSWWS provides Tier 1 warnings of severe weather to emergency organizations and to the public. Flash Messages are issued within six hours of the event, but Early Warnings, which are sent only to emergency organizations, may be issued up to five days ahead. Tier 2 warnings of hazardous conditions are mostly sent to Police and Fire services and to the BBC Travel Centre. The performance of the service is continually monitored and surveys of recipients are conducted annually. This enables the level of service provision to be improved to take account of developments in forecasting, communications and the views of recipients. This paper describes the service, summarizes the weather over the first two years of operation, and gives actual case-studies.

1. Introduction

After the Great Storm of October 1987 comments were commonplace in the Press criticizing the lack of warning given by the Meteorological Office. The emphasis had changed by October 1990 however, when, after the Meteorological Office forecast further gales, the *Daily Telegraph* reported 'since the storm of October 1987, which forecasters failed to predict, the Meteorological Office has been keen to give as much warning as possible of severe weather'. This shift of opinion by the Press reflects the efforts that the Meteorological Office has made in recent years to develop its severe weather warning service. A system now exists, established in its current form in 1990, which aims to provide the best possible advice to the emergency authorities and the public. It was developed through the Cabinet Office from the pre-existing severe weather Flash warning service to the media, and from the BBC Motoring Unit warning service. It is supplied as part of the government funded Public Meteorological Service.

As Fig. 1 shows, wind is frequently the most destructive type of severe weather since it causes immediate physical damage. The storm of 25 January 1990 resulted in 47 deaths and £2 billion damage to property across a large part of Britain. In the case of heavy and prolonged rain or snow, damage can result from flooding and from the collapse of roofs and electricity cables under the weight of snow. This is in addition to the disruption caused to transport. Foggy or icy conditions also pose a potential danger to life through their impact on travel.

Although damage can also result from the effects of severe thunderstorms, such as strong wind gusts, heavy rain or hail, these are usually localized and of short duration. Severe weather warnings are not routinely issued in

these circumstances. However, thunderstorms can be organized into mesoscale convective systems (MCS) which cover a large area and persist for several hours. Warnings will then be issued under the normal criteria.

2. Organization

There are two tiers of warnings within the NSWWS:

Tier 1 — warnings of severe or exceptionally severe weather

1a: Early Warnings of major severe weather events likely to result in widespread disruption and/or present a danger to life.

1b: Flash Messages of severe weather likely to result in considerable inconvenience to a large number of people and/or present a danger to life.

Tier 2 — warnings of hazardous conditions which might present the emergency authorities with potential operational problems.

Criteria for the issue of warnings are at Appendix A.

Recipients of Tier 1a Early Warnings include the county emergency services, local authorities, some government departments (e.g. Home Office, Cabinet Office, DOE, MOD, MAFF, DTp), and other large organizations, such as BT, which may need to take action to prevent or deal with emergencies arising out of severe weather. They also receive Tier 1b Flash Messages which are sent to radio and television stations for broadcast to the public. Tier 2 warnings are mostly sent to Police and Fire services and to the BBC Travel Centre for inclusion in their motoring bulletins.

Figure 1. The effect of severe weather. Friday 16 October 1987, Westcliff-on-Sea, Essex (top) Westbourne Grove, and (bottom) Prittlewell Chase. Photographs by courtesy of Lynn Tait Gallery, Leigh-on-Sea.

The warnings are issued by a cascade system to ensure effective and efficient distribution. They are sent first to focal points at the national and county levels who then cascade them down to other recipients. The focal points at the county level are mainly the Emergency Planning Units, but the county Fire Service may carry this responsibility instead, and so too, exceptionally, may the county Police. The Meteorological Office's responsibility is to these primary focal points, who subsequently distribute the warnings to other interested parties.

Early Warnings are issued by the Central Forecasting Office (CFO), Bracknell, when the forecasters have reasonably high confidence that severe conditions will occur. This may be for lead times of a few hours to several days. Once issued the warnings are updated each subsequent day until the event occurs or the warning is cancelled. Reference to the issue of an Early Warning will be made in the Synoptic Review issued as guidance to the regional Weather Centres, although on occasions the Chief Forecaster may decide that a Special Synoptic Review is necessary. A Press Release may be issued in conjunction with an Early Warning if the Chief Forecaster considers it appropriate.

Flash Messages are issued nearer the onset of the conditions, normally within six hours, by the regional Weather Centres, although CFO maintains a watching brief over the operation of the service, discussing the situation with Weather Centres whenever necessary. CFO also provides guidance on whether Flash criteria are likely to be exceeded in the short-period forecasts issued every six hours. The warnings will often be based upon actual reports of severe weather, providing greater detail than Early Warnings on location, duration and severity. When the severe weather is widespread, CFO may issue a composite Flash Message for national dissemination to avoid proliferation of warnings. Tier 2 warnings are also normally issued within six hours by the regional Weather Centres.

3. Weather summary — the first two years

3.1 1990/91 Season

The first full winter when the NSWWS was used operationally was noteworthy for two spells of snowy weather in the southern part of Britain. Warnings for both these events, on 8 December 1990 and between 6 and 13 February 1991, were passed to emergency authorities in good time, and the Meteorological Office received favourable Press coverage. This was despite the chaos and disruption to transport which occurred on both occasions and, after the snowstorms of 8 December 1990, the Home Secretary was quoted as saying 'what I think took people by surprise was that there was no lack of warning by the Meteorological Office'. Also during this winter there was a cold, stormy period at the end of the year which mainly affected northern Britain.

A breakdown of Early Warnings issued for severe weather events from April 1990 to March 1991 gives 11 nationwide, 2 of which were subsequently cancelled (see Table I).

Flash Messages issued via CFO for this period, which include composite messages, accounted for 57 occasions (see Table II).

Table I. Early Warnings issued for severe weather in 1990–91 and 1991–92 (April–March)

	Severe gales	heavy snow	heavy rain
1990–91	5	5	1
1991–92	5	1	2

Table II. Flash messages issued via CFO in 1990–91 and 1991–92 (April–March)

	Severe gales	heavy snow	heavy rain	icy roads	fog
1990–91	21	18	2	7	9
1991–92	34	2	17	0	30

3.2 1991/92 Season

Apart from one weekend around the middle of March, when for a short while blizzard conditions affected some parts of Scotland, the winter as a whole was not particularly noteworthy for extreme cold or snow. It was characterized by some very windy conditions however, especially over Scotland and northern districts of England. In the south of England freezing fog occurred widely in mid-December and late January.

A similar breakdown to that used for the previous season gives Early Warnings issued for 8 severe weather events nationwide (see Table I). Flash Messages issued via CFO accounted for 83 occasions (see Table II).

The difference between the above two seasons is readily seen from a more detailed breakdown of the number of Tier la warnings issued for heavy snow. In 1990/91 there were Early Warnings for four heavy snowfall events for Scotland and three for southern England. This contrasts with only one Early Warning for heavy snow in 1991/92, which was issued for Scotland. There were also 18 Tier 1b warnings for heavy snow issued in 1990/91, together with 7 warnings for icy roads, compared with only 2 heavy snow warnings during the following season. The higher incidence of fog during 1991/92 is also apparent with 30 Tier 1b warnings being issued compared with only 9 the previous season.

4. Analysis of warnings for 1991/92

In order to monitor the performance of the severe weather warning service each Tier 1 warning was assessed to determine whether the information was likely to have been beneficial or misleading to recipients. Warnings are likely to mislead under the following circumstances:

(a) expected severe weather does not occur,
(b) location of severe weather substantially different from that indicated, and
(c) incorrect timing.

4.1 Flash Messages

Flash Messages were issued on 83 occasions and gave specific advice on the location, duration and severity of the weather conditions. Flash Messages are often based upon actual reports of severe conditions to ensure accuracy and high confidence. Even so, around a quarter of the messages provided forecasts of the onset of the conditions up to about six hours ahead, with only 2 subsequently judged to have been false alarms.

4.2 Early Warnings

Early Warnings were issued for 8 widespread severe weather events, only one of which did not occur. This low false-alarm rate is a reflection of the confidence required before an Early Warning is sent. Subsequent analysis of Flash Messages issued during the season suggested that there had, in fact, been a further 13 occasions when severe conditions were sufficiently widespread that an Early Warning could have been issued had confidence been sufficiently high.

In the case of both Flash Messages and Early Warnings the aim is to issue as high a number of correct warnings as possible without this being at the expense of an unacceptable level of false alarms.

5. Case-studies

The operation of the NSWWS can best be illustrated by reviewing two events which occurred in February 1991 and October 1992.

5.1 4–7 February 1991

During this period very cold weather encroached from continental Europe with some heavy falls of snow occurring over many parts of England and Wales. The resulting disruption to transport was widely reported at the time, not least British Rail's problem with the 'wrong type of snow'.

A detailed account of the synoptic events of this particular cold spell is given by Brugge (1991). As early as 1200 UTC on Sunday 4 February reference was made in the medium-range forecast to a spell of very cold weather expected over the United Kingdom. A moderate probability of locally heavy falls of snow due to shower activity near some eastern and south-eastern coasts from Wednesday onwards was stated.

Sequence of warnings (issued by CFO)

(1) The first Early Warning of severe weather issued at 1115 UTC on Tuesday 5 February forecast snow showers over the east coast on Wednesday and the likelihood of prolonged and heavy snowfall over eastern and southern United Kingdom on Thursday and Friday. Disruption to transport was expected as a result. The forecast lead time of the warning was at least 24 hours. This was followed by a Press Release at 1215 UTC advising the public to keep in close touch with weather forecasts and warnings issued on radio and television. The forecast chart issued by CFO for 7 February is given at Fig. 2.

(2) A second Early Warning issued at 1100 UTC on Wednesday 6 February advised that other parts of England and Wales were also likely to be affected by snow. Second Press Release at 1130 UTC.

(3) A third Early Warning issued at 1000 UTC on Thursday 7 February updated the situation and advised of the continuation of snow showers into Friday. Third Press Release at 1115 UTC.

(4) A composite Flash Message was issued at 1515 UTC on Thursday 7 February. This was the first of a sequence advising of the continuation of very severe weather. The synoptic situation close to the time of issue of this first Flash Message is given at Fig. 3. Other Early Warnings were issued on 8 and 9 February forecasting the continuation of the very severe spell with a further 6 Flash Messages being issued between 8 and 12 February giving detailed advice on the extent and severity of the conditions. The Flash Messages were for areas south-east of a line from Derbyshire to Gloucestershire.

Fig. 4 shows the accumulation of snow cover over south-east England between 7 and 10 February. Despite the serious disruption to transport across much of England and Wales between 7 and 12 February because of the snow, it was reported in *The Times* on 13 February that 'local authorities across Britain praised weather forecasters for warning them about conditions'.

5.2 24/25 October 1992

The passage of a deep depression moving east across Wales and central England on 25 October brought severe gales to coastal and exposed parts of Wales and south-west England. The development of this depression was accurately forecast. In the Synoptic Review issued by CFO at 1010 UTC on 24 October it was predicted, for the following day, to become 'notably windy for a time around midday over west Wales and south-west England, these winds then moving quickly across southern England in the afternoon'. The Review stated 'very strong gradients to the rear of the depression will probably meet Flash criteria in exposed places tomorrow in the areas specified above'. A surface prognosis for midday 25 October together with verifying analysis are at Fig. 5

Sequence of warnings

(1) An Early Warning was issued by CFO at 1050 UTC on 24 October. The forecast lead time of this warning was approximately 24 hours.

Text of the warning: 'The passage of a deep depression across Wales and central England is expected to bring a period of very strong winds, initially to west

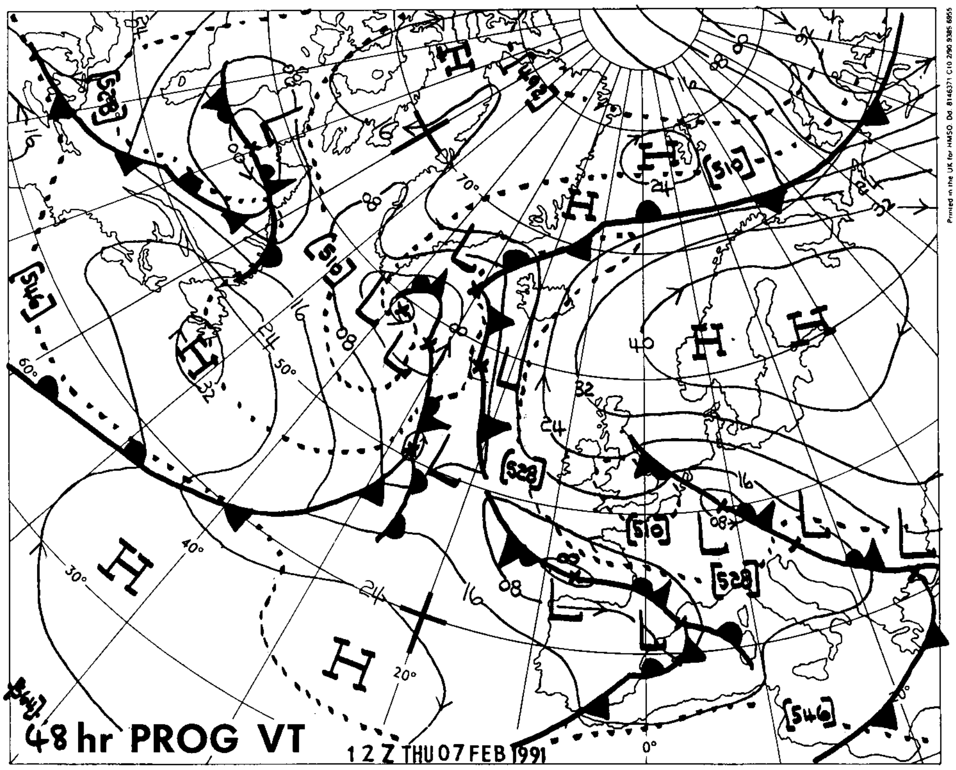

Figure 2. Forecast chart valid for 12 UTC on 7 February 1991 (issued 5 February) (1000–500 hPa thicknesses shown as broken lines).

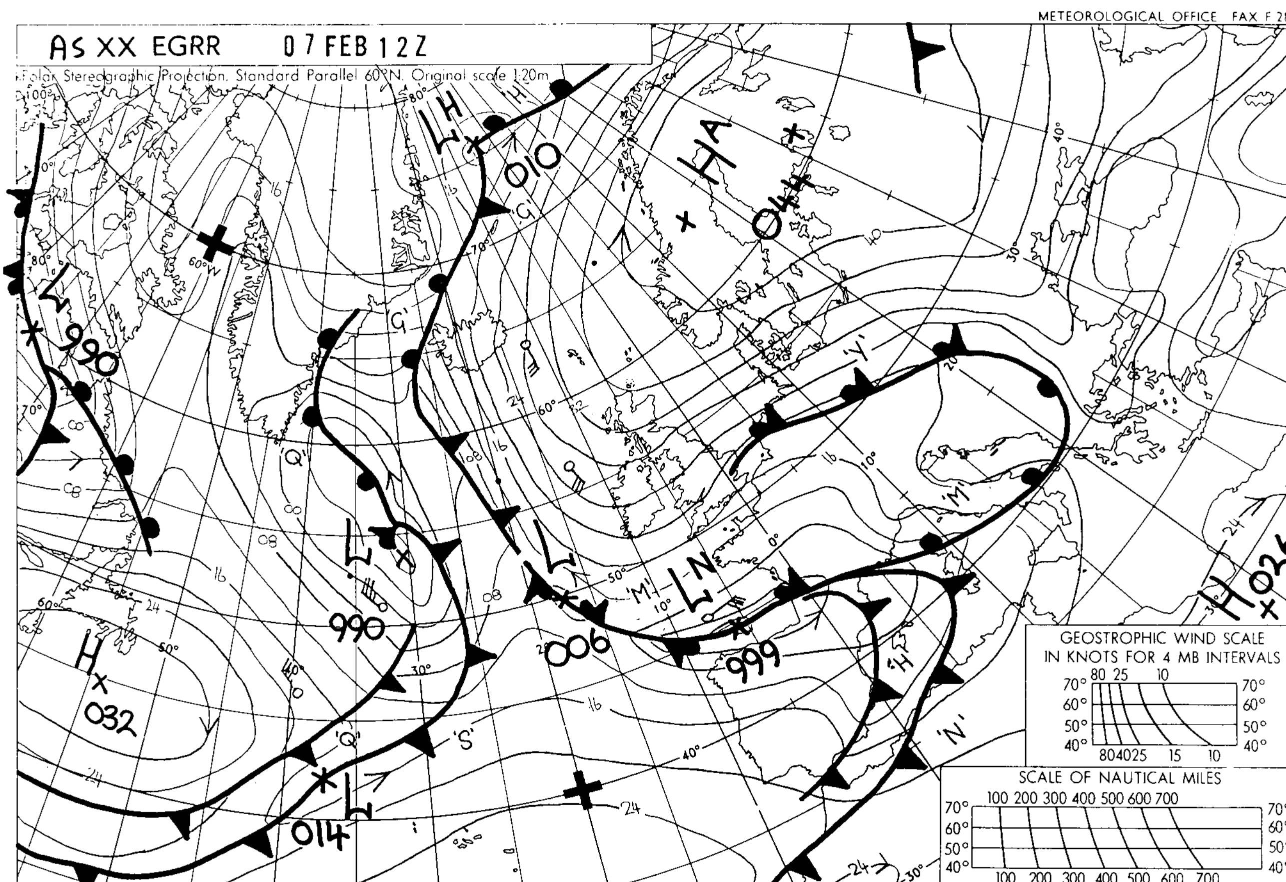

Figure 3. Surface analysis valid for 12 UTC on 7 February 1991.

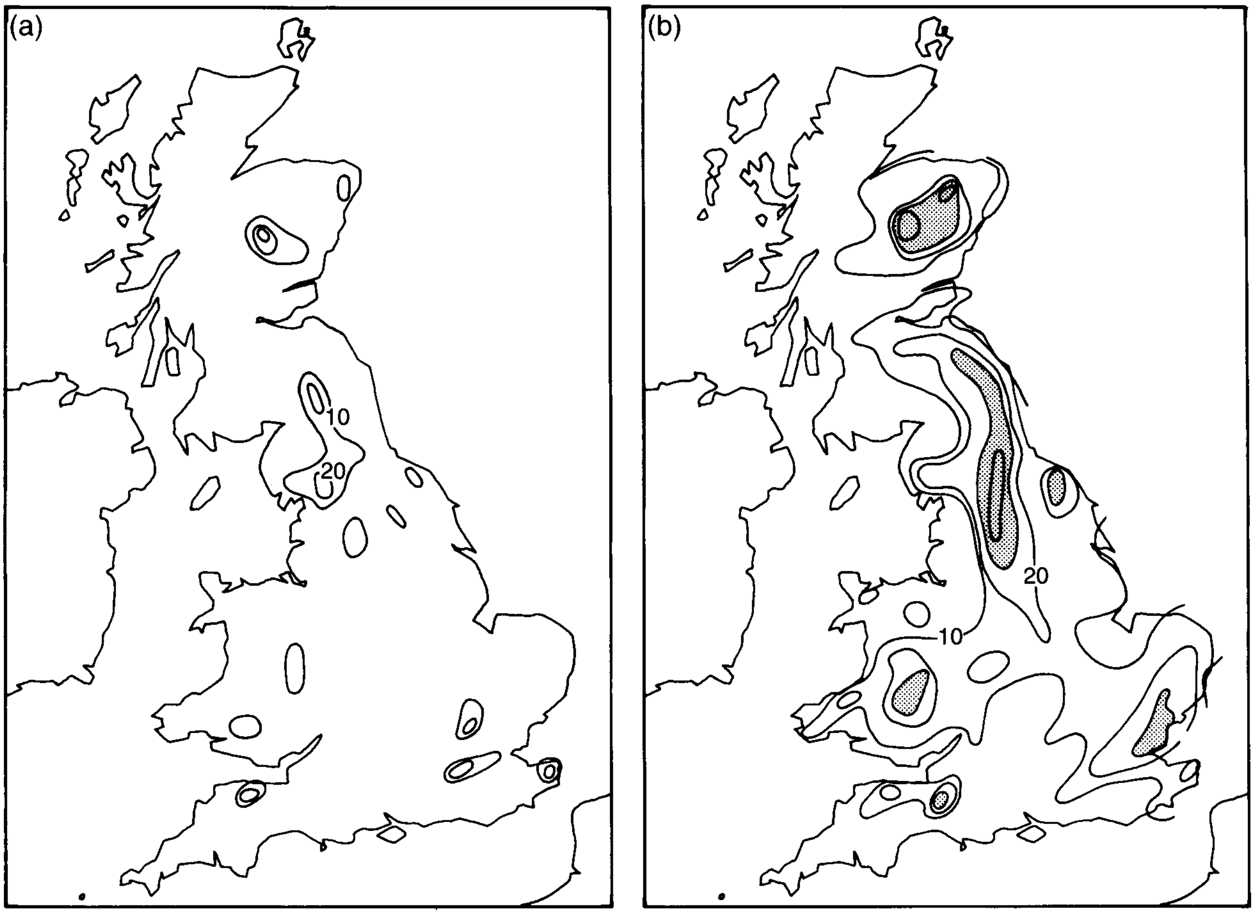

Figure 4. Accumulated snow depth (cm) on (a) 7 February and (b) 10 February 1991. Isopleths at 10 cm intervals with areas ≥30 cm stippled.

Wales and south-west England around midday tomorrow (Sunday). Winds will reach 45 m.p.h. mean speed and gust to 70 m.p.h. During the afternoon, these strong winds will also affect central southern England for a time. Heavy rain will accompany the strong winds. Damage to trees is likely, with minor damage to buildings. Driving conditions will become hazardous'.

(2) A composite Flash Message was issued early on 25 October. It was issued by CFO at 0635 UTC to cover the Cardiff, Bristol and Plymouth Weather Centre areas of responsibility.

Text of the warning: 'Very strong westerly winds associated with a vigorous depression moving quickly eastwards across central Britain will continue to affect much of Wales, south-west England, Avon, Gloucestershire, and Wiltshire today. Gusts of 70 m.p.h. or more may be expected'.

(3) The individual Weather Centres issued Flash Messages for their own areas to coincide with this composite from CFO. Fig 6 gives the maximum gust speeds reported on 25 October 1992 in knots (1 knot = 1.15 m.p.h.).

6. Customer satisfaction survey

The performance of the NSWWS is judged through the satisfaction of its customers. The results of a questionnaire distributed amongst selected emergency authorities in June of this year showed that satisfaction levels were very high with 93% either satisfied or very satisfied with the overall service, and 94% believing the detail of the information to be about right. The survey showed that 34% believed there was a tendency to over-forecast the severity of the conditions although 65% believed the warnings to be correctly forecast. This perception of over-forecasting may be partially related to the receipt of Tier 2 warnings. Of local authorities who receive these 71% identified over-forecasting as a problem. One view shared by recipients, which may also be a factor in the perceived tendency to over-forecast, is that the actual weather conditions experienced often seem to be less severe than those forecast in the warning. This is an understandable comment, the weather at one particular spot can often be different to that experienced at other localities in the area for which the warning is valid.

Severe weather warnings are also valued by the public. Their importance was affirmed by nearly 98% of those surveyed in a recent market research exercise regarding the content of weather forecasts on radio and television.

The first annual report was produced for the year 1991/92 and was distributed to users of the NSWWS, with the objective of providing information and feedback to recipients on principal aspects of the service.

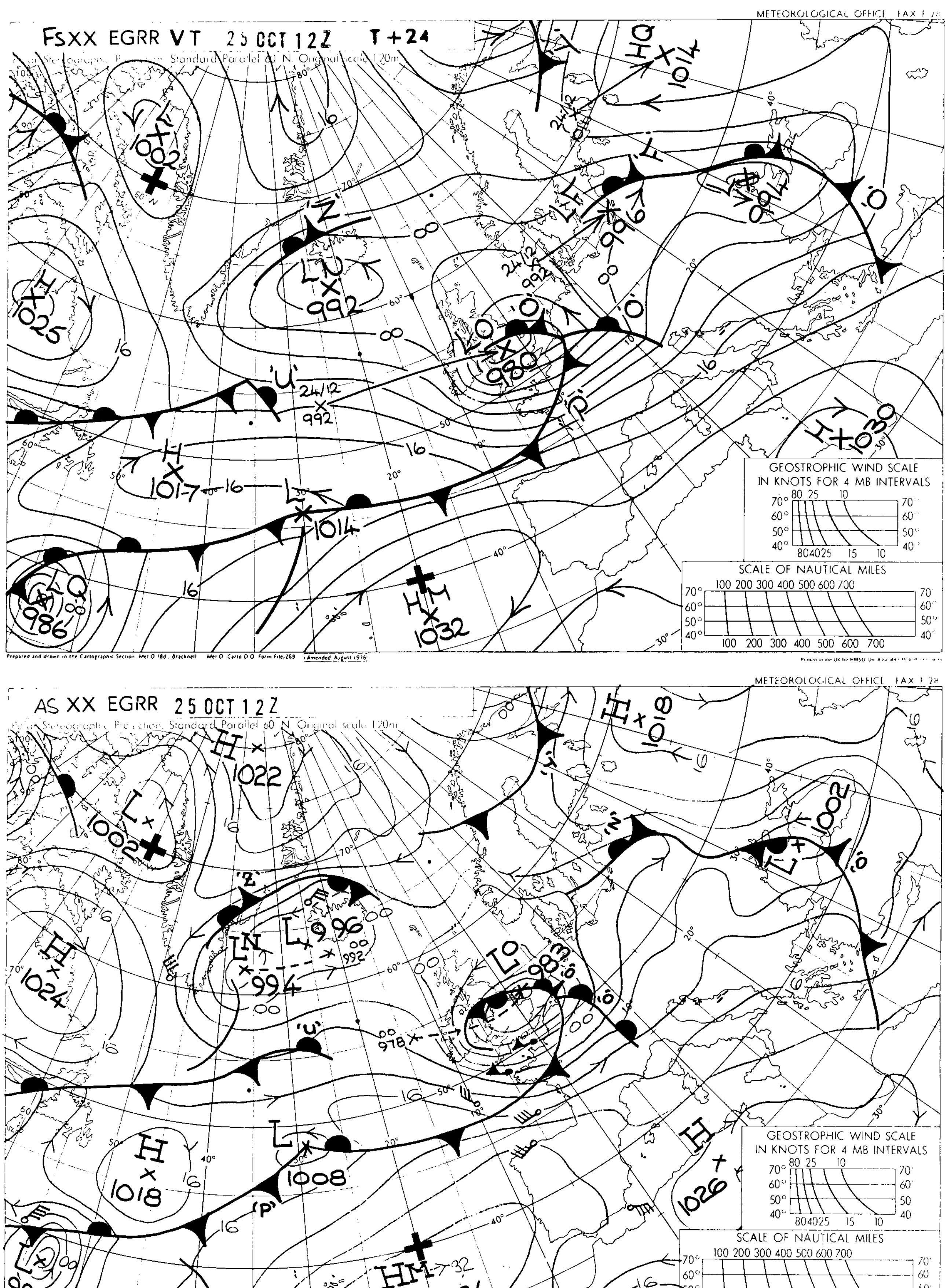

Figure 5. (top) Forecast chart valid for 12 UTC on 25 October 1992 (issued 24 October), and (bottom) surface analysis valid for 12 UTC on 25 October 1992.

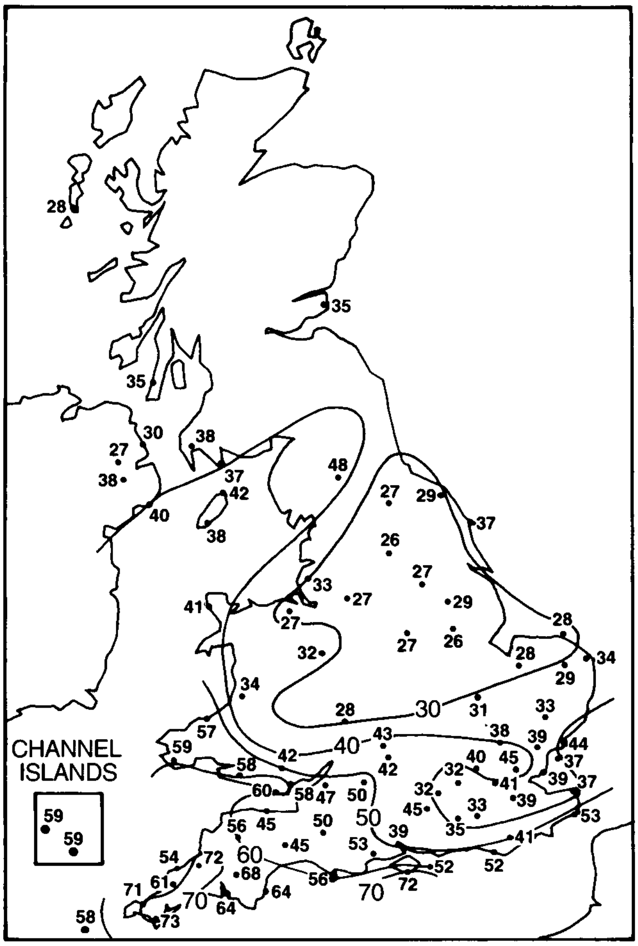

Figure 6. Maximum gusts reported on 25 October 1992.

7. Recent developments

The most recent development of the service was the introduction of Emergency Flash Messages from April 1992. These warnings are issued by CFO only when exceptionally severe conditions are expected to occur over a wide area, i.e. gusts of 80 m.p.h. or more or very heavy snow giving depths of 30 cm or more. The messages are intended to receive a greater degree of prominence from the national media.

A table of damage and advice for severe weather warnings has been constructed to assist in the phrasing of such advice and is attached at Appendix B. This was done with advice from the Forestry Commission and Building Research Establishment. The intention is to give the best possible advice to the public on the damage which can be expected, particularly those aspects likely to pose a danger to life.

Reference

Brugge, R., 1991: The cold snap of February 1991. *Weather*, **46**, 222–231.

Appendix A

Criteria

Tier 1 Warnings (Severe Weather Warnings)

The overriding criterion for the issue of warnings is the **strong likelihood** of severe weather which may cause **considerable inconvenience** to a large number of people and/or present a danger to life. Early warnings are only issued when such conditions are expected to cause disruption over a wide area.

The conditions set out below give guidance concerning the severity of the weather likely to meet this criterion.

(a) Gales
 (i) Severe gales — gusts of 70 m.p.h. or more.
 (ii) Severe gales/storms — gusts of 80 m.p.h. or more
(b) Snow
 (i) Heavy snow — snow falling at a rate of approximately 2 cm per hour or more expected for at least two hours.
 (ii) Blizzards/drifting — moderate or heavy snow accompanied by winds of 30 m.p.h. or more with visibility reduced to 200 m or less, or lying snow with strong winds giving rise to similar conditions.
 (iii) Very heavy snowfall, blizzards or drifting — expected to give depths of 30 cm or more potentially resulting in widespread dislocation of communications.
(c) Heavy rain — rain expected to persist for at least two hours giving a fall of 10 mm or more.
(d) Dense fog — visibility generally less than 50 m.
(e) Glazed frost/widespread icy roads — generally occurs when rain freezes on contact with road surfaces.

Notes
Early Warnings and Flash Messages of severe weather are issued for:
(a) Gales.
(b) Snow.
(c) Heavy rain.

Flash Messages only are issued for:
(d) Dense fog.
(e) Glazed frost/widespread icy roads.

Early Warnings and Emergency Flash Messages of exceptionally severe weather are issued for:
(a) Severe gales/storms.
(b) Very heavy snowfall, blizzards or drifting

Tier 2 Warnings (Hazard Messages)

These less stringent warnings are intended to advise of hazardous conditions which might present the emergency authorities with potential operational problems. The prime concern is of adverse weather conditions affecting road traffic. The conditions for the issue of the warnings are:

(a) Strong winds with mean speeds and/or gusts of 35 m.p.h. or more.
(b) Snow.
(c) Heavy rain persisting for at least one hour or a period of moderate rain expected to give more than 15 mm in ten hours or less.
(d) Fog with visibility less than 200 m.
(e) Icy roads.

Appendix B

Tables of damage and advice for severe weather warnings

Table I. Wind warnings.

50 m.p.h. gusts — Tier 2
- Difficult driving conditions for high-sided vehicles, especially on exposed roads or bridges.

60 m.p.h. gusts — Tier 2
- Difficult driving conditions: unladen high-sided vehicles at risk of being overturned
- Some damage to trees, e.g. falling branches.

70 m.p.h. gusts — Tier 1
- Hazardous driving conditions: unladen high-sided vehicles at risk of being overturned and motorists advised to drive with particular care.
- Damage to trees, e.g. falling branches, with some being uprooted.
- Minor damage to some buildings, particularly to tiles, slates and chimneys.

80 m.p.h. gusts — Tier 1
- Dangerous driving conditions: high-sided vehicles at risk of being overturned and motorists advised to avoid driving if possible.
- Considerable damage to trees with significant tree uprooting.
- Extensive minor damage, particularly to tiles, slates and chimneys, and structural damage to some buildings.

90 m.p.h. gusts — Tier 1
- Driving extremely dangerous.
- Widespread uprooting of trees.
- Widespread damage to buildings with potential for severe structural damage.
- Public advised not to venture out of doors unless really necessary.

Table II. Snow warnings

Snow — Tier 2
- Difficult driving conditions.

Heavy snow — Tier 1
- Dangerous driving conditions.
- Motorists advised to avoid driving if possible.

Blizzards or severe drifting — Tier 1
- Driving extremely dangerous.
- Some roads likely to become impassable.
- Public advised not to venture out of doors unless really necessary.

Table III. Other warnings

Heavy rain, fog or icy roads — Tier 2
- Difficult driving conditions.

Heavy rain, dense fog or widespread icy roads/glazed frost — Tier 1
- Dangerous driving conditions.
- Motorists advised to use extra care.
- Localized flooding (in association with heavy rain).

Editor's note: the following article is a transcript of a talk given by the author to the Royal Meteorological Society at its meeting on 18 November 1992 at Imperial College, London. The opinions expressed are not necessarily shared by The Meteorological Office and may, in part, have been designed to provoke discussion!

551.509.58:622.24

The evolution of weather forecasting services for the offshore industry in developing countries — from the stone age to the space age.

N. Lynagh
Managing Director, Noble Denton Weather Services Limited

(The author would like to acknowledge the great help received in preparation of this talk from Mr. David Hibbert, former owner and Managing Director of IMCOS Marine Ltd.)

Good afternoon ladies and gentlemen. When I started preparing this talk it very quickly became apparent that I had enough material for a talk lasting 2–3 hours. I have therefore had to be very selective, with the aim of giving something of a flavour of how weather forecasting services for the offshore industry evolved in developing countries. I'll also give my views on where I think we are today and how I think weather services to the offshore industry can be improved.

The offshore oil and gas industry is less than 50 years old. It was only after the Second World War that the first serious attempts began in the search for oil and gas under the sea. These earliest moves offshore were in the Gulf of Mexico and immediately created a demand for a new type of weather forecast service — that is, site-specific forecasts of wind and sea state for as far ahead as possible. That is still the requirement today. In the USA there was, of course, even at that time a relatively well-established meteorological infrastructure. Nevertheless, there was no forecast service which met the needs of this new offshore industry. A few entrepreneurial consultants soon set themselves up to fill this gap and there is no doubt that the leader was Al Glenn. Al, with a few associates, began providing a specialist forecast service for the embryonic offshore industry in 1946, and in 1948 they pioneered the concept of on-site forecasters working offshore. As far as I know Al Glenn is still active in the industry today.

Following fairly closely behind the developments in the Gulf of Mexico, the oil and gas industry soon began to 'get its feet wet' in other parts of the world, notably in the Arabian Gulf. For the meteorologist at that time such areas of the world might almost have been on another planet. There was no well-established meteorological infrastructure and the distribution of synoptic reporting stations was very sparse indeed.

One of the first offshore operators in the Arabian Gulf was Shell, based in Doha and using the jack-up rig MU-2. Shell were certainly conscious that there was a potential threat to the safety of this rig from the weather during location moves. As there was no worthwhile weather service available to them they established weather reporting stations themselves at Ras Rakan and Halul Island and also stationed a workboat between Qatar and Bahrain to report the weather during rig-moves. All these reports were limited to wind only and the assumption was that if all 3 had light winds it was safe to carry out the move. This was a meteorological version of Russian Roulette!

On only its third location move, during 27–28 December 1956, the rig was struck by a sudden storm whilst under tow. The rig sank with some loss of life and was a total loss. Clearly there was a need for a better forecasting service for such weather-sensitive marine operations. This loss was the trigger for that.

At that time a British company, International Meteorological Consultancy Services (better known as IMCOS) was well established in London. Its Director and owner, David Hibbert, happened to know Tom Gaskell of BP who were about to commence offshore operations off Abu Dhabi. They were cooperating with Shell in Qatar and the upshot of this contact was that IMCOS was invited to initiate a marine weather forecast service for Shell and BP in the Gulf, in 1957. The first temporary forecast office was set up on Das Island.

One problem which had to be solved very quickly was the sparsity of weather observations from within the Gulf. IMCOS encouraged co-operation amongst the growing number of operators in the area and set up an organization which eventually became known as the Oil Companies Weather Co-ordination Scheme. By 1959 this scheme had 8 members and it grew to a maximum of around 20 by the early 1980s covering all countries with a Gulf coastline. Under the scheme, the members took regular weather observations from their operating sites and fed them into a communications network which

IMCOS developed. Most of these communications were by voice and the aim was to get all the observations to the collecting centre in Doha.

IMCOS forecast offices proliferated and were set up at a number of locations in the Gulf. Some which come to mind were at Kuwait, Abadan, Kharg Island, Bushehr, Ras al Khafji, Ras Tanura, Bahrain, Doha, Lavan Island, Das Island, Abu Dhabi and Dubai (Fig. 1). The forecast offices were almost all one-man-band offices, totally dependent on radio-teletype for their information.

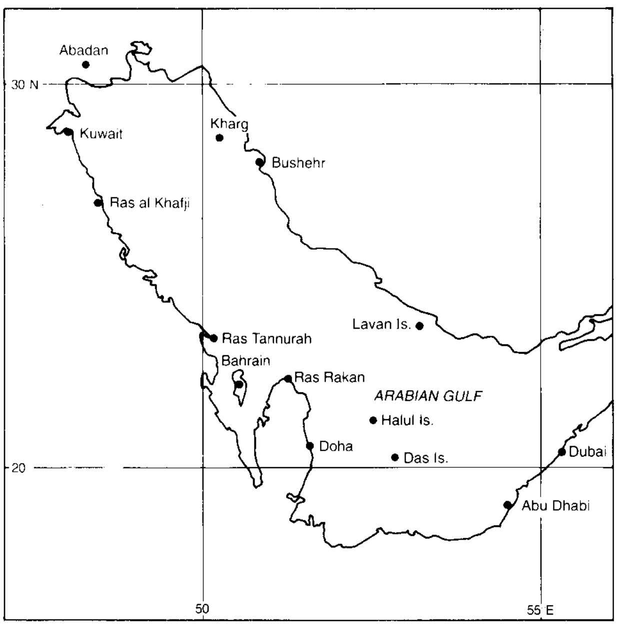

Figure 1. Map showing IMCOS offices in the Arabian Gulf.

To provide these forecast offices with the collection of observations from the Gulf and also with the growing amount of information coming from the rest of the Middle East region, IMCOS set up its own radio-teletype transmitting station in Doha. Much later this moved to Bahrain. It was known as IMCORTT (Fig. 2).

The 1960s and 1970s were the heyday of the single-operation forecast office. Although by no means the only player in the field IMCOS Marine Ltd. was perhaps the leader and over a period expanded all over the world and had forecast offices established in more than 20 countries. Each one of these was a totally independent office, usually staffed by only one man and either looking after a single operation or a group of operations for one client. In most cases the forecaster was collocated with the main operational decision maker or, at worst, he had very good telephone or radio contact with him.

To obtain the necessary data and products the forecasters were totally reliant on radio-teletype and radio-fax. They had to be extremely self-sufficient and were expected to arrive in some godforsaken part of the world with a dozen or so boxes of equipment, unpack them, install the equipment and be up and running as an operational forecast office all within 24 hours of arrival. This contrasts with the 18 days* it took for the Meteorological Office Mobile Meteorological Unit to become operational in Bahrain during the Gulf War a couple of years ago. The operational requirements were, of course, very different and the technology has become much more complex. The fact is, you do not need all that much to become operational. The bells and whistles are nice to have but they are not essential.

The supply of forecasters with the right sort of attitude and the right sort of training and experience was, and still is, limited. To help satisfy its growth requirements during the 1970s IMCOS established its own Forecaster Training School in Aberdeen where meteorological graduates were given specialist training in marine forecasting. Following training they were employed as assistant forecasters until they were ready to take a full role in the company's worldwide business which was, by then, very extensive.

A little earlier I made the point that a forecast office can be established with minimal facilities. I'll illustrate this now with a few examples. I worked regularly on the drill ship *Sedco 445* for 3 years in the early 1970s while it drilled in various locations all over the world. It was a prototype ship for drilling in deep water, a test bed for all the new equipment and in the early 1970s it pushed the water depth record beyond 4000 ft.

The weather forecast office on the rig was located in a corner of the chartroom (Fig. 3). There were two radio-teletype sets and one radio-fax. That was it. That was all that was needed to provide an efficient weather forecast service. To be located at the operational site was the key. That was invaluable and greatly outweighed any disadvantage resulting from the limited data supply. Two forecasters were assigned to the rig and the general system was to work one month on, one month off. During his month on the rig the forecaster was on call 24 hours a day and during periods of threatening weather sleep was often in short supply. Living with the weather like this resulted in a very high level of job satisfaction and this was reflected in the high quality of service provided.

Going back to earlier times, in the 1960s IMCOS established on-site forecast offices in some very primitive conditions in Brazil. The concept was the same — very basic, simple radio-teletype and radio-facsimile equipment enabling each office to become operational very quickly.

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* *W.R. McQueen MBE, MMU writes*
The comparison is wrong. Under normal circumstances the MMU can be 'up and running' almost immediately. We have very good communications equipment which allows us to connect very rapidly to our own dedicated radio-teleprinter and facsimile broadcasts. During periods of military conflict of course the security of meteorological information and output becomes especially important (for both sides), therefore the establishment of secure lines of communication was essential. One of the guiding principles during the build-up to the Gulf conflict was to ensure that everything was in position and ready to go before the expiry of the deadlines. Haste was not required.

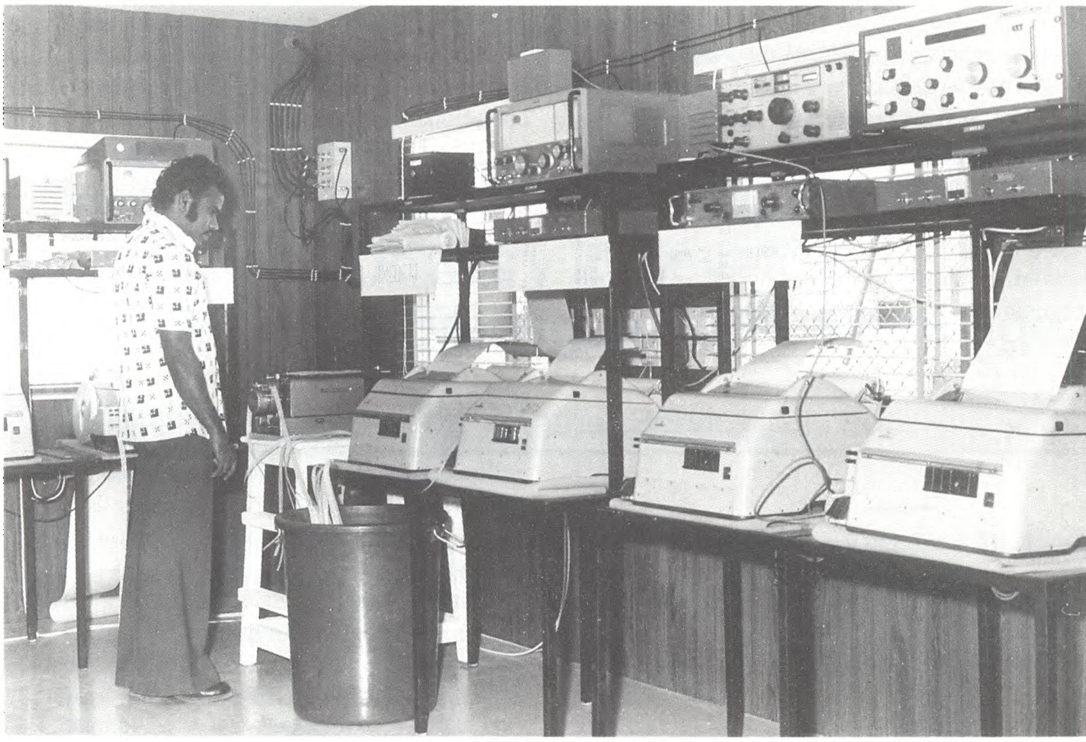

Figure 2. IMCOS radio station on Bahrein.

Figure 3. Weather forecast office aboard *Sedco 445*.

In 1970, the Italian oil company, AGIP, began an exploration campaign in the South China Sea, north of Natuna Island using the drill ship *WODECO VII* (Fig. 4).

Because of distance, the only possible location for helicopter support was Natuna Island itself so the main shore facilities were set up there. The operation was certainly exposed to a significant threat from the weather, being at the southern edge of the typhoon belt and also being totally exposed to the NE monsoon. AGIP therefore decided they needed to have a dedicated weather forecast office at the shorebase on the island. Again, the

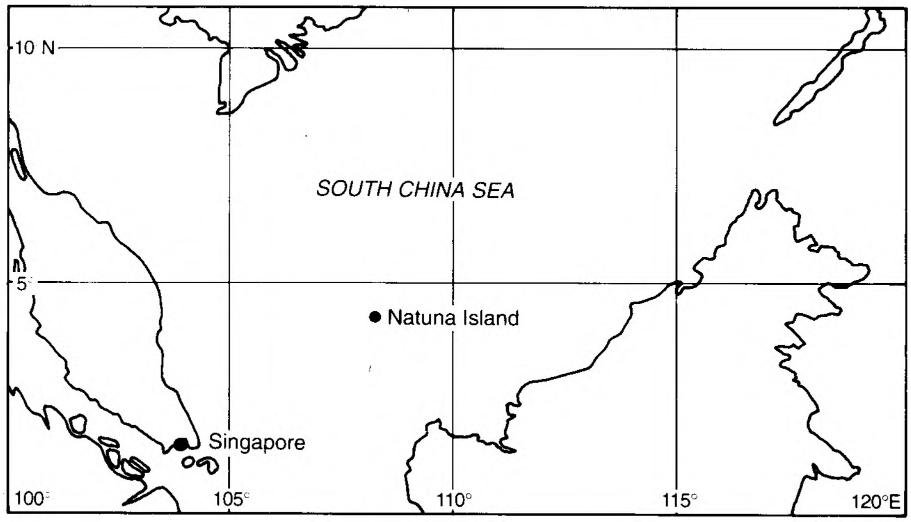

Figure 4. Map showing location of Natuna Island.

equipment in the office consisted of 2 radio-teletype terminals and one radio-fax, each forecaster did 2–3 months on the island at a stretch and was on call 24 hours a day. He had the great advantage of being in constant radio contact with the rig. His office adjoined the radio room and his accommodation was only about 20 paces away (Fig. 5). He could talk to the rig at any time and the personnel on the rig could talk to the forecaster whenever they wanted to. This was taking the meteorology to the client.

During the latter part of the 1970s and, more particu larly, in the 1980s, meteorological communications improved greatly making it much easier to obtain data covering a wider area. Also, the advent of satellite communications suddenly made it possible to transmit forecasts from any point to suitably equipped offshore installations anywhere in the world. As a result there has been a gradual process of centralization with further expansion of meteorological services coming mainly through a relatively small number of large forecast offices while the number of small offices dedicated to single operations has probably decreased.

It would be very difficult to check in detail but I suspect that today throughout the world there are fewer

Figure 5. Weather forecast office on Natuna Island in 1972.

weather forecast offices dedicated to the offshore industry that there were 20 years ago even though the industry has grown enormously in that period. Taking a very narrow accountants' view this may seem to be a movement in the right direction with increased efficiency resulting in a reduced unit cost. I don't think it's as simple as that because the quality of service suffers. Forecasters are being required to handle an ever-increasing number of operations per shift. More and more reliance has to be placed on automation and on computer products which are often of doubtful accuracy in the context of site-specific forecasts of wind and sea state. There's not enough thinking time today and less of the one-to-one contact which used to be the hallmark of weather services in the offshore industry.

It is worrying that the number of major losses in the industry directly attributable to the weather appears to be on the increase. Even more worrying is the fact that when these losses are examined in detail a common thread running through many of them is that they occurred when weather sensitive operations were being carried out in weather patterns unsuitable for such operations, that is in weather patterns in which there was a threat that severe weather might occur, even though it was by no means certain and was perhaps not even the most probable development. The fault appears to lie in lack of adequate communication between the weather forecasters and the decision makers. Following these losses the decision makers often claim they were unaware of the threat. The quality of the meteorological advice available is, potentially at least, much better than 20 years ago but we seem to be failing to get the story across to the user properly in some cases. If we were to get back to the situation where each weather sensitive operation had its own dedicated forecaster I am convinced that most of the losses could be eliminated. Ideally, the forecaster and the decision maker should be collocated as was often the case in the past but, if not, the forecaster can be anywhere provided there is good communication between him and the decision maker.

Unfortunately we live in an age where accountants tend to call the tune. In the award of contracts cheapest price is often considered more important today than level of service. This has encouraged competitive pricing amongst the various weather forecast suppliers resulting in centralization to achieve economies of scale. In terms of meteorological capability we are far ahead of where we were 20 years ago and can provide much more accurate information to operators in developing countries. Nevertheless in my opinion, we do not have sufficient forecasters living in the pockets of marine superintendents around the world. That's where we should be — at the scene of the action.

For any given level of meteorological capability an individual client gets the best possible service if the forecaster has only his single operation to consider. As soon as the forecaster has two or more operations to consider the quality of service to each one begins to suffer — the bigger the number of operations the poorer the service to each one.

To ensure the highest level of safety in operations the offshore industry needs a meteorological consultancy service, not merely a weather forecasting service. There is a great difference.

The concept of weather forecast offices dedicated to single operations is by no means dead and there are quite a number of these still operating around the world. Nevertheless, they represent a decreasing percentage of the total weather services provided to the offshore industry. I consider this to be a backward step which is having a negative impact on safety. The onus is on us, the meteorologists, to convince the operators of that and get them to ease their purse strings just a little. The price of increasing safety margins is small but the potential cost of not doing so is very high. We must convince them of that.

From the Editor

Big storm on Eastern Seaboard

Over the weekend of 13/14 March 1993 'the worst storm of the century' moved from the Gulf of Mexico to the Denmark Strait leaving a trail of broken records. If any reader was caught up in this storm and can let me have their experience in writing, or local newspaper stories, before the end of May, I would consider incorporating them in the weather notes for March. Photographs (with copyright release) will be especially welcome.

A New Moon

In the January 1993 issue I reported that a large reflector was to be launched into space in February. I have since read that it was successfully unfurled and the bright flash was widely seen during the next few hours. Other tasks on board the spacecraft were advanced and the reflector was allowed to start tumbling out of control after a few orbits. The experiment was regarded as a success.

Rime and hoar-frost depositions

W.S. Pike
19 Inholmes Common, Woodlands St Mary, Newbury, Berkshire RG16 7SX

The recent cold spell of Christmas weather over southern United Kingdom (which lasted from 21 December 1992 to 3 January 1993 in west Berkshire) produced some interesting opportunities for the photographic study of rime and hoar-frost deposition.

Fig. 1 was taken in an open field where puddles in farm tractor 'ruts' had desiccated or drained away from beneath the frozen, solidified surface. Ice begins to form from the edges of a puddle of water inwards, and this thickens into ridges where these 'frost feathers' have first crystallized; the puddle is not, therefore, a completely flat surface. This photograph shows that these ice ridges have been of sufficient amplitude to have captured some rime at 1135 UTC on 24 December 1992, after an 18-hour period of freezing fog, during which the local minimum air temperature fell to −6 °C the previous night.

Fig. 2 shows east-facing 2 cm accretions of translucent rime on a twig (in the author's garden) at 1338 UTC on 2 January 1993. An overnight minimum temperature of −5 °C had occurred in freezing fog, which was slowly lifting into low stratus by 1230 UTC. Visibility had improved to 1500 m temporarily by 1338 UTC when, although the dry-bulb was still reading near −1.5 °C, a little thawing was occurring on most surfaces, probably due to radiation beneath the lifting low-cloud layer. Hence, this rime did not have the same sharp, 'fresh-frozen', crystalline appearance (as in Fig. 4 of Pike (1992)).

Although freezing fog returned during the late afternoon and evening, this fog and all low cloud dispersed again overnight, allowing a steady fall of air temperature to reach a minimum of −7 °C by soon after dawn. During these clear, near-calm conditions, a heavy hoar-

Figure 1. Rime-covered ice ridges on a puddle in a harvested maize field at Woodlands St Mary, 1135 UTC on 24 December 1992.

Figure 2. Two centimetres of translucent rime on a twig at 1338 UTC on 2 January 1993.

frost deposition occurred onto the pre-existing rime, resulting in trees being coated with an opaque frosting (see Fig. 3) which produced a natural 'Christmas card effect'. Close inspection (see Fig. 4, taken at 0953 UTC on 3 January 1993) revealed the 'icing sugar' to have sharp, hoar-frost needles which had grown out horizontally (or near-horizontally) into the prevailing easterly 'drift' of air.

Further to the concluding remark expressed in Pike (1992), these frost needles can be interpreted as further evidence of accretion (rather than condensation) of microscopic water vapour droplets into hoar-frost depositions.

Reference

Pike, W.S., 1992: Rime deposition. *Meteorol Mag*, **121**, 217–218.

Figure 3. Trees covered by 'icing sugar' effect of hoar-frost on pre-existing rime at Woodlands St Mary (view to north along Inholmes Road) at 0948 UTC on 3 January 1993.

Figure 4. Close-up view of hoar-frost deposition showing ice needles. Woodlands St Mary at 0953 UTC on 3 January 1993.

551.509.313:551.5(09)

Richardson's Forecast factory: the $64 000 question

P. Lynch
Meteorological Service, Dublin

Lewis Fry Richardson served as a driver for the Friends' Ambulance Unit in the Champagne district of France from September 1916 until the Unit was dissolved in January 1919 following the cessation of hostilities. For much of this time he worked near the front line, and during the Battle of Champagne in April 1917 he came under heavy shelling (Ashford 1985). It is a source of wonder that in such appalling inhuman conditions he had the buoyancy of spirit to carry out one of the most remarkable and prodigious calculational feats ever accomplished. During the intervals between transporting wounded soldiers back from the front he worked out by manual computation the changes in the pressure and wind at two points, starting from an analysis of the condition of the atmosphere at 0700 UTC on 20 May 1910. Richardson described his method of solving the equations of atmospheric motion and his sample forecast in what has become the most famous book in meteorology, his *Weather Prediction by Numerical Process* (Richardson 1922). The unrealistic values which he obtained are a result of inadequacies and imbalances in the initial data, and do not reflect any flaw in his method, which is essentially the way numerical forecasts are produced today.

How long did it take Richardson to make his forecast? And how many people would be required to put the method to practical use? The answers to these two questions are contained in section 11/2 of his book, but are expressed in a manner which has led to some confusion. On page 219 under the heading 'The speed and organization of computing' Richardson wrote:

'It took me the best part of six weeks to draw up the computing forms and to work out the new distribution in two vertical columns for the first time. My office was a heap of hay in a cold rest billet. With practice the work of an average computer might go perhaps ten times faster. If the time-step were 3 hours, then 32 individuals could just compute two points so as to keep pace with the weather ...'.

Could Richardson really have completed his task in six weeks? Given that 32 computers working at ten times his speed would require 3 hours for the job, he himself must have taken some 960 hours — that is 40 days or 'the best part of six weeks' working flat-out at 24 hours a day! At a civilized 40-hour week the forecast would have extended over six months. It is more likely that Richardson spent perhaps ten hours per week at his chore and that it occupied him for about two years, the greater part of his stay in France.

Now to the question of the resources required to realize Richardson's dream of practical forecasting. Quoting again from page 219 of the book:

'If the coordinate chequer were 200 km square in plan, there would be 3200 columns on the complete map of the globe. In the tropics the weather is often foreknown, so that we may say 2000 active columns. So that $32 \times 2000 = 64\ 000$ computers would be needed to race the weather for the whole globe. That is a staggering figure'.

It is indeed staggering, when we recall that these 'computers' were living, feeling beings, not senseless silicon chips. Richardson proposed taking 128 chequers or grid-boxes around each parallel and 100 between the poles. This gives a grid cell which is roughly a square of side 200 km at 50° north and south. He outlined a scheme for reducing the number of chequers towards the poles but made no allowance for that in the above reckoning. His claim that 3200 columns or chequers would cover the globe has been questioned by Sydney Chapman in his Introduction to the Dover Edition of *Weather prediction by numerical process:*

'As to Richardson's estimates of the time and cost of full application of his methods, he made an uncharacteristic error in giving 3200 as the number of squares ... to cover the globe. His number is only a quarter of the true value, so that his required staff and his cost estimate must be quadrupled'.

So, Chapman's estimate of the staff required is $4 \times 64\ 000 = 256\ 000$. However, this is not entirely correct. The envisaged computational grid would indeed have required $128 \times 100 = 12\ 800$ chequers for global coverage — four times the value stated by Richardson. But Richardson considered the grid-boxes in pairs, one for mass and one for momentum, and it was such a pair for which he made his sample forecast and upon which he based his estimates. Thus, 6400 pairs of chequers would cover the globe and, with 32 people working on each pair, a total horde of 204 800 would be involved in a bid to race the weather for the whole globe. That is a stupendous figure!

So where did Richardson come by the figure of 3200 chequers to cover the globe? The error is inescapable but is not, I believe, a numerical slip. Richardson intimated that the weather in the tropics was sufficiently steady for variations to be neglected. But in such a case the global forecasting problem falls neatly into two parts and it is natural to consider each hemisphere separately. The northern hemisphere can be covered by 3200 *pairs* of columns. Assuming with Richardson that the values at 1200 pairs may be prescribed and assigning 32 individuals to each of the remaining pairs, one finds that $32 \times 2000 = 64\,000$ souls are needed to race the weather *for the extratropical northern hemisphere*.

If this is what Richardson intended, his 'uncharacteristic error' was not an arithmetical howler but a lapse of expositional precision. For his staggering figure of 64 000 is clearly stated to refer to *the whole globe*. Later in the paragraph he speaks of a forecast-factory for the whole globe (in fact, the word 'globe' occurs five times on page 219). In his wonderful fantasy of a theatre full of computers, the tropics 'in the upper circle' are treated on an equal footing with the temperate and frigid zones. Given that Richardson's assumption of constancy of tropical weather was over-optimistic, a full complement of 32 computers for each pair of columns in his *forecast-factory for the whole globe* would have provided work for 204 800 people.

Even this vast multitude could compute the weather only as fast as it was evolving. To obtain useful and timely predictions, the calculations would need to go several times faster than the atmosphere. Allowing for a speed-up factor of five, the establishment of a 'practical' forecast-factory would have reduced the ranks of the unemployed by over a million.

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Some analogous synoptic features associated with the ozone minima over the north-west Pacific and south-east Asia

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Summary

Global minima in total ozone occur over the north-west Pacific during the active winter monsoon period and over south-east Asia during the active summer monsoon period. The earth's highest tropopause level appears during the occurrence of ozone minimum over these regions. Further, the earth's coldest monthly mean temperature at around the 100 hPa level during the corresponding months of ozone minimum is also seen there. The data for outgoing long-wave radiation for the earth show minimum values over the north-west Pacific during January and over south-east Asia during July indicating deep convection over these areas. The monthly mean of rainfall takes the highest global value during this period. An interpretation is offered that the thickness of the ozone-rich layer in the lower stratosphere is reduced by the overshooting of tropospheric ozone-poor air by intense convective activities.

1. Introduction

The influence of meteorological processes on the normal distribution of total ozone has been pointed out by many workers (e.g. Dobson *et al.* 1946, Reed 1950; Ramanathan 1963; Schoeberl 1983; Tung 1986; Chimonas 1987; McKenna *et al.* 1989; Gary 1989, etc.). Their studies reveal that chemically produced ozone can be redistributed due to dynamical transport in the atmosphere. In my earlier work (Hingane 1990), it has been seen that, during the middle part of monsoon season (i.e. July and August), the values of ozone at subtropical stations such as Delhi (29° N, 75° E) and Varanasi (25° N, 83° E) are lower than those at tropical stations such as Kodaikanal (10° N, 78° E) and stations lying outside the monsoon trough area. This anomaly is then defined as an 'ozone-valley' in the subtropics. The qualitative analyses of corresponding meteorological processes showed that the occurrence of an ozone-valley may be a manifestation of dynamical processes.

The distribution of total ozone (monthly average) over the earth, has been presented by WMO (1985), Bowman and Krueger (1985) and Ghazi (1980). The existence of a climatological ozone minimum in the tropics is well known. It is, however, seen from the above studies that during the winter monsoon season, a distinct low in the distribution of total ozone appears over the maritime regions of Taiwan and the Philippines (north-west Pacific), and another over south-east Asia during the active summer monsoon season.

The interannual variability in various meteorological parameters would be produced by non-linear interaction among the various kind of forcing functions and transient disturbances. The influence of climate anomalies like El-Niño on monsoon circulation is well documented. Similarly, periodic meteorological phenomena such as quasi-biennial oscillation (QBO) show significant roles in monsoon circulation. The work of Ramanathan (1963), Angell and Korshover (1964), Oltmans and London (1982), Hesebe (1984), etc. have reported the existence of an equatorial QBO in temperature, total ozone, and tropopause height which is well related to QBO in equatorial zonal winds. In our study of year-to-year variability in the seasonal average of total ozone, tropopause height, and rainfall, it can be seen that during the wet monsoon period, most of the stations over India show negative anomalies in total ozone and positive anomalies in the tropopause height. For example, during the monsoon season (June–September) of the years 1975 and 1988, India received respectively 27% and 18% higher rainfall than normal. July and August of the same years showed an 8–10% decrease in the monthly mean of total ozone, and a 1.5–2.5 km increase in tropopause height. Therefore to obtain the ideal value of the normal for the above parameters, a long-term homogeneous data set (about 30 years) is necessary, but it is not available so far. However, this constraint should not inhibit efforts to identify and interpret the periodic occurrence of extreme minima in total ozone.

In this paper the importance of meteorological systems is examined in the hope of throwing some light on the mechanism of occurrence of ozone minima over the region mentioned above.

2. Deep upward motion, the earth's coldest 100 hPa temperature and earth's highest tropopause level

2.1 Western Pacific

As mentioned in the previous section, the global ozone minimum appears over the western Pacific during January which is a representative month of winter monsoon (December–February) influencing the region (Fig. 1(a)). The comprehensive work of Ramage (1975), Lau and Chan (1983a, 1983b) has shown that deep convective zones of monsoon of the northern hemisphere (NH) migrate from the summer-time positions over north-east India to the north-west Pacific near Kalimartar, Indonesia. Krishnamurti (1971) and Chang and Krishnamurti (1987) have mentioned that when fully developed, the winter monsoon convection drives a gigantic planetary-scale overturning motion both in the east–west and north–south directions. During the active winter monsoon conditions, this region experiences very deep tropical convection (the frontal activities of cold air masses travelling from the Siberian high and overriding moist warm air masses from low latitudes of the Pacific also leads to the chains of overshooting cumulonimbus clouds over a large area). These features can be seen in the satellite-measured outgoing long-wave radiation (OLR) field. During the active phase of the winter monsoon over this region, the value of OLR is always less than 225 W m^{-2} indicating deep convection (see Lau and Chan (1983a)). The deep moist convection obviously leads to the enormous amount of rainfall. The global chart of mean monthly rainfall (Fig. 2(a)) shows that the earth's highest rainfall during the month of January occurs over the western Pacific. The deep convection would lead to the overshooting of tropospheric air into the stratosphere. In the course of upward air movement and adiabatic expansion, the tropopause height would necessarily go up and the temperature of uppermost parts of the troposphere and lower stratosphere go down. The above-mentioned facts (discussed in more detail in the next section) are clearly reflected in the global chart of mean monthly 100 hPa temperature and monthly march of the tropopause height (Fig. 1(a)). In these figures the earth's extreme 100 hPa temperature minimum and highest tropopause level during January is seen over the western Pacific.

2.2 South-east Asia

The normal position of the intertropical convergence zone (ITCZ) shows extraordinary deep intrusion over south-east Asia during July. Over India, it migrates almost up to 30° N (see Riehl (1979)). This unique feature of the ITCZ is undoubtedly due to the differences in topography and land–sea contrast in this region. The east–west extension of the great Himalayan mountain wall (2500 km long with an area of over 10^6 km^2 having 14 peaks above 8000 m and 100 over 7000 m) causes orographic lifting (forced convection) of moist monsoon air brought by strong south-westerly winds. The developed heat source of the high and broad Tibetan Plateau (average height of 4.5 km) induces a reversal of the thermal gradient in the upper troposphere. The combined effect of both should lead to thermal and dynamical lifting of moist monsoon air to greater heights. Ramage (1975) as well as Lau and Chan (1983a, 1983b) have identified the deep convective zones during summer-time position as lying over north-east India. The global precipitation pattern for the month of July (see Fig. 2(b)) clearly shows that the area of maximum rainfall in July lies in south-east Asia. The deep convection should raise

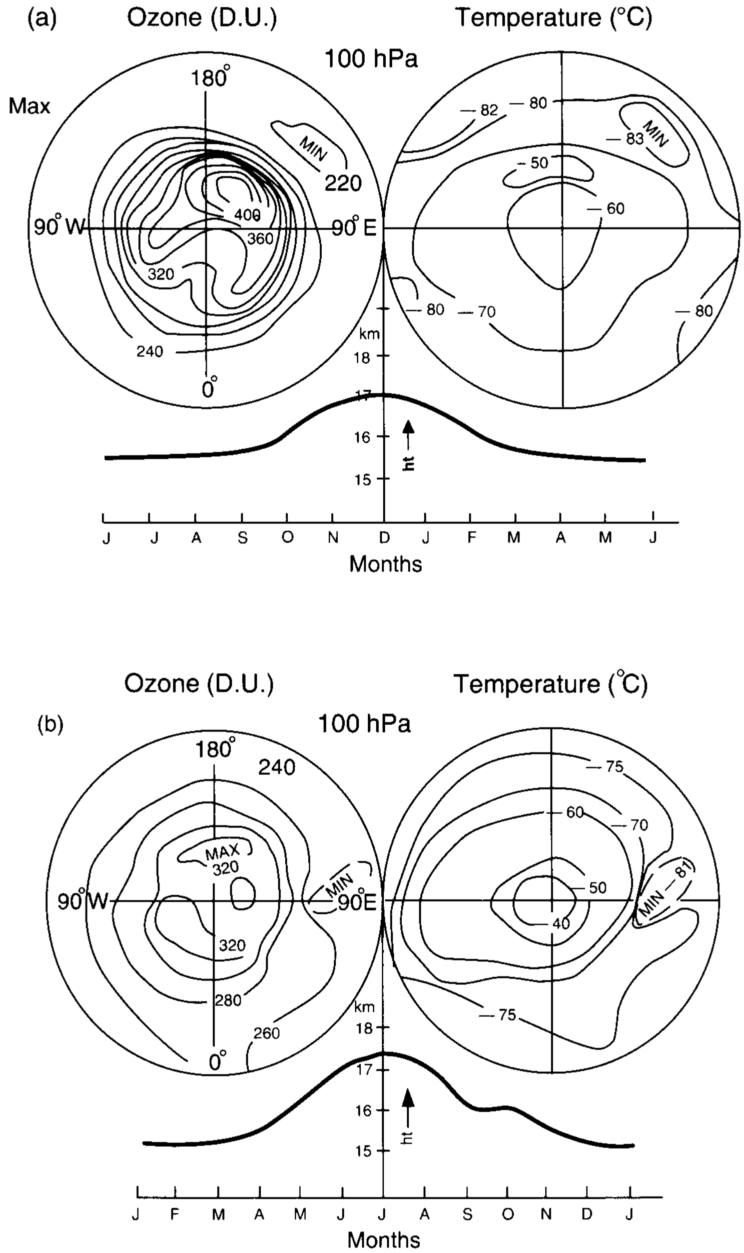

Figure 1. (a) Distributions of monthly mean total ozone (Dobson units) and temperature (°C) at the 100 hPa level for January over the northern hemisphere, and tropopause height over the western Pacific. (b) As (a) but for July and tropopause height over south-east Asia. (Sources: total ozone — WMO (1985) and Ghazi (1980): 100 hPa temperature — WMO 1980–89: tropopause height — Reid and Gage 1981, India Meteorology Department).

the tropopause height and reduce the temperature around the tropopause due to the adiabatic expansion of air coming from below (detailed discussion of this hypothesis is given in next section). Fig. 1(b) shows the global 100 hPa mean temperature chart for July and indicates the extreme minimum temperature over south-east Asia. This diagram also shows the monthly march of tropopause height indicating the highest tropopause level over this region during the month of July.

3. Discussion and conclusion

As seen in the earlier sections, there undoubtedly exists a strong upward motion during the period of occurrence of total ozone minimum over the north-west Pacific and south-east Asia. This upward motion should, in principle, cool down the upper troposphere and lower stratosphere due to the adiabatic expansion of air parcels coming from below. This mechanism could be a major cause of the occurrence of minimum temperature at 100 hPa over both the regions.

Manabe and Strickler (1964) suggested that the equatorial distribution of ozone tends to make the isothermal part of the stratosphere thinner than does the distribution of ozone in the higher latitudes, but this tendency, however, does not explain completely the sharpness of the equatorial tropopause. Their study also demonstrate

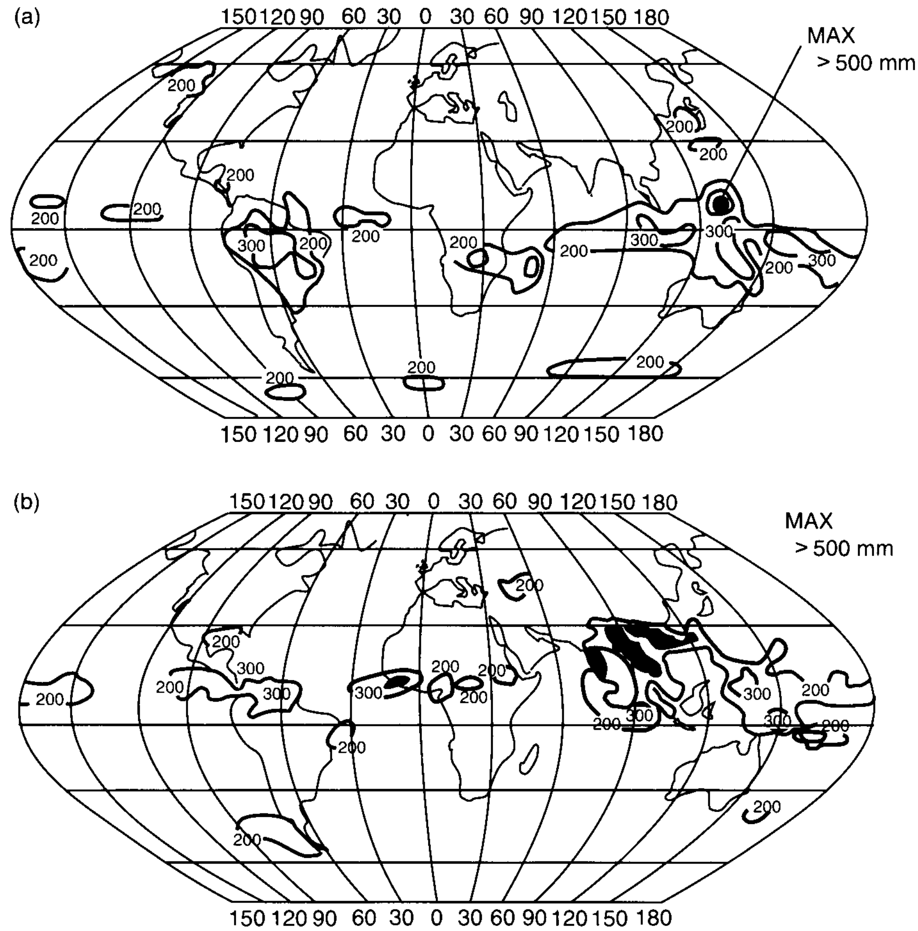

Figure 2. Global precipitation pattern (mm) for (a) January and (b) July. (Source WMO (1979)).

the importance of ozone in maintaining the existing structure of temperature in the stratosphere. The calculation of the thermal equilibrium at the tropopause and the temperature in the lower stratosphere by Goody (1949) confirm the hypothesis suggested by Dobson *et al.* (1946), that the anomalous seasonal variations in the stratospheric temperature are due to seasonal variations of ozone concentration. From these studies it can be inferred that the coldest temperatures in the lower stratosphere as seen over the north-west Pacific and south-east Asia during the time of intense convection, need not only be due to the adiabatic expansion of the air but can also be due to the decrease in partial pressure of ozone (through its optical property) in the lower stratosphere (see Held (1982)).

In Japan, an increase in tropopause height and a decrease in tropopause temperature indicates the advection of tropical air and replacement of cold air by warm fronts associated with deep upward motion. In Europe, the variation in tropopause height is associated with the intensity of events like cut-off lows, warm and cold fronts. Dobson *et al.* (1946) were the first to point out that the increase/decrease in the level of tropopause would decrease/increase the total amount of ozone. The one-dimensional model result of Chimonas (1987) show the conspicuous decreases in total ozone by a height increase of the tropical tropopause. The minimum in the mean annual distribution of total ozone is well associated with the higher level of tropopause there (Newell and Gould-Steward (1981) and Reid and Gage (1981)). As seen in the earlier section, the earth's highest tropopause appearing over the north-west Pacific during January, and over south-east Asia during July is associated with minimum in total ozone. Therefore, the possible mechanism of occurrence of ozone minimum in these regions is expected to be written in the meteorological processes prevailing during the time of occurrence of ozone minimum. It is clearly seen that there exists very deep moist convection over a large area of NW Pacific during January and over south-east Asia during July. Very deep convection or upward motion would naturally carry air masses from below and expand it quasi adiabatically with increase in altitude. The monthly mean data of tropopause height show the highest value (the temperature at 100 hPa show the lowest values) during the time of occurrence of the ozone minimum over both the regions mentioned above. The elevated level of the tropopause, and the reduced temperature around it indicate the removal or dilution of lower stratospheric ozone-rich air by tropospheric ozone-poor air. This phenomena should obviously reduce the partial pressure of ozone.

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World weather news — December 1992

This is a monthly round-up of some of the more outstanding weather events the month, three preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

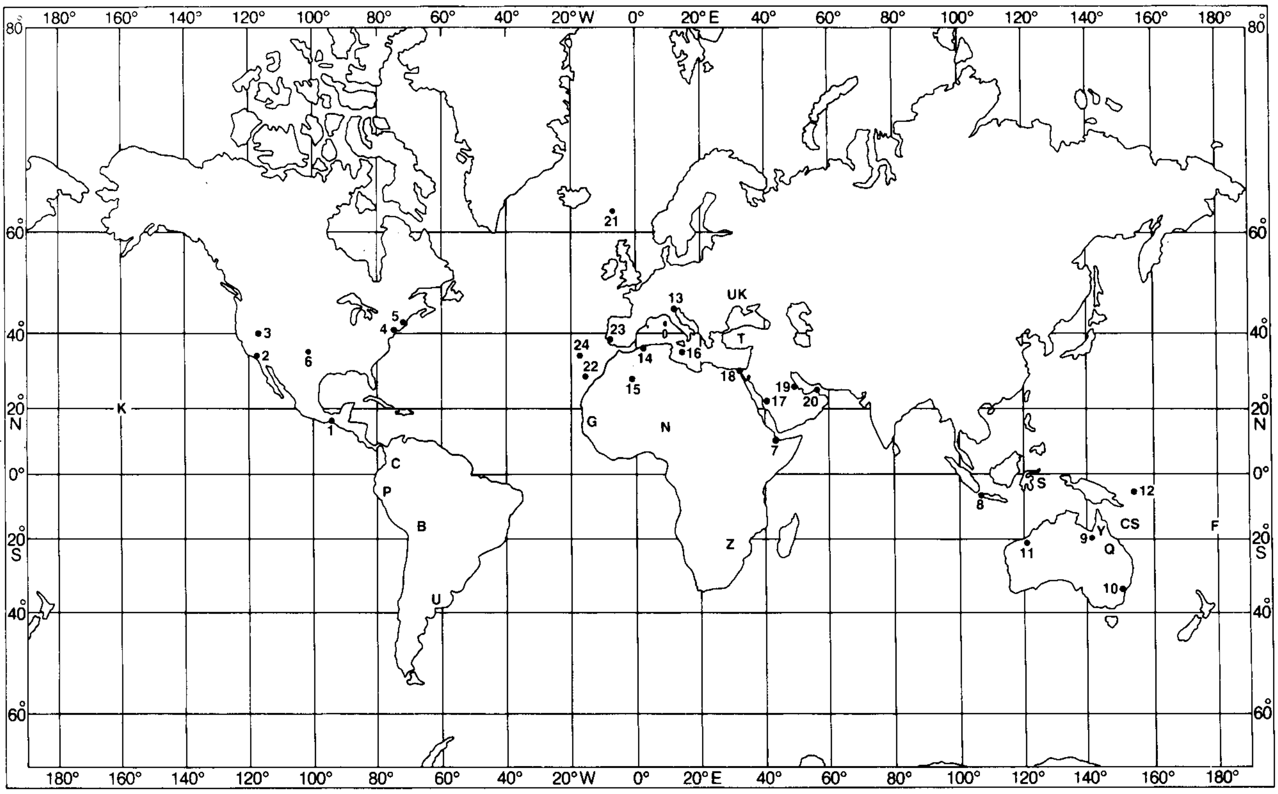
These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and press reports. Naturally they are heavily biased towards areas with a good cover of reliable surface observations. Places followed by bracketed numbers or letters in the text are identified on the accompanying map. Spellings are those used in The Times Atlas.

South America

There were few reports of notable weather from this continent but on the 6th/7th heavy rain was reported in Peru (P) with Puerto Maldorado on the border with Bolivia (B) getting 108 mm and 101 mm. On the 9th, Tipuani in Bolivia had a heavy storm and at least 150 gold miners were reported to have died in rock and mudslides. More heavy rain was noted mid-month; on the 14th Camiri on the eastern side of the Andes in Bolivia got 161 mm: next day Apertado (Colombia (C)) had a temperature of 39 °C then 100 mm of rain in the next 24 hours. On the 17th heavy rain in Uruguay (U) gave Salto 160 mm and Paso de los Toros 132 mm. In the far north it had been very hot around the Gulf of Mexico; Salina Cruz (1) on the Pacific coast of Mexico broke its December record by 1 °C with 35.0 °C.

North America

The 7th brought catastrophe to California as a low moved south-east across the state. The heavy rain gave nearly the whole month's average rain in a day in some places; Los Angeles (2) International Airport had 55 mm and flooding 'down town' was nearly a metre deep. Flooding in Malibu affected the home of some film stars. Woodland, Sacramento (3) had 130 mm and there were some 70 cm of snow in the Sierra Nevada. Total damage was estimated at about $100m and two dead.



Locations of places mentioned in text

On the 8th the island of St Paul had another stroke of lightning (see November notes).

The BIG storm afflicted the Eastern Seaboard on the 11th and 12th. The worst storm in 30 years, it gave onshore gales, heavy rain and snow, did about $650m worth of damage and led to the deaths of thirteen people. With tides as much as 2 m above normal, sea defences were severely tested: cars were submerged in Manhattan, and La Guardia airport was closed by flooding when the sea wall collapsed (the wind was 45 kn gusting 70 kn with a total of 80 mm of rain). By the 12th most of the rain had turned to snow with 10 cm in New York City (4) and 30–60 cm inland and higher up; with the gale, drifting was severe. Boston (5) collected 144 mm during the two days and of this 82 mm fell in 12 hours as snow; Boston's Logan International Airport was closed for a time! The cold front was still active when it reached Bermuda, of its 90 mm, 75 mm fell in 6 hours (the December average is 90 mm). While this was happening, the Mid West was having one its worst snowstorms since 1978 with 15–30 cm.

On the 14th many places from north Texas to west Missouri had more than 50 mm of rain from heavy thunderstorms, Amarillo (6) in Texas for example had 76 mm. Near the end of the month southern California had heavy rains with more than 70 mm and the highest noticed was at the appropriately named Running Springs with 130 mm.

Kauai (K) in the Hawaiian islands has a December average rainfall of 132 mm; this year they had 552 mm which included a fall of 127 mm in one day on the 5th!

Tropical and southern Africa

There a few reports of unusual heat; on the 9th several parts of South Africa had temperatures in excess of 39 °C followed on the 23rd by a report of the harmattan raising the temperature to 39.5 °C at Birni N'Konni in Niger (N) and 37.8 °C in The Gambia (G), both near their December records. There were some reports of heavy rains on the 10th and 11th with 50 mm in Botswana and Zimbabwe (Z) (where similar amounts were reported on the 19th and 24th). Reports of heavy rain in Djibouti (7) on the 27th are possibly related to cyclone '12A' which was earlier heading that way while dissipating.

Australasia

The month started with reports from Indonesia of Djakarta (8) having 200 mm of rain in the first three days, equivalent to the December average. Kuantan had 177 mm over the period 5th to 6th but Toli Toli on Sulawesi (S) trumped these with 255 mm in 6 hours on the 5th.

Tropical air from the Coral Sea (CS) met cooler air from south Australia over Queensland (Q) on the 4th and some severe thunderstorms broke out; several places had more than 40 mm of rain but Croydon (9) had 410 mm as the temperature fell from 39 °C to 24 °C: a similar storm gave Moranbah 350 mm. Over the next two days eighteen synoptic stations in New South Wales reported more than 50 mm, the top total was Morunga's 188 mm but almost 100 mm fell near Canberra and Sydney (11). Staying on the mainland, the next items deemed newsworthy were hot spots. Marble Bar (11) on the edge of the Great Sandy Desert, had six days with maxima >40 °C out of the seven preceding the 13th — the lowest maximum of the preceding three weeks was 37.5 °C. Not far away Broome managed 44.2 °C on the 15th.

On the 11th cyclone 'Joni' passed through the islands of Fiji (F) with winds of 80 kn gusting to 120 and over 100 mm of rain. There was coastal flooding and transport disrupted. Ten people were reported missing afterwards, most of them fishermen. There was then a two-day wet spell in Queensland with Lockhart River on the Cape York Peninsula (Y) getting 228 mm in 48 hours and Bowen 130 mm. Some places had more than 70 mm on the 19th. Then cyclone 'Nina' brought floods of rain as she crossed the Cape York Peninsular on the 26th with winds of 65 kn gusting to 80 kn; damage was minor and only ten people were temporarily stranded; Willis Island's 117 mm (in the Coral Sea) and Lockhart River's 174 mm were examples of the rainfall. By the 31st, Coen on the Cape York Peninsula had had 396 mm since the 26th. Papua New Guinea was also affected by 'Joni', in a two day spell Rabaul (New Britain (12)) had 106 mm.

Hailstorms in November and December have damaged the wheat harvest in many southern Provinces of Australia, at A$21m this is the worst since 1985. About 44% was unharvested when rain halted work and by 18 December it was being affected by fungus and sprouting.

Europe and Arabia

The month started with a strong westerly flow that brought very changeable weather to western Europe (varying from rain to heavy rain!): many areas had more than 20 mm. Over Wales a prolonged SSW gale lead to much orographic rain (about 75 mm a day) for the first three to four days of the month with consequent flooding. By the 5th cold air reached the Mediterranean, a 'Genoa low' developed and heavy rain and snow fell over northern Italy; Chioggia (13) was flooded and Venice's (13) 107 mm overnight on the 5th/6th (December average is 61 mm) helped create a depth of 145 cm of water in St Marks's Square. A fresh burst of polar air reached the western Mediterranean on the 7th to give a new low; Bejaia (14) on the NE coast of Algeria got 98 mm, snow fell on the Atlas Mountains and the minimum at Timimoun (15) in the Sahara was only +1 °C. More than 60 mm was widespread over Italy (snowfall over the Alps was heavy, e.g. 285 cm at Säntis). It was probably this low that generated a hailstorm that damaged many light aircraft parked in the open at Luqa in Malta (16).

On the 10th both Jiddah (17) and Makkah exceeded their December records with 35.0 °C and 36.2 °C respectively. Then on the 13th a new burst of cold air entered the eastern Mediterranean to generate a vigorous low over Turkey (T). Thundery rain was particularly notable over Israel with many falls of more than 100 mm — 295 mm in 42 hours at Tel Aviv was twice the December average. In Cairo (18) winds reached 30 kn and heavy rain was reported from the Western Desert. At Alexandria (18), 3 m waves closed the harbour from 14th to 16th. The storms penetrated to the Persian Gulf causing floods in southern Iran. Bahrain (19) accumulated 31 mm by the 22nd (three times the December average) and even Khasab (20) managed 61 mm in the 36 hours to midday on the 23rd.

Meanwhile 'back at the ranch' the 18th brought widespread heavy rain to the west of England and Wales: flood warnings were again issued for many rivers in these areas. The surface wind reached violent storm force off the west coast of England and the 10 000-ton *Demetros*, en route to the breakers' yard, broke its tow and broke up on the rocks at Prawle Point in Devon. In Scotland the week of the 12th to 19th had brought much snow, 45 cm at Aviemore, with light winds, creating ideal skiing conditions. Now the southerly gale with gusts to 100 kn caused severe drifting to block access roads and then a rapid thaw that brought floods. This was all brought about by several Atlantic lows combining all their energy into one centre. Pressure south-east of Iceland fell 40 hPa in 24 hours and the wind speed at Akraberg (21) in the Faeroes reached 75 kn at 0600 UTC on the 18th. The burst of cold air southwards behind these lows led to the formation of a 'cold cut-off' near the Canary Islands where Tenerife (22) had 73 mm in the week to the 20th. The low brought thundery weather to the south of Portugal where one of its early consequences was the crash of a DC-10 airliner at Faro (23) as it was caught in crosswinds or downdraughts as it landed (54 of the 327 passengers and 13 crew were killed). Not unusually the low persisted for many days with little movement but the consequences were more drastic than usual; by the 23rd there had been 186 mm in 72 hours at Faro (December average 67 mm) and Madeira (24) 83 mm (December average 77 mm) in 36 hours. A few days later the low transferred across North Africa to rejoin this story in the next paragraph.

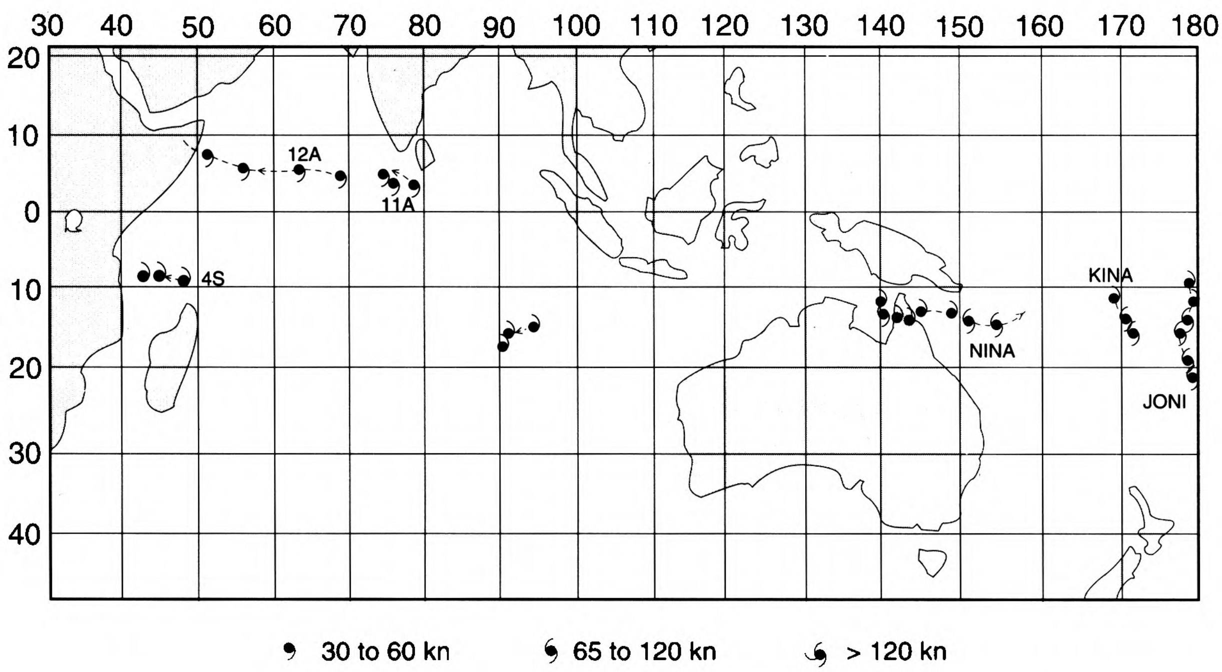
A large anticyclone over Central Europe helped drive a fresh blast of cold air south and west from the Ukraine (UK), this reached Cyprus on the 23rd. On Christmas Eve Akrotiri's maximum of +10 °C was the lowest on record and was followed by a frost next morning, −1 °C being another December record. The cold spread to Egypt and the Sudan with near freezing overnight temperatures breaking records. Further north, Venice's −4 °C was another near record. The relatively very warm sea triggered heavy showers producing more than 100 mm over many coastal areas of Italy. As a low moved east across North Africa and the European high intensified, the pressure gradient gradually strengthened and the wind reached 55 kn in parts of the Alps. By the 29th rain, snow and high winds were disrupting land, sea and air transport across Greece. As the year drew to a close near record low temperatures were being reported from Spain to Syria with snow over the Atlas Mountains (Constantine's maximum of +0.9 °C being 12 °C below the December average).

The World

The 1992 globally-averaged surface air temperature, based on measurements over land and sea, was 0.17 °C higher than the 1951–80 average. 1992 was the 10th warmest year in the near 140-year long record. Eight of the ten warmest years have occurred since 1980, and 1992 continues the general pattern of warmth which has prevailed since the late 1970s. However, 1992 was about 0.2 °C colder than 1991. There is good reason to believe that the eruption of Mount Pinatubo in June 1991 will have had a noticeable cooling effect in 1992. The end of the 1991 El Niño warm phase will also have had a cooling influence.

December tropical storms

This is a list of tropical storms, cyclones, typhoons and hurricanes active during December 1992. The dates are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during its lifetime. The map shows 0000 UTC positions.



No.	Name	Basin	Start	End	Max.
1	11A	NI	30 Nov.	3 Dec.	50
2	12A	NI	20 Dec.	24 Dec.	50
3	4S	SWI	7 Dec.	10 Dec.	35
4	Ken	SWI	19 Dec.	23 Dec.	45
5	Joni	AUS	6 Dec.	12 Dec.	110
6	Nina	AUS	23 Dec.	3 Jan.	75
7	Kina	AUS	27 Dec.	3 Jan.	125

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific: I — Indian Ocean; WI — west Indian Ocean; AUS — Australasia.

Hong Kong rainstorm — addendum

Our January 1993 issue carried an article by Dr Lam on the record-breaking rainstorm in Hong Kong on 8 May 1992. An unfortunate oversight, caused by writing the *World weather news*, resulted in the omission of the photographs that add considerable colour to the story. They are printed here with my apology to Dr Lam.

(Right) A slope failed in the heavy rain and two persons in this high-rise building were killed by the downhill rush of water-laden mud. The force of the mudslide can be gauged from the height of the stains on the wall. (Photograph courtesy of *Ming Pao Daily News*, Hong Kong.)

(Below) Roads on the steep slopes of Hong Kong Island turned into torrents. Traffic in the business districts virtually came to a stop. (Photograph courtesy of Wah Kiu Po, Hong Kong.)

Reviews

Seasonal snowpacks: Processes of compositional change.

edited by T.D. Davies, M. Tranter and H.F. Jones. 168 mm × 247 mm, pp. ix+471, *illus*. Berlin, Heidelberg, New York, Springer Verlag, 1991. Price DM288. ISBN 3 540 51760 X.

This book is the result of a NATO Advanced Study Workshop, held in 1990, on the chemical changes in seasonal snow cover. The format is a series of fourteen peer reviewed papers, mostly single authored, with shorter discussion papers following many of the main contributions. These are in fact not discussions in the sense of a recorded interchange of ideas between participants, rather they are short pieces on the same subject. The discussion papers are perhaps a weakness of the volume as they have not undergone a review process as have the main papers, thus allowing some disagreement with points raised in the main texts without reply from their authors. Some discussants used the opportunity to add additional material, often quite specific, while others stuck to actually discussing the previous paper, summing up salient points.

The majority of the main papers are reviews of different aspects of the incorporation, diagenesis and loss of chemical species from seasonal snow cover. The volume has been laid out logically: the first paper starts off naturally enough in the atmosphere with a review of the processes leading to snow formation and the effect this has on snow composition. By the second paper, the snow is on the ground, and there is a review of how dry deposition and gaseous exchange can add to the chemistry of the original snowfall. The next paper looks at the effects of the redistribution of chemistry and alteration of physical properties by wind-induced transport. Following this are two papers that consider snowpack physics and the effect of snow metamorphism on the location of chemical species and one includes an attempt at modelling these processes.

The sixth paper takes us away from the physical approach to consider how biology can affect the snowpack composition. For me, this was the strongest review in the volume, with a magnificent effort to bring together the available data. There appears to be very little good quantitative data available, and some of the argument is necessarily qualitative, but the author has gone to great lengths to put together a complete picture. The alteration of the snowpack composition by vegetation, animal life, insects and bacteria can be enormous, though often localized.

Returning to physical processes, the next paper expands on the factors affecting the snow-melt itself, and discusses the phenomenon of preferential elution of species from the snowpack. Then, two papers move away from the review format with two specific studies: one with detailed experimental data from the Alps, and one rather weak paper on urban snow. Then it is back to reviews for a paper on organic compounds in snow.

There is a temporary departure from the seasonal snowpack with two papers that consider permanent snow cover. One article sits somewhat uncomfortably within the subject matter of this volume with a discussion of records in polar snow, though the author has attempted to steer his article towards processes in compositional change during burial rather than reviewing the data obtained from deep ice-cores. The other paper considers high-altitude, non-polar ice sheets and points out the palaeoenvironmental information available from these areas is valuable for its regional bias rather than the global picture painted by those involved in polar ice cores.

The last paper makes an attempt at modelling the effect of climatic change on future snow cover, in particular the change in melt and acid run-off from seasonal snows. While there is clearly still a long way to go to produce a realistic model, the results are thought provoking. Finally, the book is rounded off with a short discussion of what has been achieved in this field and what questions remain to be answered, with some broad areas noted for further study.

The book makes a good attempt at presenting the current state of knowledge of snowpack composition. The volume works at its best when presenting comprehensive reviews of the processes involved together with substantial bibliographies, and less well when describing results from particular experiments in detail, since those included are but a small part of the wide range of studies taking place. It is a good book, though expensive, and one senses it is the result of a successful workshop. As an introduction to the subject it can hardly be bettered, with plenty of information for those entering the field or planning experiments. On this last point, one remark that will remain with me comes from the close of the review on biological processes: when choosing a site for chemical analysis, first take a good look at the biological aspects of the area.

R. Mulvaney

International weather radar networking,

edited by C.G. Collier. 160 mm × 235 mm, pp. xiii + 332, *illus*. Dordrecht, Kluwer Academic Publishers, 1992. Price £66, $110.00, Dfl 190.00, ISBN 0 7923 1706 8.

In the October 1992 issue of *Meteorological Magazine* we carried a transcript of a talk given by Mr C.G. Collier on this topic. This is 'the book of the talk', the collected papers presented at the final seminar of the COST Project 73 held in Ljubljana, Slovenia in June 1991. This is a book of remarkable contrasts and a mine of miscellaneous information. Not least of the contrasts is that between progress reported then and the subsequent political disaster there.

The first 10%, the opening ceremonial speeches, would normally be expected to be a boring space-filler, but here it shows that no budget need not mean no progress, given the good will. The rest of the book consists of papers covering almost every aspect of radar meteorology — if you can find it. I deliberately describe it as a mine; the information is the valued ore which must be won from the overburden or spoil. The lack of a subject index means that you have to rely on the titles of the papers given in the front list of contents: the list at the rear is almost the same but gives times rather than page numbers! The mathematical complexity of 'On the importance of the noise figure in reflectivity radars' is followed immediately by the short descriptive 'Operational radar measurements of rainfall: the accuracy of point measurements of rainfall rate'. 'Report by the COST Project 73 telecommunications working party' gives a full description of the BUFR code with 14 pages of tables; it is followed by a nicely illustrated 'Weather radar data distribution and presentation in Austria'.

The contrast in contents is perhaps less disconcerting than the publisher's policy of photo-reproduction of the text as received. The result is sometimes violent changes of font, a change from high-quality type to draft-mode nine-pin dot-matrix, proportional to fixed-character spacing, and most irritating of all, a density range from seven lines and twelve characters per inch to an incredible eight-and-a-half lines and twenty characters. The illustrations are generally well done with good colours.

Finally, if purchasing a copy, check through all the pages. I know that at least one batch had some pages that had been through the press twice, making them almost illegible. I think that this book is rather too costly.

R.M. Blackall

Diffraction effects in semi-classical scattering, by H.M. Nussenveig. 155 mm × 234 mm, pp. xiii + 238. Cambridge University Press, 1992. Price £35.00, $59.95. ISBN 0 521 38318 8.

The Montroll Memorial Lecture Series in Mathematical Physics, given at the University of Rochester, USA aims to provide a forum for the presentation of new developments and coherent overviews in mathematical physics. This book is the first in a new series which will make the lectures available in book form, and contains the 1988 lectures.

The central theme of the text is an analysis of the scattering of electromagnetic waves from dielectric spheres at optical frequencies, in particular critical effects such as coronae, rainbows, glories, orbiting, and resonances. The first four chapters are introductory, intended to introduce the various effects. They are largely descriptive, though they introduce the reader to the significant mathematical analysis in the later chapters. Chapter five gives a too-brief outline of the Mie theory exact solution of the problem, and describes the rapid variations which can occur in backscatter cross-section with increasing scatterer size.

The next nine chapters describe and apply complex angular momentum (CAM) theory to the various phenomena. As a prelude to the main problem, scattering by an impenetrable sphere is first considered, and leads to the concept (by analogy with quantum mechanics) of diffraction as a tunnelling phenomenon. When applied to the Mie theory, the effective potential for a transparent sphere is seen to be similar to that giving rise to quasi-bound states in atomic theory. Different types of resonances are seen to correspond to different Regge poles. Amongst its successes, the CAM theory has given an accurate quantitative theory of the rainbow and a detailed physical explanation of the meteorological glory. The final two chapters discuss applications in other areas as diverse as determination of particle size and refractive index, radiative transfer, seismology, and atomic nuclear and particle physics.

This book is born out of the author's research in the area over more than thirty years. The insight it provides into the detailed scattering mechanisms underlying observations is a valuable contribution to the literature. Another aspect of value is the application of methods from another area (high energy physics) to the understanding of the light scattering problem. The figures are clear, but I fear that the text is really too brief in places to be self-standing. In too many places the reader is referred to the literature for explanations that should have been incorporated in the text. Another disappointment is that there is only scant reference to the scattering problem at microwave frequencies, of interest to those interested in the radar remote sensing of rain.

This text is for those with a background in theoretical physics, but they will read it with considerable profit.

A.R. Holt

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Phenomena in atmospheric and environmental electricity, by R. Reiter (Amsterdam, Elsevier, 1992. $165.00, Dfl.290.00) attempts to present, define and explain the phenomena, emphasizing on levels up to 70 km. It is the twentieth in the *Developments in atmospheric science* series. ISBN 0 444 89286 9.

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The unified forecast/climate model

M.J.P. Cullen
Meteorological Office, Bracknell

Summary

The reasons for adopting a unified forecast/climate model are discussed. The model is described and related to previous forecast and climate models in use in the Meteorological Office. The software system used to implement it is also briefly described. Examples of its performance are shown in global, regional, and mesoscale forecasts, long-range forecasts, climate simulations, and upper-atmosphere forecasts.

1. Introduction

The Meteorological Office has used a global numerical weather prediction model since 1982 (Gadd 1985), and has used global climate simulation models since the late 1960s (Corby *et al.* 1977)). The global weather prediction model was based on the design of the then current climate model. Experience with the two separate models suggested that it would be advantageous to combine them at the next major computer upgrade. The opportunity occurred with the installation of the CRAY YMP in January 1990. It was also decided that the resulting unified model should be used for upper-atmosphere simulations taking advantage of the data supplied by the UARS satellite. This paper describes the justification for the move to a unified model, the model formulation and software system, and illustrates its performance in the main configurations.

2. Justification for the unified model

The global forecast and climate models implemented on the Meteorological Office CYBER 205 computer had many similarities. Both solved the equations of motion using finite difference methods on a grid regular in latitude and longitude. Both used a terrain-following vertical coordinate, with increased resolution near the ground and near the tropopause. Both included representations of the main physical processes such as boundary layer mixing, convection, large-scale precipitation, gravity wave drag, and radiation. The main differences were that lower horizontal and vertical resolutions were used in the climate model, that a different time integration scheme and arrangement of the variables on the grid were used in the two models, and that the representation of physical processes in the climate model was considerably more advanced. The program structure required for both models was similar. However, the climate model contained a large amount of ancillary software to enable output to be processed automatically during the very long integrations required.

State-of-the-art atmospheric modelling requires a high degree of scientific expertise, and it had already been necessary to share this expertise by using or attempting to use similar physical formulations in the two models. However, it is much simpler to do this if the models use the same computer code. Use of a modular program design allows easy testing of alternative formulations, and means that different representations of some processes can still be used if necessary. Either model on its own, together with ancillary programs for processing input and output data, forms a large software system. The unified model system contains at present about 150 000 lines of code. Maintenance of two separate systems is no longer practicable or justifiable. Furthermore, it had already been decided that incorporating the output processing within the forecast model, as had already been done in the climate model, was a much more efficient method of generating the wide range of products required.

In order to achieve a unified model, however, several key steps had to be taken:

(a) Successful use in the climate model of the very efficient split-explicit integration scheme (Gadd 1978), used in the forecast model. This required modifying it to ensure conservation of heat and moisture, and ensuring acceptable performance in climate mode.

(b) Modifying the boundary layer scheme to allow use of the longer time-steps permitted by the split-explicit integration scheme.

(c) Modifying the radiation and cloud scheme to allow use of the higher vertical resolution of the moisture field possible in the existing forecast model, and the planned unified model.

(d) Successful use in the forecast model of more-elaborate representations of physical processes, particularly the use of explicit cloud variables and their interaction with radiation.

(e) Design of a single maintainable software system to meet all the requirements, while achieving the same efficiency as a single-purpose model.

Following on from the initial operational implementation of the unified model, it was realized that there were considerable advantages in using the same model for the mesoscale forecast over the United Kingdom. This avoids the need to have two separate teams of scientists and two software systems, and allows the techniques used in larger-scale modelling to be rigorously tested at the higher resolution used in the mesoscale model against the detailed observations available over the United Kingdom. This experience, and the optimization of the model as a climate model, will also allow the model to be used with confidence as a relocatable limited area model anywhere in the world to meet defence requirements.

3. Description of the unified model

3.1 Equations of motion

The equations used are a more accurate approximation to the equations of motion than were used in the previous models. They are described in detail by White and Bromley (1988). They differ from those normally used in that the full three-dimensional representation of the of the Earth's rotation is included. This is necessary when planetary-scale motions are considered, and the vertical component of the Coriolis force may also be important in regions of strong vertical motion. In addition to the standard equations of motion, an arbitrary number of passive tracers can be advected by the model. This can be used to allow the model to study the evolution of chemical species, but could also be used to treat aerosols.

3.2 Grid and coordinate system

The equations are integrated in spherical polar coordinates, using a 'hybrid' vertical coordinate (Simmons and Burridge 1981). This is a function of pressure, equal to unity at the lower boundary, and equal to a multiple of pressure at the upper levels. It is chosen because terrain-following coordinate surfaces are much more convenient in the lower layers of the atmosphere, while pressure coordinates are more likely to give accurate results in the upper layers. The unified model code is designed to allow any distribution of levels. However, it is found in practice that the performance of physical parametrization schemes is very sensitive to the distribution of levels. Most users of the model will therefore be using the standard 19-level configuration shown in Fig. 1. The mesoscale model uses 30 levels, with extra levels between 25 metres above the ground and the tropopause. Upper atmosphere modelling will be using a 49-level configuration extending up to 0.25 hPa.

A regular latitude–longitude grid is used in the horizontal, with the variables arranged according to the Arakawa 'B' grid as in the operational 15-level model (Gadd 1985). The arrangement of variables in the vertical is also the same as in the 15-level model. The code can be run at any desired resolution, subject to computer memory restrictions. The operational forecast grid has spacing of 0.8550° in latitude and 1.250° in longitude. The standard climate and upper-atmosphere configurations will use 2.50° and 3.750°.

The limited-area models also use spherical polar coordinates. However, to obtain uniform resolution over the area of interest, the coordinate pole is not placed at the geographical pole. This idea was first introduced in the Irish limited-area model (Unden 1980). The unified model can be run with any choice of coordinate pole and area. The operational regional model has the coordinate pole at 30 °N, 160 °E and a grid-length of 0.44°. The mesoscale model has the coordinate pole at 37.5 °N, 177.5 °E and a grid-length of 0.15°. The integration areas for the regional and mesoscale models are shown in Fig. 2.

3.3 Finite difference scheme

The split-explicit finite difference scheme used in the 15-level model is very efficient, and there was no need to change it for purely forecast applications. However, finite difference schemes for climate modelling have to satisfy additional requirements, for instance that total heat and moisture must be conserved under advection. To meet these requirements, the Lax–Wendroff advection scheme was replaced by the Heun scheme, and the separation of calculations between the long advection step and the short adjustment step had to be altered. The new scheme is described in detail by Cullen and Davies (1991). As with the 15-level model, Fourier filtering has to be used at high latitudes in the global model in order to prevent an undesirable restriction on the time-step that can be used. However, to ensure conservation, it is

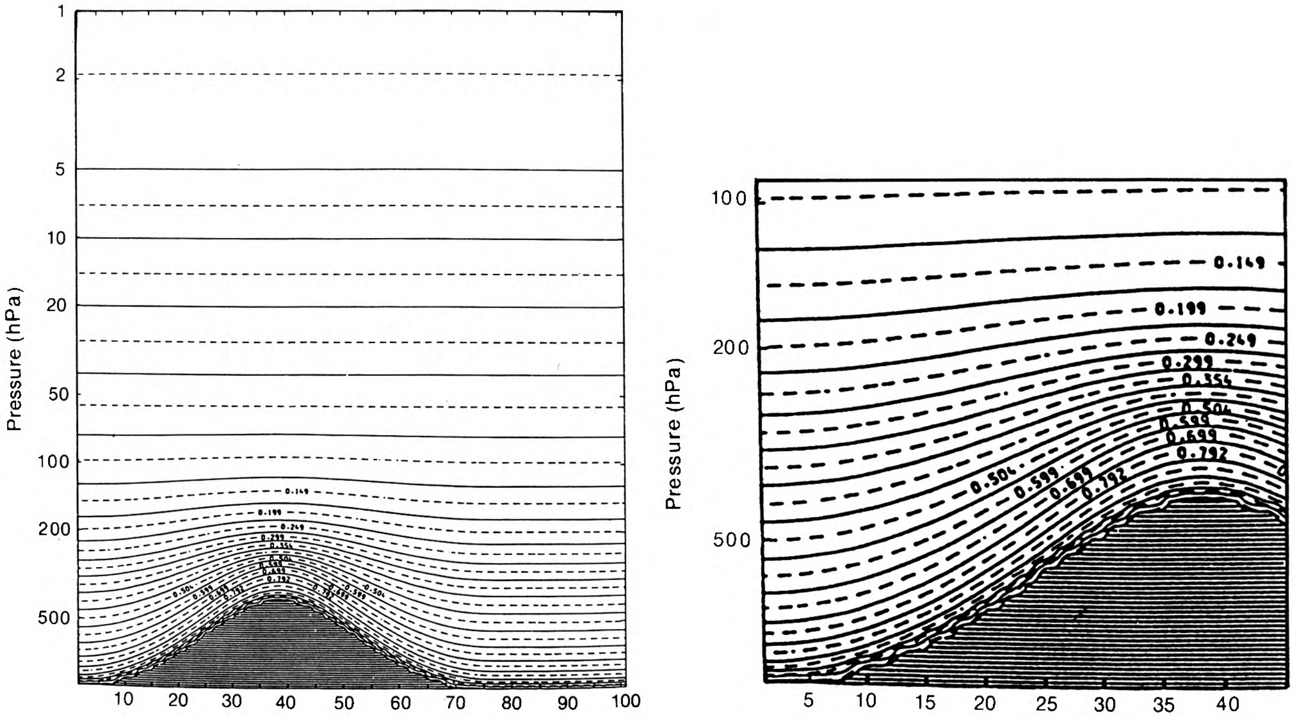

Figure 1. Standard levels for use in the unified model.

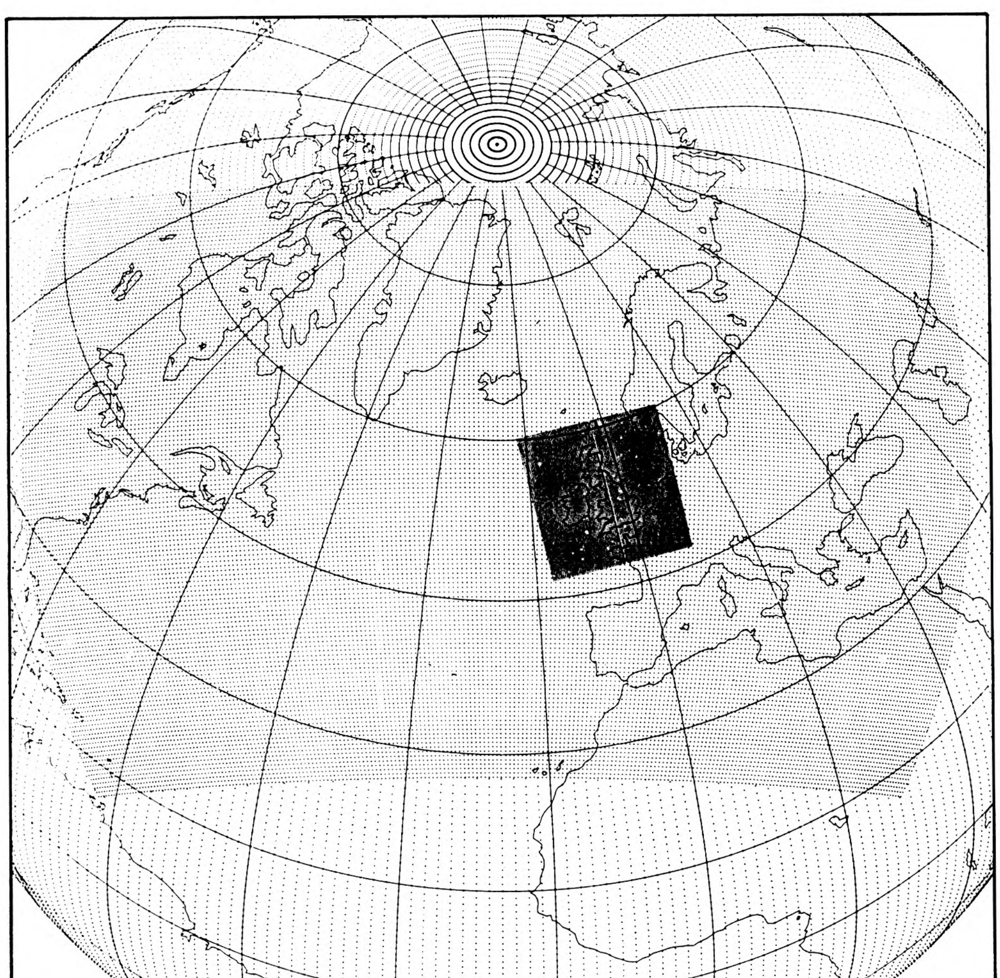

Figure 2. Integration areas for the regional and mesoscale models.

necessary to filter increments to the temperature and moisture fields rather than to filter the fields themselves. No filtering is required in the limited area model.

3.4 Parametrizations

It is expected that a library of parametrizations will gradually become available for the unified model. Those that are being used initially are described briefly below.

(a) Land surface model. A multilayer soil temperature model and a soil moisture prediction scheme are included. Different soil types are specified, and used to determine the surface albedo. A model of the vegetation canopy is included. Moisture can be retained in the canopy or transferred to the soil or atmosphere. Different vegetation types can be specified. Snow depth is predicted and used in the calculation of albedo. The scheme is described in detail by Smith (1990) and Gregory and Smith (1990).

(b) Boundary layer. Vertical turbulent transport of primary variables and tracers in the boundary layer depends on the local Richardson number. The presence or absence of cloud is taken into account in calculating the transport coefficients. The scheme is described in Smith (1990).

(c) Large-scale cloud and precipitation. Large-scale clouds are represented by their liquid water (or ice) content. The total optical thickness of the clouds is taken into account in the radiation calculations (Ingram 1990). Large-scale precipitation is calculated in terms of the water or ice content of the cloud; frozen cloud starts precipitating as soon as it forms. Cooling of the atmosphere due to evaporation of precipitation is included. The scheme is described by Smith and Gregory (1990).

(d) Convection. Sub-grid-scale convective processes are modelled using a simple cloud model; convection affects the large-scale atmosphere through compensating subsidence, detrainment, and the evaporation of falling precipitation. The scheme is described and illustrated by Gregory (1990) and Gregory and Rowntree (1991).

(e) Radiation. The radiation calculation uses six bands in the long wave and four in the solar calculation. It allows for water vapour, ozone, carbon dioxide, and the large-scale and convective cloud distributions. Cloud radiative properties depend on cloud water and ice content. The scheme is described by Ingram (1990).

(f) Gravity-wave drag. The effects of the drag caused by sub-grid-scale gravity waves is estimated using the sub-grid variance of the orography and the known absorption properties of gravity waves in a given atmospheric profile. The scheme is described by Wilson and Swinbank (1991).

(g) Horizontal eddy diffusion. This is represented by simple grid-scale filters The filters can be iterated to make them more scale selective for use at low resolution. The method is described by Cullen *et al.* (1991).

(h) Vertical eddy diffusion. This is sometimes required to remove oscillations caused by inadequately resolved quasi-inertia waves. Only the winds are smoothed. The method is described by Wilson (1992).

(i) Ancillary fields. The calculations of surface exchanges require values of a number of surface parameters. Distributions of sea-ice and snow cover must be specified. Over the open sea, the surface contact temperature has to be analysed for forecast use. Over the land, sets of parameters defining the soil and vegetation characteristics must be specified.

3.5 Coupling to other models

Various types of coupling are available.

(a) Ocean model. The atmosphere model can be coupled to both global and limited-area ocean models. It can also be coupled to a highly simplified ocean model known as a 'slab' model. The unified model system can be used to run ocean-only integrations.

(b) Stratosphere-only model. The full atmosphere model can be used to generate the heights of an isobaric surface to drive a version of the unified model covering only the stratosphere.

(c) Limited-area models. The global atmosphere model drives the regional model by generating values of the prognostic variables in a boundary zone. When the regional model is integrated, the values on the boundary are constrained to be the same as those in the global model, with those close to the boundary replaced by a weighted mean of predicted values and prescribed values from the global model (Davies 1976). A similar method is used to drive the mesoscale model from the regional model.

(d) Wave model. This is driven by 10 m winds output from the atmosphere model. It is likely that in future the wave model will be coupled to the atmosphere model and used to predict the surface roughness over the sea.

(e) Surge model. This is driven by model surface pressure and wind output.

3.6 Software implementation

An overview of the unified model software system is shown in Fig. 3.

The main components are:

(a) User interface. A panel-driven system which allows a user to run any version of the model with any choice of diagnostic output. It holds a library of previous experiments conducted by the user, so that it is easy to make small changes to a previous experiment with the model.

(b) Reconfiguration. A system for converting an input unified model data set to a new resolution, importing new ancillary or analysed data, and expanding the data set to make room for extra diagnostics.

(c) Model. The atmosphere and/or ocean model is integrated with data assimilation if required.

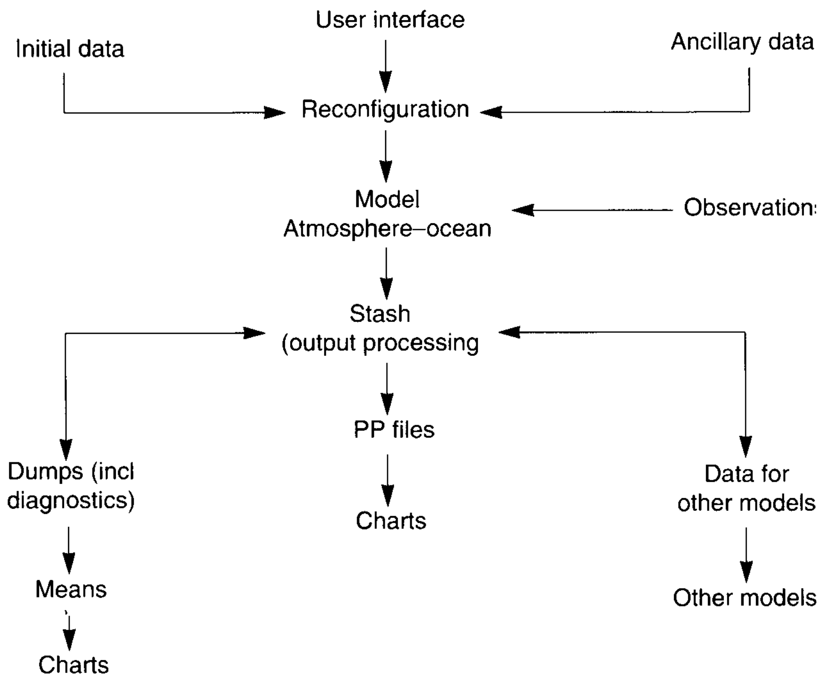

Figure 3. Unified model software system.

(d) Stash diagnostics. Diagnostics generated in each section of the model are processed as required by the user, either being output to the front-end computer or being retained for later time-averaging.

(e) Output streams. This includes the output for coupling to other models, dumps to allow integrations to be restarted, and chart output. Output can be time-meaned if required.

4. Examples of the use of the unified model.

4.1 Global forecasting

The enforcement of conservation properties in the integration scheme is the main dynamical difference between the unified model and the previous Meteorological Office forecast model. This appears to be the reason why the unified model is much better at predicting upper ridges. An example is shown in Figs 4–6. The ridge in the verification 500 hPa chart (Fig. 4) developed over the previous 4 days. Though the unified model slightly underestimates the amplitude, it is still 12 dam greater than that produced by the old forecast model. Other experiments showed that the resolution difference between the two models had only small effects on this type of development.

4.2 Regional forecast

The higher resolution and possibly the more advanced physical parametrizations of the operational limited-area version of the unified model allow it to give a more organized representation of regions of precipitation than the previous limited-area model. On occasions, the higher resolution also gives a better treatment of pressure systems. An example is shown in Figs 7–9, where the depression to the east of Scotland is much better represented by the new model 24 hours ahead.

4.3 Mesoscale forecast

The initial version of the unified mesoscale model matches the previous mesoscale model in horizontal resolution, and vertical resolution above the near-surface layer. Further development is required to include the near-surface layers and allow useful fog predictions. It is hoped to complete this enhancement later in 1993. The initial version has proved successful in adding detail to precipitation forecasts from the regional model, while retaining greater consistency with it than did the previous mesoscale model. An example is shown in Figs 10–12. The new mesoscale model gives an equivalent amount of detail to the old model, in some respects better and in some worse when compared to the verifying radar picture.

4.4 Long-range forecasting

The standard long-range forecast procedure is to run a set of nine forecasts from data times six hours apart (Milton 1990). The results are then averaged over a set of forecast periods, including days 6–15 and days 16–30. An example of an exceptionally good forecast made from the average of forecasts from data times between 18 and 20 May 1991, verifying for the period 26 May to 4 June, is shown in Figs 13 and 14. The cool north-easterly flow over the United Kingdom is very well predicted. This forecast had an anomaly correlation coefficient of 0.79. The average value of this coefficient for unified model forecasts for this range to date is 0.17.

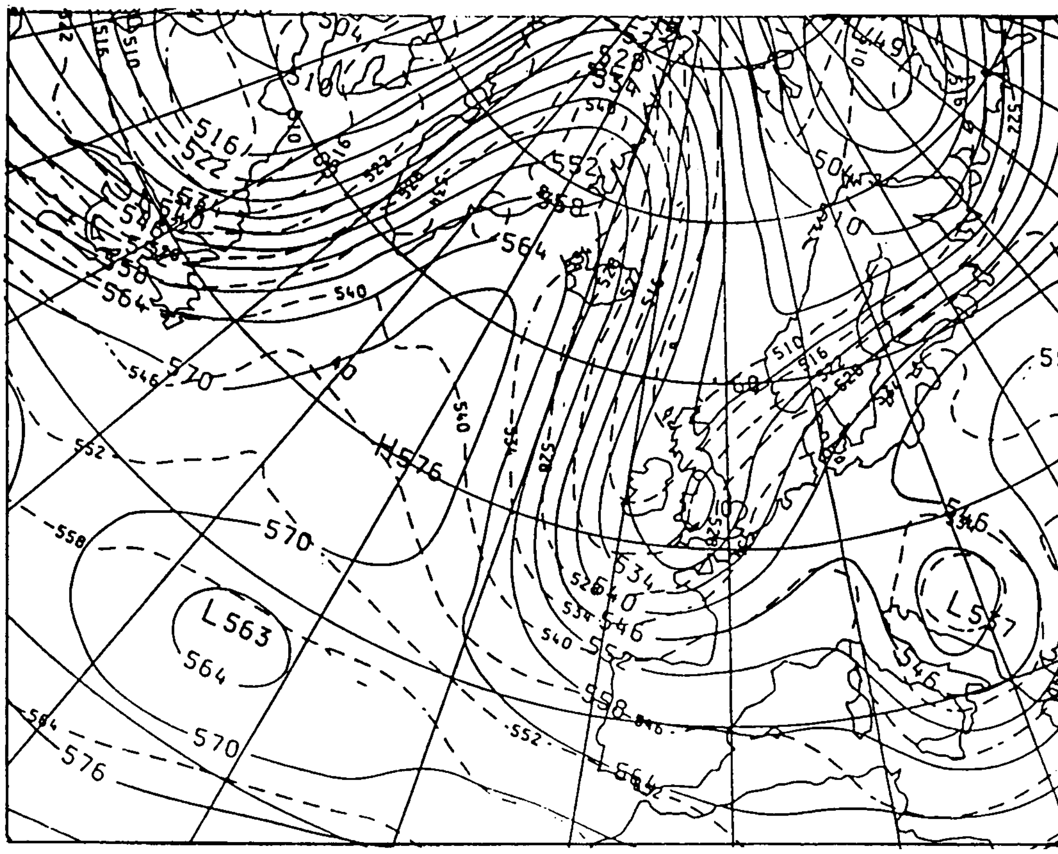

Figure 4. Analysis at 500 hPa for 00 UTC on 8 December 1990.

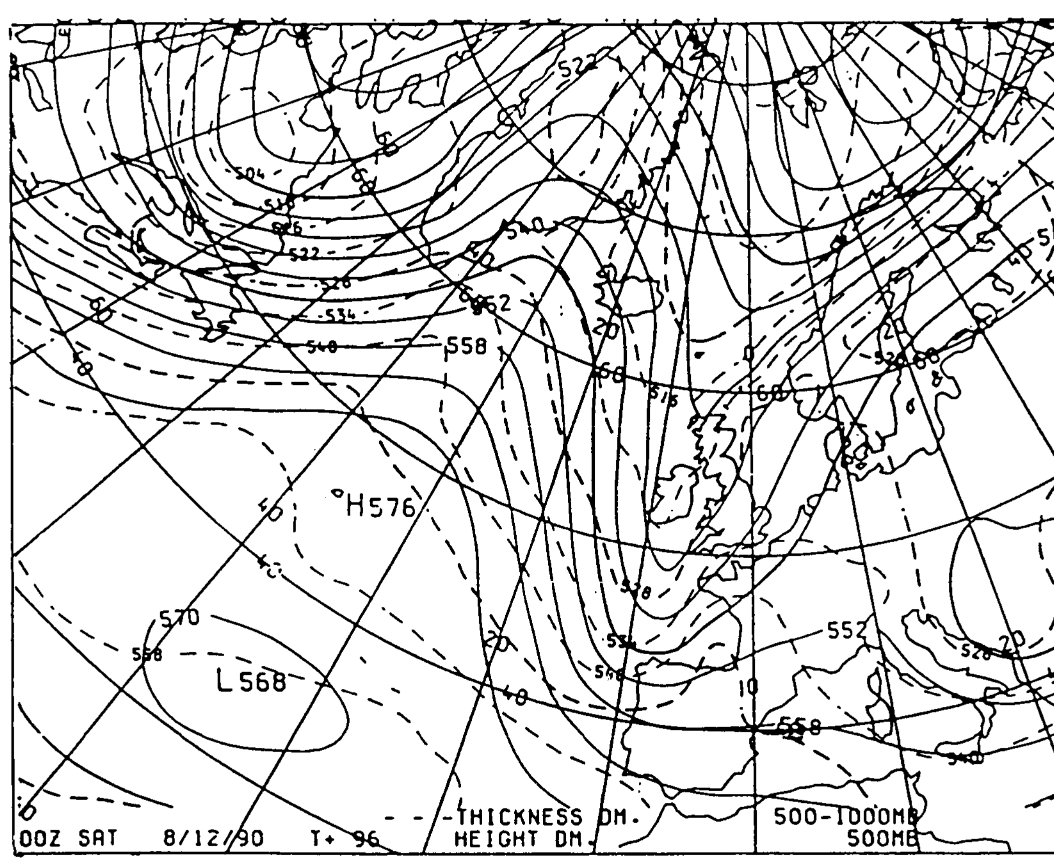

Figure 5. Four-day 500 hPa forecast valid at 00 UTC on 8 December 1990 using the previous Meteorological Office forecast model.

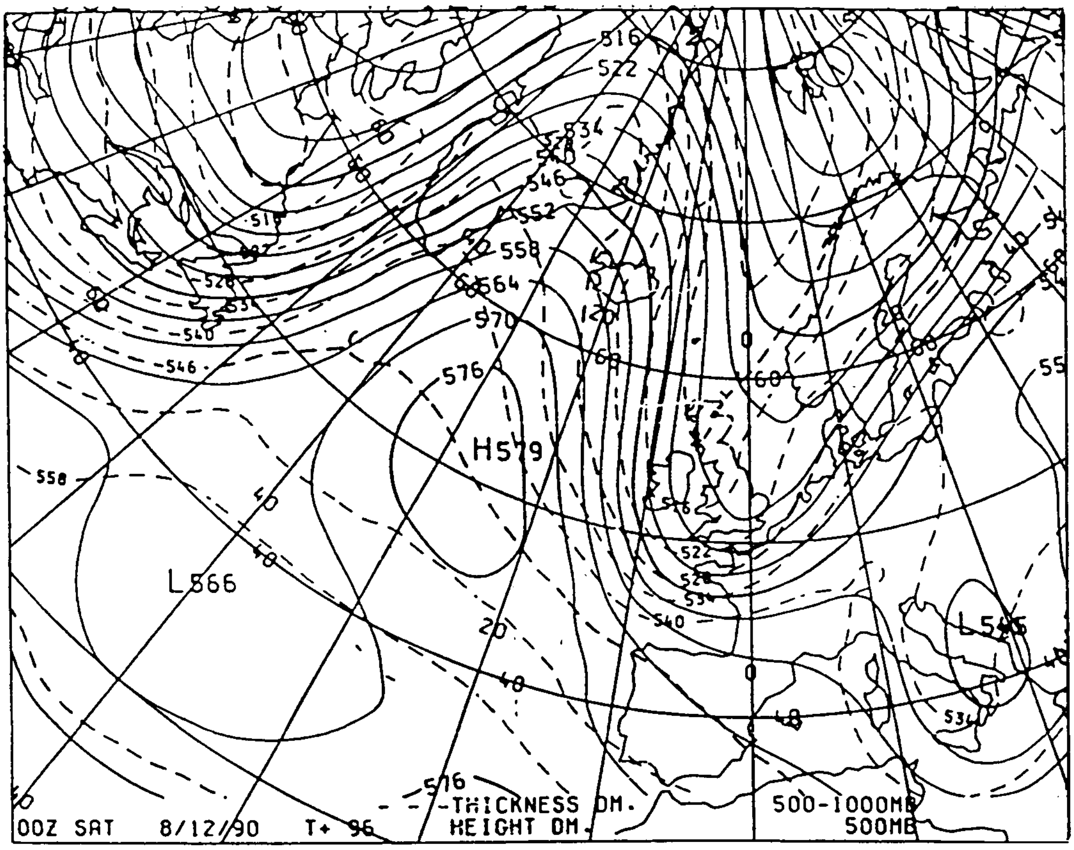

Figure 6. Four-day 500 hPa forecast valid at 00 UTC on 8 December 1990 using the unified model.

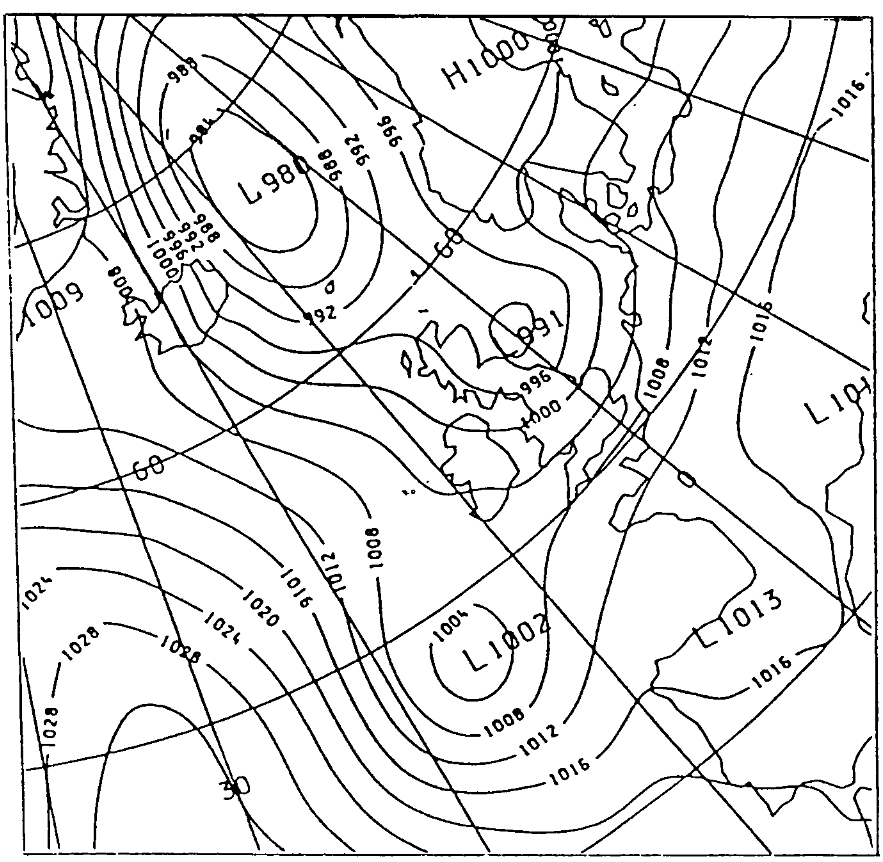

Figure 7. Surface pressure analysis (hPa) for 00 UTC on 21 March 1991.

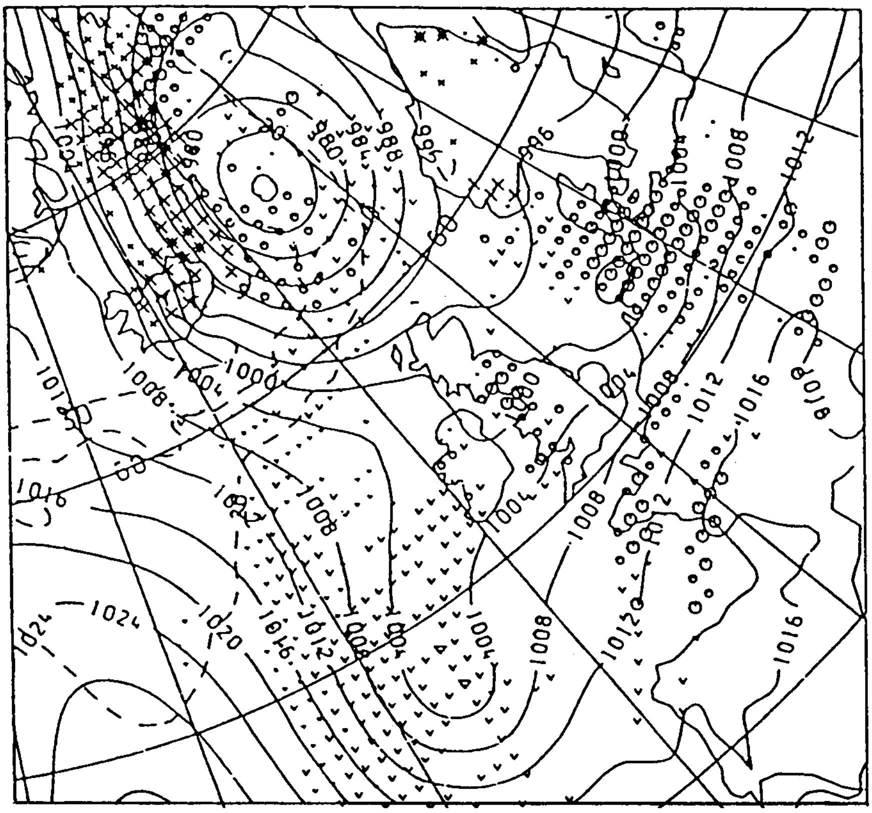

Figure 8. Twenty-four-hour mean-sea-level pressure forecast (hPa) for 00 UTC on 21 March 1991 using previous model.

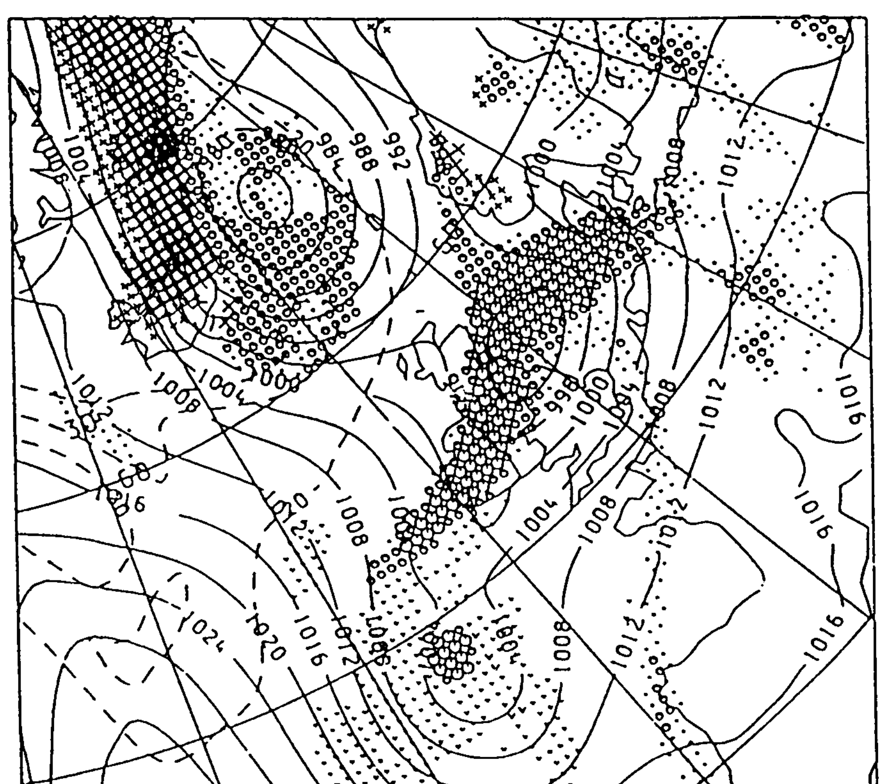

Figure 9. Twenty-four-hour mean-sea-level pressure forecast (hPa) for 00 UTC on 21 March 1991 using the unified model.

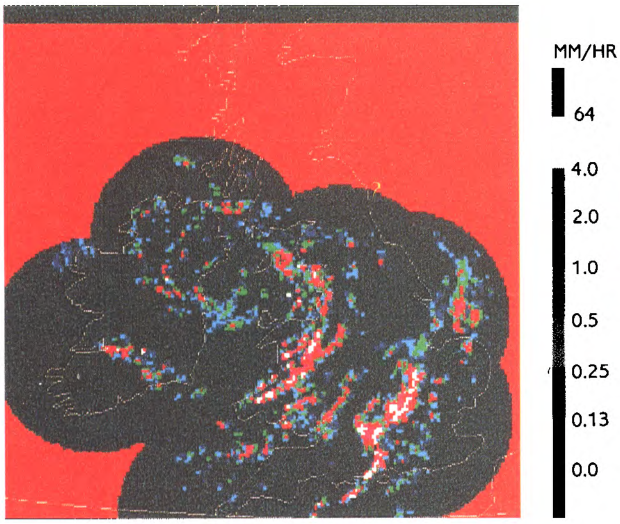

Figure 10. Weather radar network picture showing the observed rainfall distribution corresponding to the forecast in Figure 12.

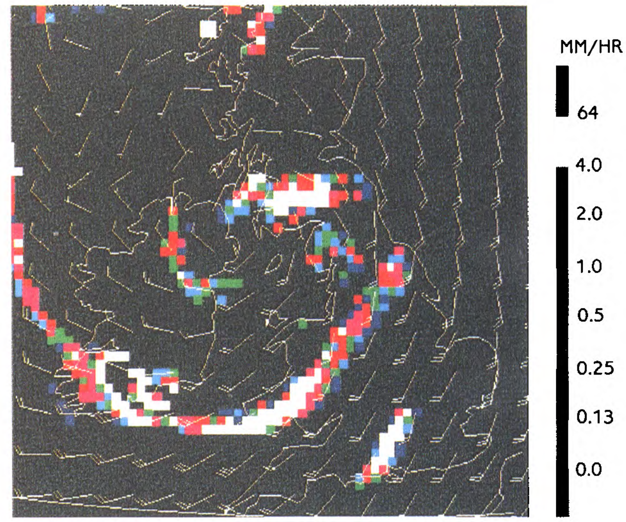

Figure 12. Twelve-hour forecast of rain bands from the Meteorological Office non-hydrostatic mesoscale model valid at 12 UTC on 23 August 1991.

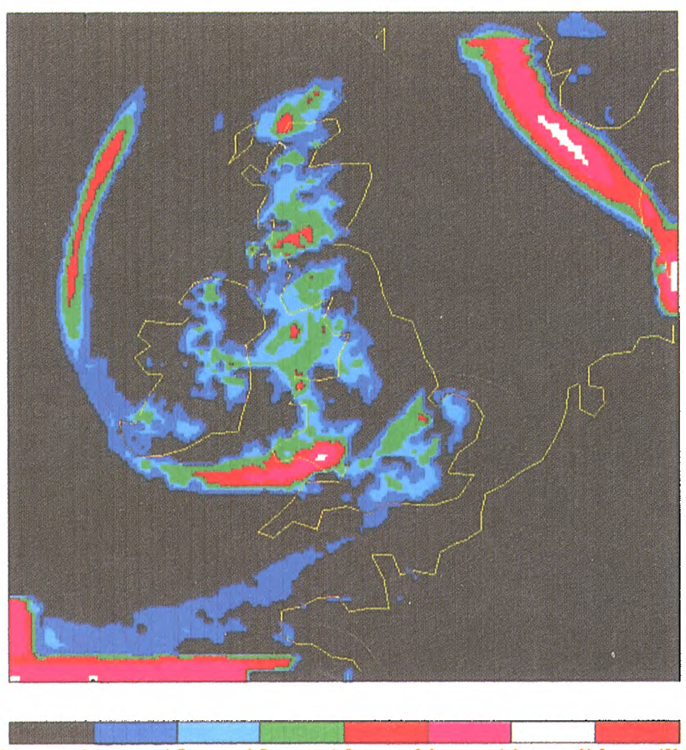

Figure 11. Twelve-hour forecast of rain bands from the mesoscale version of the unified model valid at 12 UTC on 23 August 1991.

4.5 Climate simulation.

Figs 15 to 17 show the rainfall climatology for the unified model for the northern hemisphere winter compared with climatology and the previous climate model. The unified model results are a 20-year mean, and the climatological estimate is that of Jaeger (1976). The simulations are broadly comparable. Comparisons over the full annual cycle show that the unified model gives lower monsoon precipitation over the Sahel and Venezuela when compared to climatology and the previous model. The unified model gives excessive summer precipitation over the South China Sea. The previous model gave an unrealistic zonal band of minimum precipitation along the equator in the west Pacific and Indian ocean, which is not present in the unified model.

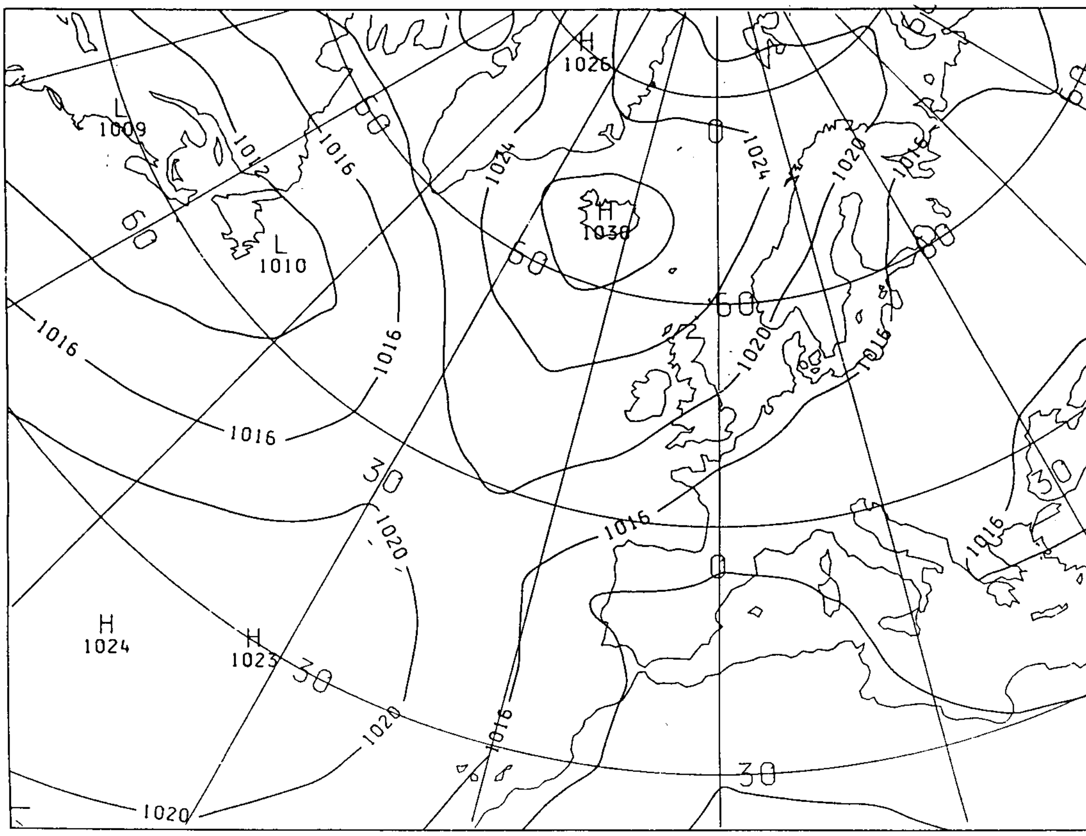

Figure 13. Ensemble mean of 9 unified model forecasts of the average mean-sea-level pressure (hPa) from 00 UTC on 26 May 1991 to 00 UTC on 4 June 1991.

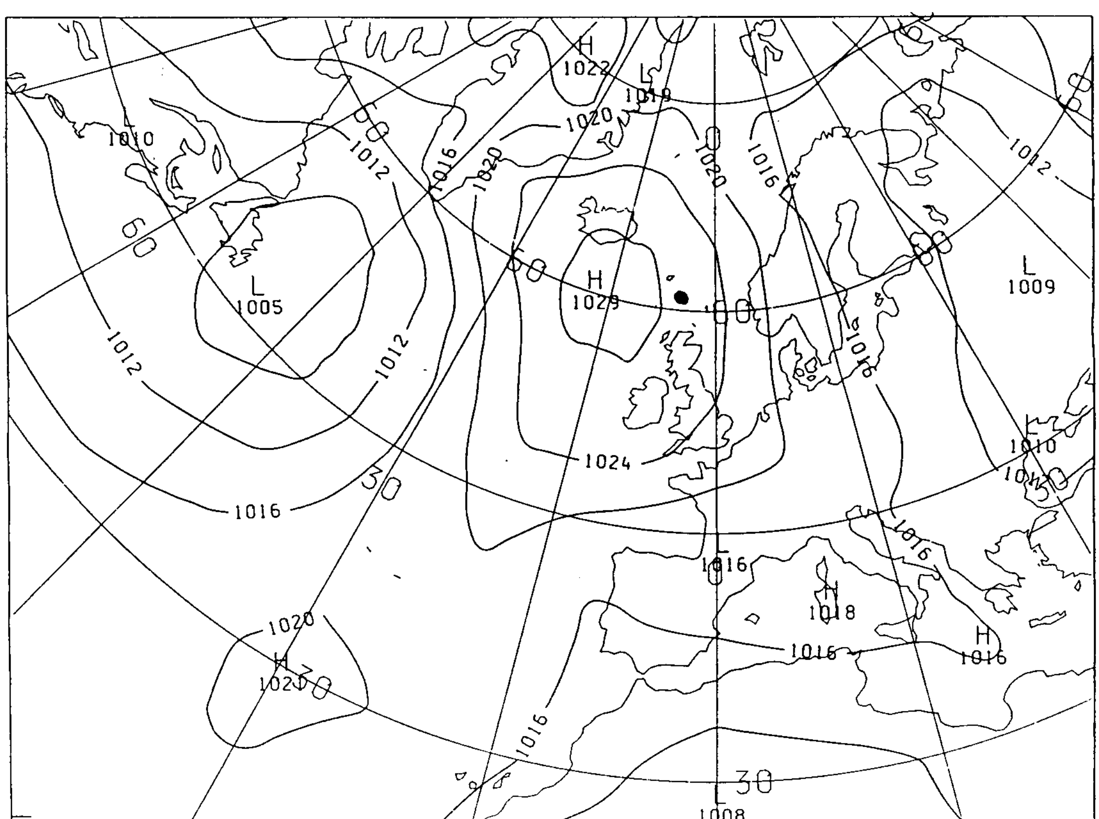

Figure 14. Ten-day mean of mean-sea-level pressure (hPa) from 00 UTC on 26 May 1991 to 00 UTC on 4 June 1991.

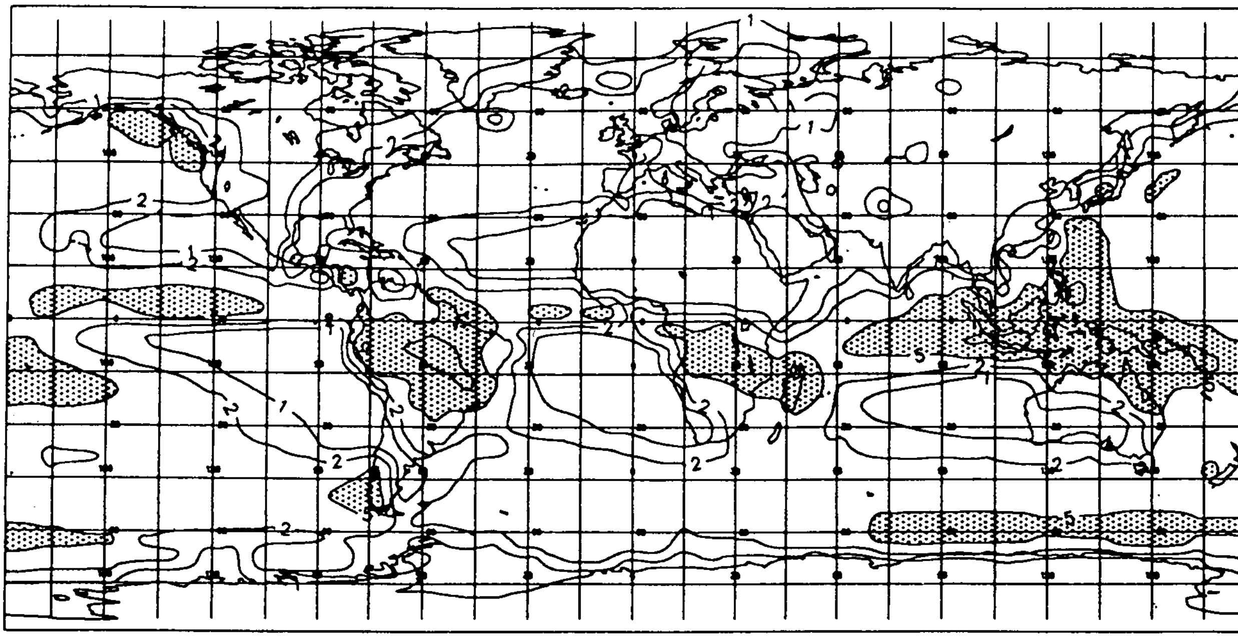

Figure 15. Climatological precipitation estimates (Jaeger) with contours at 1, 2, 5, 10, 20 and 40 mm d^{-1}. Areas over 5 mm d^{-1} are shaded.

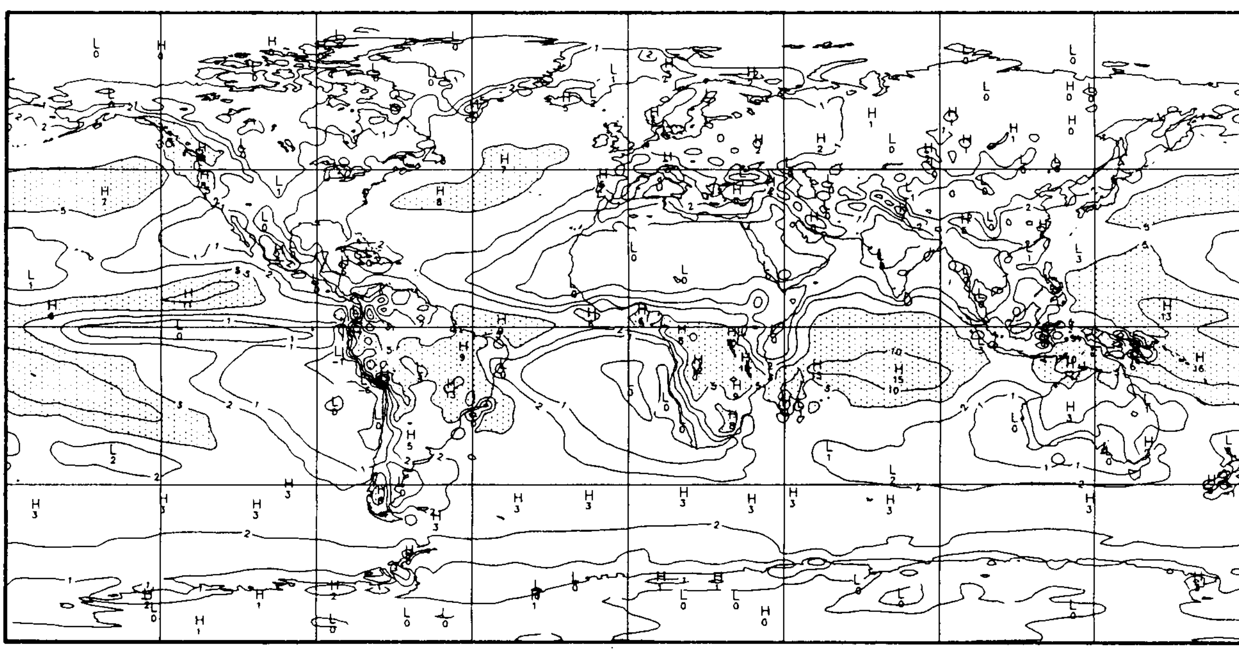

Figure 16. December–February precipitation (unified model) with contours at 1, 2, 5, 10, 20 and 40 mm d^{-1}. Areas over 5 mm d^{-1} are shaded.

4.6 Upper-atmosphere forecasting

A 5-day forecast of a stratospheric warming event using a 42-level version of the model extending to 0.25 hPa is shown in Figs 18 and 19. The 10 hPa height is illustrated. At the initial data time, there was a single polar vortex at this level. The model has correctly forecast the splitting of the vortex into two, though it has produced two separate upper-high centres rather than the cross-polar ridge shown in the observations.

4.7 Coupled ocean–atmosphere forecast

The ocean component of the unified model has not been changed from the previous CYBER model. An example of the coupled model capability of the unified model is shown in Fig. 20. This shows the 5-year mean sea surface temperature anomaly relative to climatology produced after an initial 25-year calibration period.

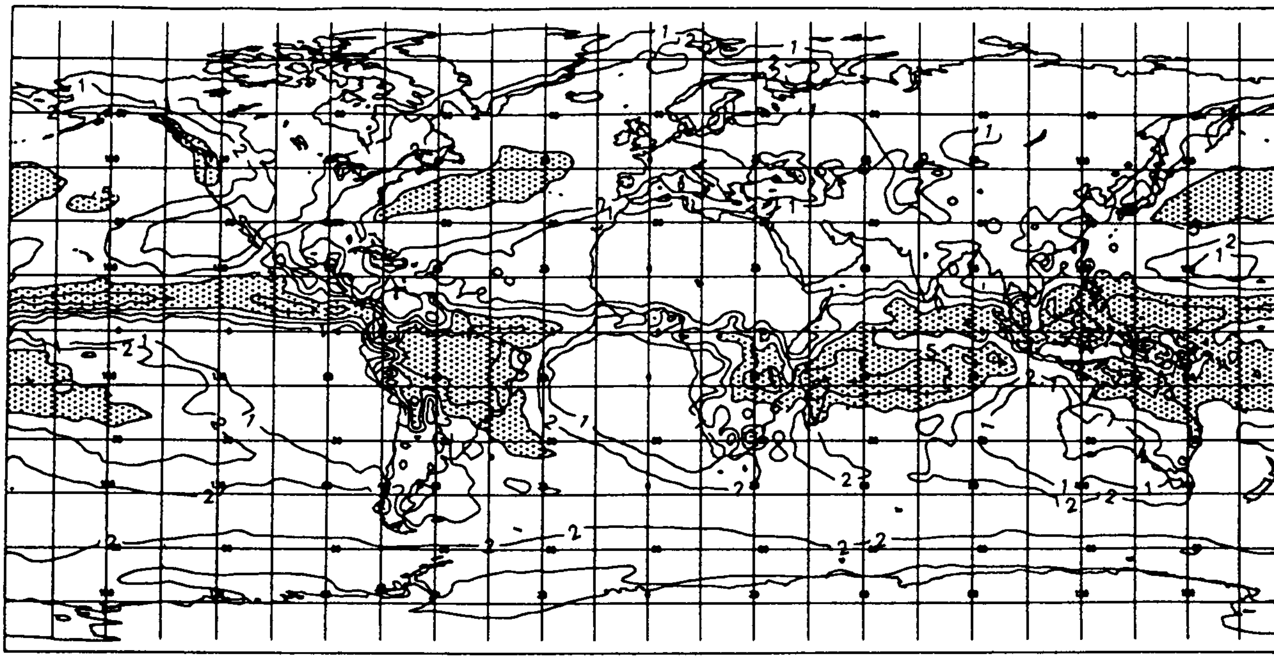

Figure 17. December–February precipitation (previous climate model) with contours at 1, 2, 5, 10, 20 and 40 mm d^{-1}. Areas over 5 mm d^{-1} are shaded.

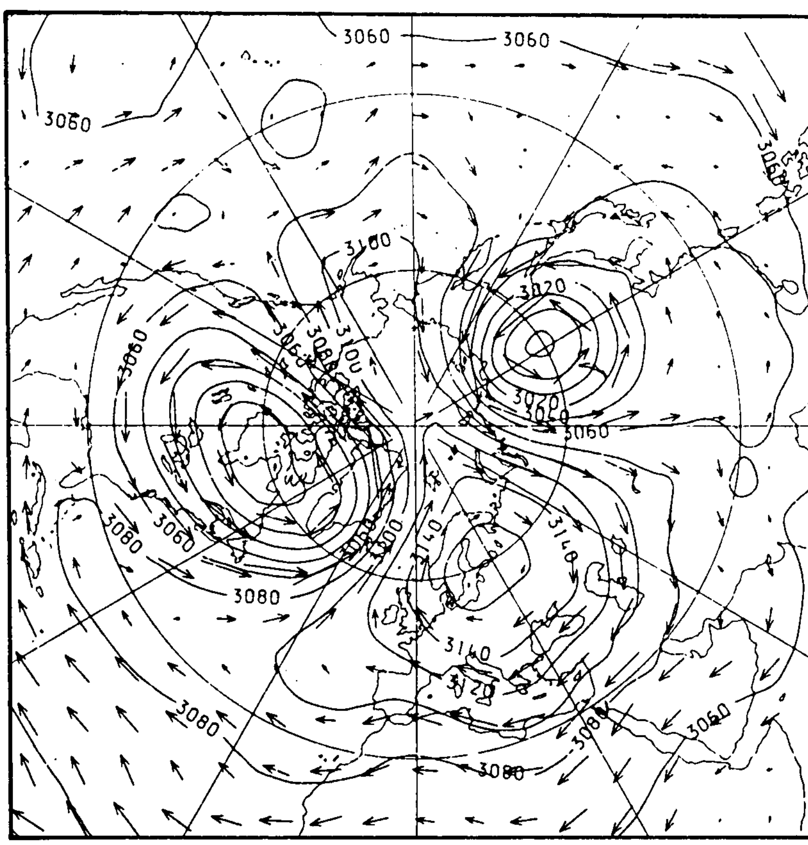

Figure 18. Height (dam) and wind analysis at 10 hPa for 12 UTC on 20 February 1989.

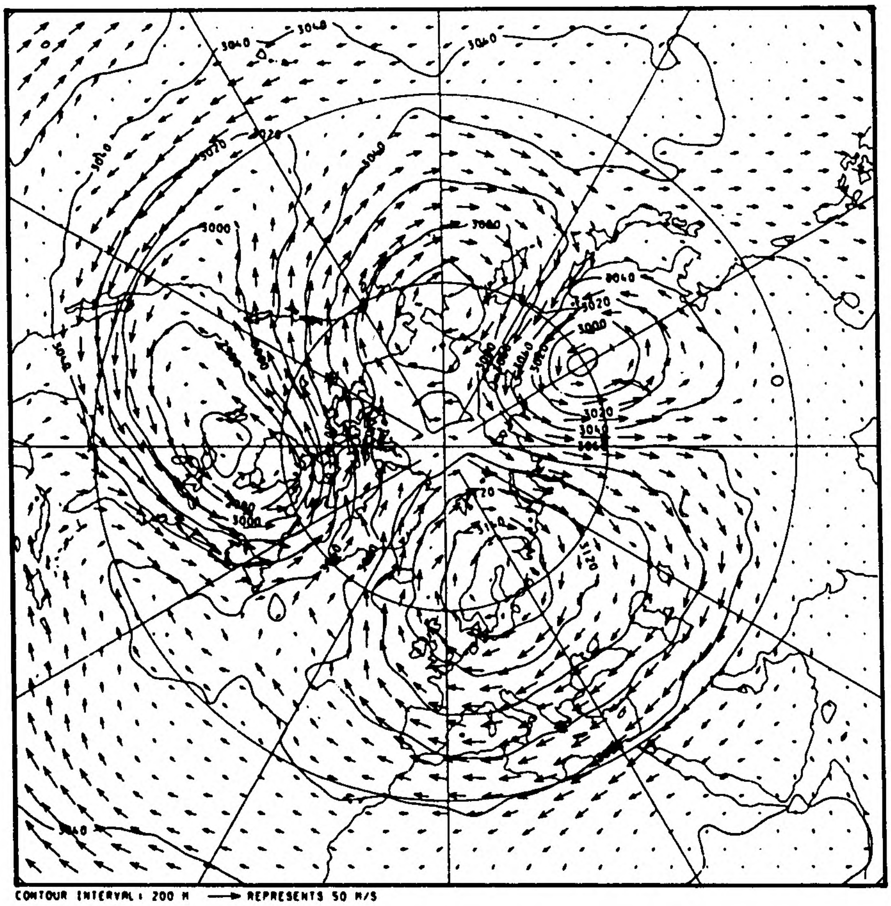

Figure 19. Five-day 10 hPa height (dam) and wind forecast valid at 12 UTC on 20 February 1989 using the 42-level version of the unified model.

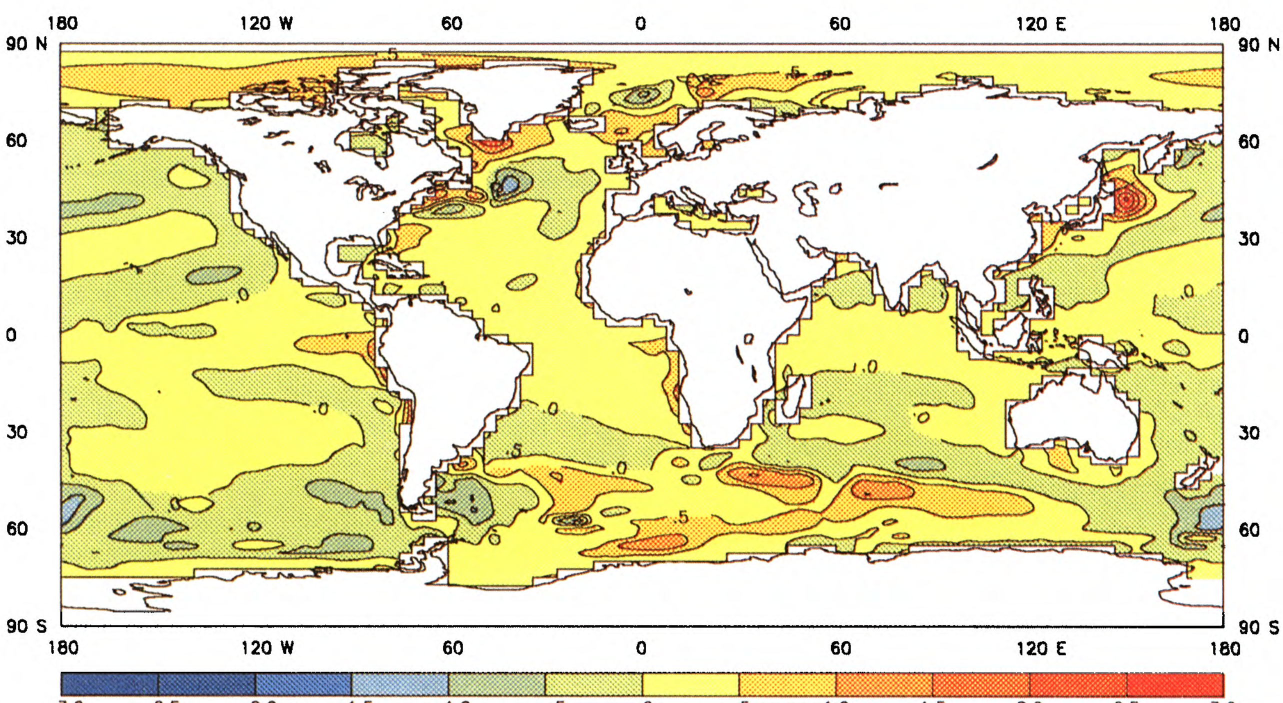

Figure 20. Five-year sea surface temperature anomaly (°C) produced by a coupled ocean–atmosphere run of the unified model.

Acknowledgements

The development of the unified model has been a cooperative project involving many staff from the Forecasting Research and Central Forecasting Divisions and from the Hadley Centre for Climate Prediction and Research. I wish to express my gratitude for their hard work and support in completing this project.

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Infrared imagery showing cloud evolution in a record(?) Atlantic low — 9/10 January 1993

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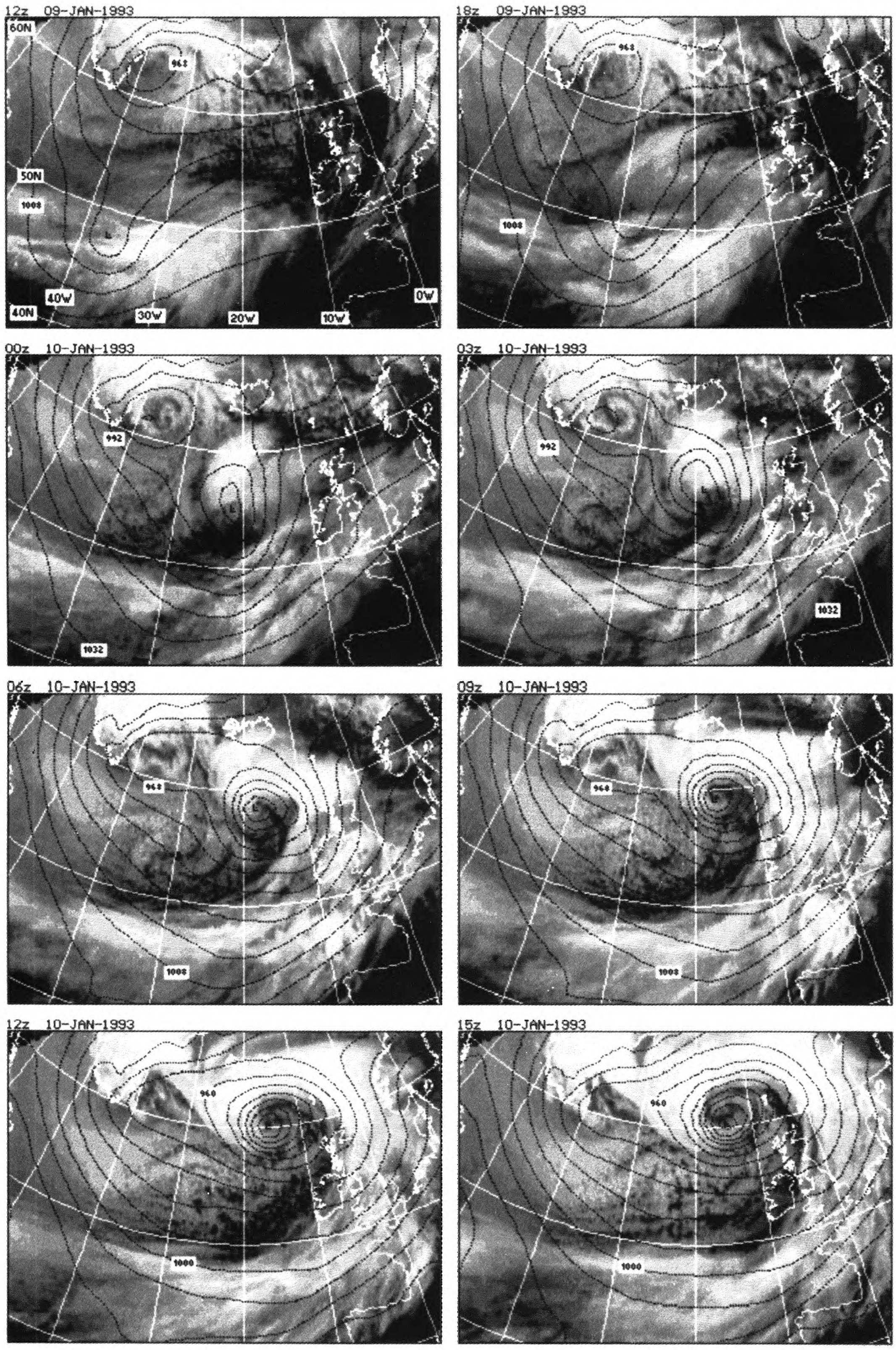
It is probable that on 10 January 1993 a new low-pressure record* was set for a north Atlantic extratropical depression. Hand-drawn analyses from the Central Forecasting Office in Bracknell indicated surface pressure minima of 916 hPa at both 12 UTC and 18 UTC on the 10th. If the analyses are accurate it is likely that pressure fell below 916 hPa between 12 UTC and 18 UTC, to perhaps 914 or 915 hPa (at about 61° N, 15° W). This would beat the previous record* of 916 hPa, set on 15 December 1986 (see Burt (1987)). The largest 24-hour fall in central pressure in the depression was about 63 hPa, between 12 UTC on the 9th and 12 UTC on the 10th. The figure provides a pictorial record of the evolution of cloud and surface pressure during this exceptional development.

* Temporal and spatial gaps in the observational network make the precise definition of a low-pressure 'record' impossible.

At 12 UTC on the 9th the low was situated in a broad baroclinic zone oriented approximately east–west, as characterized by the broad cloud-band centred around 48° N. Evidence of the strong baroclinicity can be found in the UK Meteorological Office limited-area model (LAM) 900 hPa wet-bulb potential temperature pattern in the vicinity of the low; values ranged from 16 °C (just to the south) to about −6 °C (at 53° N, 40° W).

Between 12 UTC on the 9th and 00 UTC on the 10th relatively warm cloud to the north of the low emerges from underneath the main band of colder cloud, and cools considerably. This is the result of rapid large-scale ascent ahead of the developing low, which in turn is probably linked to warm-front frontogenesis. At the same time a relatively cloud-free zone appears to develop south of the low, suggesting large-scale compensating descent, which is probably linked to cold front frontolysis.



Meteosat infrared images for 9 and 10 January 1993, with concurrent surface isobars superimposed (contoured at 8 hPa intervals). The main centre of the low referred to in the text is marked by a small black dot, with 'L' alongside. Surface pressure was calculated using values of geopotential height of the 1000 hPa surface taken from the LAM. Isobars for 00, 06, 12 and 18 UTC are based on analyses whilst those for 03, 09 and 15 UTC are based on 3-hour forecasts. 'True' model surface pressure differs only slightly from that shown (generally by less than 2 hPa). Operational hand-analyses of surface pressure were also similar in this case (suggesting the position of 'L' is accurate to within 60 n mile).

During the 10th the low circulation intensifies considerably, causing the clear and cloudy zones to become intertwined, and resulting in the spiral cloud pattern apparent at 15 UTC.

Gyakum *et al.* (1992) have suggested that the maximum 24-hour pressure fall attained within a depression should be nearly proportional to the surface vorticity at the depression centre at the start of the 24-hour period in which that pressure fall occurs; such that a large surface vorticity will precede a large pressure fall. Extreme cases such as the depression of 9/10 January 1993 provide a good test of this hypothesis. In the 30 'rapidly developing' west Pacific cases examined by Gyakum *et al.* (occurring over a 9-year period), the geostrophic relative vorticity at the start of the 24-hour period of maximum deepening ranged from 0.7×10^{-4} to 3.7×10^{-4} s^{-1}. The corresponding value for 12 UTC on 9 January 1993 (calculated using the same method) is 3.1×10^{-4} s^{-1}. Although this is close to the upper limit of the range for the Pacific cases it should be noted that in these the maximum 24-hour pressure fall was only 40 hPa, compared to 63 hPa observed here.

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Thunderstorm activity in a developing cyclone — 4 January 1993

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1. Introduction

Late on 5 January 1993 the oil tanker *Braer* capsized in gales and heavy seas just south of the Shetland Isles, an event which attracted much media coverage. The gales were associated with an Atlantic cyclone moving north-east towards the Norwegian sea. This cyclone had deepened by about 24 hPa on the 3rd, 14 hPa on the 4th and 1 hPa on the 5th. The figure relates principally to events on the 4th.

2. Observations

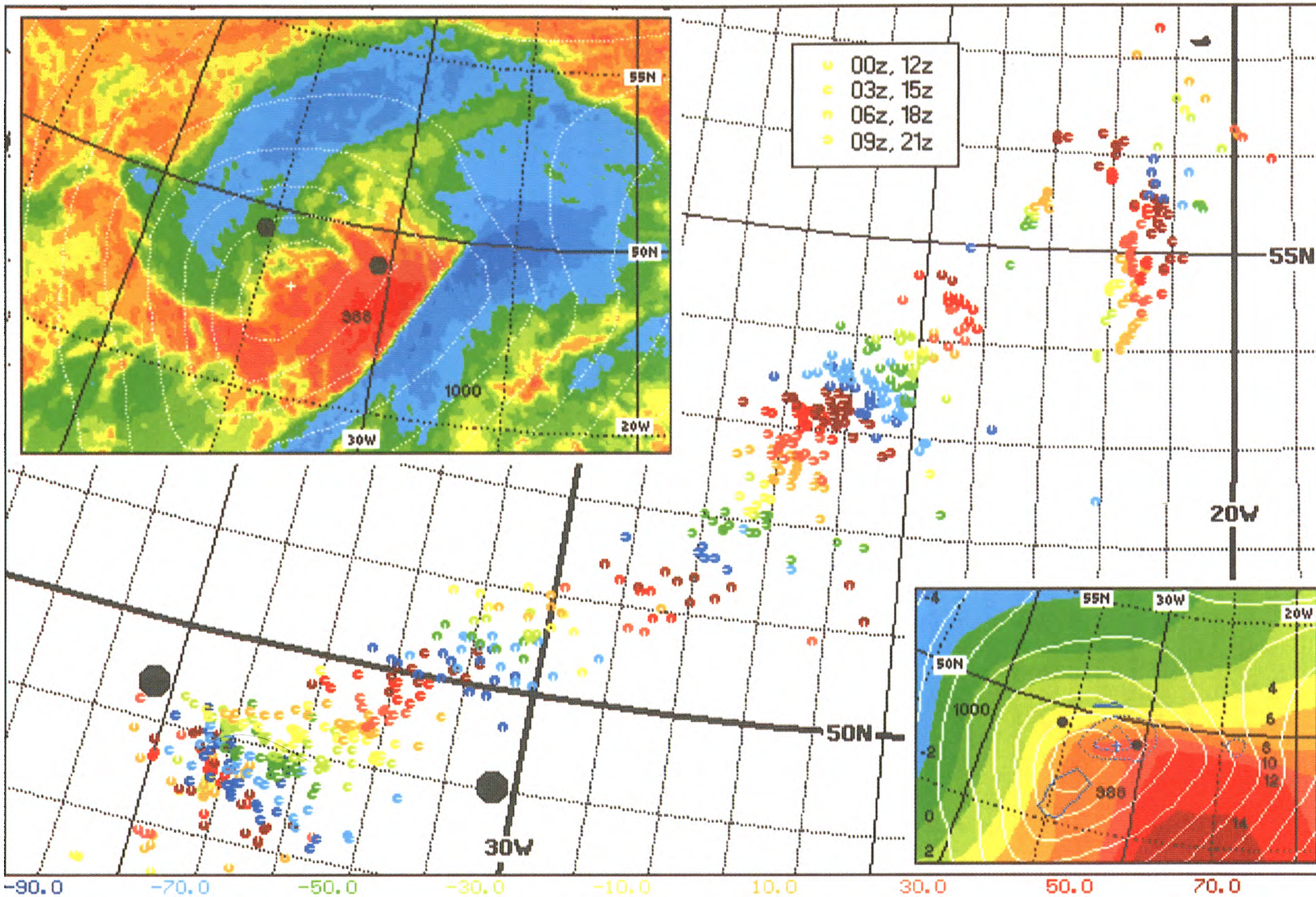
The infrared satellite image for 0300 UTC (top left) exhibits some features associated with explosive cyclogenesis, notably an extensive cloud head to the north and west of the low centre. What is unusual about this cloud head however is the isolated finger of cloud protruding from it around 49 °N, 32 °W. Animated hourly images show that this formed around 0100 UTC on the 4th, and persisted as a discernible feature for nearly 24 hours. During this period it moved north-east at 40–45 kn, remaining about 110 n mile north-east of the surface low centre, and undergoing only slight changes in orientation. On occasions during the animation small circular regions of colder cloud tops, tens of kilometres across, suddenly appear. In the subsequent 2–3 hours these regions expand and propagate westwards (relative to the system) and then south-westwards, apparently reinvigorating the cloud head. A blow-up of the eastern end of the finger of cloud at 0300 UTC indicates cloud-top temperatures above 0 °C, implying the cloud base there must be close to the sea surface.

The main figure shows that a large number of SFERIC* reports were associated with the finger of cloud. Light green and yellow symbols around 49° N represent lightning strikes between, respectively, 0230 UTC and 0250 UTC, and 0250 UTC and 0310 UTC (positional accuracy is about 10 n mile). The two black dots were plotted on this diagram to indicate end points of an axis of maximum lightning activity at the precise time of the Meteosat image (which is 0252 UTC for this part of the globe). This axis clearly propagates north-eastwards during the 4th, albeit with some fluctuations in the extent of lightning activity. Just before the activity finally died out it passed over ship Lima, at 57.2° N, 20.6° W. The 1900 UTC present weather observation from Lima was 'thunderstorm with rain' (code 95). This observation is also consistent with the 1700 UTC sounding from Lima, which indicated unstable air above 900 hPa.

3. Remarks

The finger of cloud on the Meteosat image clearly represents a persistent line of intense convective activity (hereafter referred to as LC). LC does not appear to be connected with either a cold front or a trough line; indeed surface charts for the 4th prepared at the Central Forecasting Office in Bracknell (not shown) depict an

* SFERIC reports come from the UK Meteorological Office arrival-time difference waveform-correlated lightning detection system, which operates in the VLF band.



Main figure: all SFERIC reports registered in a given region of the north Atlantic during 24 hours ending 2230 UTC on 4 January 1993. During this period lightning activity transferred from the south-west of the domain to the north-east. The time of occurrence of each lightning strike is indicated by symbol shape and colour. Each symbol *shape* represents a 3-hour time-period centred on 00 UTC, 03 UTC, etc. (using 'clock' notation as shown in the small inset), whilst each *colour* represents a specific 20-minute period within the three hours (as shown by the scale at the foot of the diagram). For example the SFERIC at 49.7° N, 30.3° W was registered between −90 and −70 minutes relative to 0600 UTC; i.e. between 0430 and 0450 UTC.

Top left inset: Meteosat infrared image for 0300 UTC on 4 January 1993; each colour band relates to a 7 °C range of (approximate) cloud-top temperatures, the darkest blue being −63 to −56 °C. The 3-hour LAM surface pressure forecast for 0300 UTC is superimposed (contour interval 4 hPa); the cross indicates the low centre.

Bottom right inset: 3-hour LAM forecasts for 0300 UTC on 4 January of wet-bulb potential temperature at 900 hPa (colours, interval 2 °C), surface pressure (white contours; interval 4 hPa), and 2h (div(**Q**)) at 900 hPa (blue contours; at -150×10^{-16} (broken), -50×10^{-16} (broken) and $+50 \times 10^{-16}$ (solid) $hPa^{-1} s^{-3}$). The cross coincides with the minimum value of 2h (div(**Q**)) within the domain, i.e. 220×10^{-16} $hPa^{-1} s^{-3}$. Black dots collocate related features on the three figures (see text).

occluded front at its eastern end. The LAM 900 hPa wet-bulb potential temperature pattern (lower right inset) seems consistent with this frontal analysis, although it could be argued that it is in fact a warm front (see Monk (1992)). The average orientation of the analysed front on 4th (in the vicinity of LC) was about 070°, whilst that of LC itself was about 120°. One would not normally expect such features to be collocated. It would be valuable therefore to understand what mechanism gave rise to LC.

Diagnostic output from the UK Met. Office limited-area model (LAM) for the 4th, suggests that the eastern end of LC is consistently in a region of high relative humidity at 900 hPa (75–100%), and low static stability ($\delta\Theta$ = 5 °C between 1000 and 800 hPa); factors which are conducive to convective activity. In addition a large vertical wind shear was in evidence along LC (the vector wind difference between 1000 hPa and 500 hPa was initially about 70 kn, reducing to 40 kn late on the 4th). This is conducive to slantwise ascent. Thus vertical motion along LC probably comprised organized slantwise ascent, with embedded upright convective cells. Slantwise convection may also have been occurring, although it is unlikely that vertical velocities associated with this would be sufficient to generate lightning. Further analysis would be required to prove the atmosphere were unstable in a slantwise (as well as an upright) sense.

Convection over sea areas usually occurs in response to relatively high sea-surface temperatures, in polar air masses. LC, however, originates in a tropical air mass; sea surface temperatures would have to have been a few degrees higher to force the release of any instability. This suggests some other mechanism was triggering LC. A first candidate for this is dynamical forcing. Perhaps the simplest way to represent this forcing *at a particular pressure level* is by using the quantity 2h div(**Q**) where h is a (pressure dependent) constant, and **Q**, the 'Q-vector', depends solely on potential temperature and geopotential height distributions at that level (see Hoskins and Pedder (1980)). In a simple quasi-geostrophic atmosphere vertical velocity is proportional to div(**Q**), negative div(**Q**) indicating ascent. The blue contours on the lower-right inset represent 2h div(**Q**) for 0300 UTC at 900 hPa· The unusually low minimum value of -220×10^{-16} $hPa^{-1}\ s^{-3}$ (blue cross) coincides almost exactly with the right-hand end of LC. The two are also collocated at 06 UTC, 09 UTC and 18 UTC. If allowance is made for a probable LAM analysis error at 12 UTC, the two would also be collocated at 12 UTC and 15 UTC.

Thus it appears that LC represents the response to strong low-level quasi-geostrophic forcing of a moist, convectively unstable atmosphere containing large vertical wind shear. However, one caveat should be added. Div(**Q**) is evaluated using derivatives across length scales of 110 n mile, which is also the separation between surface low and LC. Coincidence may thus have caused LC and the minima in div(**Q**) to be collocated.

4. Comparison with other cases

Further imagery interpreted as depicting slantwise ascent can be found in Norris and Young (1991) and Shutts (1990). Both examples exhibit a gradual decrease in cloud-top temperature when moving from warm to cold (surface) air. Such a decrease is also apparent along LC in the image above. Shutts looked also at a successful model simulation of the storm of 16 October 1987. In the region where slantwise convection was believed to be taking place (at 06 UTC on the 15th) the vertical wind shear between 1000 hPa and 500 hPa was about 75 knots — again similar to that identified above.

In the two cited cases the lateral extent of the region of slantwise ascent, being over 300 n mile, is considerably greater than in this case. The cited cases also contain many 'striations' within this region, compared to the single finger apparent here. Such differences probably relate to subsequent deepening of the surface lows, which was explosive in the cited cases, but relatively small on 4 January 1993.

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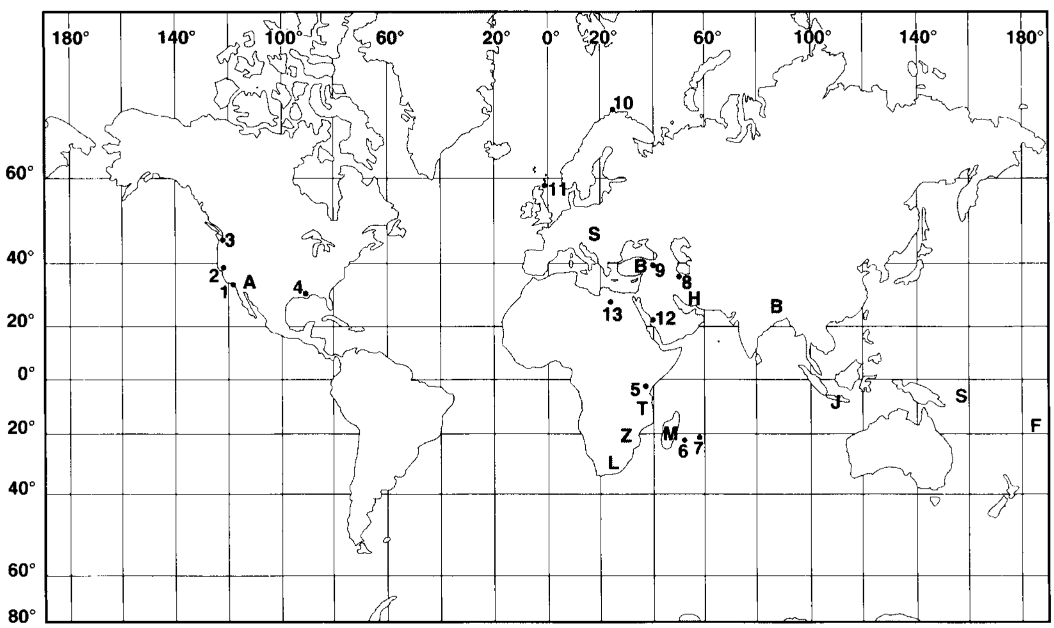
World weather news — January 1993

This is a monthly round-up of some of the more outstanding weather events the month, three preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and press reports. Naturally they are heavily biased towards areas with a good cover of reliable surface observations. Places followed by bracketed numbers or letters in the text are identified on the accompanying map. Spellings are those used in The Times Atlas.

This month has been marked by exceptional violence in the North Atlantic and the tendency for all the tropical storms to affect land. Reports of these events have forced the exclusion of many reports that would otherwise have been included.



Location of places mentioned in text.

North America

Baja California had a week of rain to start the month and then on the 7th the rain became torrential with more than 60 mm in may places. Twenty-five died in Tijuana (1) where some city streets became muddy brown rivers. There was flooding as far north as San Diego County across the border in California, while in Mexicali nine were reported as having died of the cold. At this stage damage was estimated at \$30m. On the 10th another storm threatened, and although most of Tijuana's streets were passable again, elsewhere there were mudslides and dams were close to overtopping. The threatened storm arrived on the 13th, and though the rain was not especially heavy, the saturated state of the ground lead to instant flooding with a further three drowned. Tijuana's drainage coped with this event and there were no deaths in the city though many were still unable to return to their homes.

Over the period 16th to 18th another severe rainstorm struck and the toll in Tijuana rose to 27. Seven died in southern California (a State of Emergency was declared in Orange and Santa Barbara counties). One death was reported in Arizona (A) where the floods were said to be the worst for ten years, with half the annual average rainfall in just ten days leading to the flooding of opencast mines and leaching pits. Rainfall in Los Angeles (2) reached 300 mm for the month with some major roads washed out and several 'million-dollar homes' were washed off their hillside foundations; rivers and reservoirs reached capacity, and in the nearby hills snow depths exceeded 3 m and some 25 buildings collapsed under the weight. At a submarine base in San Diego County a 'ten to fifteen foot wall of water' washed across the base overturning vehicles and stranding a helicopter. By the 17th San Diego's rainfall for January had reached 178 mm compared with the January average of 51 mm. By the 20th estimates were of \$125m damage to insured property in the area and a death toll of 43.

The west coast was battered by further severe storms on the 20th with gales and heavy rain leading to five deaths from falling trees and power lines in Washington State. Floating bridges in Seattle Harbour (3) were damaged and as far south as California gusts of 90 kn were reported. The costs run to about \$175m.

Over the 19th/20th many places in the lower Mississippi had more than 100 mm (Lafayette is rumoured to have had 250 mm). By the 24th severe flooding along the lower reaches of the Mississippi led to the closing of lock gates near Baton Rouge (4) causing long delays to coastal barge traffic for the rest of the month.

Tropical and southern Africa

The 1st brought news that 37 were feared drowned when a bus was overturned by floodwater in southern Zimbabwe (Z). On the 7th Nairobi (5) had 52 mm, just over the average rainfall for all January.

Over the period 14/15th Morombe on the east of Madagascar (M) received 246 mm (but without any reports of thunder!): this comfortably exceeds the previous 24-hour total record of 199 mm. About this time cyclone 'Colina' developed and immediately started on the standard south-westerly course. On the 18th she started intensifying and recurving and the island of Réunion (6) battened down in preparation and all road traffic was banned. The storm struck on the 20th when central winds were at their maximum; on the island, mean wind speeds exceeded 40 kn and the maximum gust recorded was 90 kn with more than 100 mm of rain. Two died and twelve were missing afterwards; several dozen homes were destroyed and tens of thousands were cut of from fresh water and electricity; landslides and fallen trees blocked inland roads. Huge waves damaged the coast roads around St. Denis whose harbour was paralysed until the 22nd.

Later, on the 22nd, tropical storm 'Desilia' crossed the south of Madagascar and the January average rainfall of 185 mm was dropped in a day: immediately afterwards the temperature shot up to 37 °C. Nearer the end of the month, Mauritius (7) was at a precautionary standstill as cyclone 'Edwina' passed within 400 km on the 28th.

At the end of the month there were reports of two disasters: forty were killed and more missed after floods in north-west Tanzania (T) washed away homes and crops in Lesotho (L). The same rainfall event may have been responsible for an unseasonal flood which weakened a bridge near Darajani: at least 117 died when part of a Mombasa to Nairobi train fell into the river. One carriage is said to have been washed 1.5 km downstream. The bridge was built in 1898 but 'rarely repaired since'.

Australasia and Pacific

Cyclone 'Nina' passed through the Solomon Islands (S) on the 2nd killing three and rendering some 10 000 homeless (apparently on the islands of Rennel and Bellona nothing was left standing apart from a few buildings). The next day Cyclone 'Kina' struck the Fijian archipelago (F) killing 16, mostly in floods and high seas although 10 000 had been evacuated. The winds reached 100 kn and many were injured by flying debris. The west coast of Viti Levu was worst hit with two of the three principal bridges destroyed by the floods. Sava Airport was closed by flooding but Nandi, on Viti Levu, which had 66 mm of rain and gusts of 55 kn, was able to stay open. Although there was great damage to crops and livestock, the sugar crop was already harvested. The cost was estimated at \$150m.Tonga reported no damage, although there had been some concern.

Over the last few days of the month cyclone 'Lena' passed close to Flores (devastated by a tsunami late last year); heavy rains caused floods that killed five, and many boats were carried away by winds of 30 kn: in neighbouring East Jawa (J) and South Sulawesi fifteen were killed by floods. Damage was also done in eastern Jawa where many vessels were damaged around the port of Tanjung. Cyclone 'Lin' struck western Samoa on the last day of the month but nothing newsworthy seems to have resulted.

The weak tropical storm '14P' trundling over the north of Australia was producing winds of around 25 kn and, in a period of 60 hours up to the 29th, 330 mm of rain fell as temperatures dropped by 10° to 27 °C.

Asia

On the 8th and 9th there were reports of two tornadoes in north-east Bangladesh (B), these are said to have killed 76, injured about 3000, killed several hundred head of cattle and razed 15 000 bamboo huts. About the same time heavy snowstorms struck Iran causing chaos in Tehran (8) and closing many of the country's airports for some hours. Over the last few days of the month the Transcaucasian Highway was comprehensively blocked by avalanches near Vladikavkaz and Tbilisi. The death toll, in excess of fifty, including three at a research station on Mount Elbrus.

Europe, Arabia and North Africa

The month started very cold; in Turkey, Erzurum (9) had its all-time low temperature of −34.6 °C, resetting the record for the third time this winter. In Slovakia (S) more than 60% of the Danube was covered by ice, and all shipping movements were stopped because of the dangers. The 2nd and 3rd were the coldest days in central and southern Italy for seven years and there was a lot of snow, especially in Calabria (the 'toe') where the totals were the largest since the 1970s: Messina had its first snow for 25 years. Bari had a minimum of −2.1 °C and Cagliari −1 °C

Overnight on the 3rd/4th an intense, but not especially deep low, moved east near North Cape (10) and the Finmark area of Scandinavia experienced hurricane force winds of about 100 kn; these did several million pounds worth of damage but caused no fatalities even though a floating dock was destroyed. Early on the 5th the 90 000-tonne tanker *Braer* suffered a main engine failure and was subsequently driven ashore in the Shetlands, very close to the observing station of Sumburgh (03003) (11), by a 56 kn south-west wind with gusts to 74 kn. Waves of 12 m prevented the crew of a tug from boarding the vessel to fix a towline. The tanker's crew had been airlifted to safety earlier when a previous grounding threatened. A major ecological disaster seemed imminent.

With pressure over south-east Europe over 1040 hPa at this time there was plenty of scope for 'bora' and 'mistral' type winds: next day two more ships met trouble, but in the Mediterranean this time. The 4000-tonne *Coty 1* with a cargo of cement encountered a force 10 with 12 m waves near the island of Kithira. After a temporary engine failure the ship took a severe list and the crew abandoned ship but many were lost when the lifeboats were swamped. The *Marineta* was carrying kaolin when she took on water and grounded in heavy seas whipped up by a force 7 near Crotone on the 'heel' of Italy. Strong westerly winds on the 6th brought blizzards to the north of Saudi Arabia though Jiddah (12) still managed 34 °C (beating the January record). Further west, Siwa (13) in north-east Egypt had 13 mm of rain; not a big deal until compared with the January record of 4 mm! Cairo had its coldest day of the winter so far on the 7th when the maximum was only 12 °C.

Back north, on the 9th the 689-tonne *Stavfjord*'s cargo of fertilizer, detonators and 200 tonnes of dynamite shifted. During the attempted salvage the tow line broke three times in hurricane force winds and mountainous sea. The crew were airlifted to safety, but two days later the cargo exploded off Skjervøy, north Norway. A different kind of explosion now occurred: in the early hours of the 10th explosive cyclogenesis occurred north-west of the British Isles. Between 0400 and 0500 UTC pressure fell 10 hPa at OWS *Cumulus* and as the low deepened to 916 hPa the ship was battered by winds reaching 105 kn with 10 m waves. At the time of writing this, in April, it still seems that the resulting tumultuous seas dispersed the entire cargo of oil from the *Braer*, which unsurprisingly broke up. Over the period of 9th to 11th the Stratfjord oilfield off Norway was virtually closed down because waves of up to 17 m prevented any tankers approaching to load the oil normally stored in the hollow legs of the platforms. Production was restarted on the 14th when waves were only 4.2 m. Tankers were again prevented from approaching on the 16th and 17th and, later, on the 21st.

The storms of the first half of the month were so severe, that on some of the islands of northern Britain, archaeological sites have been destroyed but others revealed.

The heavy rain of the 11th/12th in Belgium caused the worst flooding there since 1926 when both the Meuse and the Ourthe rivers burst their banks. On the 13th, a small but intense low raced east-north-east across southern Britain, winds gusted to 85 kn in the south-west and pressure changed 15 hPa (both down and up) in three hours. It then moved on to give the southern North Sea and Baltic wild weather. Winds of 90 kn in north Germany uprooted trees, traffic lights and removed roofs. Heavy rain raised the Elbe to 5 m above normal, closing the centre of Lübeck to traffic: in Hamburg a State of Emergency was declared for a few hours during the night. Copenhagen port was a dangerous place as empty containers were shifted by the wind and a coal crane was blown over; 75 cars were 'sandblasted' by small debris. In Lithuania and Latvia the storm was the worst since 1967 with winds speeds of over 65 kn: six were killed, vessels broke their moorings and were blown out to sea, 21 railway stations lost their electricity supplies as 7800 sub-stations failed, depriving the grid of 350 MW. At Vilnius airport a Boeing 737 was blown off the runway onto rough ground just after landing, but there were no casualties. In Poland the storm brought a thaw and the pressure of ice caused the collapse of the longest (about 1400 m) wooden bridge in Europe — over the Vistula at Wyszogrod north of Warsaw. The 3000-tonne Polish ferry *Jan Heweliusz* sailed from Sweden into the storm and 52 were drowned when she capsized, nine survivors were rescued from the mountainous, icy seas. There is a theory that despite the winds of nearly 90 kn the enclosed bridge insulated the master from the storm to the extent that he did not realize how violent conditions were.

On the 17th a larger, very intense, low moved north-east just off the Hebrides, severe gales and heavy rain brought a rapid thaw of deep snow to Scotland. At Kirkwall in Orkney the hourly mean speed reached 66 kn with a gust to 94 kn. Other notable gusts were 91 kn on Fair Isle and 130 kn on the summit of Cairn Gorm. During this period Aviemore's rainfall total reached 209 mm for a new January record, and the 50 cm of snow lying on the 14th melted to a mere 1 cm by the 19th. As a result flooding was widespread and the River Tay rose to 4.25 m above normal. RAF helicopters rescued twenty from flooded houses and the Army used inflatable dinghies to evacuate a housing estate. Most north–south road and rail links were cut and the cost was later estimated at about £10m.

In contrast to all the excitement in the north, southern Europe was stagnant under high pressure and cars were banned from central Athens on the 19th because of dangerous levels of smog. On the eastern side of the high severe cold weather swept into the 'Near East' around the 18th. In Bayburt province (B), north-east Turkey, an avalanche killed 58 and injured 25 when 43 out of the 96 houses in one village were overwhelmed after 2 m of snow fell in a blizzard. Later, widespread flooding was reported in south-east Iran in Hormozgan (H) and some flooding in Jiddah. The recent rains in this latter area have created favourable breeding conditions for the desert locust and swarms have been reported along the Red Sea coasts.

Wild weather continued in higher latitudes when a low of about 952 hPa passed close to Scotland, and Glasgow had a wind of 76 kn. This pales to insignificance compared with the (new record?) speed of 147 kn on Cairn Gorm. The last low in this viscious series tracked a little further south with north-westerly winds in its rear: on the 24th the Baltic coast of Poland was battered by severe gales that caused widespread damage and closed ports. Coastal communities were put on standby for evacuation as the storm surge flooded Kaliningrad and surrounding areas.

The storms in the first half of the month did about £155m worth of damage in the United Kingdom in addition to about £15m in the Perthshire floods.

Stop Press — *Africa*

The following is part of a news release from the World Climate Programme of WMO.

'In Kenya and in neighbouring East African states, January is perceived as a dry month; the short rains are over by mid or late December and the hot dry north-easterly monsoon banishes the rain clouds. They would not be expected to return before late March. January 1993, in Kenya, was not hot and dry. It was cool and very wet. Rainfall was unprecedented, unexpected and disastrous.'

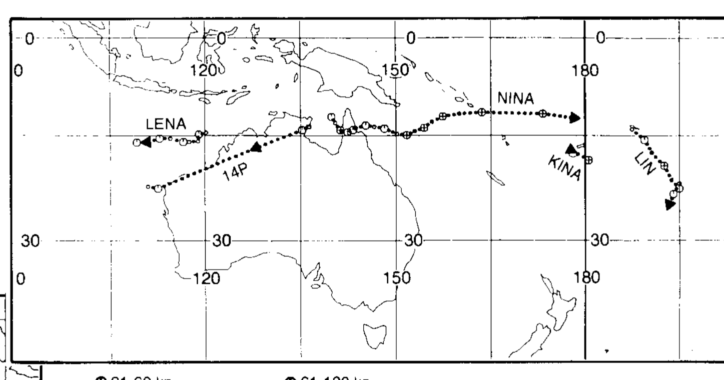
More details next month.

January tropical storms

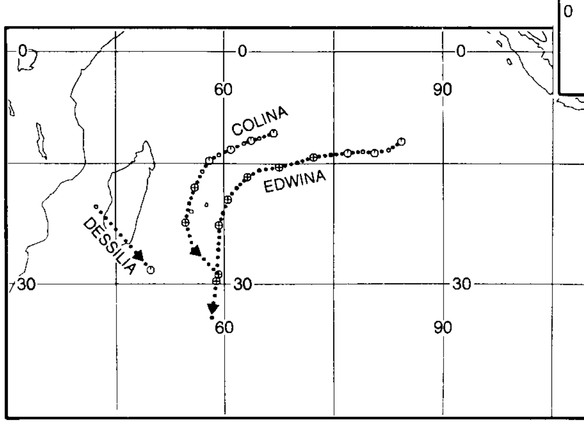
This is a list of tropical storms, cyclones, typhoons and hurricanes active during January 1993. The dates are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during this month. The maps show 0000 UTC positions: for these I must thank Julian Heming and Susan Coulter of the Data Monitoring group of the Central Forecasting Office.

No	Name	Basin	Start	End	Max. (kn)
1	Colina	SWI	14/01	21/01	105
2	Dessilia	SWI	20/01	23/01	35
3	Edwina	SWI	20/01	29/01	120
4	Nina	AUS	23/12	03/01	75
5	Kina	AUS	27/12	03/01	100 in January
6	Lena	AUS	24/0I	29/01	55
7	14P	AUS	26/01	27/01	35
8	Lin	AUS	31/01	—	55

Basin code: SWI — west Indian Ocean (south); AUS — Australasia.



Australasia



West Indian Ocean

Awards

Meteorological Office scientists win international award

On Tuesday 23 February 1993 four Meteorological Office scientists were presented with the prestigious Professor Dr Vilho Vaisala Award by the Secretary-General of the World Meteorological Organization (WMO), Professor G.O.P. Obasi.

David Griggs, Wynn Jones, Martin Ouldridge and Bill Sparks won the Award for their intercomparison of visibility instruments carried out on behalf of the WMO during 1988–89.

Their paper not only described the conduct and results of the intercomparison but also recommended accuracy standards and ways to use the instruments operationally. This information will be of considerable value to meteorologists around the world in choosing the right visibility instruments for their individual needs and gaining maximum benefit from the data. It will also be useful to motorway and airport authorities and others who need to measure the visibility for their various applications.

The winners of the Award worked within the Observations Division of the Met. Office to produce the paper, entitled 'The first WMO intercomparison of visibility measurements'. Wynn Jones was the Project Leader, David Griggs was Technical Manager and Bill Sparks and Martin Ouldridge were in charge of data processing and analysis.

Left to right. Martin Ouldridge, Professor Obasi, David Griggs, Richard Pettifer (Vaisala UK) and Bill Sparks. Wynn Jones was unable to attend the ceremony.

The work was carried out as part of the continuing survey of atmospheric sensors and meteorological observing systems which is one of the Office's functions as the National Meteorological Service. The results of such studies are available to all.

This is the seventh presentation of the Award — and the fourth time it has been won by staff members of the Office. The Award consists of a diploma, a medal and a cheque for $2500 each.

Professor Obasi, in presenting the Award, said 'This research work is a valuable contribution to the work of the World Meteorological Organization (WMO) and to the advancement of instrumentation. I congratulate the winners and convey to them the warm congratulations of the President of WMO, the Members of the Executive Council and indeed all Members of the WMO.'

Meteorological Office wins six major TV awards

The Met. Office won six awards at the International TV Weather Forecasters Festival ending on Friday 12 February in Paris.

Siân Lloyd from the Meteorological Office's International Weather Productions (IWP) ITV National Weather was equal first in the Prix des Presèntateurs, being chosen by all the other presenters from 55 entries from 40 countries. Bill Giles for the BBC Weather Centre and BBC World Service Television was third.

In the Prix des Scientifiques, awarded for scientific content, the BBC came second and IWP fourth.

In the most prestigious award, the Trophee du Festival, IWP was voted second, and the BBC World Service TV came third.

The winner of the Trophée du Festival, Danny Roup of Israel, told the audience that he owed his award to IWP for all the help, training and information they had given him over the last two years. This accolade was reinforced by other presenters in Germany and Switzerland. IWP has been developing international business during the year through a range of services, including TV2 in Norway provided in collaboration with the Norwegian Met. Service.

IWP has made several changes to the ITV National Weather during the course of the last year, modifying design, animation, map colours and cloud shapes in response to market research. IWP has also been working closely with the Met. Office's network of Weather Centres to develop a wide range of new services in the ITN regions, including LWT, Carlton, and HTV.

Siân Lloyd has been working for IWP as a presenter for ITV National Weather since 1990. Before then she worked for BBC Wales, Channel 4 Wales and the Mid Wales Development Board. Siân has a background of languages and journalism, and has been trained in meteorology at the formal course in Meteorology for Weather Presenters at the Met. Office College near Reading.

Bill Giles has been head of the BBC Television forecasting team since 1983. He joined the Met. Office in 1957 and has been forecasting for radio and television most of the time since 1972.

The BBC Weather Centre, combining BBC and Met. Office skills and resources, produces the BBC national and international forecasts. World Service TV includes weather information for all over the world, with detailed inserts for Europe, Asia and Africa.

Correspondence

Hoar-frost deposition

The letter from N. Gait and T. Hewson (*Meteorol Mag*, **121**, 268) suggested that when hoar frost is localized, the road hazard may be less obvious to motorists, and so more dangerous through being intermittent and unexpected. If this logic is accepted, the same would apply to the dampness caused by road salting. Although its dampening effect is usually extensive and persistent, it is not consistently so. Depending on humidity and other factors, there are often periods during the afternoon and early evening when the salt dries temporarily. During these periods, occasional damp patches remain where the sun has not reached. Presumably these patches could be regarded as disproportionately dangerous because motorists may not be expecting them.

By the same logic, it could be argued that icy patches left on unsalted roads are made more dangerous by the salting of main roads (because the residual ice will be more of a surprise to motorists). Many journeys begin or end on unsalted surfaces: it is not practical to salt every minor road and side street, and local authorities do not attempt to do so.

I suggest, however, that such arguments should not be overemphasized. In practice, whenever there is serious and widespread ice, there is a spate of ice-related accidents. The more ice there is, the more ice-related accidents there are. The obviousness of the hazard does not seem to make up for its extensiveness. Similarly when roads are generally wet, from salt or any other cause, there are more accidents than when they are mainly dry, despite the occasional damp patch.

None of this detracts from the potential usefulness of the original paper (*Meteorol Mag*, **121**, 1–21). It showed that the hazard from hoar-frost deposition is particularly associated with circumstances such as short day length, a shallow layer of moist air, and a definite but gentle breeze accompanying clear skies, especially after successive clear nights. These findings could be very useful in preparing forecasts for highway authorities. But no practical benefit will ensue unless forecasters are prepared to adjust their road-ice forecasts in such a way as to advise against salting on some occasions when it might otherwise have taken place.

Experience of personal observation during the 1992/3 winter was that the surfaces of unsalted side streets were only rarely (and briefly) affected by ice from hoar-frost or any other mechanism. The number of occasions on which main and intermediate roads were salted was much greater. In addition there were long periods during which roads were not subject to fresh salting but were still affected by residual salt from previous operations (in the absence of rain since the last frost). These observations relate mainly to the Home Counties around the northern edge of London. It seems that in practice, significant ice problems on untreated roads are much rarer than would be expected on the basis of road surface temperature (RST) below dew-point (when below 0 °C).

R. Mansell

8 Curthwaite Gardens
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Middlesex
EN2 7LN

Dear Sir,

Congratulations on your new feature on world weather in the January issue of the *Meteorological Magazine*.

These days meteorologists have fewer opportunities of experience in tropical and sub-tropical regions than people of my generation had. I spent nine years between 1943 and 1963 on three overseas tours, covering south-east Asia, the Middle East and the Mediterranean, so that references in your first article to weather events in places familiar to me were especially interesting — and nostalgic! For most younger meteorologists their experience of weather overseas is usually limited to short holidays!

It is good for all of us to be aware of the international nature of weather. The destructiveness and economic cost of some weather events overseas put weather happenings in the UK into perspective.

R. Murray
(Met. Office 1939–1977)

Wokingham
Berkshire

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (IBM-compatible or Apple Macintosh) can be labour-saving, but only a print-out should be submitted in the first instance.

References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

Tables should be numbered consecutively using roman numerals and provided with headings.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS1991: Part 1:1976 and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

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Illustrations

Diagrams must be drawn clearly, preferably in ink, and should not contain any unnecessary or irrelevant details Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text. The sequential numbering should correspond with the sequential referrals in the text.

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Design rainfall profiles for upland areas
World weather news — February 1993

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Sea-surface temperature measurements by the ATSR

R.W. Saunders and A.H. Smith
Meteorological Office, Farnborough
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Meteorological Office, Bracknell

Summary

The Along Track Scanning Radiometer has been producing global sea-surface-temperature values since September 1991. The UK Meteorological Office has been assessing these by comparing them with their operational analysis and by carrying out a dedicated aircraft validation experiment. The initial results show an improvement in the sea surface temperature values obtained when the dual-view retrieval is used rather than a conventional nadir-only multichannel retrieval. The radiative effect of volcanic aerosols at 11 μm and 12 μm was also measured by the C-130 aircraft and found to be small but not negligible.

1. Introduction

The Along Track Scanning Radiometer (ATSR) was launched into a sun-synchronous orbit on the European Remote Sensing Satellite, ERS-1, on 17 July 1991. The primary objective of the ATSR is to measure sea-surface temperatures (SSTs) globally to an accuracy of better than 0.3 K (Barton *et al.* 1989) which is a significant improvement on previous satellite SST products (e.g. Meteosat, AVHRR/MCSST). There are several features of the ATSR described below which make this improvement possible.

This paper gives a brief description of the ATSR and outlines the results from two very different and complimentary assessments of the ATSR SST product, carried out by the UK Meteorological Office (UKMO). The first compares the ATSR near-real-time (NRT) product, which is averaged over 0.5° × 0.5° and gives good coverage between 55° S and 55° N over the earth's oceans, with the UKMO conventional SST analysis. The second assessment was a dedicated validation experiment in which the C-130 aircraft of the Meteorological Research Flight made infrared radiance measurements coincident with ERS-1 overpasses over the tropical Atlantic Ocean.

2. The Along Track Scanning Radiometer

The ATSR is a radiometer with a conical scan, inclined at an angle, so that a nadir view and forward view at a nadir angle of 47° (which translates into a zenith angle of 55.5° on the earth's surface) is obtained for each revolution of the scanning mirror. It also views two black-body targets for calibration of the infrared channels. A schematic drawing of the instrument is shown in Fig. 1 which also shows the microwave radiometer on the side of the instrument which measures total column water vapour amount. The ATSR has four channels, one at near infrared wavelengths (1.6 μm) for daytime cloud clearing, and three at thermal infrared wavelengths (3.7, 11 and 12 μm) for sea-surface temperature retrievals and cloud clearing. The field of view of the radiometer gives a 1 km pixel size at nadir on the earth's surface and the width of the ATSR swath is 500 km.

The particular features of this radiometer, which enable it to make improved retrievals of sea-surface temperatures over previous satellite radiometers, are:

(a) the combination of two views, through different path lengths of the atmosphere, allow a more accurate

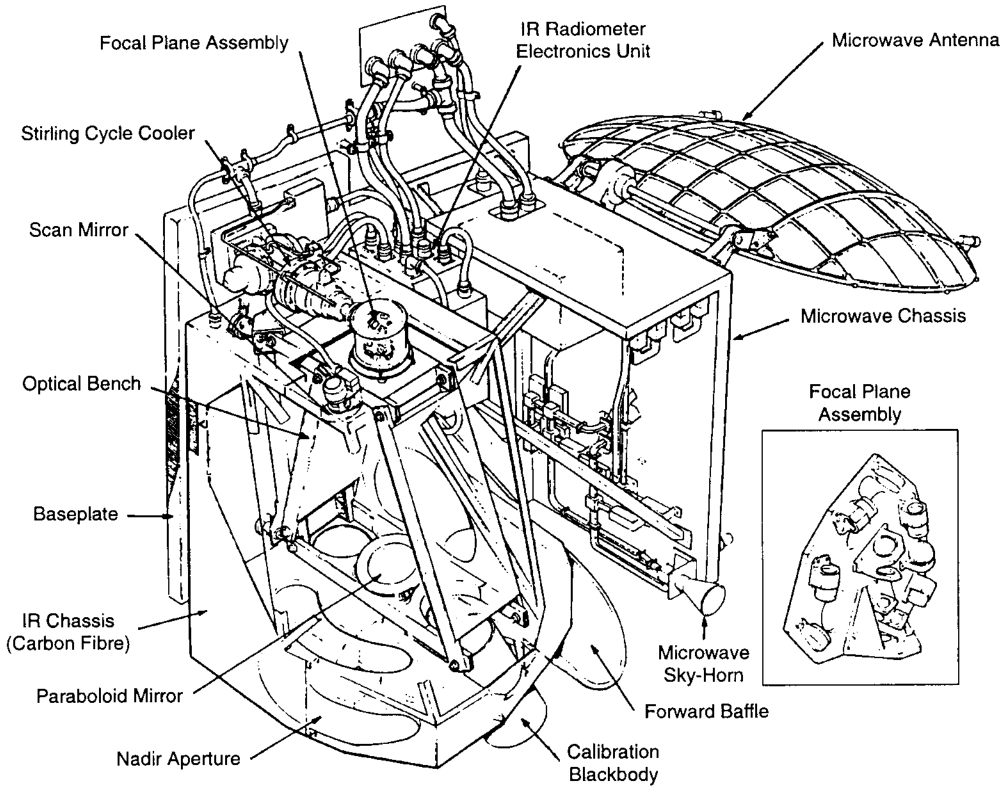

Figure 1. A schematic diagram of the Along Track Scanning Radiometer (including the microwave water vapour sounder).

correction for the intervening atmospheric absorption/emission to be made,
(b) careful design of the two calibration targets, which operate at 263 K and 303 K to encompass the full range of SSTs that are ever likely to be measured, ensure an accurate absolute calibration (< 0.1 K) can be made, and
(c) lower system noise temperatures (< 0.05 K) than achieved on other imaging infrared radiometers.

The ATSR was designed and built by a consortium of UK groups, including British Aerospace, Rutherford Appleton Laboratory, Mullard Space Science Laboratory, and the UKMO. The assembled instrument was tested in a purpose-built vacuum chamber, at the Department of Atmospheric, Oceanic and Planetary Physics, University of Oxford, to verify, among other things, the accuracy of the calibration. A more detailed description of the instrument is given by Edwards *et al.* (1990) and on the calibration by Mason (1991).

An example of an ATSR 3.7 μm brightness-temperature image over the Gulf Stream is shown in Fig. 2. The high spatial and radiometric resolution of ATSR is clearly evident in this image which shows the detailed structure of the boundaries between the hot and cold water.

Since the launch of ERS-1 the instrument had performed without any problems until 27 May 1992 when the 3.7 μm channel suddenly stopped producing data. The reason for this failure is still being investigated. The main impact of the loss of this channel is a reduced ability to detect low cloud at night.

The SST can be obtained from the measured ATSR top-of-atmosphere brightness temperatures in several different ways. During the daytime the 11 μm and 12 μm nadir brightness temperatures can be combined according to:

$$SST = \alpha T_{11} + \beta T_{12} + \gamma. \qquad (1)$$

This is the conventional 'split window' equation which has been used for many years for AVHRR SST retrievals. As β is negative, it is effectively the difference between the 11 μm and 12 μm brightness temperatures which is used to give a measure of how much infrared radiation is absorbed by the atmosphere.

In order to obtain a better correction for the atmosphere ATSR takes two measurements of the sea surface 2.5 minutes apart. The forward view at 55° to local zenith has almost twice the path length through the atmosphere compared with the nadir view. Thus a combination of the two views should give a better estimate of the effects due to the intervening atmosphere. By expanding equation (1) the dual-view retrieved SST is computed according to:

$$SST = \alpha_N T_{11N} + \alpha_F T_{11F} + \beta_N T_{12N} + \beta_F T_{12F} + \gamma \qquad (2)$$

where N and F denote nadir and forward views. The coefficients used in equations (1) and (2) have been

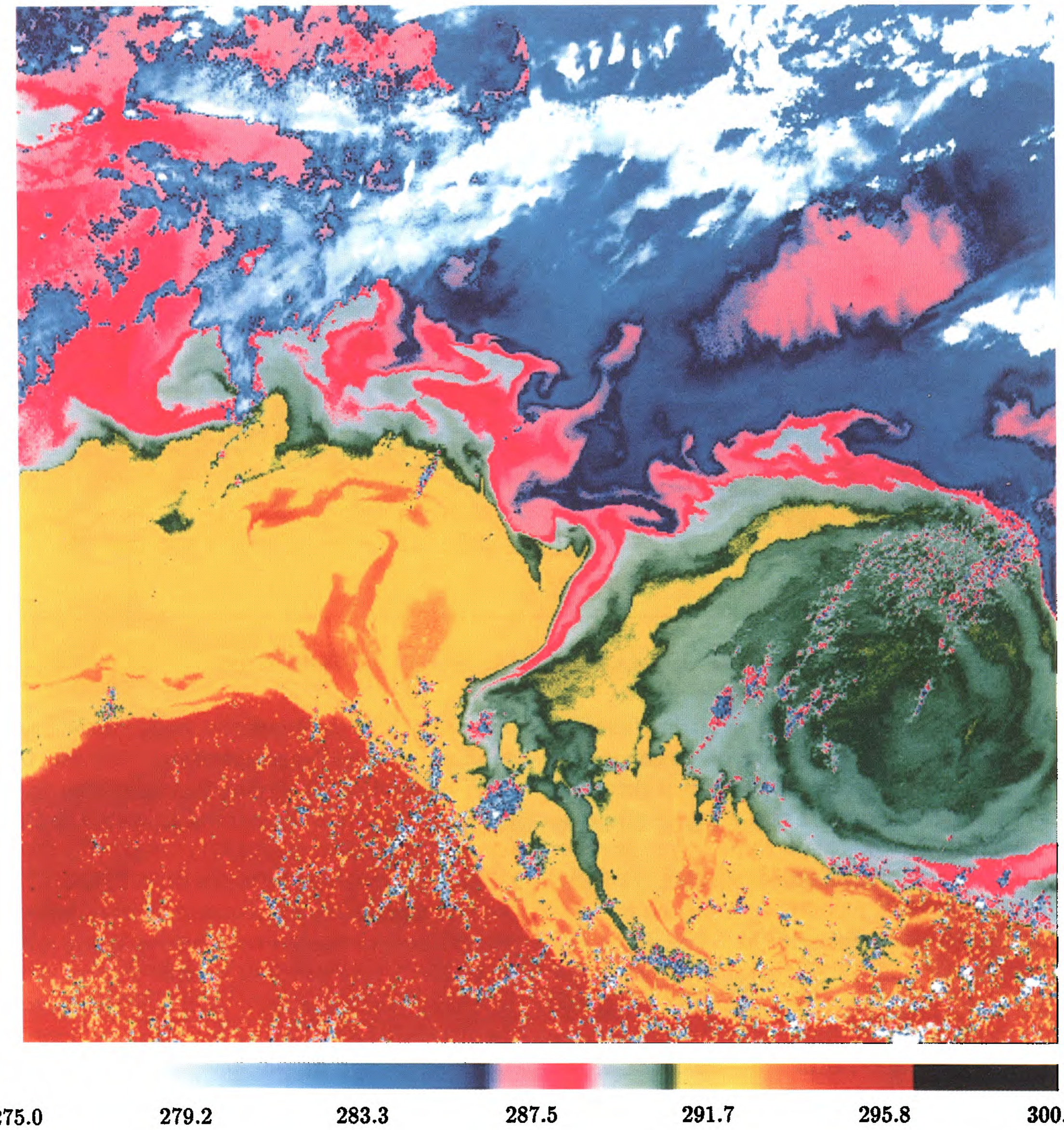

Figure 2. An ATSR nadir view 3.7 μm brightness temperature image (K) of the Gulf Stream and a warm core ring (Courtesy of Rutherford Appleton Laboratory).

derived from a radiative transfer model to give the optimum performance in a given set of atmospheric conditions (e.g. mid-latitude, tropical, polar). The coefficients also vary with across-track position. For a comprehensive review of empirical and theoretical algorithms used to retrieve SST from infrared radiometers see Barton (1992).

3. Assessment of ATSR near-real-time SSTs

The ATSR near-real-time (NRT) demonstration project was established in order to address the needs of Meteorological centres for fast-delivery (FD) data. It is a joint venture between Rutherford Appleton Laboratory, Tromsø Satellite Station and the UKMO, who is the pilot user of the data. The aim of the project is to show that the data processing and transmission system devised can provide data, of high quality and in near-real-time, to an end user. If this can be achieved then it is hoped that the system will eventually be adopted by ESA as part of the ERS-1 FD service, which currently includes products from the scatterometer and radar altimeter.

NRT products from the ATSR have been received by the UKMO since November 1991. The raw data are processed at Tromsø Satellite Station to form 0.5° × 0.5° average sea-surface temperatures (ASSTs) and the products are quality assured using data from the satellite's engineering reports. The quality-assured products are then transmitted to the UKMO within 24 hours of acquisition. On average, approximately 14 000 ASSTs are received per day. Reasonable coverage for latitudes between 55° N and 55° S is generated in around 10 days, as indicated by Fig. 3. At present, only sparse quantities of data are obtained for higher latitudes. This is due to

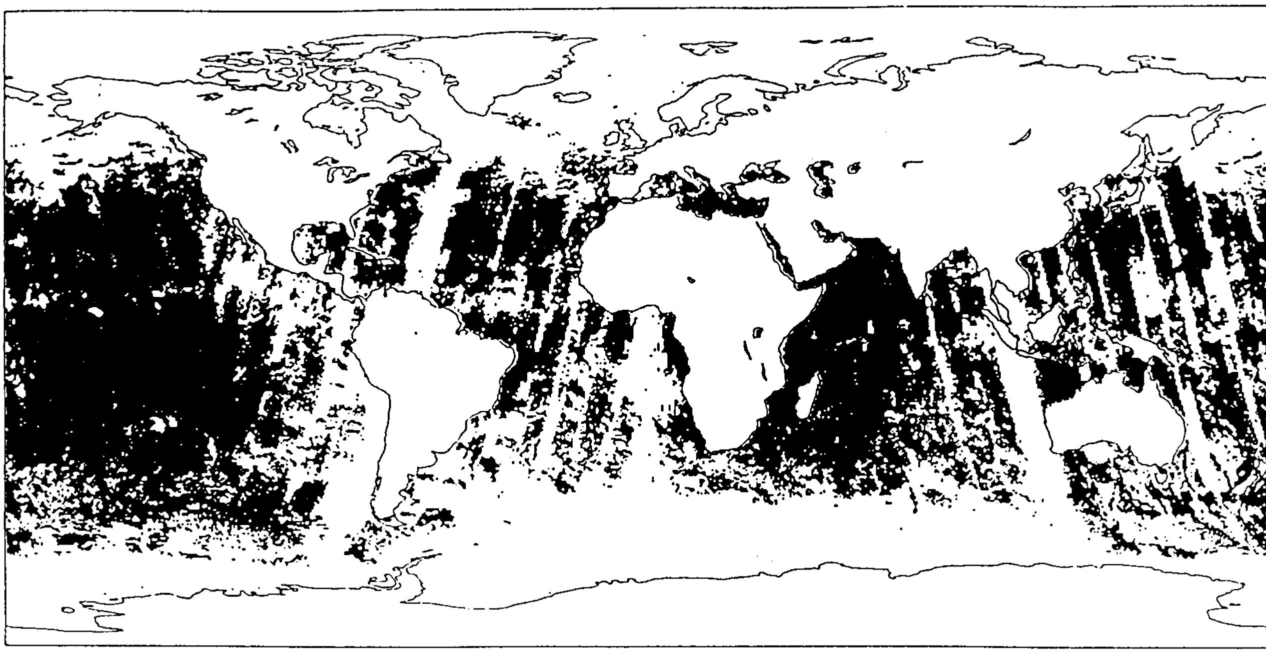

Figure 3. Distribution of ATSR ASSTs for the period 1–10 September 1992.

imperfections in the cloud screening procedure causing an overestimation of the number of measurements contaminated by cloud. Optimization of the cloud detection thresholds has proved a complex task, and is still going on. Future modifications should go some way to improving the coverage obtained at mid/high latitudes.

The quality of the NRT products are assessed primarily by comparison with coincident SSTs from the UKMO's operational analysis. The analysis is performed once per day and incorporates observations from surface marine sources (i.e. ships, buoys and bathythermospheres) received, via the GTS, in a 24-hour period. The observations undergo quality control and then a background field, simply the previous analysis, is updated by incorporating the new observations using an iterative assimilation scheme. A detailed description of the operational SST analysis scheme is given by Jones (1991). The comparison of this *in situ* analysis and the NRT product has been useful in several respects. During the initial period of ATSR operation, anomalies in the NRT processing system were rapidly identified and corrected, and the impact of subsequent changes to the data processing system could be easily evaluated.

A global mean bias of approximately −1 K with respect to the SST analysis has been persistent throughout the lifetime of the project. Part of this negative bias can be attributed to the genuine difference between the radiative skin temperature of the oceans, as measured by the ATSR, and the sub-surface bulk temperature measurements from ships and buoys. This is generally of the order of several tenths of a degree Kelvin, but varies with a number of factors including surface wind stress, solar insolation and cloud cover (Schluessel *et al.* 1990). Other factors which may contribute to the detected bias are diurnal effects and the incomplete screening of cloud. The use of SST measurements made via the engine intake of ships in the SST analysis scheme may also be a factor. This method of observing has been shown, in many cases, to produce temperatures with a warm bias of around 0.3 K (Kent *et al.* 1991).

An additional study in which ATSR NRT products were compared with collocated drifting buoy measurements has been carried out. Drifting buoys are generally considered to be the most reliable sources of SST measurements and have been used extensively to calibrate the AVHRR SSTs. Spatial and temporal limits for collocated ATSR and drifting-buoy observations were set at 0.5° latitude/longitude and ±3 hours. Fig. 4 shows ATSR drifting-buoy temperatures plotted for day and night-time observations made during July 1992. The day-time data show an overall bias of −0.5 K: but the night-time bias increases to −0.8 K. The daytime results are very encouraging as the remaining bias can largely be explained by the skin-bulk temperature difference. The poorer performance of night time ASSTs is the result of the loss of the 3.7 μm channel and the consequent problems in identifying low-level cloud at night. These results further highlight the limitations of ship SSTs and their impact on the quality of the operational analysis.

The difference between ASSTs calculated from single-view data and those derived from dual-view data has been examined. ASSTs based on single-view data are returned where only one view is cloud-free. Table I shows the bias with respect to the bulk analysis for both single- and dual-view data and demonstrates the increased agreement attainable using the dual-view algorithm. This is not surprising: the single-view algorithm is intrinsically less successful in correcting for atmospheric attenuation and the single views tend to originate from more cloudy areas and are hence more prone to error

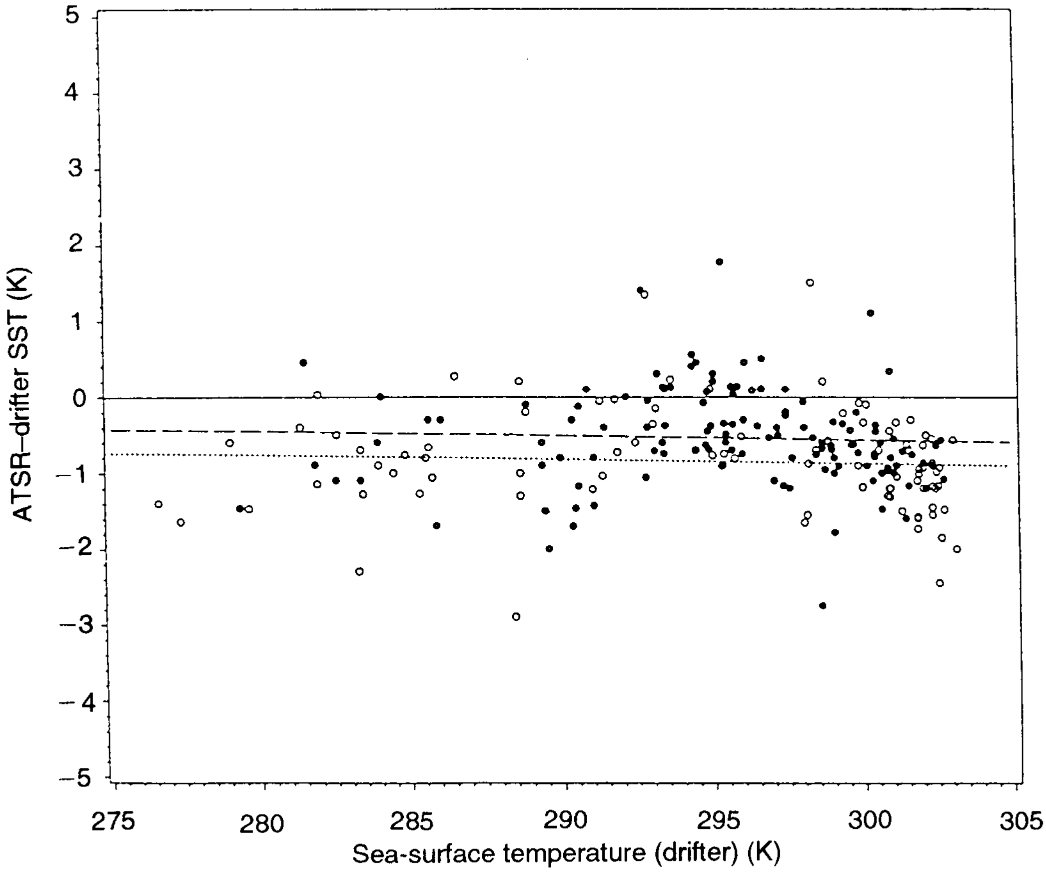

Figure 4. Collocated ATSR and drifting buoy observations for July 1992 for day (solid circles, dashed line) and night (open circles, dotted line).

Table I. Bias with respect to the SST analysis of ATSR single- and dual-view data for September 1992. O is observation, A is analysis and C is climatology.

Latitude	No. of ASSTs Single	Dual	Mean O–A Single	Dual	Stnd Dev O–A Single	Dual	Dual-single
60–90°N	186	N/A	−1.70	N/A	0.88	N/A	N/A
30–60°N	15150	12176	−1.07	−1.06	0.74	0.80	0.23
0–30°N	25078	61389	−1.85	−1.13	0.65	0.62	0.46
0–30°S	28779	82544	−1.53	−1.00	0.55	0.56	0.38
30–60°S	32826	25452	−1.66	−1.35	0.75	0.80	0.30
60–90°S	1996	44	−1.57	−1.87	0.61	0.51	0.04
All	109703	15	−1.58	−1.10	0.67	0.63	0.38

(Lorenc *et al.* 1992). Further evidence of the increase in performance possible using the dual-view technique is obtained by looking at the difference between dual-view ASST and the corresponding ASST derived from the nadir view only. The differences are plotted in Fig. 5. The areas where the largest discrepancies occur are concentrated around the tropics which coincides with the location of the greatest concentration of water vapour and hence largest atmospheric correction. Although the improved performance demonstrated by the dual-view technique is very encouraging, the results are by no means conclusive: the improved performance may simply be a reflection of errors in the single-view retrieval algorithm.

One reason for the evaluation of ATSR NRT data is to deduce whether the data are of sufficient quality to be used in the UKMO operational SST analysis scheme. Other sources of satellite data have been used in the past: AVHRR and Meteosat data were used until shortly after the eruption of Mount Pinatubo in June 1991, when it became evident that aerosols forced into the stratosphere as a result of the eruption were having a detrimental effect on the quality of the SST retrievals (Reynolds 1991). The dual-view technique of the ATSR should mean that accurate SST retrievals are possible even under conditions of high aerosol concentrations. Validation statistics for dual-view ATSR NRT data and other sources of SST data are shown in Table II. The

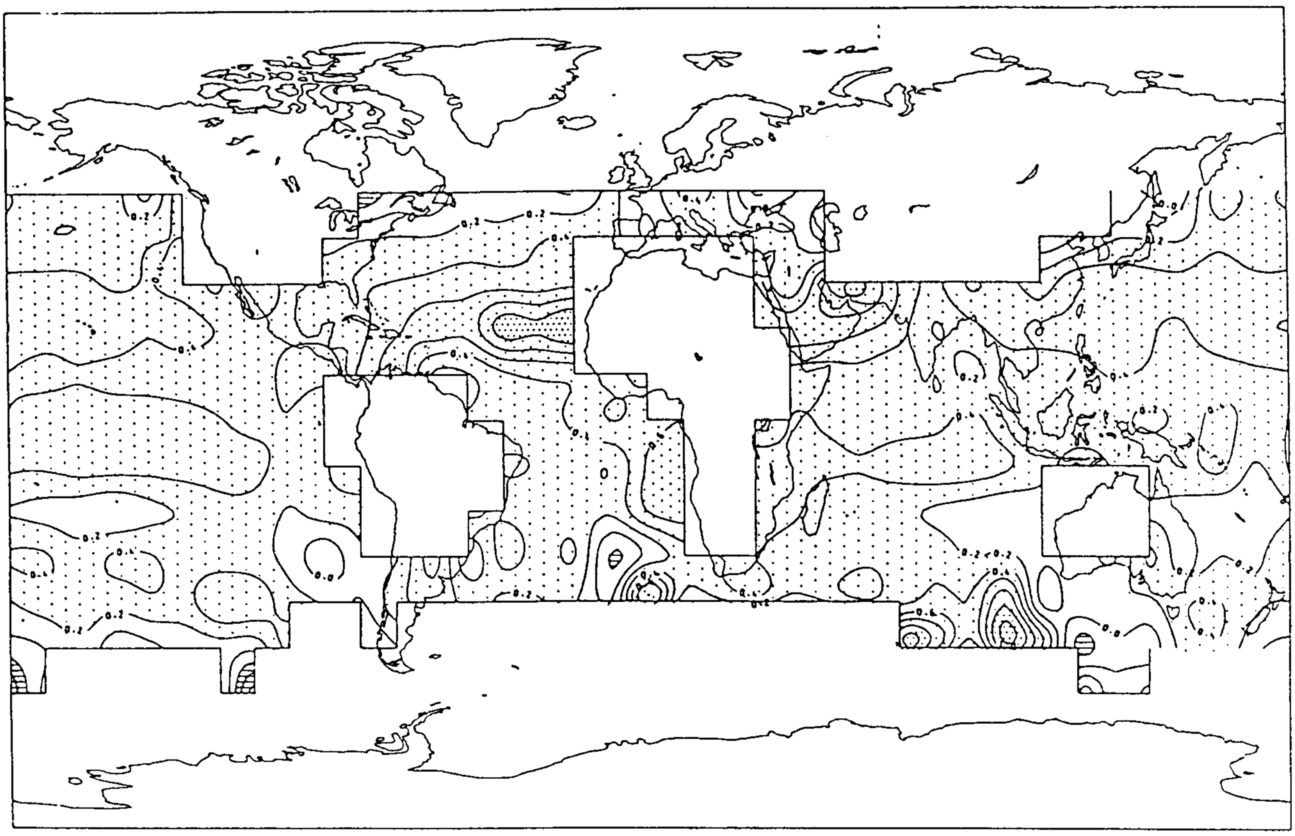

Figure 5. Global distribution of differences between dual and single-view ASSTs for September 1992 (ignore values over land).

Table II. Global statistics for all SST observation types for September 1992. O is observation, A is analysis and C is climatology.

Observation Type	N	Mean O–A	Mean O–C	Standard deviation O–A	Standard deviation O–C
Ships	55127	0.06	0.24	1.05	1.17
Moored buoys	43978	−0.02	0.19	0.52	0.68
Drifting buoys	35182	−0.04	−0.09	0.36	0.56
Bathythermospheres	1186	0.18	0.44	0.41	0.53
Meteosat	30998	−0.47	−0.49	0.75	0.72
GMS	15884	−0.97	−1.90	1.12	1.16
AVHRR (NOAA-11)	90987	−0.13	−0.08	0.68	0.70
ATSR (ERS-1)	181605	−1.10	−1.01	0.63	0.65

other satellite-derived SSTs (from the NOAA polar-orbiting satellites with AVHRR and the European (Meteosat) and Japanese (GMS) geostationary platforms) are derived using algorithms that are empirically calculated against *in situ* data. They are therefore estimates of bulk SST and have smaller biases than obtained from ATSR dual-view data but comparable standard deviations. The standard deviation for ship data is considerably larger. Trial analyses using only ATSR data have been produced (Fig. 6). Differences between these and the *in situ* analysis have been investigated and show little dependence on geographical location. This illustrates the potential value of ATSR data once a suitable method for eliminating the bias between the *in situ* and radiative SSTs has been established. One short-term solution is to devise an empirical bias correction scheme based on selected high-quality surface observations. A better approach is to parameterize the skin effect using model-derived surface-wind stress and heat fluxes but this will take some time to develop.

4. The First ATSR Tropical Experiment

As part of the ATSR validation programme the UK Meteorological Office Research Flight carried out the First ATSR Tropical Experiment (FATE) in November 1991. The primary objective of FATE was to validate ATSR top-of-atmosphere radiances and retrieved SSTs in tropical atmospheres using a multichannel radiometer (MCR) (Kilsby *et al.* 1992) on the C-130 aircraft. Two of the channels on the MCR were closely matched in spec-

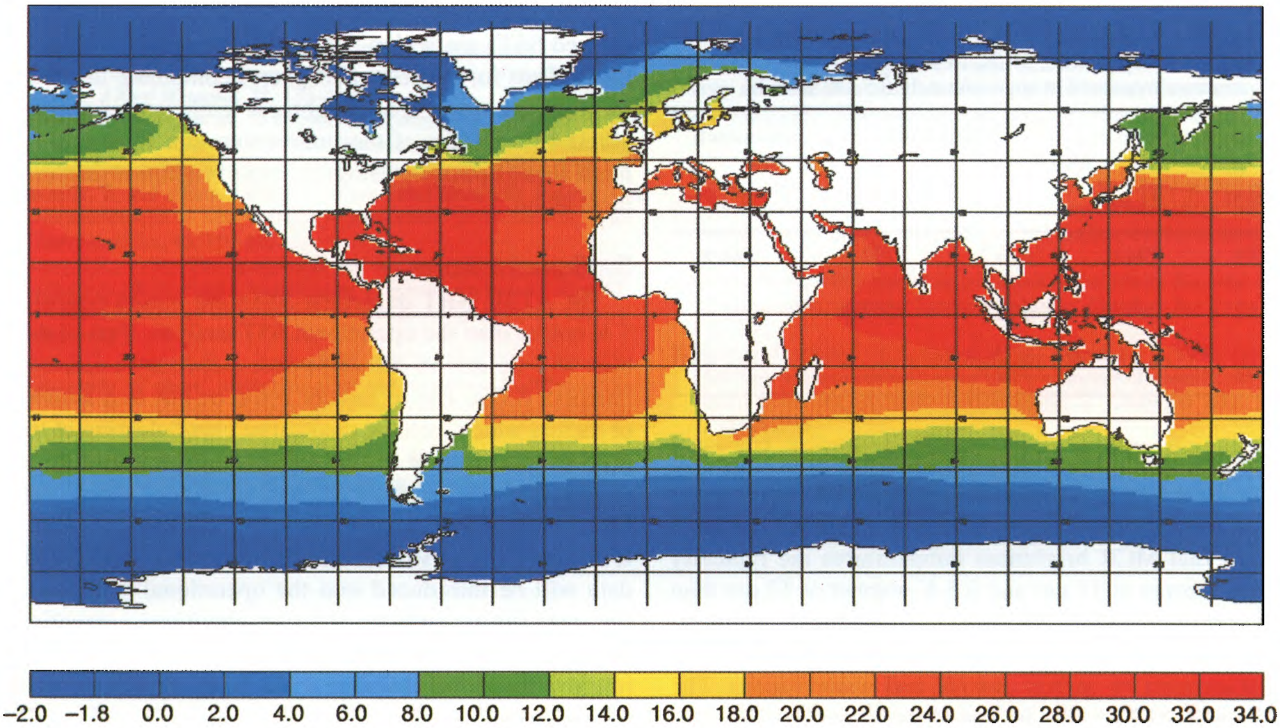

Figure 6. SST analysis (°C) from ATSR data valid for 18 August 1992. This analysis is derived initially from climatology and then replaced by ATSR data up to 10 days old.

tral response to the 11 μm and 12 μm channels of ATSR. MCR radiances were also measured at a number of levels between 70 m and 8 km altitude to provide a radiance profile which could be compared with that predicted by the Rutherford Appleton Laboratory radiative transfer model used to derive the SST retrieval coefficients for equations (1) and (2). These profile data are not presented here but in a more comprehensive paper on the FATE measurements (Smith *et al.* 1993).

Fig. 7 shows the region around Ascension Island (8° S, 14° W) where FATE was carried out. The areas flown for three clear-air flights A139, A143 and A144 (1, 7 and 8 November 1991, respectively) are shown with the ERS-1 sub-satellite track for flights A139 and A143 superimposed. During each of the three clear air flights, the MCR was recording brightness temperatures at a height of approximately 6.5 km within five minutes of an ERS-1 overpass of the area. Table III shows the averaged

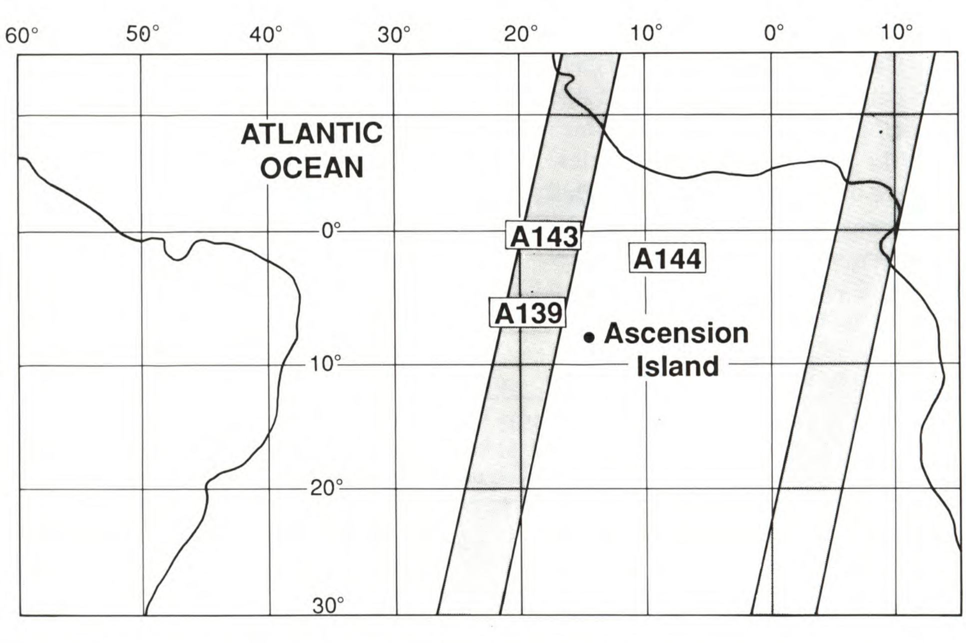

Figure 7. Locations of C-130 clear-air flights A139, A143 and A144 during FATE. The shaded area is the ATSR swath for flights A139 and A143.

Table III. Comparison of ATSR 11 μm brightness temperatures (K) with coincident MCR 11 μm and 12 μm brightness temperatures measured at approximately 6.5 km altitude.

	Nadir view			
	ATSR		MCR	
Flight	11 μm	12 μm	11 μm	12 μm
A139	294.0	293.2	295.0	293.9
A143	293.3	292.0	293.9	292.4
A144	292.0	290.8	292.7	291.3

nadir MCR and coincident ATSR brightness temperatures for the three clear-air flights. Each MCR average is taken over a run of approximately 5 minutes. The table shows that MCR brightness temperatures are typically 0.7 K warmer at 11 μm and 0.5 K warmer at 12 μm than the corresponding ATSR nadir view brightness temperatures. Half of this difference is due to residual atmospheric absorption by carbon dioxide and water vapour. The remainder (0.3 K) may be due to the presence of stratospheric aerosols at a level between the aircraft (6.5 km) and ATSR (777 km), as seen by other instruments on the C-130 (Saunders 1993).

Approximately 100 minutes after the ERS-1 overpass, the C-130 aircraft flew down to a low level above the sea surface in order to measure the radiative SST (i.e. the measured sea-surface brightness temperature corrected for reflected sky radiation) using the MCR and the PRT-4 (8–13 μm) radiometer on the C-130. Both of these radiometers have an absolute measurement accuracy of 0.3 K. The measured radiative SST was averaged over a period of approximately five minutes for a nadir view 70 m above the sea surface. The nadir and forward ATSR 11 μm and 12 μm brightness temperatures in Table III are used to estimate the SST according to equations (1) and (2). The results of both computations are given in Table IV which show that for all three flights, the SSTs which are derived using only 11 μm and 12 μm nadir view brightness temperatures are on average 2.2 K cooler than the actual radiative SST as measured at low level by the C-130. When the ATSR forward-view brightness temperatures for the 11 μm and 12 μm channels are combined with the nadir views according to equation (2) the ATSR-derived SSTs are within 0.8 K of the measured radiative SSTs. Thus for tropical atmospheres combining the nadir and forward view ATSR brightness temperatures enables a better correction of the intervening atmosphere to be made than is possible using the nadir brightness temperatures alone.

5. Conclusions

The ATSR NRT dual-view SSTs are biased typically 1 K colder than the operational SST analysis. Part of this bias will be due to the difference between *in situ* and radiative SSTs. The remainder could be due to a number of factors which include: inadequate cloud clearing of the ATSR data, biases in the retrieval algorithm due to uncertainties in the radiative transfer model and/or ship SSTs from engine intakes biasing the analysis too warm. It is likely that AVHRR and daytime dual-view ATSR data will be introduced into the operational analysis in the near future with initially an empirical correction based on *in situ* data applied. This will dramatically improve the global coverage provided by the various SST data sources.

For a tropical atmosphere, the aircraft radiometer measurements also show a cold bias of the retrieved dual view ATSR SSTs of about 0.7 K when compared with low-level aircraft radiometric SST measurements. This bias increases to greater than 2 K when only single-view retrievals are used. The effect of the volcanic aerosols from the Mount Pinatubo eruption was to reduce the nadir ATSR 11 μm and 12 μm brightness temperatures by up to 0.7 K and 0.4 K, respectively

Acknowledgements

The ATSR was funded by the UK Science and Engineering Research Council and the NRT project was funded by ESA. Thanks are due to Wing Commander Blake for allowing the UK Meteorological Research Flight C-130 to operate out of Ascension Island and the RAF aircrew for their expert flying and continual guidance in planning and executing this campaign. The Space Science Department of the Rutherford Appleton Laboratory provided the FATE ATSR data and also gave helpful advice on analysing these data. The ATSR analysis was provided by C.P. Jones (Meteorological Office).

Table IV. Comparison of ATSR retrieved SSTs and brightness temperatures (K) measured at 70 m above the sea surface by the MCR 11 μm channel and the PRT-4 radiometer (8–14 μm). Each value is an average of a 5-minute straight and level run.

Flight No.	ATSR nadir view	ATSR nadir + forward views	MCR 11 μm B temp.	PRT-4 8–14 μm B temp.
A139	296.0	297.4	298.0	298.0
A143	296.6	298.2	299.0	299.0
A144	295.0	296.6	296.9	297.3

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Editor's note. The technique below has been developed by an outstation forecaster. Purists may argue that it should be supported by tables of statistics and deep theoretical justification. Either requirement would probably suppress this work. Instead I offer it to all as it stands and will welcome comment on its efficacy. Sceptics should note that the method described below is in close accord with that suggested by W.E. Saunders (1950) at the end of his original paper on fog forecasting. It is a long time since a work of this type was printed here. I hope it will inspire others to exercise their minds and not rely entirely on output from a powerful, remote computer.

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Stratus forecasting

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Until recently at Meteorological Office, Wattisham

What follows is a method of forecasting stratus but is, perhaps more importantly, a new way of looking at the basic concept of instability and applying this to the forecasting of cloud (and visibilities up to a point) in the boundary layer.

When I first became a forecaster I was, I remember, very surprised to discover that on some summer evenings the relative humidity rose very quickly, to the point where I became worried as to whether we were going to get fog: in fact the visibility remained good, perhaps 15 miles. It was clear to me even at that time that there must be a limit beyond which the visibility would decrease. This limit eventually became my 'critical visibility line' — what I now call the **Critical Theta-W (CTW)**.

Having selected the most relevant ascent, I draw in the saturated adiabatic through the wet-bulb temperature from the base of the boundary layer inversion (there usually is one) down to the surface isobar and call this the CTW. Occasionally it may be necessary to use the wet-bulb at a somewhat lower level if this is significantly moister. I believe that the air beneath the boundary layer inversion continues its slow overturning as cooling progresses — note the continued twinkling of any lights — until the surface wet-bulb temperature passes below this value. On the tephigram this is when the surface wet-bulb temperature passes to the left of the CTW. This also means that the cloud which forms as a result, to the left of the line, is basically stable and of the true stratus type,

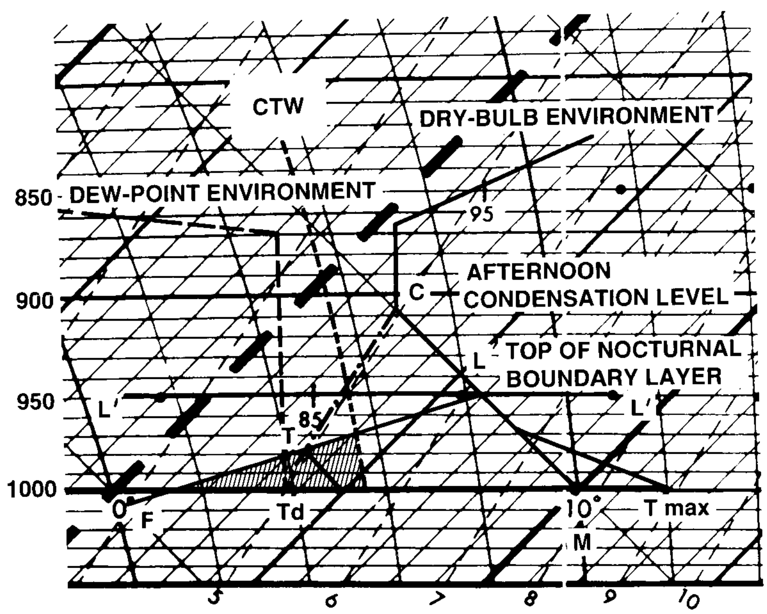

Figure 1. The stratus construction lines (on a tephigram) on an ideal sounding with a gradient wind of 30 kn. True stratus forms in the shaded area, 'cumulostratus' in the area between ML at the CTW.

whereas cloud forming to the right of the line is basically unstable and convective (although it may be at, say, 200 ft).

I regard this concept of the CTW as fundamental to the forecasting of cloud within the boundary layer. Let me give you an example of the way in which it works.

In February 1993 there was a cooling anticyclonic inversion at around 3000 ft, beneath which there was a persistent Sc sheet. The wind across the United Kingdom was south-easterly and the thickness of the Sc decreased to around 1000 ft early in the night. About this time the cooling at the inversion caused the CTW to drift to a value below the surface dew-point and Cu formed with a base of 800 ft: this supported the Sc sheet until surface cooling brought the dew-point back below the CTW and convection stopped allowing the stratocumulus to disperse.

The method for forecasting stratus (refer to Fig. 1)

(1) Construct the night cooling curve — using a proven method for your station.

(2) Find the best (usually the only!) upwind ascent and plot the lower layers on an open-scale tephigram.

(3) On the tephigram mark the θ_w line representing the **CTW** as described above.

(4) Mark on the station surface pressure line FM.

(5) On the surface pressure line mark the **fog-point**, F. The Saunders method is probably the best method in the United Kingdom.

(6) The next task is to assess the mean depth of the nocturnal mixing layer. Unless the gradient is clearly changing it is expedient to use the actual — usually mid-afternoon — value. It has proved reasonable to take the depth to be 10 hPa for every 6 kn of gradient. For example a gradient of 30 kn gives a nocturnal mixing layer some 50 hPa deep. Draw onto the tephigram the line representing the **top of the mixing layer**, L'L' (in this case — 50 hPa above the Surface Pressure Line). Note where the **top of the mixing layer** line cuts the **environment curve**, at L, and join this point to the fog-point, F from para. (5) to form the '**line**', LF. The **line** represents the top of any stratus cloud that may form. The position of the Normand point for surface temperature and dew-point represents the cloud base. Stratus forms when, during the cooling process, the Normand point passes to a level below the **line**. Note that a thickness of about 150 ft is necessary for stratus to be visible.

(7) Now, as cooling progresses the task is to monitor progress by plotting successive Normand points, noting the direction which these are taking (unfortunately these sometimes behave badly at first but they usually settle down — airstreams are not often homogeneous). When a reasonable pattern emerges and the Normand points are heading for the **line** it may be necessary to take readings (T, T_d) more frequently. Note where the Normand point curve seems likely to pass below the **line**, T: read off the corresponding surface temperature and the time for it from the cooling curve. Plotting the Normand point curve in this way does give the outstation forecaster an enormous feeling of confidence in the outcome, especially when surface humidity is high and neither fog nor stratus has been mentioned in the briefing!

General remarks

I have noticed that, during cooling, the Normand points usually lie on a curve that takes the form of an arc of a circle with its centre somewhere near where the environment dew-point curve crosses the level of the afternoon condensation level (above when the air is drying out, below when the air is moistening) passing through the Normand point at T_{max} and the fog-point. It will be noticed that in winter the curves are very flat, indicating a preponderance of low cloud of the 'cumulostratus' type. In summer there is a larger proportion of cases where the curve is a quarter circle giving a good intercept with the **line** and a majority of cases of genuine stratus. (I remarked on the rapid increase in humidity in the early stages of cooling in the preamble.)

Let me now mention briefly the factors which will, clearly, alter the relative position of the **line.**

(a) A significant change in the gradient speed; a change of some 10 kn or so is necessary before we need to recalculate, bearing in mind that we will not be sure about the fog-point variation. With winds of over 35 kn there is very little nocturnal cooling at all, whereas a decrease to below 18 kn or so should point to the likelihood of fog rather than stratus!

(b) A significant change in the fog-point; this is difficult to forecast but, while following the Normand point plot as cooling proceeds this will be easy to see as the curve turns off towards the left or right and eventually aims at the new fog-point!

(c) A combination of increasing gradient and increasing fog-point will cause the line to gyrate and may leave the important section of the **line** in the same place!

It is useful to note that the highest stratus base seems to be related to the 10 m wind directly by the relation

N kn gives base N 00 ft.

A certain reluctance to forecast stratus with insufficient wind to support it seems prudent — unless the air is basically unstable, i.e. unless the Normand point is to the right of the CTW. We often see TAFs forecasting, say, 1000 ft with only 7 kn of wind: how can this be? Ignoring the vagaries of the TAF code; there are two possibilities, namely: instability — stratus forming for cumulus reasons and, of course, precipitation.

Our country being an island, it is always appropriate to have in mind the relationship between the upwind coastal dew-points and the sea temperatures, together with their Normand point and the CTW off the only upwind ascent. It is vital to realise that in autumn and winter sea temperatures are relatively high and more prone to produce low convective cloud given sufficient moisture at these levels, whereas in spring and summer the trend is for the more conventional stratus.

It should be noted that the descent of air down the lee side of nearby hills will have a significant effect which should be reflected in the forecasts.

With all this in mind, let us now look at the various types of stratus:

1. Nocturnal — formed by radiative cooling.
2. Post-mist — with rising temperatures.
3. Instability — stratus forming for cumulus reasons.
4. Precipitation.
5. Lifted fog — enough said!

1. Stratus forming by nocturnal radiation

Note the station maximum afternoon temperature and its dew-point. It does, of course, sometimes happen that one can take more appropriate temperatures off stations upwind, if so, then even better. Now draw the cooling curve and start the construction.

2. Post-mist stratus

After a fine night of cooling when temperatures have failed to reach the fog-point, with sufficient wind to support it, there may still be a danger of low cloud forming as temperatures rise. Clearly, as temperatures fall at night so do the dew-points (both might eventually reach the fog-point). This means that when the morning forecast is being prepared, say at 0500, the dew-points on the latest British Isles chart may be considerably below those that will be prevalent at, say, 0900, because as temperatures rise, due to solar heating, so will the dew-points. From the above it is clear that if the Normand point were to reach a position below the surface inversion (from an amended upwind midnight ascent), then stratus will form and at a time than can be predicted from tables of available radiation. The problem is to assess the progress of the dew-point. What to do? To calculate the likely maximum dew-point I have three suggestions:

(a) use the wet-bulb from the previous afternoon,
(b) use the actual (0500) upwind coastal dew-point, or
(c) use divine inspiration!

Plot the best one of these onto the chosen ascent (with its HMR line). Then draw on the dry adiabatics through the forecast hourly temperature values and just see whether at any stage in the rise of both temperature and dew-point it really is possible to find a Normand point in a position where stratus could form, however temporarily. Remember, sufficient wind is also required.

3. Instability stratus

As I have suggested, it usually helpful to keep a constant check on the relationship between the coastal temperatures and their relatively high dew-points and the position of their Normand point relative to the CTW on the upwind ascent. Stratus will not form easily at this natural condensation level unless there is moisture present at around the 800 to 1500 ft level. It does, however, sometimes occur (usually unexpectedly!) with onshore winds with quite normal fair-weather-cumulus-type midnight ascents, especially, though not necessarily, with freezing levels low enough to allow for light showers. I have seen quite a few situations over East Anglia with such 'cumulostratus' with bases as low as 300 ft, arriving mid-morning and dispersing, as is normal with cumulus cloud, during the evening.

With instability and moisture at low level this type will very occasionally form during the evening as cooling progresses, but will usually last no more than three hours or so before dispersing. Care should be taken when forecasting a major case of nocturnal stratus advection that low cloud on the chart during the evening is not of this type!

I have seen a few occasions of this evening 'cumulo-stratus' cloud — characterized by its variability, both in time and space — where, as the temperatures fall, the Normand point traverses gradually to the left aiming towards the fog point and eventually crosses the CTW line, at which point the low cloud is suddenly transformed into 7/8–8/8 of the genuine, persistent variety. This means, of course, that on a particular chart these two types can be in juxtaposition.

4. Stratus in precipitation

I don't really know that I have anything useful to add about this but, here goes: I must admit to being too fond of over-forecasting low cloud in rain, mainly because I don't know how to forecast it in the first place! Of course, what we normally do is to follow developments upwind, unless upwind is out over the sea. With a good solid pre-warm-frontal rain area and stable conditions I often use the cloud bases at Boscombe Down as a good guide for forecasting stratus bases at Wattisham (with a south-easterly surface wind), and I am sure many of us do this sort of thing. I think it is useful to follow the natural condensation levels (as dew-points rise) and relate these to the CTW. I suggest that a good solid three hours or so of light rain gradually becoming moderate is very likely to produce cloud at these, often very low levels especially in southern England; further north the mountains complicate matters. However, especially if the air is basically unstable — note my definition above — this cloud is very dependent indeed on the presence of the rain and, should it stop, it will be off like a shot. So in this instance we can only be as good at forecasting the lowest stratus as we are at forecasting rain! On the other hand, reports of *drizzle* do seem to indicate moisture in the critical 800–1500 ft zone and really are a good indicator of the formation of persistent low cloud. Do watch out for showers by coalescence being reported as drizzle — especially in East Anglia!

Conclusion

I have just one more small point; such subjects as 'advection', and 'upslope motion' seem to me very much side issues in the local forecasting process. If one follows the evolution of temperatures at stations, stratus will form as and when the Normand point is in the right place no matter if the nearest upwind station has stratus or not.

Reference

Saunders, W.E., 1950: Method of forecasting the temperature of fog formation. *Meteorol Mag*, **79**, 213–219.

551.577.2:551.577.37:556.161(410)

The derivation of design rainfall profiles for upland areas of the United Kingdom

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Summary

The application of techniques for design flood estimation requires an understanding of the temporal variability of storm rainfall. Current practice relies on the definition of design storm profiles which seek to display a typical pattern of variability in rainfall intensity throughout an event. The paper evaluates methods of design profile construction for a range of durations from 1 hour to 11 days. In particular the effects of data type and data interval on the form of design profiles is examined.

The paper reviews various methods of design profile derivation for a range of durations and compares the results for both point and areal extreme rainfall events. Several data sources are utilized including daily rain-gauge data from north Wales and north-west Scotland and hourly data from the Hameldon Hill radar in north-west England. The synoptic meteorology giving rise to some notable rainfall events is investigated and the statistical characteristics and seasonal distribution of both the observed and the design rainfall profiles are examined.

1. Introduction

Most rainfall run-off methods for design flood estimation require the construction of rainfall profiles to distribute a design rainfall depth through time. It is difficult to characterize temporal patterns of rainfall because the precipitation process is highly variable. This paper addresses the problem of deriving temporal profiles for design applications in upland areas. The results outlined are taken from a wider study of the spatial and temporal variations of rainfall that affect reservoir safety in upland areas of the United Kingdom.

Current practice in the United Kingdom is to use the Flood Studies Report (FSR) method which represents the design rainfall by a symmetrical and unimodal profile (Natural Environment Research Council 1975). This technique is recommended only for durations of up to several days (FSR II.6). In Scotland a method has been developed to calculate design profiles for durations longer than those recommended in the FSR, as critical durations in some multi-reservoired catchments can be as long as 7 to 10 days. The method is based on the use of a number of profiles of observed rainfall events chosen subjectively (Stewart and Reynard 1991). This paper presents further results from the average variability method (Pilgrim *et al.* 1969) and analyses, among other things, the effects of season, duration and areal averaging on the form of the rainfall profiles.

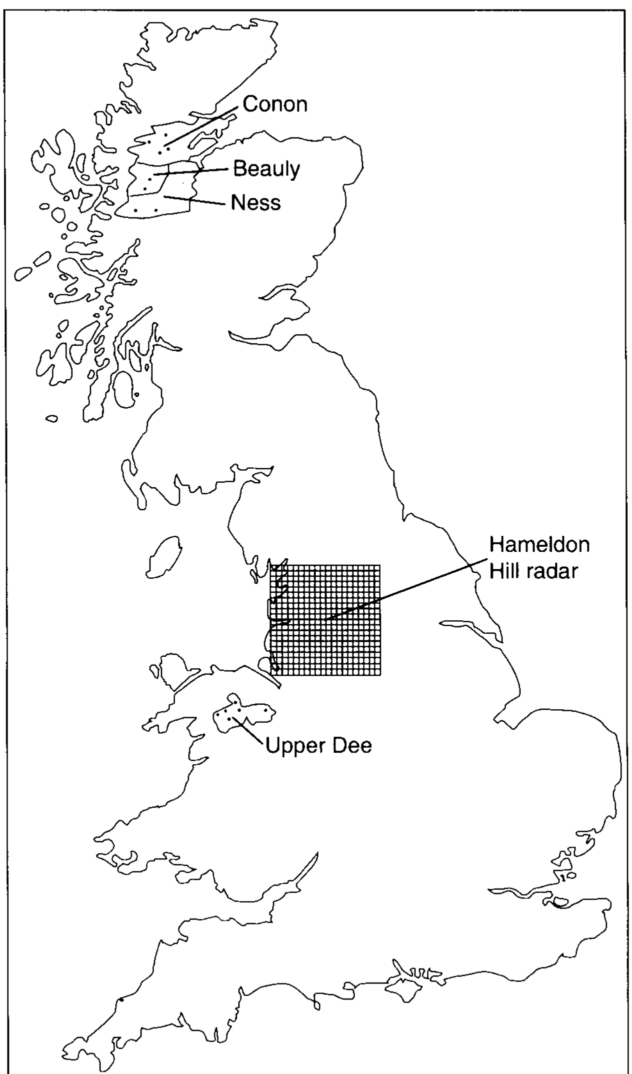

Figure 1. Upland regions for which data were available to the study.

2. Location of study areas and data available

Three predominantly upland areas (Fig. 1) were chosen to provide a cross-section of data types and durations.

In the Upper Dee catchment of north Wales, where average annual rainfall ranges from 900 to 2000 mm, data were selected for ten gauges from the dense network of 15-minute recording rain-gauges. The network was installed in the early 1970s as part of the Dee Weather Radar Project and 15-minute data are available for the period from September 1971 to March 1975 (Central Water Planning Unit 1977).

In north-west England hourly peaks-over-threshold (POT) data from the Hameldon Hill radar were used, which represent the areally averaged data used in the analysis. The radar field consisted of 400 five-kilometre grid squares, with hourly data available for 183 non-continuous rainfall episodes between 1981 and 1987. The average annual rainfalls in this area range from 750 mm to over 1500 mm.

In north-west Scotland the series of daily annual maxima were abstracted for 12 rain-gauges in the Conon, Beauly and Ness catchments. From all 12 gauges annual maxima data were derived for a range of durations for the 27-year period between 1961 and 1987. All three are complex, multi-reservoired systems and, as such, critical design storm durations are in excess of those for which the FSR technique is recommended (FSR II.6). Average annual rainfalls for the selected gauges in this region range from 1100 mm to over 2200 mm.

Tables I to III list the number of profiles extracted both annually and seasonally for north-west Scotland, north-west England (Hameldon Hill radar data) and the Dee data, respectively. Data in Tables I and III are annual and seasonal maxima; the Hameldon Hill radar data (Table II) were extracted using a POT criterion.

The distribution of extreme events through the year (in terms of the proportion of events in each season) is the same for all the data types, but changes with duration. As the duration increases the proportion of those events occurring in winter also increases, while the proportion in summer decreases. This is particularly true with the daily data interval, when the summer convective storm (typically producing only one or two days with an extreme rainfall depth) accounts for a higher percentage of the annual maximum events. These summer convective storms also produce some of the greatest intensities of rainfall over very short periods, which means they also tend feature in the much shorter duration summer maximum events.

Table I. Number of annual and seasonal profiles: daily rain-gauges in north-west England.

Duration	Total	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
3-day	523	146	71	123	183
5-day	523	149	58	136	180
7-day	523	172	61	113	177

Table II. Number of annual and seasonal profiles: hourly Hameldon Hill radar data.

Duration	Annual	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
4-day	1364	440	318	227	379
6-day	1180	379	277	191	333
12-day	865	280	215	125	245

Table III. Number of annual and seasonal profiles: 15-minute rain-gauge data from north Wales.

Duration	Annual	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
1-hour	512	110	34	175	193
2-hour	533	140	40	145	208
4-hour	524	154	43	122	205
6-hour	474	149	35	110	180
12-hour	354	124	27	65	138

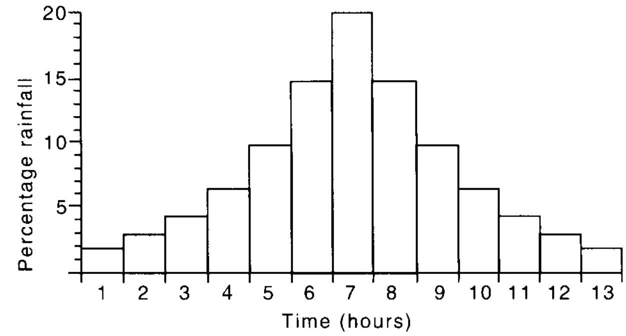

Figure 2. The winter 75% percentile profile using the FSR technique.

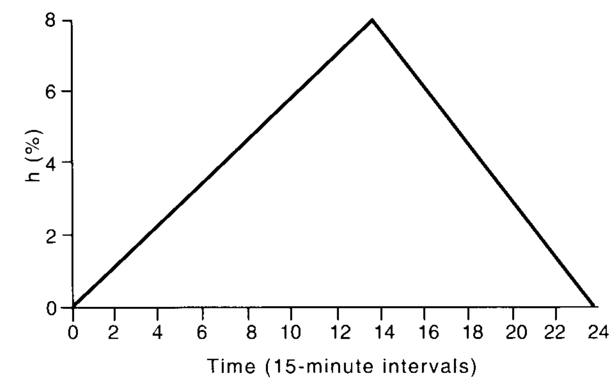

Figure 3. The winter 6-hour design profile for the Upper Dee data using the triangular moments method.

3. Methods of design profile derivation

Most current methods used to distribute design rainfall depths through time are objective techniques based on observed patterns of rainfall intensities. It is possible to distinguish three types of method currently in use around the world: those derived from averages of observed profiles, those involving the fitting of models to observed hyetographs, and more flexible empirical methods.

3.1 Averaging methods

Included in this category is the approach based on mass curves (for example, Huff (1967)), which produces dimensionless, cumulative plots of rainfall depth against time. Huff's method segregates storms according to the quartile in which the heaviest rainfall was recorded. Additionally in this category is the FSR technique which uses 24-hour storms, centred on the period of most intense rainfall. This produces unimodal and symmetrical profiles as illustrated in Fig. 2. The frequency of occurrence of profiles of varying sharpness is expressed through the use of percentiles. The winter, 75-percentile profile is generally recommended for flood design in predominantly rural catchments in the United Kingdom (FSR II.6).

These averaging techniques have the advantage of being relatively simple to implement and relate reasonably directly to observed rainfall events. The methods tend to produce design profiles that are so smooth and symmetrical, however, as to be unlike any of the input storm events, and their use becomes less realistic as the design duration increases.

3.2 Model-based methods

This group of methods uses a particular model to approximate the form of the observed profiles (for example, Keifer and Chu (1957), Yen and Chow (1980), Sutherland (1983)). The triangular model proposed by Yen and Chow uses a triangle to represent periods of non-zero rainfall and is fitted using a method of moments. The triangular hyetograph is defined by three parameters: the time to peak (a), the proportion of the duration occurring after the peak (b), and the peak magnitude (h). An example is shown in Fig. 3.

Although these techniques have been found to produce good results, the parameters vary with location and duration and prove difficult to generalize. In particular these methods do not take account of the variability in the observed storm events. The triangular-moment method (Sutherland 1983) was designed to be applied to real storms and not fixed duration events, so it is unclear how it may be used in design applications.

3.3 Empirical methods

The third group of methods includes the so-called average variability method, developed in Australia by Pilgrim *et al.* (1969). The method was developed to produce design profiles for durations of between 10 minutes and 72 hours and seeks to characterize the mean variability of rainfall intensity during observed periods of heavy rain. The main advantage of the average variability method is that the mean position of the observed peaks is conserved. This allows the design profiles to be asymmetrical and multipeaked, a feature evident in observed profiles due to the inherent variability of the rainfall process itself, when observed at a stationary point. A 6-hour profile produced by the average variability technique is shown in Fig. 4. The average variability method can be seen to provide more detail than the other methods (Figs 2 and 3). A negative skew is apparent in both Figs 3 and 4, although this is less obvious in the triangular profile. Because the average variability method provides a rainfall depth for each 15-minute interval, a more detailed profile is produced.

A somewhat similar approach was developed by the SOGREAH group in France. The method produces a median pattern centred on the period of most intense rainfall (Hall and Kneen 1973). More recently, Srikanthan and McMahon (1985) have developed a technique to take account of the persistence from one sub-duration to the next, especially for durations of less than one day. As all observed profiles are centred on the period of heaviest rainfall, some data from the more unusual events are discarded when using this technique.

4. Results and discussion

The results presented in this paper concentrate primarily on the average variability method and compare the effects of data type, data interval, season, duration and areal averaging. The discussion section is divided into two parts: the first dealing with the short-duration profiles (up to 12 hours), the second looking at the much longer design profiles (up to 11 days)

4.1 Short-duration design profiles

Figs 5 and 6 illustrate the design profiles produced using the average variability technique for the 4-hour duration. The profiles were split according to season with winter comprising December, January and February, and summer defined as June, July and August. Figs 5(a) and 5(b) compare the summer and winter results from the 15-minute Dee data. Close inspection reveals that, not only is the variability between each sub-duration greater in the summer than in the winter, but there is also greater variability within each sub-duration; the latter is represented by the error bars which corresponds to the inter-quartile range. This range has been used rather than the standard deviation as the distribution of depths within the very low sections of the profile is far from normal. However, the factorial standard error cannot be used as the depths within the peaks of the profile approximate a normal distribution, hence the inter-quartile range has been shown.

A statistical analysis of the input profiles showed that those from the Upper Dee were not significantly different from those derived from the radar data at the same durations. This made it possible to compare the point data from the Dee catchment with the areally averaged Hameldon Hill radar data. Fig. 6 shows the summer and winter average variability design profiles produced using the hourly radar data for the 4-hour duration. The most notable feature of Figs 5 and 6 as a group is the extent to which the Dee point data are in agreement with the radar data. Table IV compares hourly depths for the Dee data (obtained by summing the four 15-minute intervals within each hour) with those for the radar data. While the actual percentages are not the same, the broad patterns are very similar, with the more peaky nature of the summer profiles and the negative skewness being reproduced in both data types.

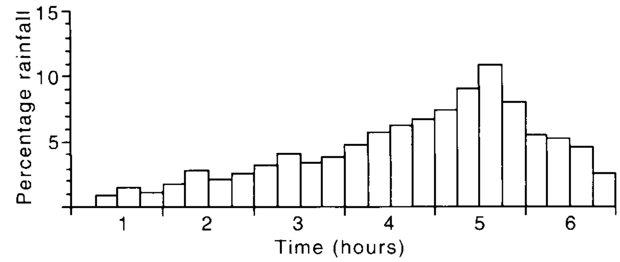

Figure 4. The winter 6-hour design profile for the Upper Dee data produced using the average variability method.

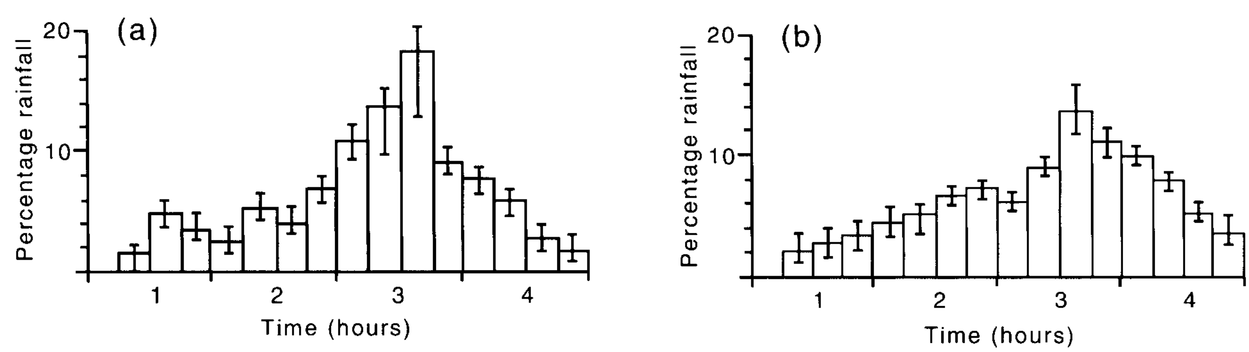

Figure 5. The 4-hour average variability design profile using Upper Dee data, (a) summer, and (b) winter.

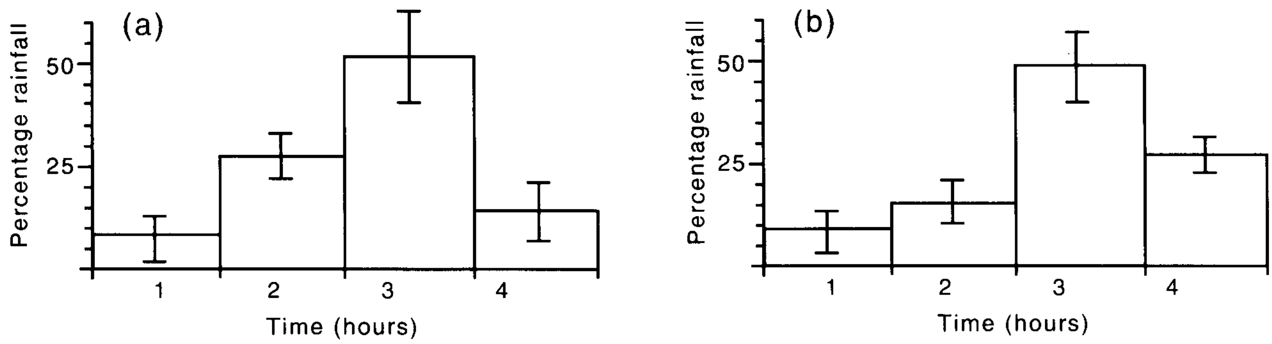

Figure 6. The 4-hour average variability design profile using Hameldon Hill radar data, (a) summer, and (b) winter.

Table IV. Comparison of hourly totals, in percentages, for point (Dee) and areal (Hameldon Hill radar) data for the 4-hour duration.

Time interval	Winter (DJF)		Summer (JJA)	
	Radar data	Dee data	Radar data	Dee data
1	9	8	8	9
2	16	24	27	19
3	48	40	51	53
4	27	28	28	19

Table V and Figs 7 and 8 show the corresponding results for the 12-hour duration and show many of the features of the 4-hour profiles. The summer profiles are again more variable from interval to interval and within intervals. The shape of the design profiles at this 12-hour duration are different, however. The summer radar data produce an early peak, while a late peak is evident in the summer Dee data, although both profiles display double bursts. This difference in the shape of the two profiles may arise because of the difference between the areally averaged radar data and the point Dee data, although this is not apparent in other seasons or at other durations. Given the similarity between the 4-hour profiles (for both seasons) and the 12-hour winter profiles, the difference probably occurs because of the nature of the available radar data. Although hourly radar data are held between 1981 and 1987, the record is far from complete. Very often the full 12 hours either side of a selected 12-hour event were not available, so it is unknown whether or not the event was centred correctly, or indeed whether the event was the most extreme.

Table V. Comparison of hourly totals, in percentages, for point (Dee) and areal (Hameldon Hill radar) data for the 12-hour duration.

Time interval	Winter (DJF)		Summer (JJA)	
	Radar data	Dee data	Radar data	Dee data
1	0.4	0.3	0.5	3.9
2	1.5	2.8	5.0	11.6
3	3.1	7.3	33.9	9.7
4	13.5	15.6	20.1	7.3
5	10.2	11.6	9.4	3.0
6	31.3	22.2	12.9	1.7
7	19.3	9.1	2.9	0.4
8	5.7	13.6	1.5	1.2
9	7.7	9.5	2.1	6.7
10	4.1	4.8	3.8	29.2
11	2.3	1.3	7.0	16.6
12	0.8	1.9	0.9	8.9

The important feature to note from Figs 7 and 8 is the multipeaked nature of the design profiles. The average variability method generally produces multiple peaks once the number of data intervals exceeds about four. This may be at durations of greater than four days with daily data, or even at the 2-hour duration with 15-minute data. This flexibility is not found with any of the other methods and reflects the variability of the rainfall process.

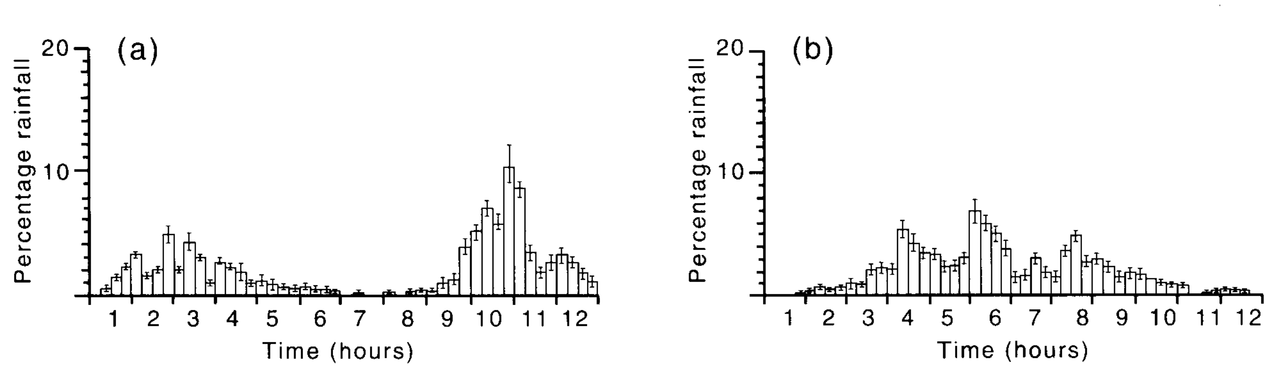

Figure 7. The 12-hour average variability design profile using Upper Dee data, (a) summer, and (b) winter.

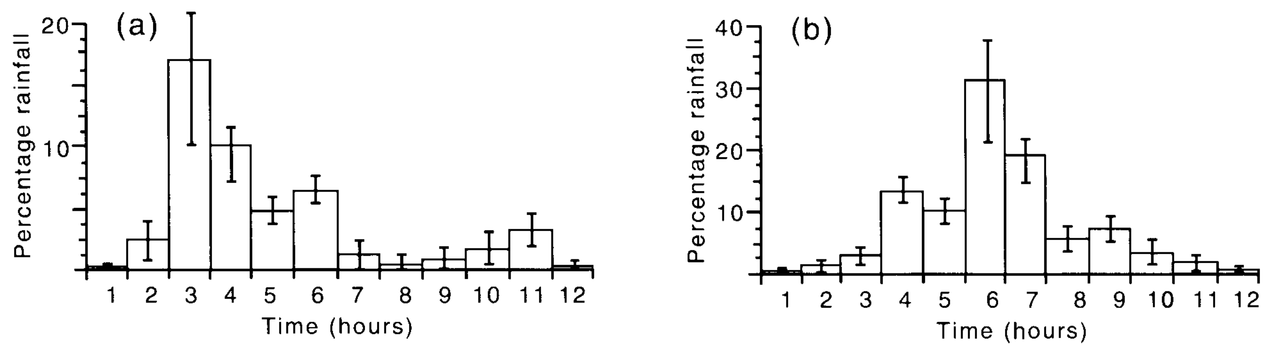

Figure 8. The 12-hour average variability design profile using Hameldon Hill radar data, (a) summer, and (b) winter.

4.2 Long-duration design profiles

Fig. 9 illustrates the results from applying the average variability method at the 3-, 7- and 11-day durations using annual data (all the annual maxima events were included) from north-west Scotland. For comparison, the results of the alternative method (Srikanthan and McMahon 1985) for the same durations are also shown. The 3-day profiles of the two methods are very similar, as indeed they are for the SOGREAH, FSR and modelling methods, being broadly triangular. Thereafter the similarity between methods ends. The average variability method produces a design profile at the 7-day duration

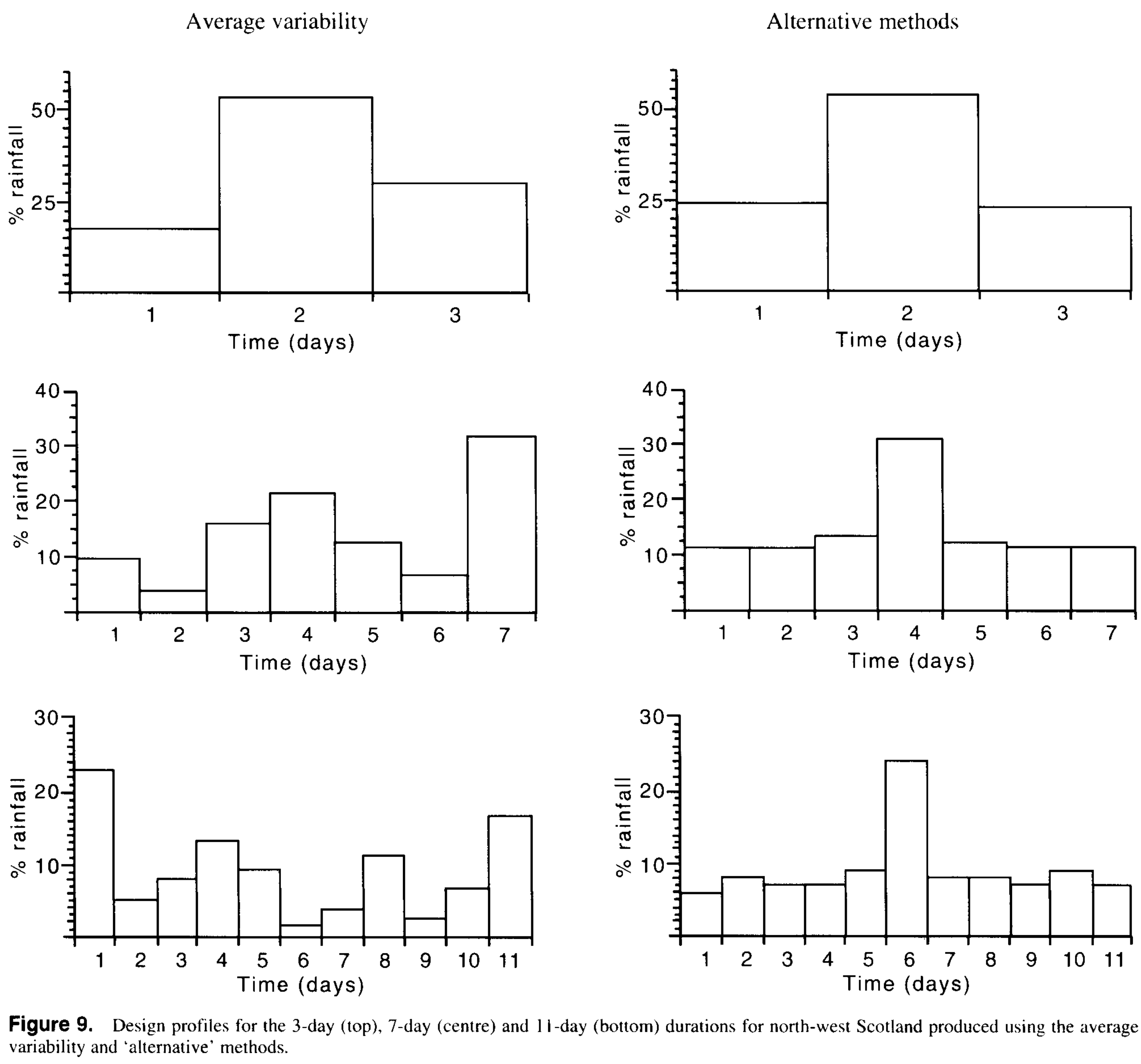

Figure 9. Design profiles for the 3-day (top), 7-day (centre) and 11-day (bottom) durations for north-west Scotland produced using the average variability and 'alternative' methods.

with three distinct peaks (in fact multiple peaks first appear at 4 days). At 11 days there are four obvious peaks. In contrast, the shape of the profiles produced by the alternative method remain the same throughout, being unimodal and symmetrical.

It is the apparent physical realism of the average variability design profiles that is so important as the durations move beyond a few days. Section 4.3 describes a typical annual maximum event from one of the Scottish rain-gauges and so highlights the intensely variable nature of daily rainfall. The event chosen is centred on 16 December 1966 when the daily rainfall total was well over 100 mm at the chosen gauge. Fig. 10 illustrates the 15-day profile centred on the 16th.

4.3 An example

The initial, fairly small peak on days 1 and 2 of the profile (corresponding to 9 and 10 December) represents the cold front of a relatively weak depression that had cleared Scotland by the 11th. Within four days a second, much deeper system passed over northern Scotland. This system was occluding as it crossed and deposited copious amounts of rain during the 16th and 17th producing the dominant 2-day peak in the profile (this 2-day rainfall was so extreme that the same two days appear in the annual maximum profiles for all durations from two to 12 days at this rain-gauge). The cold front associated with this depression was left trailing over the United Kingdom in a strong westerly flow. This led to the development of a wave depression that crossed Scotland on 21 and 22 December and accounted for the third peak in the profile (Fig. 10).

The above description is for only one annual maximum event, but at all durations greater than a few days a similar multiple peaked shape is evident. Given the inappropriate nature of the recommended FSR design profiles for these very long durations and the importance of these events in some slowly responding, multi-reservoired catchments, engineers in Scotland have developed their own local method of deriving rainfall profiles for design applications (Jarvis, personal communication).

The nature of the average variability method means that, from any number of extreme rainfall events, it can objectively produce a long-duration design rainfall profile of a 'realistic' form, rather than relying on just a few selected extreme events, as does the rather subjective method currently used for longer durations in Scotland. It is the flexibility and physical realism of the average variability profiles that suggests this is a more appropriate method for deriving design rainfall profiles, especially at the longer durations, although its performance within the overall design context is yet to be compared with the other methods.

5. Conclusions

Design rainfall profiles have been derived using a number of data sets from the upland areas of the United Kingdom. Several methods were used in order to reassess the applicability of the FSR method, especially at longer durations.

The observed profiles are generally multipeaked for durations longer than four times the data interval, as might be expected under a simple scaling assumption (Dwyer and Reed 1993). For instance, the daily profiles have more than one peak at durations greater than four days, while the 15-minute profiles exhibit multiple peaks at durations greater than one hour. It seems appropriate that any design profile should bear some resemblance to the profiles used in its derivation and only the average variability method is flexible enough to allow multiple peaks in the design profiles.

The comparison of the seasonal design profiles produced using the average variability method suggests that there is greater variability in the summer. This is evident across all data types and all durations, although it is less obvious in the Scottish annual maximum data. This pattern is also to be found in the observed profiles. The reason for this seasonal difference is due to the rainfall process itself with the (more temporally variable) convective rainfall responsible for a significant number of the summer extreme events and the (more temporally persistent) frontal rainfall being totally dominant during the winter.

Specific recommendations for the use of design rainfall profiles within a rainfall run-off method of flood estimation fall beyond the scope of this paper. It has been

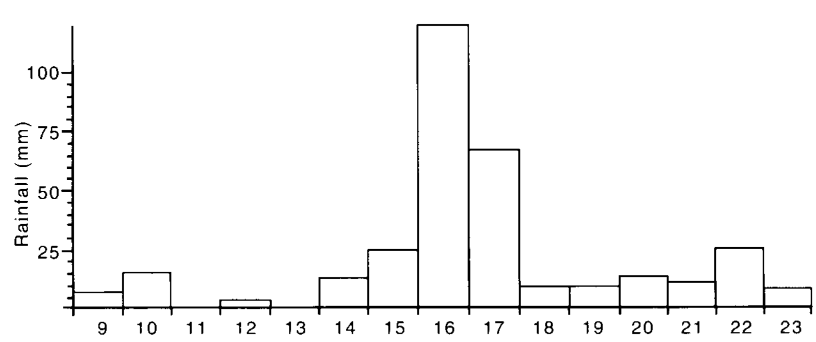

Figure 10. The 15-day profile for gauge 713571 in north-west Scotland, centred on 16 December, 1966.

shown that the application of the average variability design profiles, as opposed to the traditional bell-shaped profiles, produce lower peaks in the design hydrographs (because of the greater distribution of the rainfall) and hence the use of the unimodal profiles tends to produce a somewhat conservative design estimate (Aron and Adl 1992). It is the view of the authors that the average variability method (Pilgrim *et al.* 1969) offers a simple and flexible method of design profile derivation that appears to cope well with the great natural variability of the rainfall process.

Acknowledgements

The analysis presented in this paper forms part of a wider study of the spatial and temporal variability of extreme rainfall events in upland areas of the United Kingdom, commissioned by the UK Department of the Environment (contract no. PECD7/7/190). Strategic research on flood and rainfall estimation is funded by the Ministry of Agriculture, Fisheries and Food. The assistance of Mr R.M. Jarvis of Scottish Hydro-electric plc in providing details of current design practice is gratefully acknowledged.

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World weather news — February 1993

This is a monthly round-up of some of the more outstanding weather events the month, three preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and press reports. Naturally they are heavily biased towards areas with a good cover of reliable surface observations. Places followed by bracketed numbers, or areas followed by letters, in the text are identified on the accompanying map. Spellings are those used in The Times Atlas.

South America

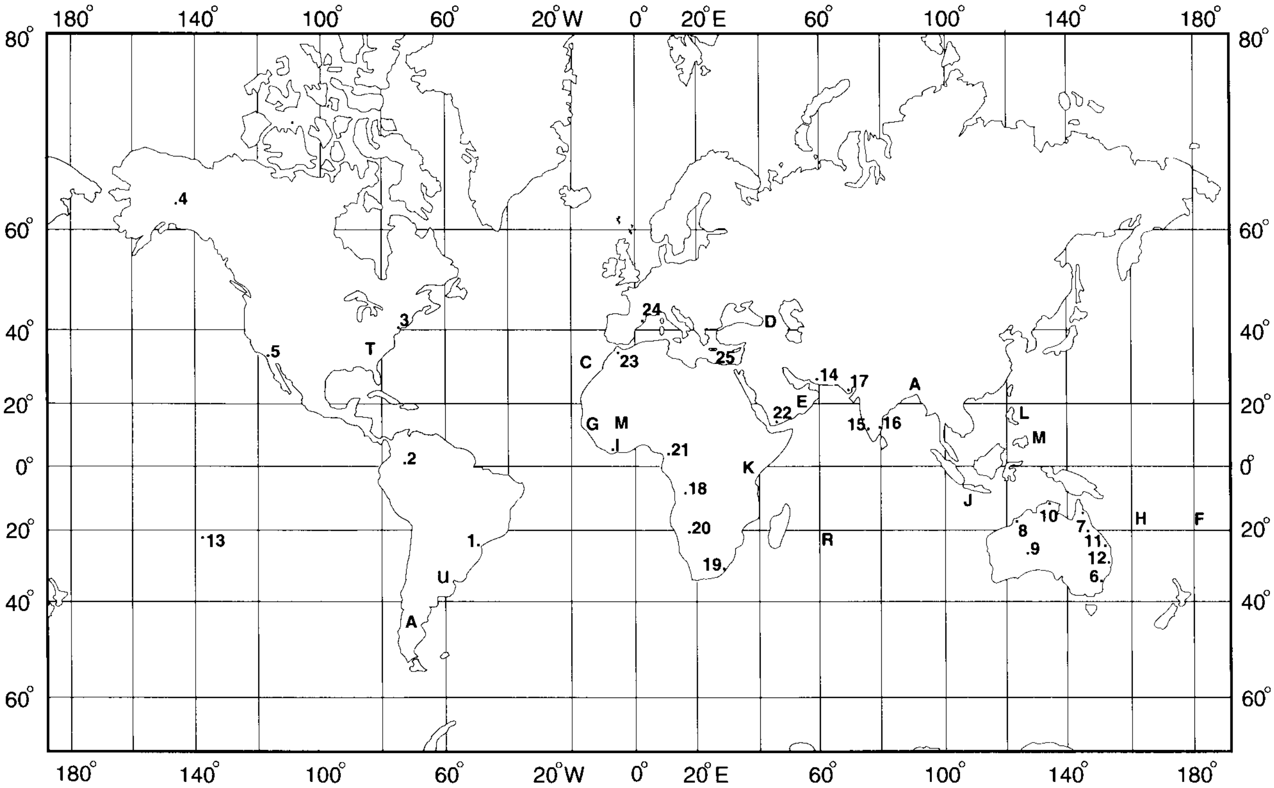
Over the 7th a vigorous depression brought unseasonal cold, heavy rain and winds gusting to 50 kn to Uruguay (U) and Argentina (A): at least 15 are believed to have been killed. There was severe flooding around Buenos Aires as both the Rivers Parana and Plate burst their banks (the latter was at its third highest mark this century). The winds raised big seas and a storm surge caused a lot of coastal flooding and about $50m damage; the port of Mar del Plata was closed until the 10th.

On the 11th, heavy thunderstorms occurred SW of Sao Paolo (1), Brazil, where the town of Parangua had 209 mm in only six hours. Further north in the Colombian capital, Bogota, after a spell of average weather, the night minimum temperature fell to +1 °C; this is 4 °C lower than the previous record.

North America

New York (3) started the month with the passage of a cold front that knocked temperatures down to −13 °C with a near-gale from the north. All things are relative — on the 3rd there were reports that in Fairbanks (4), Alaska, where the AVERAGE for February is −13 °C, the temperature got down to the record low for the month of −50 °C: meanwhile winds of nearly 100 kn had closed the port of Valdez. It must have been cold over Canada as well, because the port of Montreal was badly affected by dangerous ice-jams on the St Lawrence Seaway for the first three weeks of the month.

Los Angeles (5) average rainfall is 66 mm this month; 86 mm fell during the 7th and 8th. However I saw no reports of flooding in California until the 18th. Then a storm deposited around 75 mm on the saturated ground.



Location of places mentioned in text

Some 100 hillside homes had to be abandoned as the ground started to slip, and floodgates were opened at 13 dams which were in danger of being overtopped. It seems that there has been nearly 600 mm of rain in Los Angeles since the storms started in December (the long-term average would be 250 mm but for the last six years it has been 150 mm), their drought is now officially over!

It was much the same story on the 24th when more heavy rain (and 20 cm of snow in the hills) caused two lanes of Interstate Highway 5 to buckle in Los Angeles County; they were to remain closed for the rest of the month. The railway line from L.A. to San Diego was closed as well (until 9th March) by a landslide which included parts of four houses. Meantime over in Arizona the Gila River, almost dry not long ago, had become a raging torrent, spilling over nine dams and threatening to rise higher as mountain snow started to melt. Many bridges over the river were unusable because of the water level. Shallow lakes in the area were rapidly filling and threatening shoreline developments. In all damage reached about $200 m.

Between these last events, on the 21st, there were severe thunderstorms over the eastern State of Tennessee (T) where there were several tornadoes and baseball-size hail.

Australasia

A large tropical depression over Western Australia has provided some newsworthy weather for the start of the month; the south has had blistering heat and the west remarkable rainstorms. The heatwave brought temperatures of up to 42 °C in Sydney (6) on the 4th (this is can be compared with the February average maximum of 26 °C: twelve deaths have been attributed to the heat. On the 5th things were back to normal with a maximum of 26 °C. The lack of reports of drowning elsewhere is surprising. Among the reports received in the first few days of the month were Cooktown (7), north Queensland, 157 mm in 6 hours, part of 255 mm in 48 hours; Lagrange (8), Western Australia, 139 mm in 24 hours; Carnegie (9), central W. Australia, 290 mm in 24 hours; Milingimbi (10), in the north of Northern Territory, capped them all with 304 mm in 24 hours to 0100 on the 5th.

Cyclone 'Oliver' temporarily closed the Port of Hay Point, Mackay (11), Queensland, on the 8th as it passed nearby. Reports of heavy rain kept coming in during the month, one station near Brisbane (12) had 190 mm in 24 hours on 2nd.

Heavy rain does not require a continental land mass to trigger it. The island of Mururoa (13) in the far east of Polynesia, had 412 mm in the four days to the 8th (the monthly average is 130 mm). At times the wind approached 30 kn and visibility reduced to fog limits. This could have been due to the early stages of T/S 'Mick'. Later in the month T/S 'Polly' developed in the New Hebrides (H) and the island of Taro in the neighbouring Solomons got 103 mm on the 24th. A few days later on the 27th, and about 1000 miles east of 'Polly', there were amazing downpours in the Fijian (F) archipelago. Nandi Airport recorded consecutive 6-hourly totals of 22, 93, 90 and 77 mm; the total of 284 mm is practically the average February total.

Asia

Heavy rain at the end of January and the beginning of this month caused much misery in the south-east. Mindanao (M) declared a state of calamity because of the severe flooding in the north of the island after two weeks of heavy rain; about 23 are reported drowned. Jawa (J) has featured much in these notes since they began: again flash flooding and landslides claimed at least 80 lives in the first few days after 'heavy' rain in central and eastern parts of the island. Jakarta collected 250 mm between the 4th and 8th; further east, Tegal on the north coast had 130 mm in 24 hours on the 7th. Parts of Semarang were under 4 ft of water and the airport was closed. Road and rail traffic was severely disrupted and as many as 0.5 million were evacuated to higher ground. In Jakarta traffic was almost at a standstill, and in Kudus and Demak provinces about 5000 had to live on their roofs for three days! Damage runs to at least $23m. At sea 10 were drowned but 79 saved when a vessel foundered in heavy seas.

Further east the island of Timor managed 223 mm in 12 hours to the 14th. On the 2nd there was a sinister development in the south-east of Luzon (L) when the volcano Mount Mayon threatened a major eruption. Initially there were a dozen deaths from falls of red-hot rocks, but then heavy rain mixed with fresh ash to cause 'lahars' killing another 50 or so. A considerable area around was then evacuated and there were eruptions on and off for the rest of the month. The biggest explosion was on the 12th which sent ash 6 km upwards.

Heavy rain at the start of the month brought flooding to much of western Iran by the 8th, with some 150 000 homes damaged or destroyed: 15 000 km of roads were reported washed away along with 1000 bridges and 250 000 head of livestock. The human toll is believed to be about 500 killed, at least 225 of these in Bandar Abbas (14) which was particularly badly hit. Floodwater and avalanches were still causing disruption on the 25th.

Indian subcontinent

High temperatures in the south were the early focus of attention; Colombo, Sri Lanka, started the ball rolling with a new February record of 36.2 °C on the 4th: this was repeated a few days later, and on the 15th 36.6 °C was a new record on the mainland at Coimbatore (15), Kerala. The 16th brought near-record 36s in Gujarat, and 38.8 °C to Nellore on the east coast just north of Madras (16) on the 18th: then the emphasis switched to rain.

In Assam (A) and north-east Bangladesh there was a 'freak' storm on the 19th which produced flash flooding that killed eight and injured 500, destroyed 15 000 homes and made 70 000 homeless. The floods destroyed the main railway bridge link in the area. Storms of this type are more usual in April rather than so early.

Heavy rain fell in south Pakistan on the 24th/25th leading to four deaths around Karachi (17) which was virtually paralysed. The cold front triggering the storm brought maximum temperatures of only 10 °C in its wake. Despite the chaos, the local meteorological service is quoted as describing the 12 mm of rain 'as normal for February' (*I think 'as the normal for the whole of February' was meant*). Bhuj-Ruramata by the Gulf of Kutch had 22 mm in 3 hours (this month's average is 4 mm and a properly wet February day is expected once in 120 YEARS).

Africa

Man's arbitrary division of the year into months is sometimes inconvenient when the weather forgets to recognize them. In Kenya, the weather of January had effects which spilled over into February, as reported by the World Climate Programme of WMO, quoted below.

'The perception among Kenyans that January is a dry month is unfounded. Six months of the year are wetter but, on average, there are five drier months. In the past 48 years there has been zero rainfall at Nairobi on only five occasions. Most of January's rainfall occurs during a couple of wet spells, often thundery, which add up to 50 mm on average at Nairobi. The mountain areas of Kenya are much wetter, for example, Kimakia Forest Station on the Aberdare Mountain Range averages twice the rainfall of Nairobi. Yet Nairobi recorded 237.2 mm in 1993. It rained on 21 days with a maximum of 39.4 mm falling on the 16th. Rain was widespread. Amboseli National Park, a prominent tourist attraction boasting all-weather roads, was closed at the end of the month because of flooding.

'Nothing remotely like this had hit Kenya before except in 1957 when 235.2 mm was recorded, mostly from violent storms during the last ten days of the month.

'A new meteorological record is always of interest and the situation could be described as a 1-in-25-year event. Records are insufficiently long to confirm anecdotal estimations that the event of 1957 was, until this year, unique in the century and about double the next highest January rainfall recorded or remembered.'

Amboseli was still closed during the first week of February.

Heavy rains were still around in this month. notable falls were 100 mm in about 6 hours in Kinshasa (18), Zaire, and Newcastle (19), South Africa, on the 8th. Rundu (20) in north-east Namibia (February average 133 mm) managed 183 mm in the week to the 18th including 77 mm in 3 hours. In the Cameroon, Douala's (21) 99 mm on the 18th easily beat the previous 24-hour record for this month. Two days later just round the Gulf in Ivory Coast, 82 mm in a day was twice the monthly average. Similar wetness affected Zimbabwe on the 21st when thunderstorms dropped about 100 mm on several places in the course of the day.

Temperatures were extraordinary in quite a few places, noteworthy reports include 41.6 °C at Banjul, The Gambia (G), on the 10th, when a light south-easterly helped break the annual extreme record of 40 °C. On the 22nd Tombouctou, Mali (M), had a maximum of 37 °C; then a cold front passed south and next day it only reached 28.5 °C while, 200 miles to the east Gao, got 99 mm of rain in the middle of its dry season. N'Guimi at the north-west end of Lake Chad reached 41.7 °C on the 27th, 1.7 °C above the previous record for this month. South Africa has also had a heatwave, temperatures exceeding 40 °C in several places in the middle of the month.

The Canary islands (C) had a force 7 northerly on the 27th, during which the 1000-tonne *Isla de la Gomera* sank off the Moroccan coast while on passage from Cadiz to Las Palmas: most of the crew of 15 were rescued. On the other side of the continent in St Denis, Réunion island (R), there was some of the type of weather not mentioned in the holiday brochures: 353 mm of rain over the last two days of the month and 606 mm over the last eight days. This was no fluke! Earlier in the month there had been 331 mm in the five days to the 17th (including 173 mm on the 16th): my old reference book gives the February average rainfall as 1400 mm for a gauge nearby.

Europe and Arabia

Severe storms over the Kola Peninsula (K) on the 2nd brought down powerlines near a nuclear power station leading to its temporary shutdown. Large areas of Murmansk were without electricity; trains stopped running and some factories had to close. The same storm raised waves of more than 7 m in the northern North sea, temporarily closing down the oilfields there and driving the mv *Rhino* aground south of Bodø where she stayed fast for several weeks; her crew of eight were rescued by helicopter.

This is the prime month for cold fronts to work their way right down the Arabian Peninsula; the effects can be spectacular round the Gulf, but are usually very short-lived. This year it seems to have been different. On the 1st, Dharan (February average 15 mm) kicked-off with 40 mm in 6 hours. Similarly Bahrain had 24 mm in 12 hours on the 4th, Doha had 18 mm and Khaber, north Saudi Arabia capped them all with 96 mm. Then it was the turn of Emirates (E). Here there had been sandstorms with temperatures up to 30 °C on the 4th, then came the rain with totals of around 75 mm in 36 hours in many places (top of the table was Ras al Khaimah with 129 mm) with temperatures down to about 23 °C: on the 6th, under overcast skies, they were barely reaching 16 °C. Over the period 6th to 9th there were sketchy reports of serious flooding in South Yemen which killed at least ten. In Aden (22), serious damage to homes and 50 cars wrecked was noted. (I spent two years in Aden and have seen the effect of 20 mm of rain in a morning: it would not require much more to have this effect.)

Staying on the boundary of the region, in mid-month a story emerged from Dagestan (D) in the Caucasus (see November weather notes). It seems that winter snowfalls have been of unprecedented length making farming almost impossible, and supplies to populated areas are becoming critical.

At the other extreme of this region, by the Strait of Gibraltar, a levanter was diverted south-westwards by a small low over the Atlas and the forced uplift gave Tetuan (23) 168 mm of rain in four days to the 8th (monthly average is 107 mm); the neighbouring towns of Cueta and Melilla had just over 40 mm each in the same period.

High winds in the North Sea were back in the news on the 21st when winds of near hurricane force, accompanied by heavy snow showers, forced the operators to part an accommodation platform (with nearly 500 aboard) from its oil rig about 10 miles south-east of Aberdeen — the waves threatened to batter the two together. Potentially fatally confusing were problems experienced by the *Nordqueen* and *Norqueen*. The former, a 500-tonne grain carrier suffered engine failure and capsized after its crew of nine had been rescued by helicopter: the latter was in collision with a trawler in a mere force 7. Ill-timed engine failure also caught the 2300-tonne *Linda Buck* off a lee shore and she was driven aground near Terschelling. It was not much safer on land: more than 600 people were evacuated as a precaution as a storm tide, described as of a 'once in decade' height, caused some East Anglian sea defences to collapse. The sea was only one metre below the level of the 1953 catastrophe; in Lowestoft the water reached 2.2 m above the astronomical prediction and jammed the bridge to the inner harbour. In Ostend a 45 metre-high crane was blown down damaging cars and buildings in the vicinity, and dropping a 3-tonne weight through a bedroom, just missing the occupant.

As the cold air swept south, a low formed south of the Alps winding up the mistral. It had been up to storm force on the 19th for a time before dropping away temporarily. Next day, the 21st, it was back full blast with Cap Béar (24, near Perpignan) clocking 68 kn at one stage before easing at midday down to 54 kn gusting 76 kn. Off Palermo the gale broke the moorings of the 2500-tonne *Gidara* and drove her onto the rocks. A few days later, on the 26th, an Aegean force 7 drove a ferry onto a sandbank off the Cycladean island of Sifnos (25).

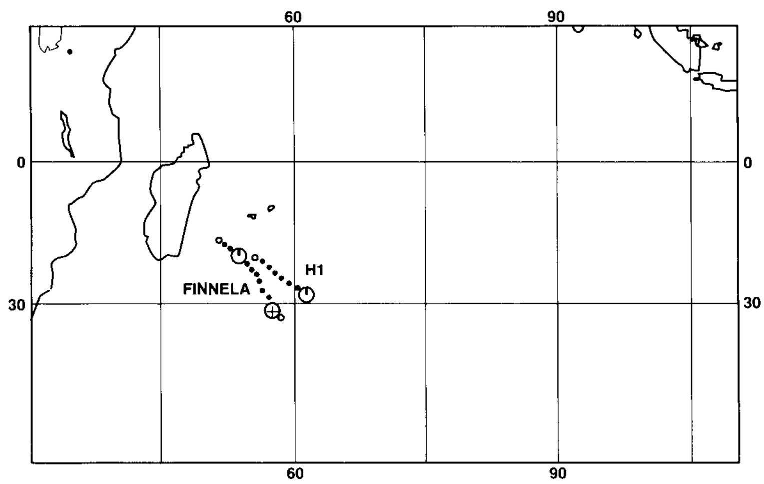
About 20 cm of wet snow fell at Kargaburan in Turkey on the 25th: shortly afterwards the 620 ft LORAN transmitter tower there collapsed.

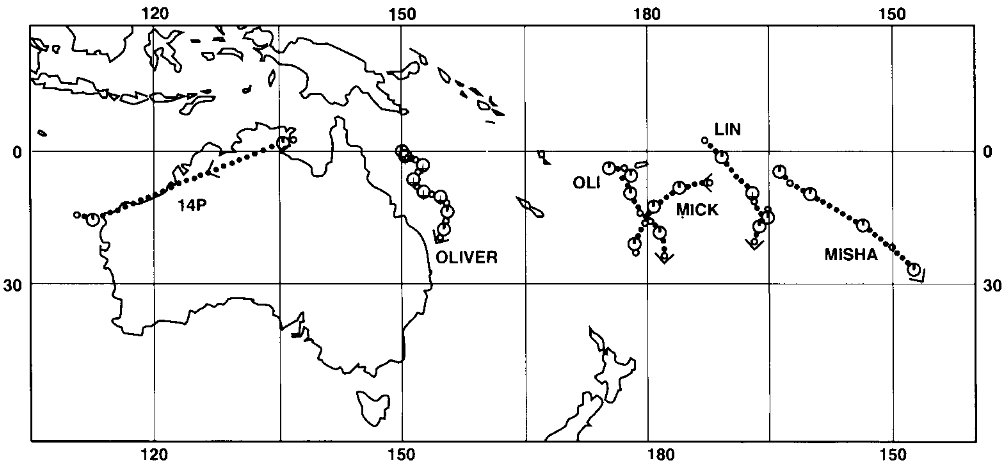
February tropical storms

This is a list of tropical storms, cyclones, typhoons and hurricanes active during February 1993. The dates are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during this month. The maps show 0000 UTC positions: for these I must thank Julian Heming and Susan Coulter of the Data Monitoring group of the Central Forecasting Office.

No	Name	Basin	Start	End	Max. (kn)
1	14P	AUS	26Jan.	7Jan.	35
2	Lin	AUS	31Jan.	4 Feb.	65
3	Oliver	AUS	4 Feb.	12 Feb.	110
4	Mick	AUS	5 Feb.	9 Feb.	45
5	Nisha	AUS	12 Feb.	16 Feb.	60
6	Finella	SWI	13 Feb.	15 Feb.	75
7	Oli	AUS	15 Feb.	18 Feb.	50
8	Gracia	SWI	21 Feb.	23 Feb.	30
9	H1	SWI	24 Feb.	26 Feb.	40

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific; I — Indian Ocean; WI — west Indian Ocean; AUS — Australasia.





Obituary

Martin Morris

After a struggle with cancer Martin Morris passed away on Tuesday 5 January 1993 in Hammersmith Hospital. Since July 1992, Martin had been Head of the Central Forecasting Office (CFO), a newly created post in which he hoped bring his expertise and ideas in forecasting to fruition. Martin was no stranger to the Central Forecasting Office as he had been Assistant Director of Central Forecasting in the five years leading up to Agency — a period when techniques where changing to accommodate the more sophisticated modelling of the atmosphere. Martin developed ideas which assisted the forecasters in the CFO to extract from the model as much information as they could using model diagnostics. Martin felt that the whole of forecasting revolved around the omega equation and insisted that if only the forecasters could understand this they would have the key to success. With this in mind he strove to provide the forecasters with the derived fields of advection and ascent from the model and encouraged them to link these diagnostics with the real world as indicated by real data and especially satellite imagery.

Martin Morris was a forecaster at heart and an ardent ambassador for ensuring that our prestige was well known. When on the Senior Forecaster's roster in the early 1970s, the days of the 10-level model, he would tear the model to pieces when it came up with 'unmitigated rubbish from north to south and east to west'. But on a later posting as Head of the London Weather Centre he was quick to see the value of the numerical model to the rapidly expanding oil industry and he extolled the plus points of the model to those involved.

Born in the West Riding of Yorkshire in March 1937, Martin developed an early interest in Meteorology taking observations while at the Silcotes School near Wakefield. He entered the Meteorological Office in 1954 as an Assistant but while doing his National Service he realized that his ambition to forecast would not be possible unless he went for higher qualifications. With this in mind he obtained his degree in Applied Mathematics at the City University and so entered his scientific career in the Office. Soon after, he was posted to Cyprus and while there he had time to ponder the atmosphere and set about drafting chapters for a possible book. Although the text was never published it formed the vehicle for his thinking in the following years.

He was Assistant Director of Met O 7 (Public Services) for four years following his spell at London Weather Centre. In 1988 he returned to Central Forecasting as Assistant Director. One of his particular achievements during that period of four years was the work he did in making known the success of the Bracknell model in predicting tropical storms. As a direct result of his efforts routine messages are now sent to Guam, Beijing, Melbourne, Pretoria and Mauritius advising them of the model output relating to tropical cyclones in their areas of responsibility. Another achievement during that time was the setting up of a Specialist Group on Weather Forecasting within the Royal Meteorological Society. Martin also used every opportunity to promote the work of the Meteorological Office, giving up valuable time to give talks to groups ranging from after dinner speeches to the informal talk to a group in a local hall.

During his career Martin published several articles and was co-author of a book on climate. His interest in the North Sea oil industry while at London Weather Centre brought him into contact with the E & P Forum, an interest he maintained until his death. This interest in the oil industry resulted in an article in the *Meteorological Magazine* dealing with the accuracy of the wind and wave forecasts issued by London Weather Centre. The advection of warm air on the forward side of an upper trough to the west of Biscay in the summer period always held a fascination for Martin and he wrote an article detailing the 'Spanish Plume', a particular event which brings prolonged rain to parts of Britain. He wrote in connection with the October 1987 storm, an event which absorbed a good deal of his time for months afterwards. His latest passion was the concept of probability forecasting and in an effort to make forecasters more aware of the ideas and value of such forecasts he published a paper in the *Meteorological Magazine*.

After the Meteorological Office became an Agency he moved from Assistant Director of CFO to a new post in Product Development in which he was able to develop new products for the rapidly expanding commercial market. It was during this period that ill health began to dog him despite his healthy lifestyle. He invariably cycled in from Crowthorne (some five miles) each day in his rather striking purple shorts, he played squash, and felt something was missing if he didn't have his daily swim. Indeed he loved sport generally, especially cricket, and he rarely missed a rugby match that was on the television. It was during a swim while in Vancouver for a conference in the Autumn of 1992 that his health took a serious turn for the worse. He managed with great difficulty to deliver his presentation the following day but then returned home and into hospital. With great determination he fought his illness and was even able to visit the Office in late November, but in the end recovery was not to be. Many of his friends and colleagues took part at a Service of Thanksgiving for his life prior to his cremation on 12 January 1993. He is survived by his wife, Barbara, two sons and a daughter.

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe results of research in applied meteorology or the development of practical forecasting techniques.

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Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (IBM-compatible or Apple Macintosh) can be labour-saving, but only a print-out should be submitted in the first instance.

References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

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June 1993

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Forecasting difficulties in showers
The storm of 10 January 1993
World weather news — March 1993
Retirement of Raymond Hide

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The calibration of ERS-1 scatterometer winds

D. Offiler
Meteorological Office, Bracknell

Summary

The European Remote Sensing satellite, ERS-1, was launched by the European Space Agency (ESA) on 17 July 1991. One of its instruments, the Wind Scatterometer, is a radar system from which measurements of near-surface wind vectors can be derived. During the Autumn of 1991, ESA coordinated a campaign of in situ *wind measurements in order to calibrate this instrument. This paper gives a brief description of the campaign, the data resulting from it, and how the* in situ *measurements have been used to improve the quality of the ERS-1 winds.*

1. Introduction

The scatterometer on ERS-1 measures the returned radar power, σ°, using three antennae which form a swath 500 km wide to one side of the satellite's ground track. Winds derived from the three values of σ° per measurement 'cell' have an accuracy requirement of 2 m s^{-1} or 10% (whichever is higher) in wind speed and 20° in direction. An empirical relationship between surface wind vector and σ° ('CMOD2') was established prior to launch (Long 1986) using aircraft scatterometers. This relationship — or 'model' — needed to be validated for the satellite instrument, and if necessary, modified for operational use to meet the stated accuracy. Offiler (1987) gives an overview of the scatterometer operation and the derivation of winds using such a model.

During the period 16 September to 10 December 1991, ESA coordinated a campaign to calibrate the geophysical wind and wave products derived from the ERS-1 satellite (the calibration of 'engineering' quantities, such as σ°, being a separate issue). The campaign, known as RENE-91, involved making *in situ* measurements off the coast of Norway using a variety of platforms, i.e. buoys, ships and aircraft, with participants from several European countries. For part of the campaign period, the Meteorological Research Flight C-130 (Hercules) aircraft was based in Trondheim — the campaign's operations centre — measuring low-level winds over the campaign area at times when the ERS-1 scatterometer was also operating. A German Dornier Do-228 aircraft similarly measured winds using its normal navigation system; it also carried a radar scatterometer so that the back-scatter measurements could be compared with those from ERS-1.

Data from most of the platforms participating in the campaign, together with NWP analyses made by the Norwegian Meteorological Institute (DNMI) and ERS-1 wind and wave products were delivered to a local data-base, generally within 24 hours of their measurement time. This database was used to form a 'best-estimate' wind field covering the campaign area which could be used to (a) compare with the ERS-1 winds for day-to-day quality monitoring during the campaign, (b) form a high-quality data set which could be used for calibrating or tuning the scatterometer wind model and retrieval algorithms, and (c) validate such tuning.

2. Wind measurement from the C-130

Depending on the needs of particular experiments, the C-130 can carry a wide range of instruments for measuring various atmospheric parameters, including chemistry, radiation (infrared and microwave) and clouds (Readings

1985). For winds, only the standard sensors are required; principally the Inertial Navigation System (INS), giving the aircraft's position, ground velocity and heading from true north and dynamic pressure for air speed. Other navigation aids (in particular GPS) are used during ground processing to correct the INS in order to obtain the best aircraft ground velocities; the air temperature and static pressure are also used to correct for true air speed. The wind speed and direction is then the vector difference of ground and air velocities, with an expected r.m.s. accuracy of about 0.5 m s^{-1} and 5° (Axford 1968).

The scatterometer-derived wind speeds are specified to be those equivalent to a measurement at a height of 10 metres in a neutrally stable atmosphere (a quantity known as U_{10}). In order to compare and calibrate the scatterometer winds, all the *in situ* measurements need to be to the same standard. The C-130 flight level winds were therefore converted to U_{10} using an agreed boundary layer model, using flight-level wind speed, temperature, humidity and static pressure, radiometric sea-surface temperature, radar altitude and temperature lapse rate (the latter determined by profiling in the lowest 1 km of the atmosphere).

While ERS-1 was in its initial 3-day repeat orbit, scatterometer passes were scheduled to give good coverage of the campaign area three times every three days. The C-130 flew missions on two of these opportunities in each 3-day cycle — the southbound pass at around 1050 UTC on the first day of the cycle, and the 1015 UTC southbound pass on the second day. Each flight pattern covered the width of the swath and about 500 km along it. Fig. 1 gives an example flight track and the derived winds for a 'Day 1' pattern. The nominal flight altitude was 200–250 ft (60–80 m), with a profile between 3000 ft (915 m) and 50 ft (15 m) at each corner of the pattern, and passing over at least two buoys for cross-comparisons. A typical flight duration was around 6 hours, so there is obviously a time difference between

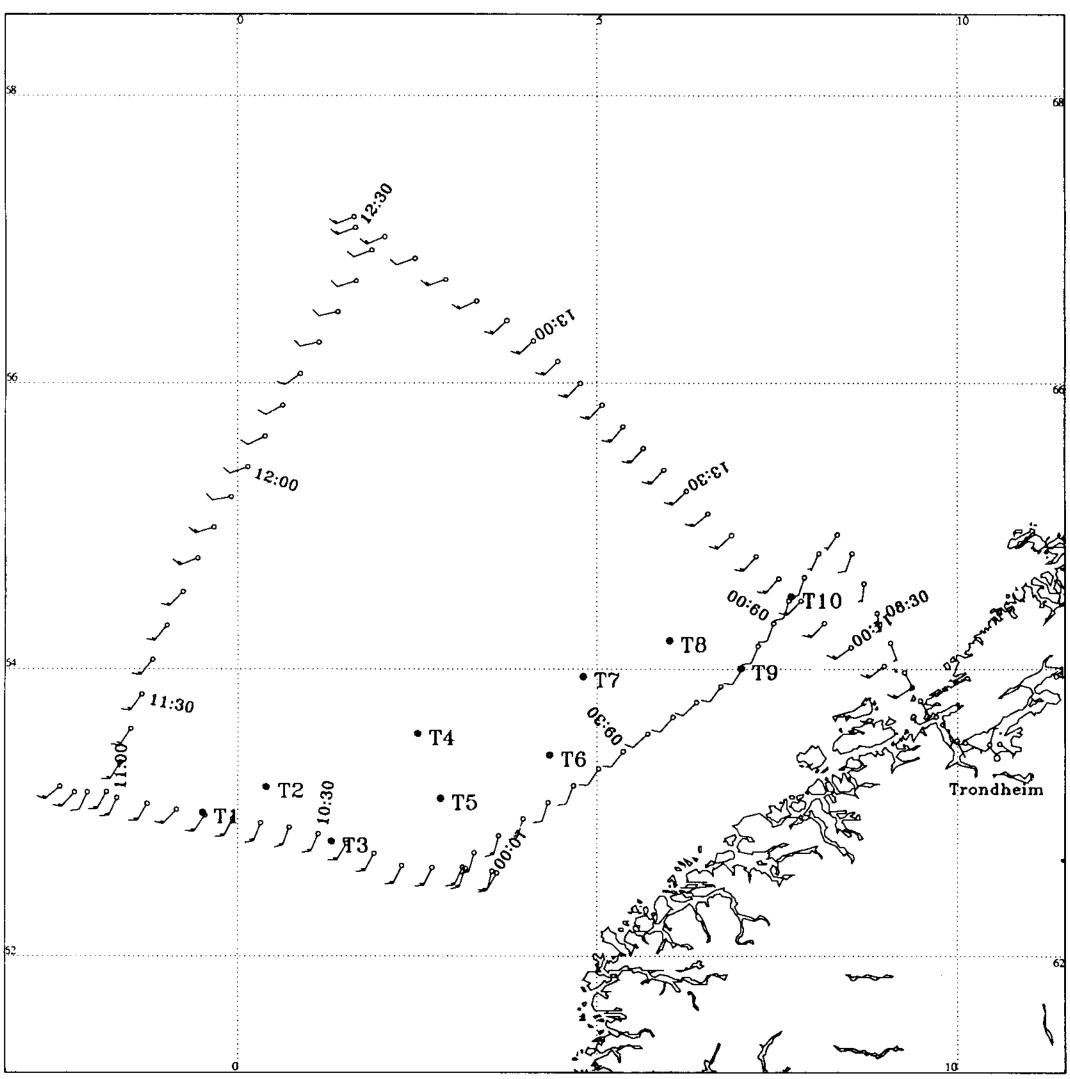

Figure 1. Example C-130 flight track and derived 10 m winds for 0800–1425 UTC on 2 December 1991. The wind symbols are plotted conventionally, with each full feather representing 10 m s^{-1}. The location of the Tobis buoys are labelled T1 to T10.

the some of the aircraft and scatterometer measurements; the flight was planned so that the C-130 would be over the buoy position T1 at the time of the ERS-1 overpass. On the 'day 2' passes, the swath was closer to the coast and further north; on these flights, the rendezvous point was T10, travelling up-swath. All tracks were flown in a clockwise direction.

A total of 18 flights were made when good data were obtained; on two flights, the INS drifted badly and, although the aircraft position could be recovered with the GPS, the aircraft velocities could not be derived with sufficient accuracy to obtain good winds. Only one planned mission was lost, due to an engine problem, and a total of more than 100 hours were flown by the C-130 during the campaign. The final data from each flight were delivered to the local database in Trondheim, in a common format, the day following a flight.

3. Wind analyses

When comparing meteorological satellite data with *in situ* measurements, it has been traditional to use one of two methods:

(a) collocate one *in situ* measurement with one or more nearest satellite points and within some time limit, on an essentially one-for-one basis. This has the disadvantage of introducing collocation errors because of spatial or time differences, and also not comparing like with like, since the *in situ* measurement is usually taken at a point over a time average, and the satellite is an areal average at an instant in time. Such collocations tend to be few in number and rarely cover the whole range of desired parameters.

(b) assimilating the *in situ* data into NWP models and interpolating the required parameter from the analysis grid to the satellite footprint location. However, such models tend to have rather coarse horizontal resolution compared with the satellite, and are generally tuned to the synoptic scale, which tends to smear out or miss small-scale features which might be represented in the satellite swath. The data also need to be available very quickly so they can be used in these operational models.

In the case of the RENE-91 campaign, the *in situ* data, although gathered quickly by campaign standards, could not be delivered to weather centres in time for their numerical models' operational runs. Instead, the RENE-91 winds and DNMI background fields were analysed using a simplified scheme, developed by the Meteorological Office, which could be run on a workstation at the operations centre. A 25 km grid size was chosen as comparable with the scatterometer cell spacing, with the grid covering the campaign area. Because all the RENE-91 data sets were supplied in a common format, wind from all available sources could easily be incorporated into the analysis; the actual sources and quantities varied from day to day, but the following have been used in at least one analysis:

Aircraft — C-130, Do-228,
Radar — Radar Airborne C-band System (RACS) on Do-228,
Buoys — up to 6 of the 10 Tobis-3 buoys,
Ships — Weathership Mike, R/V Gauss, Håkon Mosby,
Platforms — Gullfax,
Models — DNMI wind-field analyses.

All of these contain U_{10} wind speeds or have measurements made close to 10 m; each data source is complementary in that they are made at many different locations over the analysis area and by different sensor and sampling systems. Of course, not all sources were available for every scatterometer pass.

Fig. 2 shows an example of data coverage for one analysis. In this case, the C-130 track from Fig. 1 is plotted, as is the Do-228 track though the centre of the C-130 loop. The latter actually contains RACS-derived winds outbound and Do-228 winds — extracted from their navigation system when flying at low level — on the return. This case also uses data from three Tobis buoys, Weathership Mike (just below the northernmost part of the C-130 track) and the Gullfax platform to the south; the grid of wind symbols is from the midday DNMI NWP analysis. The analysis scheme also calculates a 'quality index', QI; this parameter is related to the local quality, quantity and consistency of the original measurements, and to the time difference from the satellite overpass.

The advantages of this analysis method are that it maximizes the number of collocations, particularly by covering the whole width of the swath and it minimizes the effects of systematic errors in any one platform or poor individual observations. Also, the spatial average is more comparable to a scatterometer measurement, although there will still be a tendency to smooth very-small-scale features or sharp gradients over one or two grid lengths, or when there are rapid changes with time.

The analysed winds then are interpolated from the grid to each of the scatterometer cell locations; Fig. 3 shows the RENE-91 gridded analysis made from the data in Fig. 2, together with the ERS-1 winds. The contour is a threshold QI value, inside which the analysis is almost entirely derived from the *in situ* measurements, and outside which it is influenced only by the DNMI background wind field. Over most of the swath, the scatterometer shows good agreement with the analysis except in the north-west part of the contour, where there are differences in wind direction of 20–30°; this is probably due to an active front passing through the area between the time of the satellite pass and the C-130 track 1–2 hours later. The frontal position can be identified from the wind direction changes in Fig. 1 along the north-east- and south-east-bound C-130 legs.

A total of 81 scatterometer passes were processed, with analyses made using the technique described here, creating nearly 22 000 individual (but not totally independent) collocations within the QI threshold contour. Not all of these passes have good coverage of *in situ* data or have DNMI backgrounds available, but the QI value is a good filter for poorly covered cases. Some passes, like the example shown, have frontal systems which may give rise to 'errors' in the analyses — these may need to be excluded by inspection of the data and by consulting the corresponding synoptic charts before being used for calibration purposes. These collocation files have also been delivered to the ERS-1 database for use in model tuning by other groups.

These analyses cover the wind speed range 1–21 m s^{-1} with directions mainly from the south-west to the north; but as the passes are both northbound and southbound the wind directions relative to the satellite are spread more uniformly. Taken over the whole data set, the r.m.s. differences between the scatterometer winds and analysed winds are 2.7 m s^{-1} in speed and 21° in direction. This shows that against the RENE-91 analyses, the ERS-1 wind directions are generally acceptable, but the wind-speed retrieval from the then operational wind model (CMOD2) required tuning if the scatterometer specification of 2 m s^{-1} was to be met.

4. Wind model tuning

Although the global, near real-time scatterometer winds derived using the prelaunch model, CMOD2, compared favourably with conventional synoptic observations from ships and buoys, some deficiencies were clear, and ESA felt that the product was capable of improvement. Several groups, some involved in the RENE-91 campaign, have used different sources of wind data either to tune the CMOD2 empirical relationship or to define a new one. These groups include ESA themselves, the European Centre for Medium-range Weather Forecasts (ECMWF), the French Meteorological Office (Meteo-France), the French oceanographic institute (IFREMER) and the Universities of Hamburg and Oregon; the wind data used have included the RENE-91 collocations described above, sub-sets of the RENE-91 *in situ* measurements, deep-water NOAA buoys and NWP models. Most of this work is reported in Wooding (1992).

Since launch, the Meteorological Office has reprocessed the near real-time σ° values to winds (using our own algorithms) in order to make use of our NWP wind fields in the ambiguity removal processing (Offiler

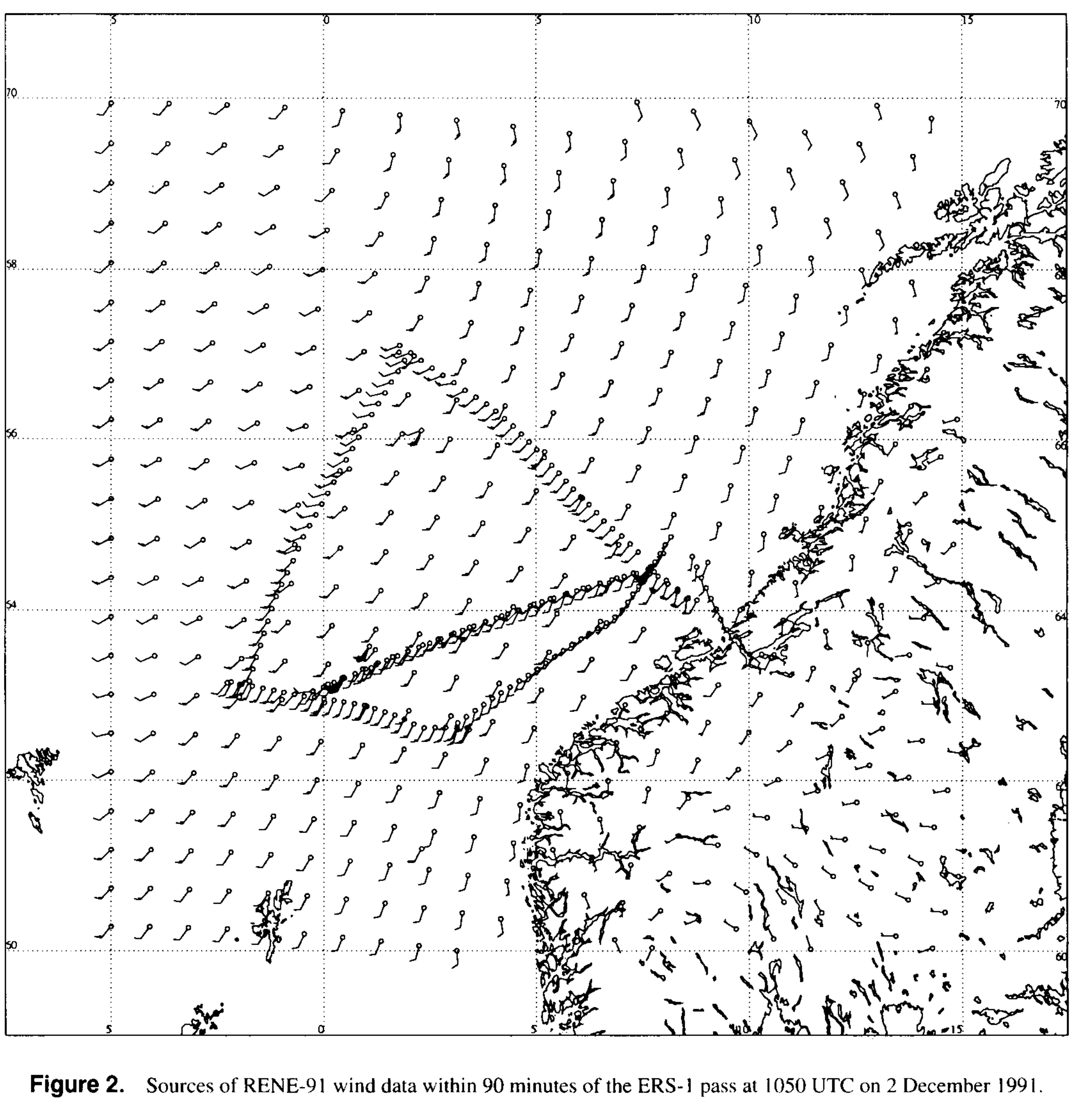

Figure 2. Sources of RENE-91 wind data within 90 minutes of the ERS-1 pass at 1050 UTC on 2 December 1991.

1987). We could therefore use this scheme off-line to reprocess the RENE-91 σ° data, substituting any of the candidate models developed by the other groups. The performances of these models were judged by comparing the quality of the wind vector retrievals against the analysed RENE-91 campaign winds, sub-divided by (for example) wind speed or cell position across the swath. Parameters included the mean and standard deviation of differences in wind speed and direction and r.m.s. vector differences when compared with the RENE-91 analyses. The models were also validated using global, near real-time data, with a comparison against our NWP fields.

ESA were keen to improve their operational wind product, so each group sent their initial candidate model to the Meteorological Office for evaluation during March 1992; results were returned to all participants, including the ESA calibration managers, and were discussed at a geophysical calibration workshop, held in April (Wooding 1992). Most of these candidate models improved upon CMOD2, and a short-list was drawn up; the workshop recommended the model provided by ECMWF, and this was implemented as 'CMOD3' by ESA for operational processing since June 1992.

However, between the model tuning exercise, and the implementation of the new model, ESA had independently updated the engineering calibration of the σ° values — the major effect being the introduction of a 1 m s^{-1} low bias on the retrieved wind speeds. There were still problems in retrieving wind directions on the inner edge of the swath, so the tuning and model validation exercise was repeated using the latest calibration standards. This has recently been completed and we have recommended to ESA that a modified version of the original ECMWF formulation offers the best performance improvement of the latest set of candidates. The bias has now been removed, and wind directions are significantly better on the inner edge. ESA implemented this model as CMOD4 in February 1993, and it is likely that this model will then remain in place for the remaining lifetime of the satellite. Table I summarizes the performances of the old (CMOD2), intermediate (CMOD3) and new (CMOD4) models in terms of differences from the RENE-91 analyses, and Table II similarly for an extended validation against operational NWP fields. These results clearly show the overall improvements obtained by tuning the wind vector–σ° relationship.

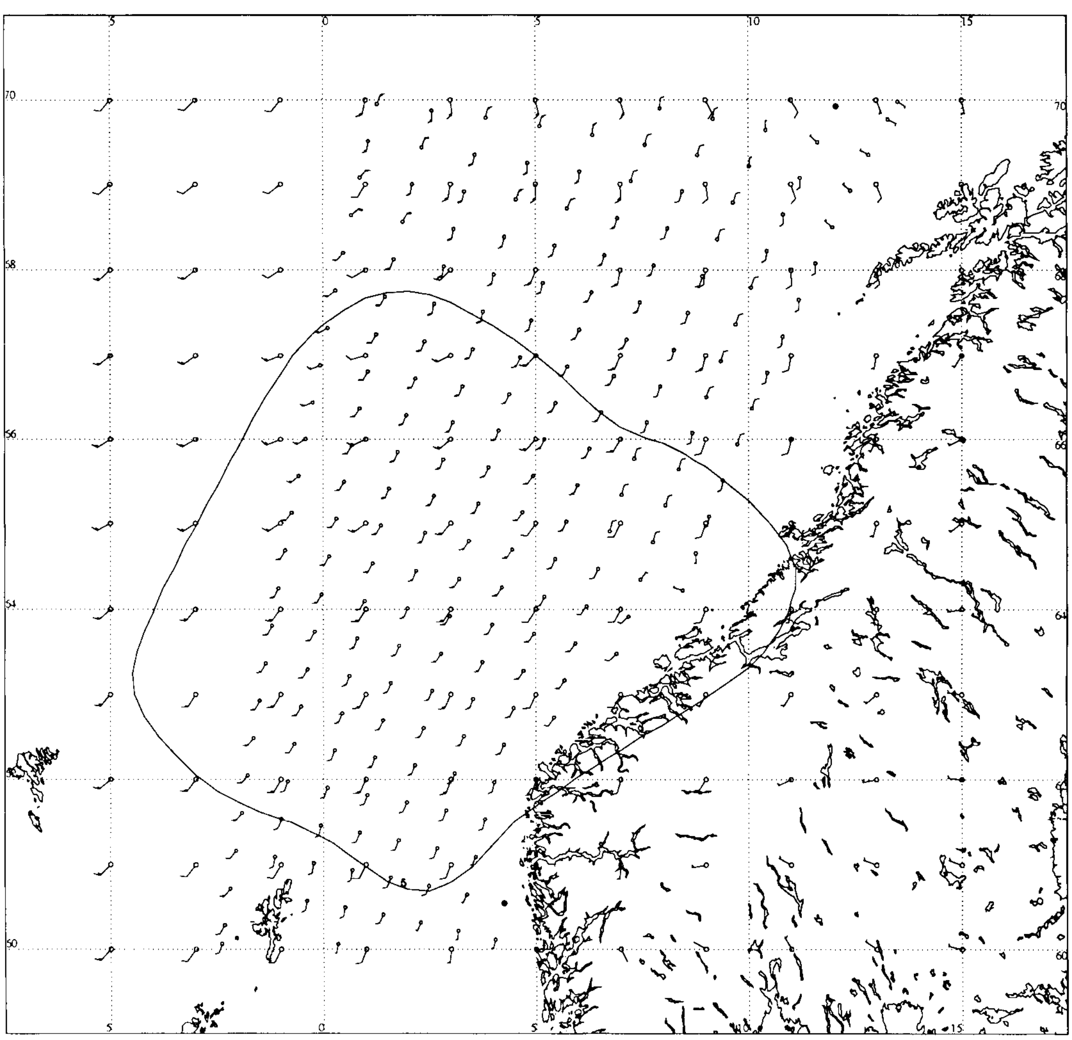

Figure 3. Collocated scatterometer and RENE-91 analysed winds from Fig. 2.

Table I. Summary of a comparison of ERS-1 winds against RENE-91analyses. (These statistics exclude winds < 4 m s^{-1}.)

Model identification	No. of cells	Speed (m s^{-1}) Bias	SD	Direction (°) Bias	SD	Vector (m s^{-1}) R.M.S.
CMOD2	18898	−1.4	2.8	−2.3	20.2	3.9
CMOD3	18898	−1.0	2.0	−1.2	17.5	3.3
CMOD4	18898	0.1	1.9	−1.6	17.2	3.2

Table II. Summary of a comparison of ERS-1 winds against Meteorological Office global NWP analyses 15–30 March 1992 (14 October–4 November 1992 for CMOD4).

Model identification	No. of cells	Speed (m s^{-1}) Bias	SD	Direction (°) Bias	SD	Vector (m s^{-1}) R.M.S.
CMOD2	820374	−1.3	2.6	1.4	22.7	4.1
CMOD3	820374	−0.9	2.2	1.1	21.1	4.0
CMOD4	1437910	0.0	2.1	1.2	20.9	3.6

5. Conclusions

The RENE-91 campaign has provided a high-quality set of wind measurements from aircraft, ships and buoys, which have enabled us to construct analysis fields covering a three-month period. We believe these fields to be the best available estimate of the true wind which can be used to compare with those from the ERS-1 satellite, albeit limited in area and lacking in the higher wind speeds. These and other data sources have been used by other groups to 'tune' the empirical relationship between the near-surface wind vector and satellite radar backscatter measurements.

We have independently evaluated several candidate models by using a common retrieval scheme and on the same data (the RENE-91 collocated scatterometer measurements and analyses). One of the interim models was recommended to ESA, and replaced the prelaunch model in their operational 'fast delivery' products from June 1992. Further tuning by the groups involved has resulted in a new model with significantly better performance, and ESA have been using this model since February 1993.

In the future, small improvements (by modifying the empirical functional form and/or tuning the model's coefficients) may be possible, but these will probably not be worthwhile implementing in ESA's operational system. Effort is now turning to improve the complete wind retrieval scheme and ambiguity removal algorithms — originally developed some years ago — to reflect the characteristics of the new model. For instance, in prelaunch simulations, the CMOD2 model, based on aircraft σ° data, was able to discriminate upwind–down wind ambiguities in most cases. In practice, the differences in the satellite-measured values of σ° are much smaller, making successful ambiguity removal more dependent on some prior knowledge of the general wind direction — as is already the case in the Meteorological Office's scheme. Looking even further into the future, the use of 'neural nets' — which may be able to learn how to relate the σ° measurement directly to a single wind vector — might be able to provide a means of bypassing the need for a fixed, explicit model.

Acknowledgements

My thanks are extended to all the participants in the RENE-91 campaign for providing their data so quickly and allowing it to be used in this validation experiment. Thanks also to my colleagues who supplied their model formulations and updates to coefficients to meet the deadlines placed upon this study.

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Forecasting difficulties in showery situations

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Summary

The problems encountered by forecasters when they use numerical weather forecasts to predict the occurrence of showers are discussed. Forecasts from the Meteorological Office's Limited Area Model for a thundery day in June 1992 are used to illustrate the problems.

1. Introduction

Throughout the evolution of Numerical Weather Prediction models, there has been much emphasis laid on the importance of the 'man–machine mix' in the forecasting process. The numerical models may be expected to provide pointers to the general atmospheric developments and a guide to likely distributions of the various weather elements, whilst the forecaster can use his experiences of the behaviour of the atmosphere and of the numerical models to fine-tune the model forecasts.

Forecasters may take into account errors in the model's analyses (the starting points for the forecasts), which can be identified when the analyses are compared with the human interpretation of the data. These errors could be carried forward into the forecast, thereby reducing the value of the model products. The forecaster may also know about deficiencies in the model's guidance in the given type of weather situation, such deficiencies having been identified over an extended period of use of the model. In addition, forecasters need to use their understanding of the atmospheric processes to assess the overall value of the model's forecasts.

The man–machine mix has a number of steps. The forecaster at the main or central forecast centre evaluates the model products in a broad sense, taking into account likely global developments and their impact on the weather pattern over the country as a whole. He provides overall guidance on the interpretation of the model products for the other forecasters around the country. The forecasters at the regional and local centres use the overall guidelines to interpret the model results for their parts of the country, adding their local knowledge, to provide the detailed forecasts required by their clients. The man–machine mix works well when the forecast model provides a good overview and is an acceptable starting point for the fine-tuning of the output by the forecaster. When, however, the forecaster has only a low confidence in the details, as frequently happens when deep convection is expected, the forecaster makes the major or perhaps the total input to the collective result.

2. The man–machine mix in showery situations

Although the mechanisms that can lead to the development of convection are well known, their scales and complexities have made them difficult to quantify both for the human forecaster and by the numerical models. Small changes in the details of the weather elements involved in the convective processes, such as the humidity through the atmosphere or the shape of the upper-level flow, even in the surface wind such as at sea-breeze fronts, can make large differences to the extent or distribution of the convection. The processes are often on a scale below that of the numerical models. As a result, most numerical models can provide relatively little guidance for the forecaster, beyond perhaps identifying that convection is likely and the more favoured locations or times for it to occur. The forecasters, in turn, appreciating the problems inherent in forecasting convection, have to make subjective judgements about the value of this limited model guidance, and try to add value to the forecast based on their knowledge and experience.

When guidance from the models is consistent, a more confident forecast will result. If, however, the solutions shown by the models vary, either from one model to another or between successive runs of the same model, then decisions on accepting the model guidance are more difficult, and confidence in the forecast is lower than when the model output is consistent. In the example given below, the difficulties of interpreting very variable model forecasts in a convective situation are highlighted. It is not the intention to try to identify general model inadequacies in convective situations.

3. An example of a convective situation on 29 June 1992

A good example of the thundery breakdown of a short fine spell, a situation often encountered during the summer months, occurred on 29 June 1992. The surface and upper-air analyses at 1200 UTC on 29 June are shown in Figs 1 and 2. The forecasts were based on the Meteorological Office's Limited Area Model (LAM) which gave a particularly variable sequence of forecasts of the rainfall. By midday the thundery breakdown had started. A cold front across northern Scotland had been slow moving for several days, giving a good deal of rain in that region. Further south, a high centre, which had been over the United Kingdom the day before, had been eroded and displaced to the east, as pressure falls

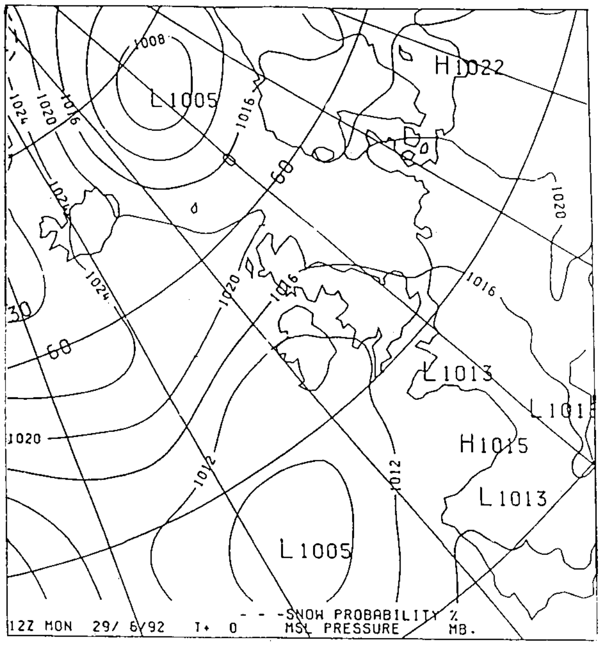

Figure 1. Surface analysis for 1200 UTC on 29 June 1992.

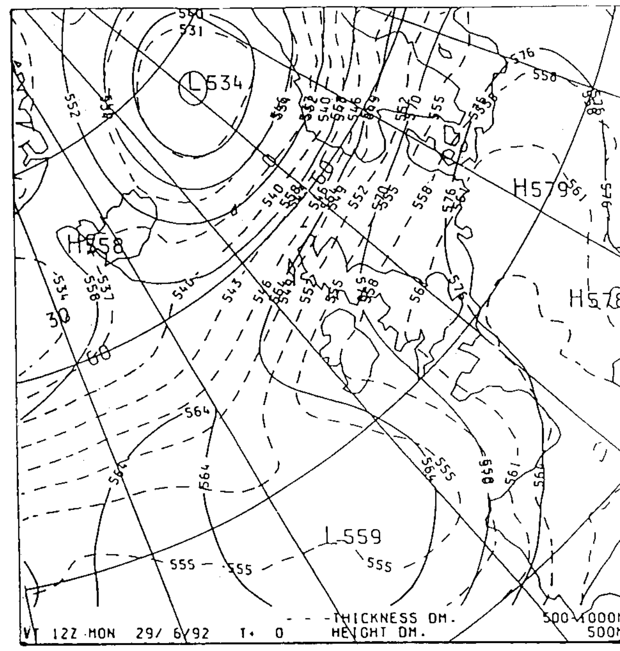

Figure 2. Upper-air analysis for 1200 UTC on 29 June 1992 showing fields of 1000–500 hPa thickness and 500 hPa contours (both measured in dam).

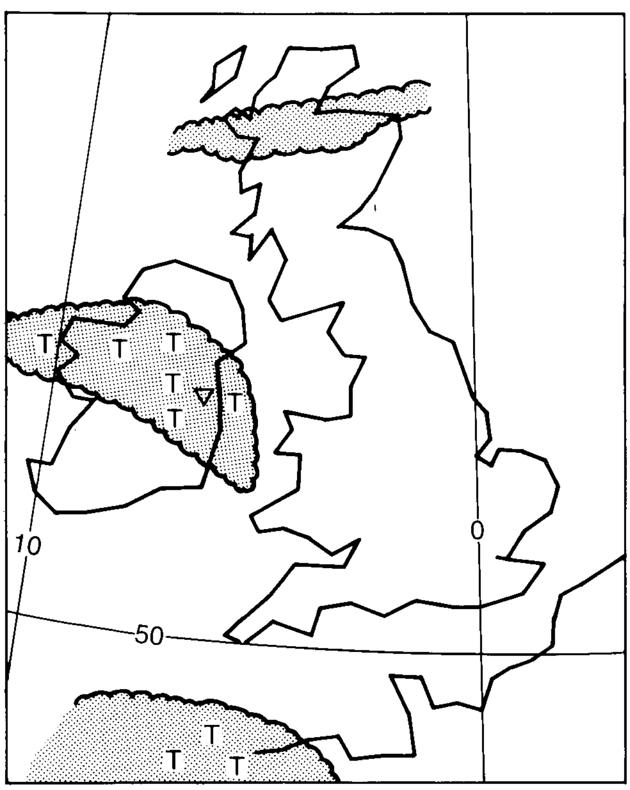

Figure 3. Sketch map showing areas of rain at 1200 UTC on 29 June 1992. T represents reports of thunder.

occurred ahead of the advancing upper vortex to the west of the Bay of Biscay. A preliminary band of thundery showers had moved north from the Biscay area and was over Ireland at that time, whilst a further band of thundery rain was moving north from north-west France. The areas of significant weather over the United Kingdom at 1200 UTC on 29 June are shown in Fig. 3.

It is of interest to review the forecasts from the LAM valid at this time, to show the problem that the model has in ascribing correct details to an overall correct solution, and as a corollory to highlight the problem for the forecaster, who normally would expect to use the model products as the basis for the forecast.

The LAM forecasts of surface pressure and rainfall for 1200 UTC on 29 June 1992, with lead times decreasing from 36 hours to 6 hours, are presented in Fig. 4. It can be seen that the model provided good forecasts of the pressure field over and around the United Kingdom at that time, when compared with the analysis in Fig. 1.

The 36-hour forecast upper-air pattern for 1200 UTC on 29 June, shown in Fig. 5, is also similar to the actual analysis, see Fig. 2. However, some errors in the shape of the trough to the south-west of the United Kingdom may be discerned, whilst the forecast thermal contrast across the United Kingdom is weaker than in reality, especially close to the cold front over Scotland.

A comparison of the T+36 forecast of the 850 hPa wet-bulb potential temperatures close to the United Kingdom valid at 1200 UTC on 29 June (Fig. 6) with the analysis of the same field (Fig. 7) again reveals close agreement in general terms.

The shorter-term forecasts of these parameters were similar. Thus it may be reasonably suggested that the LAM was providing good overall guidance of the likely atmospheric structure, even 36 hours ahead of the event.

In terms of the forecast precipitation patterns (Fig. 4), the result is much less satisfactory, with significant changes in the distribution between successive forecasts

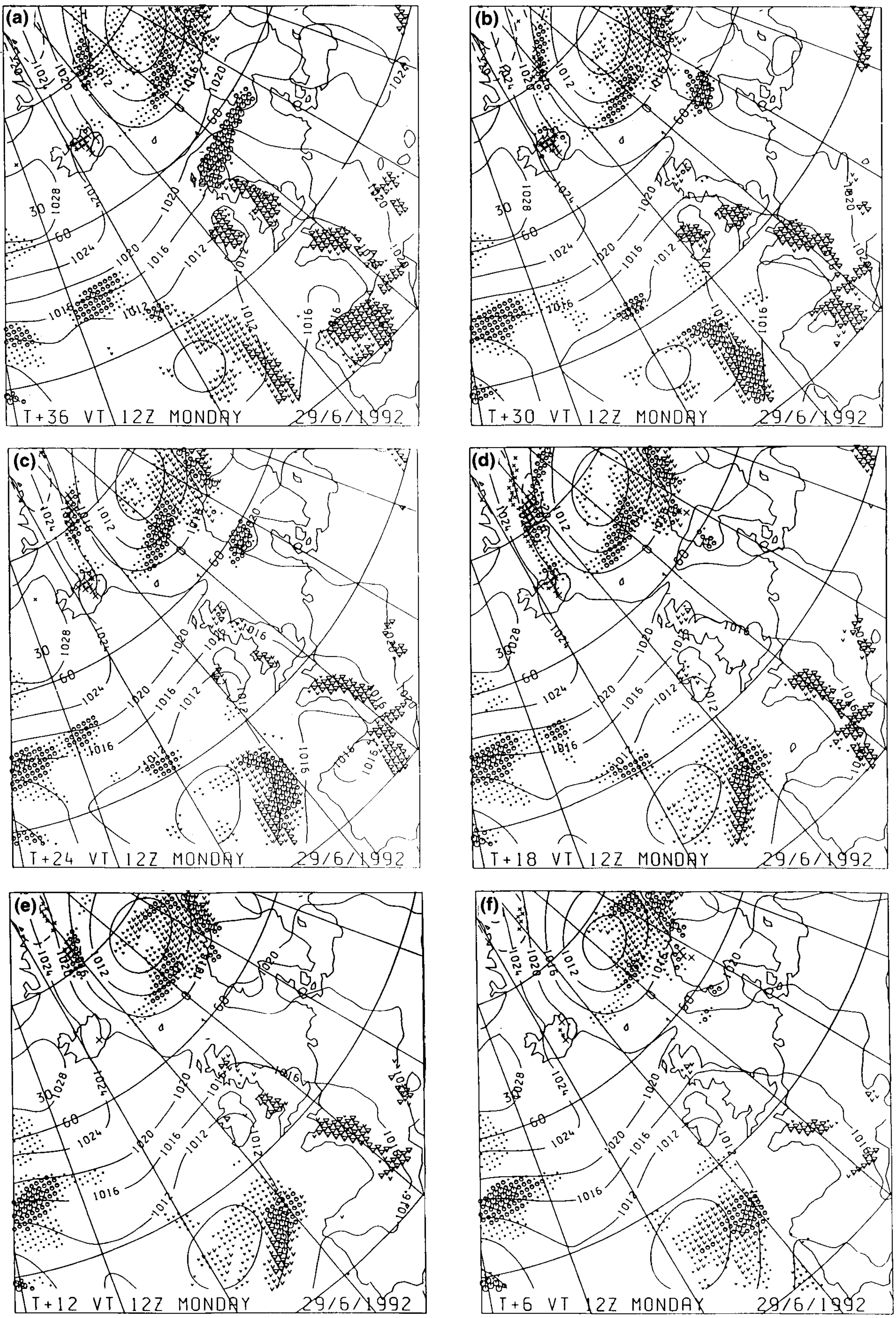

Figure 4. Limited area model forecast of surface pressure and rainfall valid for 1200 UTC on 29 June 1992, with forecast lead-times decreasing from 36 hours (a) to 6 hours (f) in 6-hourly steps.

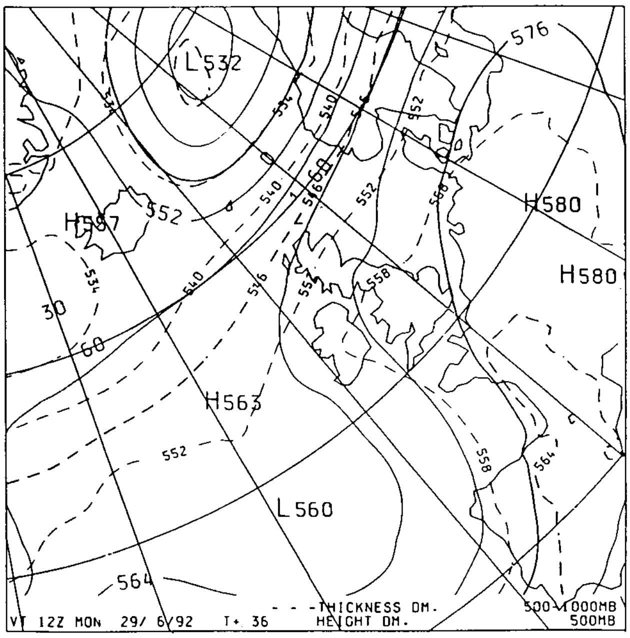

Figure 5. Limited area model 36-hour upper-air forecast valid for 1200 UTC on 29 June 1992.

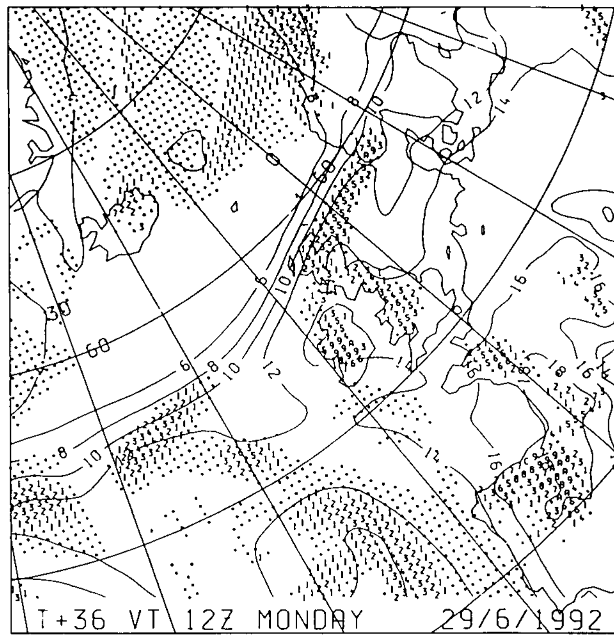

Figure 6. Limited area model 36-hour forecast of field of 850 hPa wet-bulb potential temperatures valid at 1200 UTC on 29 June 1992.

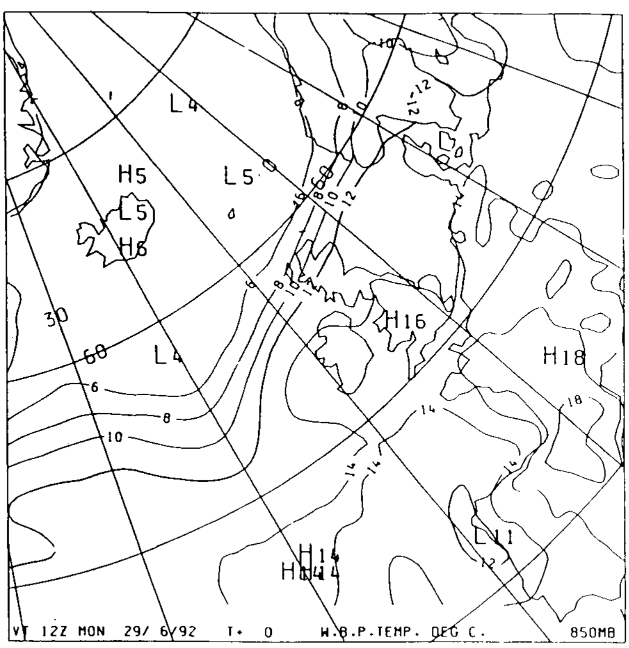

Figure 7. Analysed field of the 850 hPa wet-bulb potential temperature at 1200 UTC on 29 June 1992.

and a low correlation with what actually occurred, as shown in Fig. 3.

3. Discussion of the problem

One of the problems for the forecaster is that taken in isolation, each forecast appears to have merit, if the fine points of the upper patterns, the humidity profiles, surface pressure or other fields produced by the model are accepted. Reasons for the distribution of convection shown by the model may be formulated, perhaps in terms of dynamical and local forcing factors. However, when successive model runs giving markedly different rainfall fields are considered, it becomes increasingly difficult to ascribe convincing arguments to support the model solutions, as each run may suggest different forcing mechanisms. These runs are likely to show significant local differences in the details of the key parameters from run to run.

For example, the forecast upper pattern shown in Fig. 5 has some very minor troughs in the flow, such as the one just to the east of Scotland. Later forecasts, despite showing the same overall shape, did not feature the same minor troughs. The presence or otherwise of these is likely to have had an impact on the forecast shower distribution. Until the lead-time is relatively short, perhaps 12 hours or less, when the forecaster may be able to identify such minor troughs from satellite cloud images, it is very difficult to know whether the troughs should be believed.

Another parameter which has a vital impact on the distribution of the showers is the vertical humidity profile. It is well known that this can vary a good deal over small distances and short time-periods when the weather is showery. There are also large spatial variations in the vertical humidity profile in model forecast fields and these appear to vary significantly from one model forecast to another for the same validity time and place. Indeed, differences in the forecast humidity fields for particular locations between the forecast runs probably had the greatest impact of all possible factors, in leading to the differences in the rainfall forecasts in Fig. 4. Given the relative sparseness of reports of the humidity profile, it is difficult to know what the correct spatial or temporal variation of the parameter should be, and hence to know

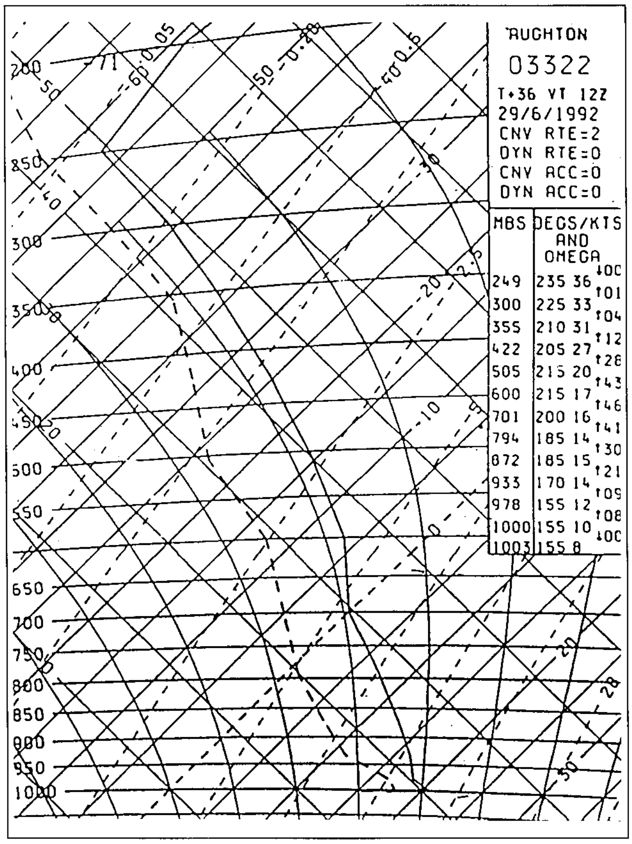

Figure 8. Limited area model forecast tephigram for Aughton, north-west England, valid at 1200 UTC on 29 June 1992.

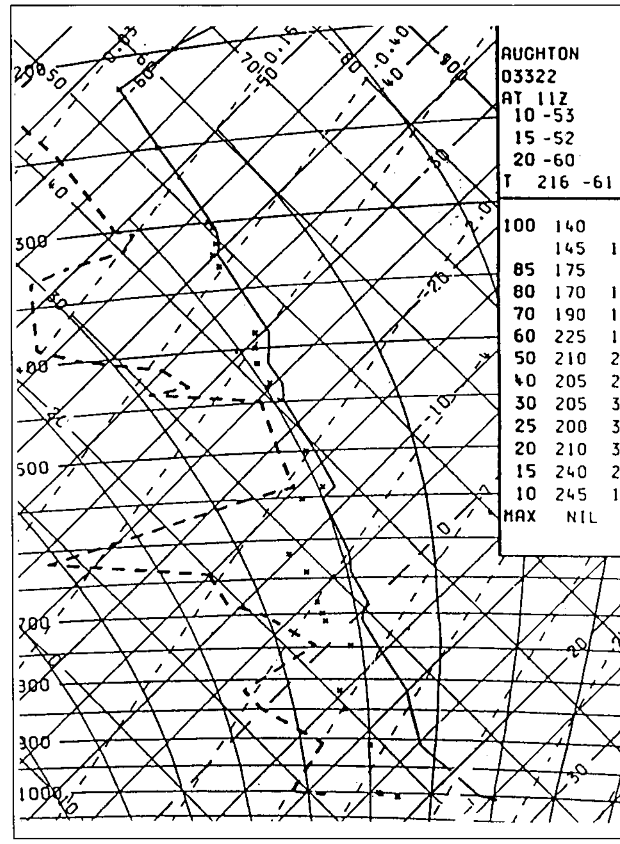

Figure 9. Actual tephigram for Aughton at 1200 UTC on 29 June 1992.

if the model's solution is helpful. Again satellite images can provide useful pointers to the distribution of moisture, but not until close to the time of the event. Radar is also a powerful tool in this respect, but again is only useful for adjusting the forecast at very short lead times.

An example of the importance of errors in the model's forecast vertical fields can be seen by comparing the forecast and actual tephigrams for Aughton, in north-west England, which was in an region of deep convection on the 36-hour forecast rainfall field (Fig. 4(a)). Comparing the 36-hour forecast tephigram for Aughton (Fig. 8), with the actual ascent for Aughton at about 1200 UTC on 29 June 1992, shown in Fig. 9, it may be seen that the model gave a reasonably correct forecast of the degree of instability, but was seriously in error with the vertical moisture profile and hence with the rainfall. Similar errors are likely to be common in forecasts of convective situations, but the dilemma for the forecaster is to try to identify such errors from amongst the correct signals.

4. Conclusions

Forecasters have a daily problem of whether to believe the model products, which are provided to give them a basis for their forecasts. On many occasions the answer is positive, although normally some limited improvements can be envisaged. However, in showery situations, it appears that the numerical models should not be relied upon to too great an extent, particularly on occasions of deep convection moving north into the United Kingdom, as the known or perceived problems inherent in them in this weather type will lead to either significant errors in the forecasts or at least to a lack of confidence in them. The models may be used to give valuable pointers to the broad-scale developments and to the likely occurrence of convection, both spatially and temporally. However, until the lead-time is short enough to allow the forecaster to become more aware of the real smaller-scale features of the atmosphere — for example, the availability of evidence of the structure of the humidity fields or of the development of local convergence zones — the finer details of the convection shown by the numerical forecasts should be treated with a good measure of caution.

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The storm of 10 January 1993

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Summary

The evolution of the severe storm of 10 January 1993, has been described elsewhere by Hewson and by McCallum and Graham, who christened it the 'Braer *Storm' because of its unfortunate consequences for the stricken tanker. This article looks at the problems of forecasting such an explosive development and highlights some data problems that arose from the extremely low sea-level pressure.*

Fig. 1 shows the surface analysis for 12 UTC on 10 January when the storm was probably at its deepest. Fortunately for any sailors involved but less so for the meteorological community, there were no ships in the vicinity of the storm centre. The lowest pressure recorded at this time was 926 hPa by a buoy at 61.5° N, 13.4° W, about 120 n mile to the north-east. This near-record low developed during a period of very disturbed conditions. An intense baroclinic zone over the eastern Atlantic between unusually cold air over the Canadian arctic and very warm air pushing north-east from Florida gave rise to a series of depressions forming to the south or south-west of Newfoundland which then deepened rapidly as they tracked north-east to pass close to northern Scotland. Some, like the low that deepened to 940 hPa east of Iceland at 00 UTC on the 8th were, by normal standards, very intense depressions. They were reasonably well forecast by numerical models but without any indication of an extreme event. Then the Bracknell Global Model (GM) forecast from 00 UTC on the 7th showed a dramatic change from the run 12 hours earlier. The earlier forecast gave no hint of any major development. The T+96 forecast for 12 UTC on the 10th (Fig. 2) showed an open wave with a central pressure of 978 hPa just north of Scotland. T+96 forecasts from ECMWF and Germany were very similar. However the GM T+84 forecast (Fig. 3) shows an extremely intense depression only 8 hPa shallower and 50 km east of the actual low. The forecast then took the low north-east between Iceland and the Faeroes, threatening northern

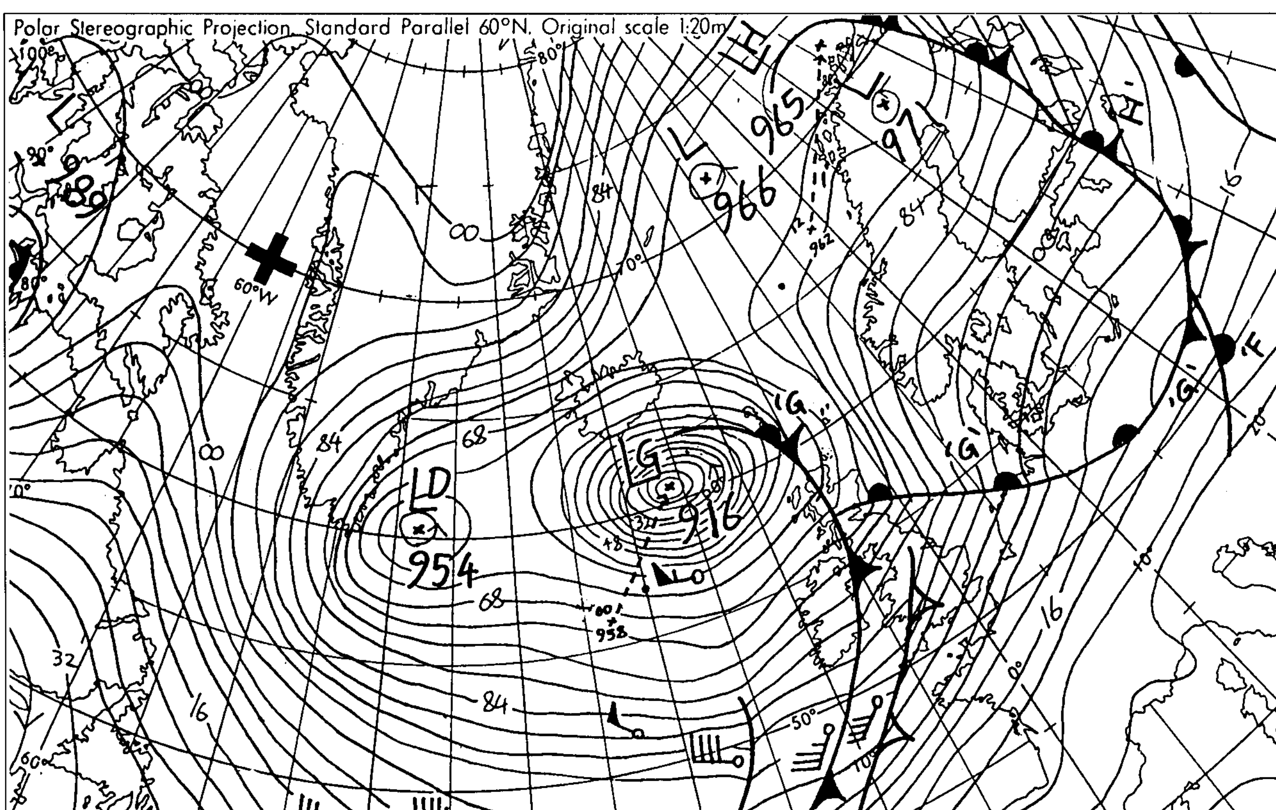


Figure 1. Surface analysis, 12 UTC on 10 January 1993.

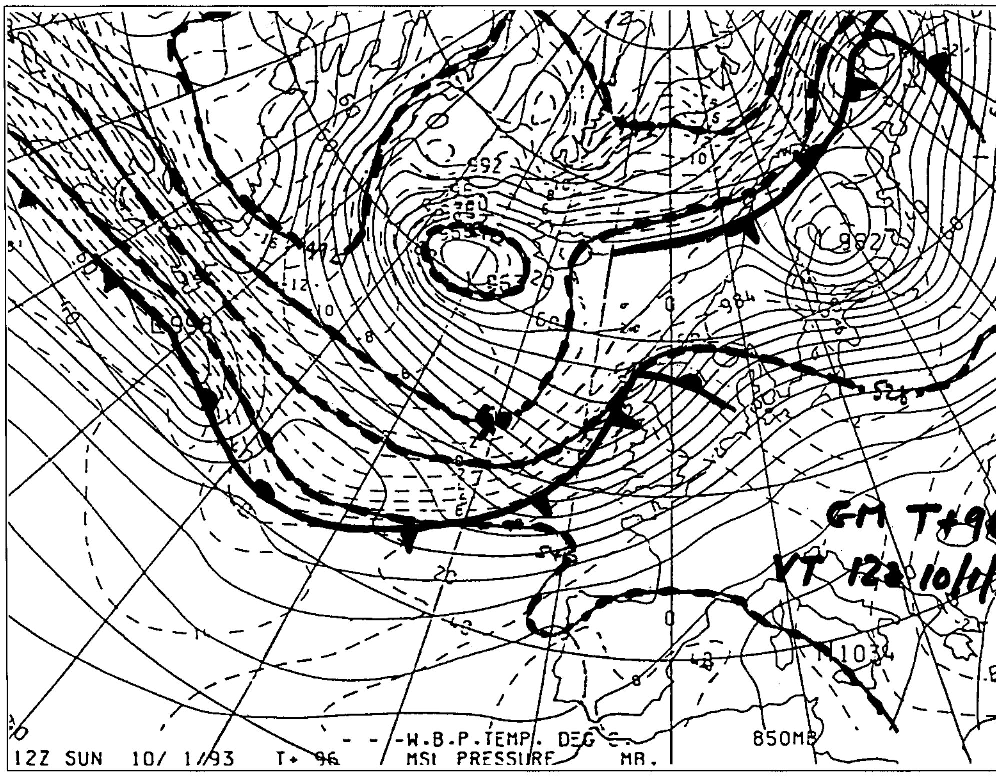


Figure 2. Global model 96-hour forecast MSL pressure verifying at 1200 UTC on 10 January 1993. Frontal positions estimated from model parameters such as 850 hPa wet-bulb potential temperature. Thick pecked lines are 1000–500 hPa thickness.

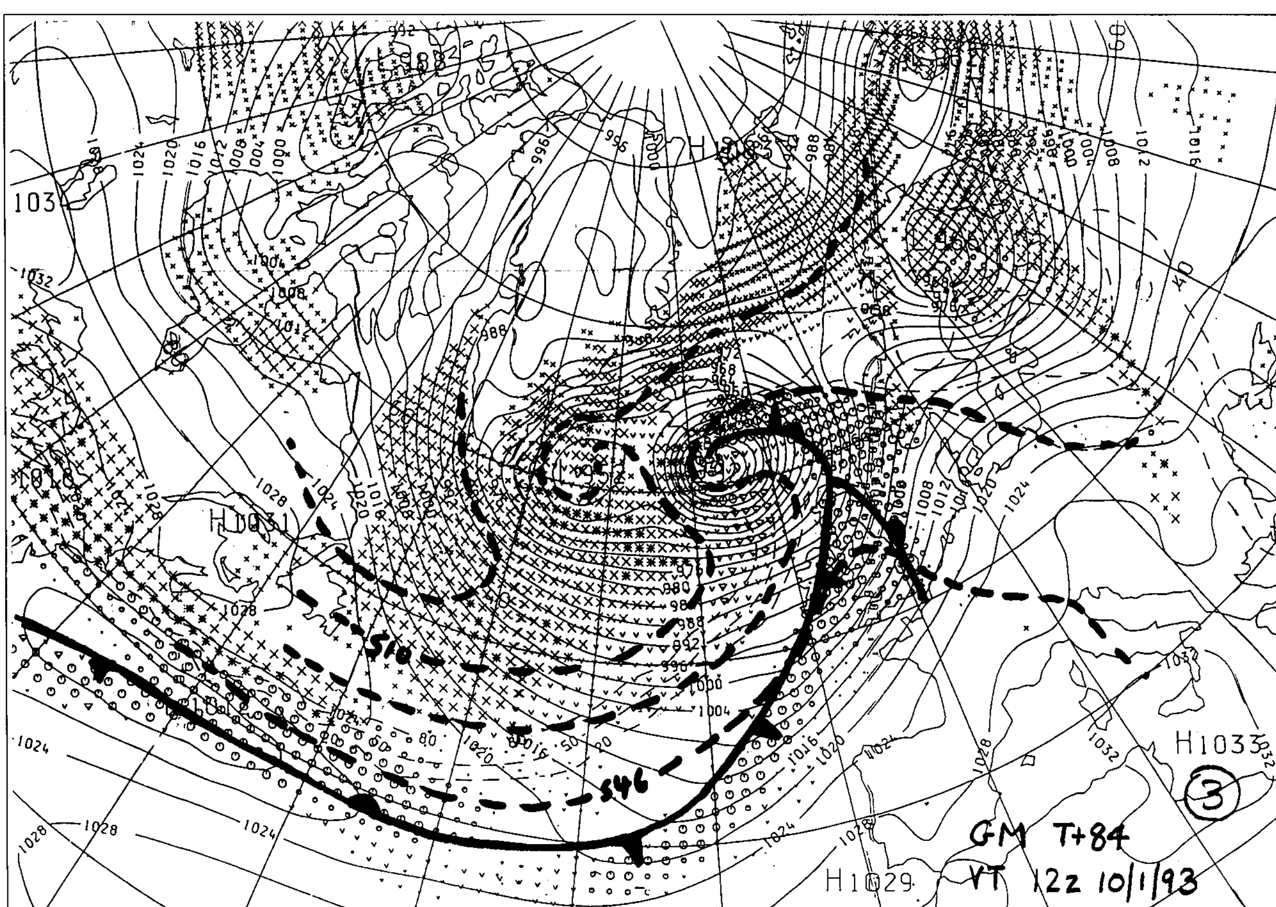


Figure 3. As Fig. 2 but 84-hour forecast.

Scotland with damaging winds. Should this new story be believed? This dilemma was soon resolved as all subsequent runs from all forecast centres predicted an unusually deep low in more or less the correct place (Fig. 4). However, no forecast before the GM T+84 hinted at this (ECMWF forecasts are only made once a day from midday data). The German T+84 forecast went part way towards this solution with a low of about 940 hPa 500 km to the north-east of the actual position. It is interesting that no global model forecast from any of the centres appeared to over deepen the low, though the values used here may be higher than the lowest grid-point pressure since they have been taken from plotted charts which almost certainly have lower resolution than the basic model grids. Later UK limited-area model forecasts did over-deepen the low but only by about 8 hPa at most.

Fig. 5 compares the track and central pressure of the developing depression with the predicted track from the first good forecast. This forecast was remarkably accurate throughout the life-cycle until the mature stage. At no time was the pressure more than 8 hPa out or the position more than 150 km adrift in spite of the explosive deepening and rapid movement. What then was the difference between this forecast and the one 12 hours earlier? The storm can be traced back to a shallow wave over North Carolina at 00 UTC on the 8th. At this stage the surface pressure forecasts for this area were almost identical, both with a wave in the correct position. At 500 hPa some slight differences were discernible. A trough to the north-west of the Great Lakes was slightly sharper and extended further south in the later forecast, but it is doubtful if these differences would been seen as significant without the benefit of hindsight. As the right entrance area to the powerful westerly jet ahead of the upper trough moved east across the Great Lakes, pressure fell generally over the eastern seaboard, but more so in the case of the good forecast where the right entrance region was better defined and slightly further south. This had the effect of increasing the warm advection ahead of the wave and extending it further north which in turn caused the pressure to fall faster and further north than in the previous run, nudging the wave track northwards and into the path of the developing upper trough. This is shown schematically in Fig. 6(a). Up until midday on the 9th, the deepening of the wave was largely due to warm advection, but after this time the vorticity advection ahead of the trough enhanced the ascent due to warm advection ahead of the low; the two became 'phase locked' and the explosive deepening phase began. Fig. 6(b) shows that in the poor forecast the warm advection never extended far enough north to force the wave into the path of the upper trough, which until the feedback from the rapidly deepening low began, was handled in a very similar manner in both forecasts. In the poor forecast the forcing from the upper trough eventually led to the development of a separate wave further north which subsequently passed close to northern Scotland (Fig. 2) but there was no pre-existing low-level circulation to phase in with the upper trough and no exceptional development took place; though in the forecast sequence this low was subsequently deepened to 940 hPa over Finland. Figs 7(a) and 7(b) show the Meteosat infrared images for 1200 and 1800 UTC on the 9th, respectively. Not until the 1800 image is the rapid deepening obvious from the imagery. This could have posed a problem for forecasters

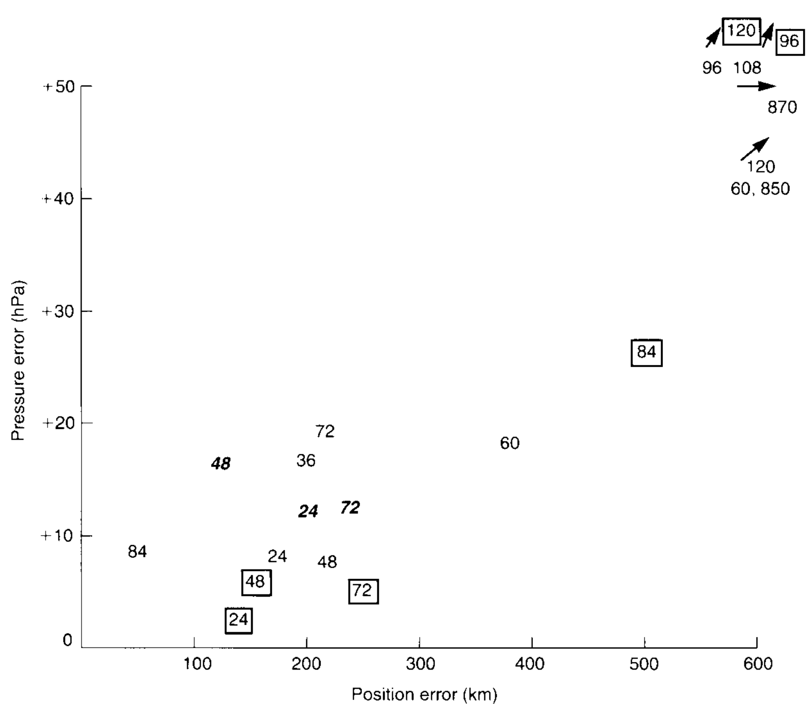


Figure 4. Position and pressure error of various forecasts valid at 1200 UTC on 10 January 1993. Numbers indicate lead time of forecast. Forecasts are the UK global model, ECMWF (bold italic) and the German (boxed).

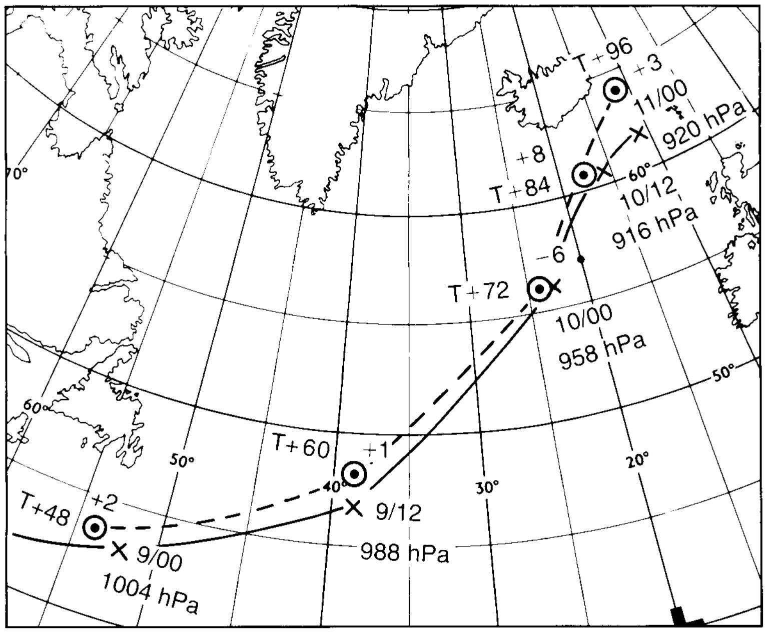


Figure 5. Track of developing storm (solid line) and track from forecast from 0000 UTC on 7 January 1993 (pecked line). Times and estimated central pressure are plotted alongside the observed track. Numbers along forecast track give the forecast lead time at each point and the error in the forecast central pressure at that time.

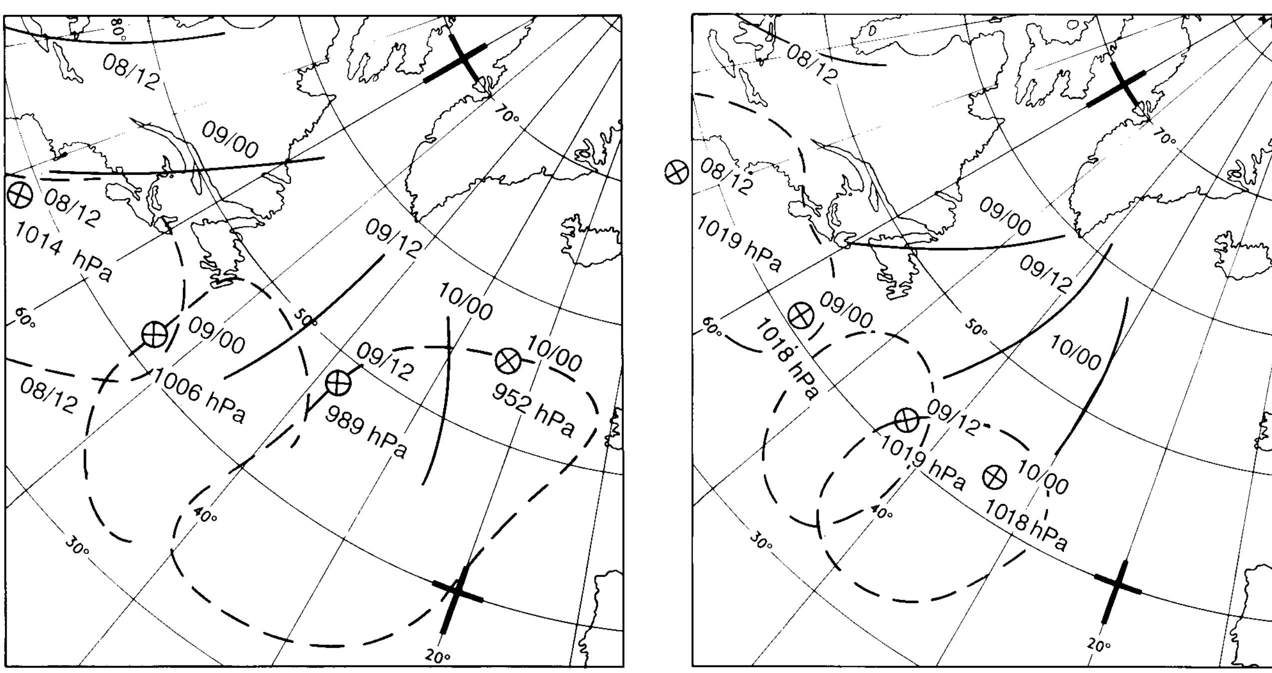


Figure 6. Positions of upper trough (thick solid line), surface low (circled cross) and area of warm advection (pecked line), for various times from (left) the forecast from 0000 UTC on 7 January 1993, and (right) 1200 UTC on 6 January 1993. The warm advection has been omitted for 0000 UTC on 10 January 1993. At this time warm advection covers a very large area ahead of the low in (a) and an area had developed in (b) ahead of the upper trough independent of the original wave.

had it not been for the complete coherence of all forecast runs at this stage and the fact that several ships in the area at midday confirmed the models' forecast of a rapidly developing system.

Once the forecast of an exceptionally deep low passing close to the Faeroes was accepted, the problem remained of predicting the wind strength. Limited-area model level 3 winds (roughly 2000 ft or gradient wind level) of up to 110 kn were predicted close to northern Scotland, with 60–70 kn over much of the rest of the United Kingdom at some stage during the passage of the low to the north. These winds turned out to be good guidance in general

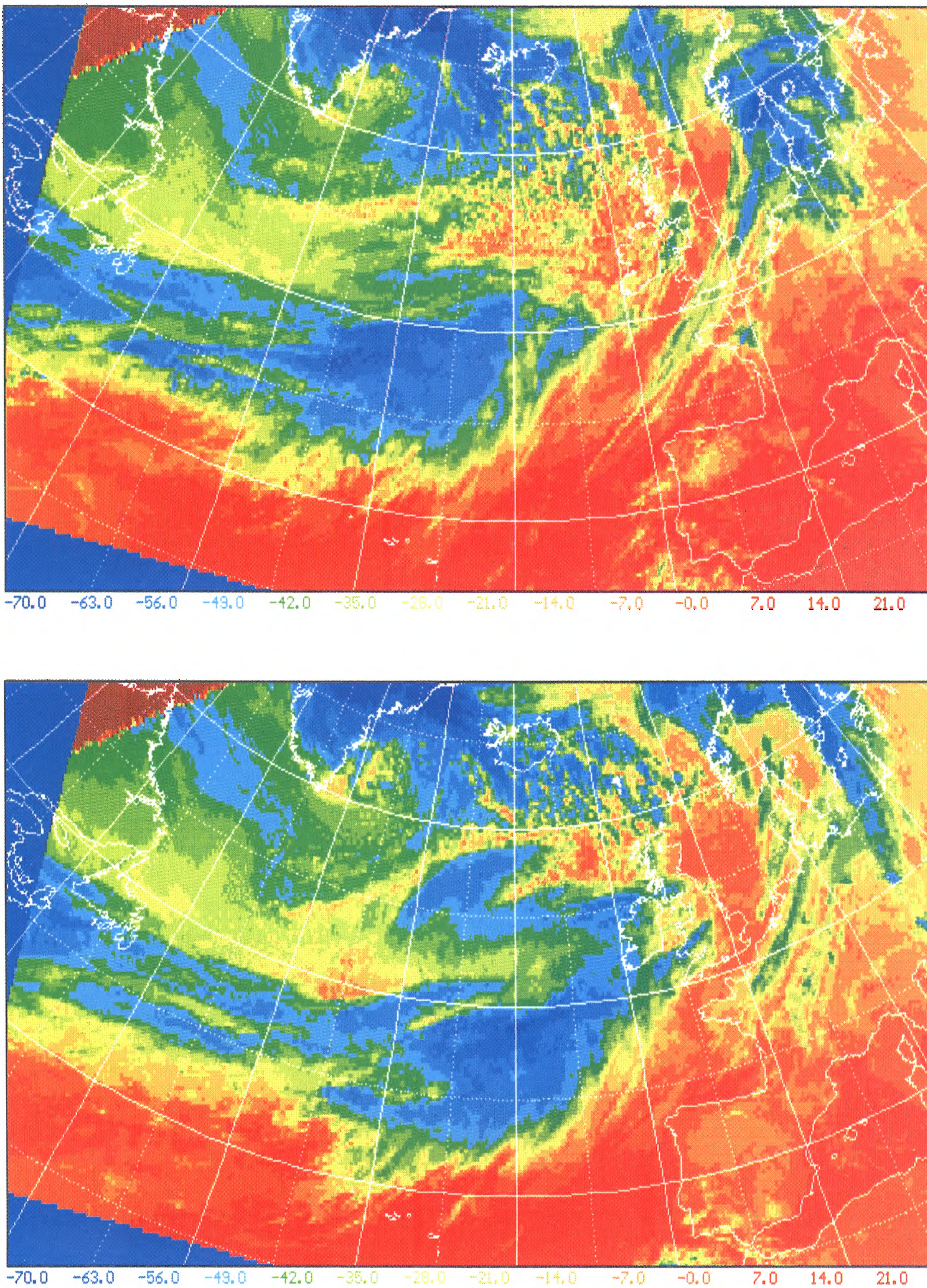


Figure 7. Meteosat infrared images for (top) 1200 UTC on 9 January and (bottom) 1800 UTC on 9 January 1993.

but care is needed when assessing the likely mean surface wind and gust strength. The pressure trace for OWS *Cumulus* along with selected surface wind observations is shown in Fig. 8. At 2300 on the 9th with strong warm advection taking place ahead of the warm front the ascent was stable, though only just so, with a 925 hPa wind of 180° 59 kn and a surface wind of 40 kn and no significant gusts. By 0400 on the 10th the mean wind had increased to 53 kn with gusts to 78 kn. However, at 0500 a temporary lull to the rear of the cold front came at a convenient time for the launch of the morning ascent, before the wind increased even further. Nevertheless the crew and observers must be congratulated on completing a full series of ascents during this extremely stormy period. The 1100 ascent is shown in Fig. 9. By this time the air was highly unstable with a surface temperature of only 0.6 °C, more than 8° colder than the sea surface temperature, and with convection up to about 550 hPa. The surface wind had moderated a little to a mean of 60 kn, but this was only 7 kn less than the 925 hPa wind and the gust speed of 91 kn, greater than the wind at any level within the troposphere, must have been enhanced by a cumulonimbus downdraught. By way of contrast, overland in the warm sector at Hemsby, the surface wind was only 21 kn even though the 925 hPa wind of 70 kn was slightly stronger than at the weather ship. However, when the gradient wind increases beyond 70–80 kn, even in the warm sector the stability may not be enough to prevent the stronger winds mixing down to the surface as happened in the October 1987 storm and to a lesser extent over southern England, only three days after the *Braer* storm.

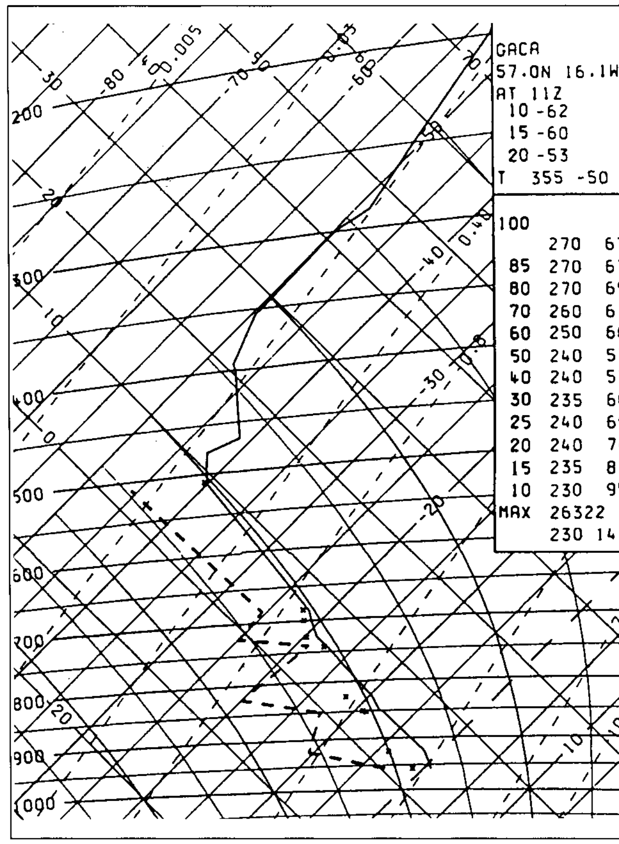


Figure 9. Ascent for 1100 UTC on 10 January 1993 from OWS *Cumulus*. Winds at standard heights are given in the inset.

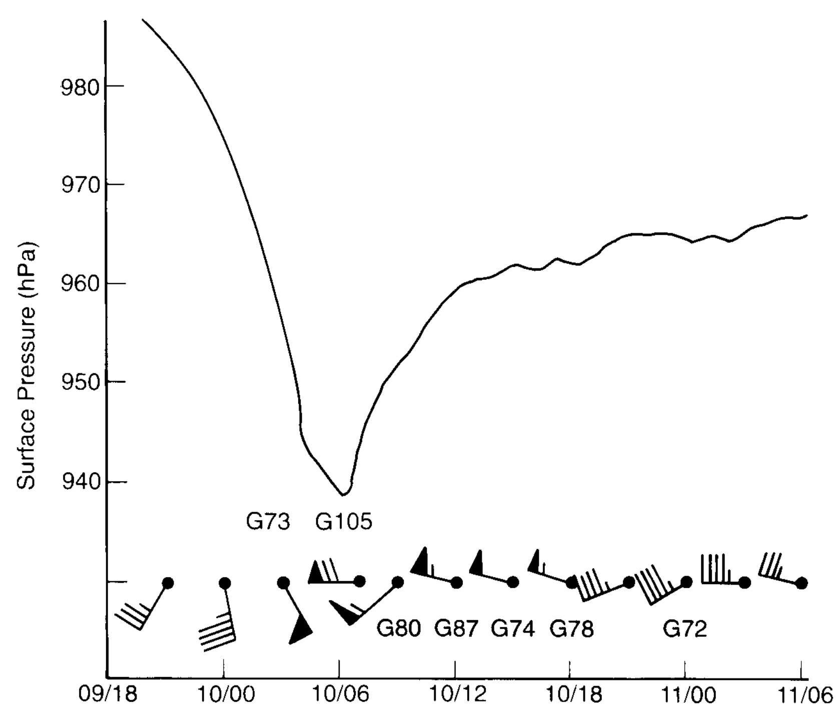


Figure 8. Surface pressure at OWS *Cumulus* (approximately 56° N, 16° W) from 1800 UTC on 9 January to 0600 UTC on 11 January 1993, with selected surface wind observations.

The extreme low pressures associated with the storm brought to light two problems associated with data collection and dissemination. The buoy already mentioned above as recording the lowest pressure on the midday chart, reported a pressure of 924 hPa at 1300 UTC. Thereafter no pressures were reported until about 0300 on the 11th, when the pressure was again given as 924 hPa, though wind observations continued throughout. After this time pressures were again reported as normal, but all values were above 924 hPa as the pressure rose quickly to the rear of the low. It appears that an internal quality control check rejected pressures below 924 hPa. At the time the pressure fell to 924 hPa, the 3-hourly tendency was −22 hPa. Extrapolating the pressure curve to the time at which the winds veered from south-east to south-west gives a lowest pressure of about 913 hPa. This is consistent with the extrapolation of the rising trend backwards to the time when the wind veered further from south-west to west and the pressure could be expected to begin to rise. As the storm centre passed very close to the buoy at about the time of maximum development, this lowest pressure is probably the best estimate of the lowest central pressure of the low. The other data problem thrown up by the low pressure concerns the TEMP code for upper-air ascents. When the surface pressure is below 1000 hPa the height of the 1000 hPa surface below the station is estimated to enable 1000 hPa height fields to be drawn and thicknesses to be calculated. To show that the height is negative 500 is added to the 3-figure code. Since the value is given in metres a minimum of −499 m is allowed for. At Thorshaven in the Faeroes at 2300 UTC on the 10th the surface pressure was 932 hPa giving a 100 hPa height of −564 m, which could not be coded correctly. The observation gave a code of 000 which lead to a reported thickness of 473 dam instead of 529 dam. Fortunately the numerical models analyse temperatures and not thicknesses.

In this article an attempt has been made to show some of the difficulties faced by the forecaster when an extreme event is predicted by the numerical models. In this case confidence was high and timely warnings issued because all model runs were in agreement. It would have been quite a different proposition if the good forecast run had not been supported by the other models. It would have been very difficult to assess which forecast was correct from the small differences apparent as the low began to develop over the eastern seaboard of the USA. It was not until the afternoon of the 9th, only 18 hours before the maximum development that the explosive cyclogenesis became apparent from the satellite imagery.

World weather news — March 1993

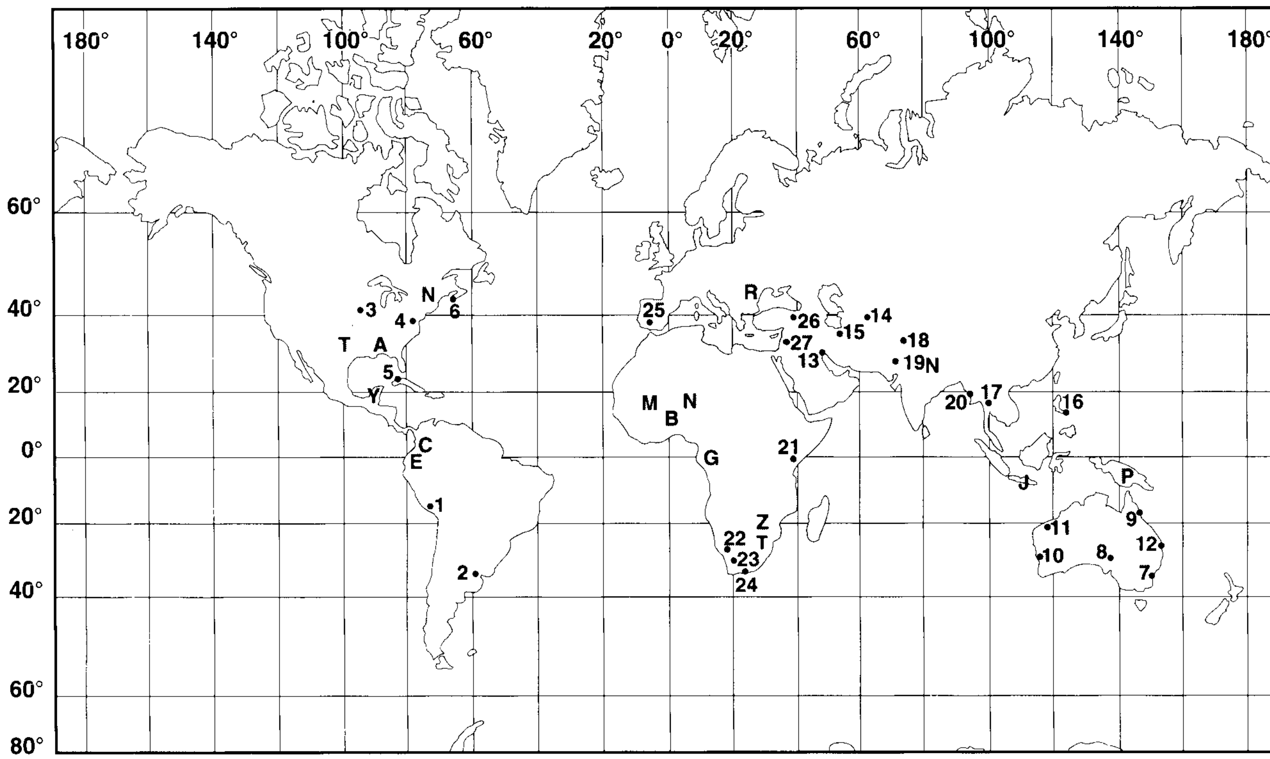
This is a monthly round-up of some of the more outstanding weather events the month, three preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and press reports. Naturally they are heavily biased towards areas with a good cover of reliable surface observations. Places followed by bracketed numbers, or areas followed by letters, in the text are identified on the accompanying map. Spellings are those used in The Times Atlas.

South America

On the 12th there were reports of heavy rain in the northern highlands of Peru which has caused an artificial lake to overflow in Marka, 400 kilometres north-east of the capital Lima (1): 80 are reported missing. Later in the month, in Columbia (C), the volcano Mount Galeras was in the news again, it killed 9 vulcanologists on 14 January. This time on the 23rd mild tremors preceded showers of flaming rocks which destroyed the monitoring stations near the crater. However, there are no indications at this time that a significant amount of ash had been injected into the atmosphere.

Late in the month in Ecuador (E), heavy rain caused widespread flooding and mudslides in an area about 300 miles south of Quito in the Andes: some 300 were killed or missing, 1500 were made homeless. Additionally 40 km of paved roadway were lost, 43 km of railway and 5 bridges were washed away. By the 21st the flood water was threatening two Andean towns and was held back by a single earth dyke which was expected to fail soon. Interestingly this earth dyke was made of 5 million cubic metres of landslide that made a 330-foot dam, and a lake 12 miles long. This eventually grew to



Location of places mentioned in text.

submerge 6 towns. On 2 May this dam was breached in a relatively controlled manner and a violent discharge of water went down a previously prepared channel. Though a lot of damage was done there were no casualties as the area had been evacuated in preparation.

Buenos Aires (2) was having maxima up to 33 °C mid month, though this eventually triggered thunderstorms which gave 59 mm on the 14th. Two days later Bolivar, 200 miles to the south-west, got 132 mm (monthly average is 87 mm).

North and Central America

On the 5th there were reports that the St Lawrence Seaway had been freed of their worst ice jams in about 20 years. Then on the 8th came reports from Nebraska of the worst flooding in 15 years as the thaw set in and ice jams drifted down rivers causing them to overflow. By the 11th the floods were still rising and the rivers Platte and Loup were particularly mentioned. The former was 5 to 8 miles wide in places and it was forcing the river Missouri to back-up and the flooding was worst nearest Omaha (3).

A big storm affected much of the north-eastern USA on the 4th and 5th with heavy snow around the Great Lakes giving depths of around 20 cm. Near the coast the wind gusted to 65 kn on Long Island and Washington's (4) 48 kn gust equalled their March record gust.

It was on the 13th that the 'Storm of the Century' developed in the Gulf of Mexico. The first to suffer badly was Cuba when the cold front swept across the island, five were killed and 100 were injured. Winds gusted to over 60 kn; heavy rains and high seas caused flooding on north coast and in Havana (5). Some 40 000 homes were reported to have been damaged and 1500 destroyed. Many western provinces were without electricity for some hours and six aircraft were damaged at the airport. A lot of damage was done to crops and livestock on the island — so much so, that international aid was being sought. The storm then swept up the east coast of United States causing havoc from Florida to the Canadian border. The death toll on land was about 40. Very high seas driven by near-hurricane force onshore winds caused a lot of beach erosion, as bad as the storms earlier this year. Snowfalls were up to a metre in some places and there were reports of as much as a foot of snow as far south as Alabama (A) and Tennessee, places which did not have snowploughs because snow does not normally fall at all. In Florida there were reports of about 50 tornadoes which caused 26 deaths and cut electricity supplies to around 2 million. A significant number of the deaths were due to heart attacks as people struggled to push stuck cars and dig away the effects of a foot of wet snow blown by strong winds. Some of the worst conditions were experienced in New England (N) where a lot of the precipitation fell as rain or sleet which turned to large sheets of ice as the temperature fell below freezing. At sea, 10 m waves and hurricane-force winds caused a predictable amount of havoc to shipping. The worst instance seems to have been the loss of the 26 000-ton gypsum carrier, *Gold Bond Conveyor*, which capsized and sank with the loss of 33 lives off Cape Sable Island (6). Just before sinking they reported 50 to 70 knot winds and 30 m waves. In total the damage due to the storm seems to be in the order of $1.6 billion. (The meteorological details of this interesting storm will appear in our next issue.)

High temperatures around the Gulf of Mexico, consistently above 35 °C on the Mexico/Guatemala border, and a March record of 38 °C at Merida on the Yucatan (Y) on the 29th helped provide the moisture for some hefty storms and tornadoes in the southern USA. Texas was visited by damaging hailstorms and high winds on 25th and 26th with golf-ball-size hail in Austin which broke a lot of glass and damaged cars, the total damage was estimated at $125m. A couple of days later in Kansas rather less damage was done by another hailstorm and high winds. This time the hailstones were reported as being marble to baseball size around Wichita; they did a lot of damage to sheet metal roofs: never to be outdone, Langtry, Texas (T) managed tennis-ball-size hail on the 29th. Top rainfall may have been 89 mm in a day at Mobile, Alabama on the last day of the month.

Australasia

First an apology: in the notes for December 1992 I reported rainfalls of 410 mm at Croydon and 350 mm at Moranbah. A coding or transmission error made these too high by a factor of 10. I am grateful to the Australian Bureau of Meteorology for bringing this to our attention and providing the material below.

There were some notable thunderstorms this month. In New South Wales flash flooding occurred in some suburbs of Sydney (7) on the 7th, also affected by fierce storms on 20th and 26th. Hailstones reached 4.2 cm diameter in a storm near Kempsey on the 9th. The 26th also brought severe thunderstorms to South Australia. In one near Marree (8) gale-force winds blew away some sheds while 36 mm of rain fell — 27 mm of these in a mere eight minutes! In Western Australia the storms on the 19th in the south covered one road with 30 cm of hail, flash flooding burst some dams and drowned sheep. Rainfall totals of around 90 mm in 24 hours set new daily records for March in several places. In contrast the far north of Queensland had the driest March on record.

North Queensland was also hot. New March records of nearly 38 °C were set at Townsville and Cairns (9) on the 15th and 18th respectively while some other places had record mean maxima. In Western Australia persistent southerly winds led to record low mean maximum temperature at Geraldton (10) of 28.1 °C (onshore winds) and a record highest mean maximum of 38.7 °C at Port Hedland (11) (offshore winds).

Further afield a tropical depression gave Jinjo in Papua New Guinea (P) 99 mm on the 10th. This low became tropical storm Roger. From the 16th to 18th Roger passed well offshore of the Sunshine Coast but the Port of Brisbane (12) was closed for a time by the very high seas and strong winds.

Asia

From Iran there came reports on the 8th of 750 villages in the south and west being cut off by floods: these were in provinces affected by February's catastrophic floods. The Karun river burst its banks in near Khorramshahr and damaged the town of Abadan (13). A few days later there was a report from Uzbekistan that five had been killed and several bridges had been washed away when 'two months rain fell in one day' in the mountains near Samarkand (14). The report added that 50 km of irrigation channels were blocked by silt washed into them. Heavy rain returned to Iran towards the end of the month. On the 26th there were reports that heavy rain had led to landslides: five had been killed in the south in one incident where a hillside had collapsed into a river and diverted it. Deep erosion channels are beginning to appear around Ardad, 400 km south of Tehran (15).

In the Philippines, Mount Mayon near Legaspi (16) was still being potentially dangerous: there was a considerable number of eruptions, six on the 21st which ejected ash to a height of about 6.5 km; on the 24th there were 26 big blasts and the mountain was still going strong at the end of the month.

No report in this section would be complete without some mention of heavy rains in the islands, though I have not seen any reports of life-threatening events. Tasikmalaya on Jawa (J) managed 141 mm on the 4th (about half the month's average). Luang-Prabang in northern Laos outdid this with 160 mm in 12 hours on the 11th and followed this with a near gale and more rain. Yogyakarta, on Jawa, used to have a record March 24-hour record of 56 mm, 96 mm fell on the 21st. To prove it is not all rain at this time of year, Tak (17) in Thailand managed a maximum temperature of 41.5 °C on the 29th, 1.5 °C above the previous record.

Indian sub continent

The second half of this month seems to have been very disturbed. In Pakistan, westerly disturbances were causing substantial amounts of rain in the higher provinces with 5 to 45 mm falling in 24 hours ending on the 14th with snow on the hills. Starting about the 10th there was heavy rain in the Northwest Frontier which caused waterlogging and there are reports that 20 people had been killed by collapsing buildings. Peshawar (18) got 86 mm of thundery rain in 24 hours to the morning of the 11th (the average March total is 62 mm). The train service between Quetta (19) in Pakistan and Zahedan in Iran was suspended because long sections of the track had been undermined. On the 20th in Bangladesh, Cox's Bazaar on the coast of the Bay of Bengal had 20 injured and 15 000 made homeless by a violent hailstorm which battered the Kutubdia Islands 45 km offshore: hailstones were reported to have weighed 1 kg. Later the storms affected Chittagong (20) but no serious injuries were reported there. There was a similar event on the 23rd, this time there was 55 mm of rain with winds gusting to 48 kn in a 90-minute storm; fifty were injured and thousands made homeless. A further violent storm arrived on the 27th and swept the area around Chittagong; about 300 were reported to have drowned in one squall with gusts of over 50 kn and 91 mm of rain in 6 hours. Some 22 small vessels vanished and a ferry carrying 250 capsized. In all 25 000 were made homeless. It was said that 2500 houses were destroyed in three minutes in one district. About the same time storms were affecting India and Nepal. On the 24th and 25th in the Indian foothills of the Himalayas 30 are reported to have been killed by flash floods north of Jamu as water washed away houses during the night. Two are reported to have been killed by lightning: and the Punjab may have lost 10% of its winter wheat. Dehra Dunn, 120 miles north-east of New Delhi, and the surrounding area, had over 50 mm on the 24th, about twice the average for the whole of March. In Nepal (N) over the 26th to 28th two days of thunderstorms killed two and injured 37. There were 200 gm hailstones near Janakpur in south-east Nepal and 100 gm hailstones in the Chitwan district. The winter wheat is reported to have been severely damaged here as well. In Calcutta 39 mm fell in thundery showers on the 30th.

Africa (except the Mediterranean coast)

The approach of Summer became apparent in western Niger (N) early in the month with temperatures well above 40 °C, Dori in neighbouring Burkina Faso (B) reached 44.2 °C on the 6th. A bit further south in Cameroon thunderstorms on the 7th gave more than 100 mm in overnight storms; Bafia's report of 190 mm was about the average for the whole of March. At Koundja the morning reading on the 10th of 108 mm would have been a new March record if it had not been reset at 134 mm on the 6th! In Mali (M) temperatures reached 43.2 °C on the 17th then a breeze from the Sahara kept the night minimum to 31.2 °C (cf. mid-March average 19 °C). At Mayumba on the Gabon (G) coast heavy thunderstorms on the 23rd/24th dropped 222 mm for a new March daily record: then on the 25th there was a further 82 mm; the week's grand total was 312 mm, 62 mm more than the monthly average.

On the other side of the continent, Makindu (21) near Nairobi had some weather which struck us as atypical on the 23rd when thundery showers produced 16 mm of rain but with winds that started easterly/30 kn and later veered southerly/34 kn before slowly dying down overnight.

My thanks go to the South African Weather Service for providing information on their part of the continent.

Autumn brought some startling extremes to South Africa with a maximum of 42.7 °C at Vioolsdrif (22) on the 16th and a minimum of 0.8 °C at Sutherland (23) on the 30th. The rainfall varied from a record low of 0.5 mm at Cape St Francis (24) to 379.6 mm in 24 hours at Graskop in Eastern Transvaal (T) (out of a monthly total of 688 mm). However, the emphasis seems to have been on continuing dryness with less than 75% of normal over a wide area. Fortunately rainfall was about normal in the main agricultural areas of Transvaal and Natal.

There seems to have been three periods with rain. Over the first few days of the month an easterly trough caused widespread rain from Zimbabwe (Z) to south-east Transvaal: local flooding caused two deaths. An unseasonal cold front brought needed rain to southern Natal between 11th and 15th though the tornadoes near Dundee on the 15th were probably less welcome. Another cold front affected the same area on the 21st to 23rd which is probably when Graskop got its rain. At the end of the month a deep low developed in the interior bringing more rain to Natal where Mkuze got 104 mm.

Europe (plus North Africa and Arabia)

The month opened with cold air over much of the continent and a deep low over the western Mediterranean (980 hPa near Sardinia). Sevilla (25), Spain awoke with a temperature of −2 °C, two degrees below the previous March record; further east Barcelona collected 37 mm of rain and snow. Gibraltar's snow was the first since February 1954. During this time Bulgaria and Romania (R) experienced some of their heaviest snow storms for several years with communications largely paralysed by blizzards. In Bucharest many buildings lost their water supplies for the second time this year. Many Bulgarian towns were cut off by drifts and some were without electricity. Conditions were particularly bad near the Black Sea. There were rumours that the Bucharest meteorologists were on strike at this time. On the 8th severe blizzards continued, in Bucharest there was a metre of packed snow with 65 cm of fresh snow on top. Danube Locks were closed and the port of Constanza was blocked with some 70 vessels. These were advised to put to sea, but gales and 6 to 7 m waves deterred them. Romanian air traffic was diverted to Timisoara and Arrad near the borders of Hungary and Yugoslavia. However, there were no international flights because the passengers could not reach the airports. By the 10th traffic was starting to move again in Bulgaria, and the Danube ports reopened.

Mid-month brought renewed reports of cold weather in the south. Erzurum (26) in central Turkey managed to continue is record-breaking streak with a new record March minimum of −25 °C on the14th. Near freezing conditions occurred elsewhere in the eastern Mediterranean with a new record minimum of 3.8 °C on the 18th in Asyut, Egypt and a near record −3.2 °C in Dimashq (formerly Damascus) (27) on the 20th.

Near the end of the month there was yet another big wind storm in the North Sea which forced the empty tanker *Freja Svea* aground near Redcar in high winds of around 50 kn and huge seas of about 10 m. The ship broke its mooring chains; the main engines were started but it could not hold position as the anchor dragged.

Tailpiece

Vostok in the Antarctic had a maximum of −60 °C on the 23rd, this was followed by a minimum of −69 °C. This is cold even by their standards!

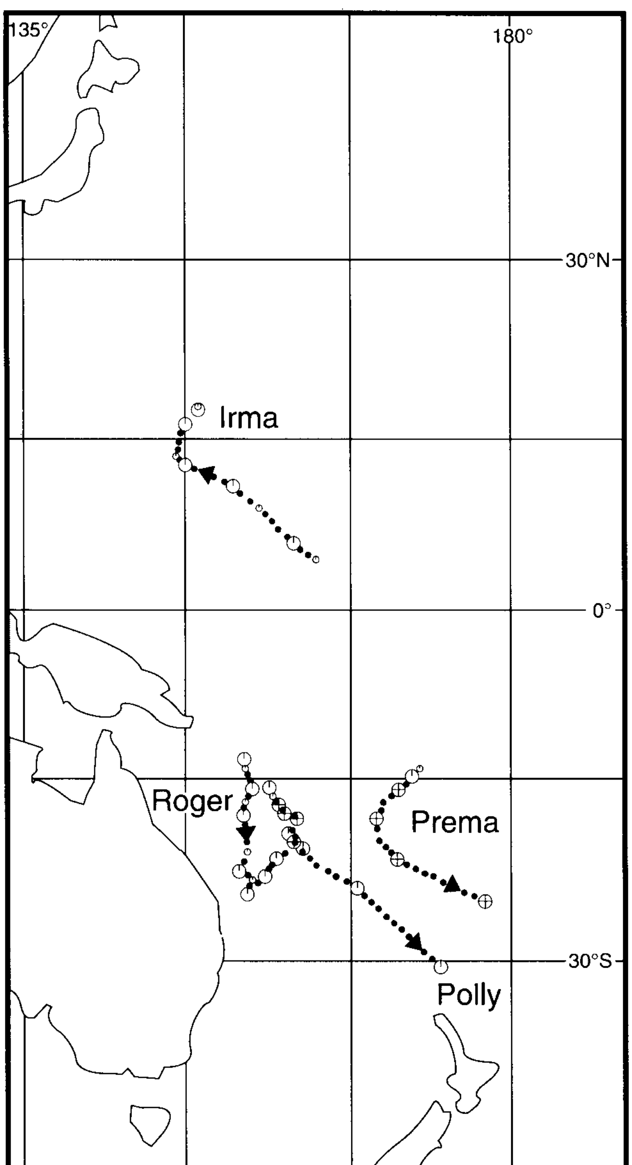
March tropical storms

This is a list of tropical storms, cyclones, typhoons and hurricanes active during March 1993. The dates are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during this month. The maps show 0000 UTC positions: for these I must thank Julian Heming and Susan Coulter of the Data Monitoring group of the Central Forecasting Office.

No	Name	Basin	Start	End	Max. (kn)
1	Polly	AUS	25/02	03/03	100
2	Irma	NWP	10/03	17/03	55
3	Roger	AUS	12/03	21/03	50
4	Prema	AUS	27/03		120

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific; I — Indian Ocean; WI — west Indian Ocean; AUS — Australasia.

Notes: Roger never reached full cyclone status and followed a very erratic track. Polly followed a nearly straight path and was a full cyclone. Prema was still active at the end of the month.



Review

Exploration of the solar system by infrared remote sensing, by R.A. Hanel, B.J. Conrath, D.E. Jennings and R.E. Samuelson. 175 mm × 254 mm, pp. xvi + 458, *illus.* Cambridge University Press, 1992. Price £75.00, $125.00. ISBN 0 521 32699 0.

The title is a little misleading: the book is mainly about the physics of remote sensing of atmospheres, only fairly incidentally about its application to the detailed study of solar system atmospheres, and not very much at all about what one would normally call exploration, although that certainly comes in to it. This minor observation is hardly a criticism of a really superb and very useful and timely book, by accomplished authors who know their material thoroughly.

Dr Rudy Hanel was one of the pioneers in the business of remote sensing of atmospheres from space. At a time when most other instruments were fairly simple low-spectral-resolution radiometers, he was developing the Michelson interferometer as a tool for remote temperature sounding and ozone monitoring. The detailed spectral coverage which results from the measurement of continuous spectra gives a lot of additional, though notionally redundant, information, which can be priceless when unknown or unexpected factors enter the data interpretation problem. This was a not uncommon state of affairs in the early days of weather satellites and is an unavoidable one when it comes to extending similar studies to the mysterious atmospheres of the outer planets. Building successful experiments around such complex and often temperamental instruments as interferometers has been an outstanding achievement by Hanel's team from NASA's Goddard Space Flight Center, three of whom are his co-authors in this book.

Their treatment is quite quantitative and detailed. It begins with the relevant atmospheric physics: radiation theory, radiative transfer, molecular spectroscopy, and multiple scattering by clouds and aerosols. These are the tools by which one solves the direct problem, i.e. computes the radiation field which emerges from an atmosphere whose structure and composition is known. The next third of this fairly long book deals with the theory of space hardware for infrared measurements, and includes examples of real instruments (mostly from the direct experience of the authors — others tend to get rather shorter shrift). Finally, the inverse problem, where the measurements of outgoing radiation are converted back into atmospheric quantities such as vertical temperature profiles, is expertly covered, as we would expect since Dr Conrath in particular is an acknowledged leader in this field. The results which are obtained from this process are generously illustrated with examples of the investigation of atmospheric composition, structure, dynamics and energy balance on the planets, especially Mars, Jupiter and the large Saturnian moon Titan. Again, much of this is drawn from the authors' own work on the overwhelmingly successful Mariner and Voyager missions in which they participated.

Along with non-interferometric instruments there is another significant near-omission, and it is a major one — the Earth. All of the chapters on theory and instrumentation, constituting two thirds of the book, are just as relevant to our own planet as to the others, and even the results on Mars and the rest are relevant to understanding the equivalent processes on Earth and can usefully be compared. The authors are experienced terrestrial remote sounders. Most of their potential readers and buyers are focused on the Earth, for obvious practical reasons including gathering data for weather forecasting and other applications, which are much bigger business than solar system science. The Earth is a planet and a member of the Solar System. Why doesn't it get at least equal time with, say, Titan? It is not ignored altogether by any means, and in a way it is refreshing to see the usual bias reversed — but it seems a little curious, like the title.

An appreciation of the new understanding of the atmospheres of the Solar System which is coming, in part, from remote sensing from spacecraft requires work on the part of the reader as he or she works through the detail in each of the chapters. This is a book for the specialist, or the student wanting to get deeply into the field, rather than the interested amateur or bystander. It is very well done, nearly error-free (if the complete garbling of the name of an unimportant British researcher, near the beginning of the book, is overlooked), nicely produced, and highly recommended.

F.W. Taylor

Retirement of Raymond Hide

In September 1992, Raymond Hide retired from the Meteorological Office, 25 years after he joined in 1967. Raymond was born and brought up in Doncaster and his interest in science led to a first class honours degree in Physics at the University of Manchester. He then undertook a PhD at Cambridge with Keith Runcorn as supervisor and pioneered experimental studies of convection in a rotating fluid annulus. These highly original studies with novel experimental techniques and critical analyses of the results paved the way for some 40 years of continuing work into that, and related systems. They also started Raymond in a multi-disciplinary career being as familiar with fluid dynamics and meteorology as with geophysics.

From his PhD, Raymond's national service led to research at Harwell on shock tubes and magneto-hydrodynamics followed by a brief foray into astrophysical problems with Professor Chandrasekhar at Chicago. From 1957 to 1961 he was a lecturer in the Physics Department, University of Durham, Kings College (at Newcastle-upon-Tyne) and progressively established a research group concerned with what was to be called geophysical fluid dynamics. With students he continued studies of convection in a rotating fluid annulus and started new work involving other rotating fluid phenomena, including Taylor columns. In 1959 he married Anne and, we are advised, somewhat changed his lifestyle.

His great scientific insight was recognized by his appointment in 1961 as a full Professor at MIT A number of his existing students at Newcastle accompanied him to MIT and he established a very active and productive laboratory concerned with wide ranging laboratory experiments, mainly concerned with rotating fluid dynamics. Raymond was recruited into the Met. Office in 1967 by Sir John Mason, who was at that time the recently appointed Director General with the expressed intention of enhancing training and research in fluid dynamics. This recruitment as a Deputy Chief Scientific

Officer was exceptional, and reflected Raymond's distinguished track record for scientific productivity. Raymond brought with him from MIT a considerable amount of experimental equipment, which was crucial to the rapid establishment of his new group. The transport was not however, without problems, bringing Raymond into the first of many clashes with what he saw as excessive bureaucracy in the Civil Service.

From the moment Raymond arrived, the Office benefited from a dynamic source of new energy. Extra lecture series were organized and challenging questions emerged from the back of the room even in existing lectures and colloquia. Within a year Raymond had established a new Met. Office Branch, then Met O 21, known as the Geophysical Fluid Dynamics Laboratory. Most of Raymond's staff were new entrants to the Office and were quickly infected with his energy, and enthusiasm to challenge and learn with sharp scientific methods. One of the first problems encountered by a new member of the group was to attempt to work systematically through the wide range of suggestions and ideas which he put forward; their number far exceeded the capacity of a group much larger than this. However, having embarked on a task, Raymond was always interested in its progress and would willingly discuss it with the most junior member of staff. This was an eye-opener to those who had served in other parts of the Office where even PSOs (now Grade 7) were regarded an unapproachable by young Scientific Assistants. Whilst he always liked a written and well planned approach, most Met. Office correspondence was judged not to apply to him and was conveyed to the rubbish bin. This was not well accepted by the management but support from his secretary gradually enabled satisfaction of most demands.

Raymond always saw one of the main functions of his new group as providing training, beyond that which might be provided by the Training School, and specifically to give wider insight to that subset of Geophysical Fluid Dynamics which comes under the heading of Meteorology. This need for a small number of staff to have more advanced scientific training perhaps foreshadowed the current participation of the SO course in the University of Reading MSc courses.

The staff of Met O 21 grew to about 9 by the mid 1970s and the programme of work developed steadily as Raymond continued to develop new ideas. He pioneered training interactions with universities by hosting the Office's first CASE research student. This small branch and Raymond himself were very productive with over 200 publications being produced by the branch. Impressive as this is, Raymond's personal publication list comprises a large fraction of the total.

Much of the work of the staff concerned laboratory studies of rotating fluid dynamics. These experiments presented a technical challenge demanding precise engineering and the advancement of electronic measurements. These were not without incident however, one member of the group attempting to extinguish a small fire with the aid of a beaker of ether, with spectacular results! In spite of the sophisticated instrumentation which worked reliably, the plumbing of various apparatus proved less reliable giving rise to the occasional flood! Those working for Raymond found him a stimulating fund of ideas and a great enthusiast for the introduction of automation and computers. As well as guiding his group at the Office, Raymond also became increasingly interested in planetary atmospheres as well as maintaining his long-standing involvement in magnetohydrodynamics. Early in the 1970s, the branch also diversified into numerical methods and sought to use precise numerical simulations to complement the laboratory studies. Although these studies made it possible to obtain more detailed information than would have been possible in the laboratory, they were of equal value in providing a test bed for numerical methods.

Raymond received honours too numerous to list fully here but in 1971 was elected Fellow of the Royal Society. In 1974–76 he was President of the Royal Meteorological Society and in 1983–85 he was elected President of the Royal Astronomical Society. In 1985 he was appointed a Commander of the British Empire (CBE).

From the early 1970s until the mid 1980s, Met O 21 continued to develop its laboratory and numerical experiments to increasing sophistication and precision. Raymond continued to be very productive and one of the new foci of his attention became atmospheric angular momentum fluctuations and the associated tiny changes in the length of the day. The latter providing an integral check on the whole atmospheric circulation.

In the 1980s in the face of increasing pressure from the resource challenges of satellites, and the Office's growing range of numerical models, the decision was taken to wind down Met O 21, and by mutual agreement, for Raymond to establish a new laboratory at the University of Oxford in the Hooke Institute.

Raymond put a great deal of effort into transferring his laboratory to Oxford and also helping to run the other collaborative activities in the Hooke Institute. He was understandably very disappointed when, at the time of his retirement, this formal Met. Office collaboration with NERC and the University of Oxford Hooke Institute ceased. In his retirement from the Office, he now remains active at Oxford where the leadership of his laboratory has passed to Peter Read.

During his uniquely rich career in the Office, Raymond provided training, advice and encouragement to all around him and those who passed through his branch. His sound and friendly advice was always sought after and willingly given. He has left a lasting impact in the Office and we look forward to continuing interactions with him at Oxford.

Peter Jonas
Paul Mason
Peter Read

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe results of research in applied meteorology or the development of practical forecasting techniques.

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Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (IBM-compatible or Apple Macintosh) can be labour-saving, but only a print-out should be submitted in the first instance.

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Noctilucent clouds 1992
Management of change
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'Blizzard of the century' — the storm of 12–14 March 1993 over the eastern United States

G.S. Forbes
Professor of Meteorology, Pennsylvania State University, USA
R.M. Blackall and P.L. Taylor
Meteorological Office, Bracknell

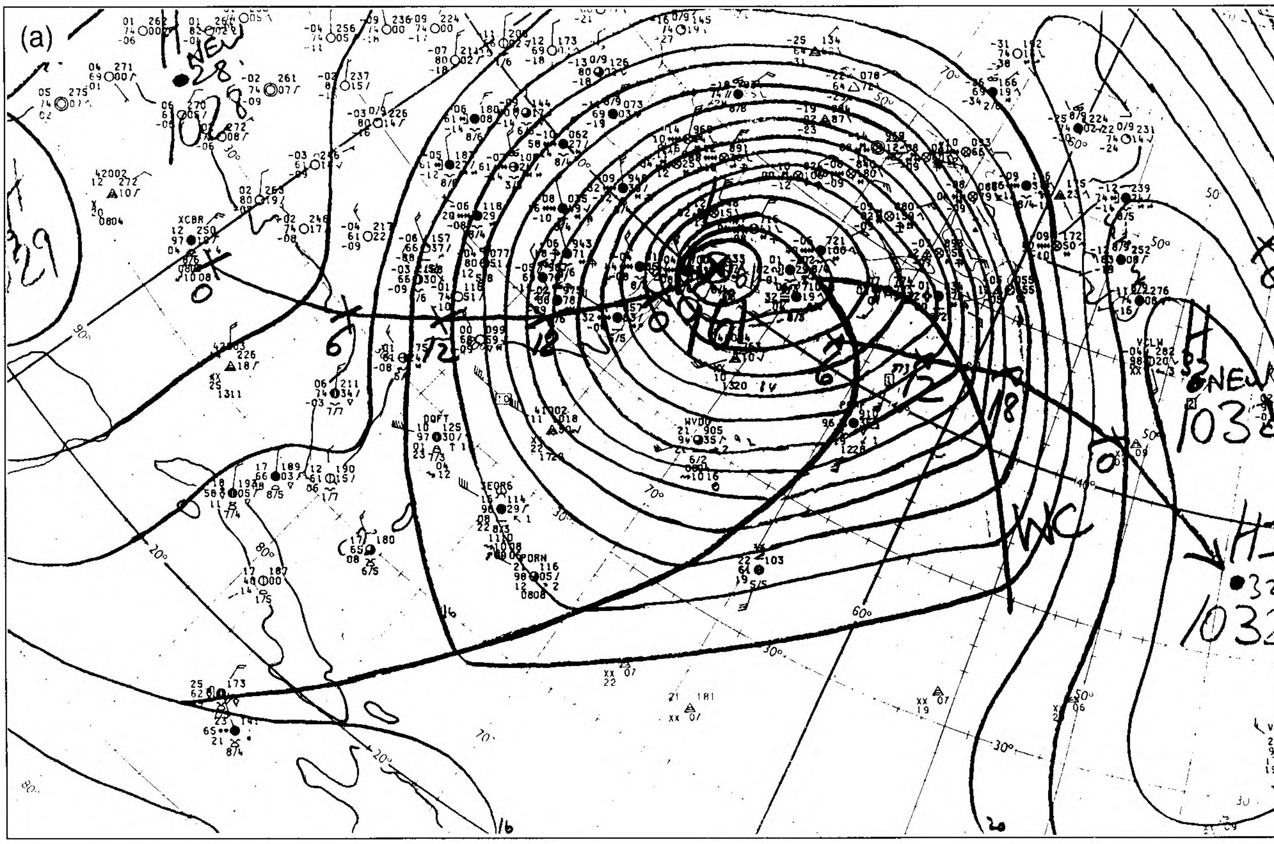
This article was commissioned of Professor Forbes as a recent example of cyclogenesis to illustrate a chapter in Images in weather forecasting, *a massive work on the interpretation of satellite and radar pictures to be published for the Meteorological Office by Cambridge University Press at the end of this year. Shortly after the paper was received, Taylor gave the Editor a demonstration of the ATD system's capabilities. Forbes has kindly allowed this to be included and the whole paper to be printed here.*

A storm described by some as the 'blizzard of the century' swept across the eastern portion of the United States on 12–14 March 1993. Fig. 1(a) is a copy of the United Kingdom Meteorological Office (UKMO) working chart at 0600 UTC on the 14th and Figs 1(b) and 1(c) are Meteosat views of the storm at 0000 UTC on the 14th and 0000 UTC on the 15th, respectively. In the latter, note the landmarks of Florida and the Great Lakes. The vigorous low-level convection just offshore can be seen to have moved from the Gulf of Mexico to the Eastern Seaboard as the storm has moved north-east. Fig. 2 shows the track and central pressure of the surface low-pressure centre. A number of stations in the south-east attained all-time low-pressure records as the storm passed.

Many locations from the mid-Atlantic states (e.g. Pennsylvania, PA) southward experienced their greatest all-time single storm snowfalls or 24-hour snowfalls, and achieved record depths of snow on the ground. Governors of several states (e.g. PA and West Virginia, WV) banned all but emergency travel. Fig. 2 shows the swath of the heaviest snowfall, exceeding 30 cm. The majority of the outlined area received 50 cm or more of new snow from the storm. Most locations within the heavy snow area experienced a period of snow falling at a rate in excess of 2 cm h^{-1}, and rates in excess of 7 cm h^{-1} were reported. Many stations within the heavy snow area also experienced a period of thunder accompanying the snow. Locations along the eastern edge and just east of the heavy snow track experienced an initial period of heavy snow, followed by or mixed with ice pellets and freezing rain. Often the ice pellets were driven by wind gusts of 40 kn or more.

At least 112 fatalities were attributed to the storm, including at least 26 deaths from tornadoes, severe thunderstorms and flooding which ripped across Florida on the evening of 12 March (FL on Fig. 2). Other causes of fatalities included traffic accidents, exposure, and heart attacks while shovelling snow. At least 15 died in Pennsylvania, three in Cuba, and four in Quebec, Canada. The storm also produced strong wind gusts in many places, and caused high tides and beach erosion.

(a)



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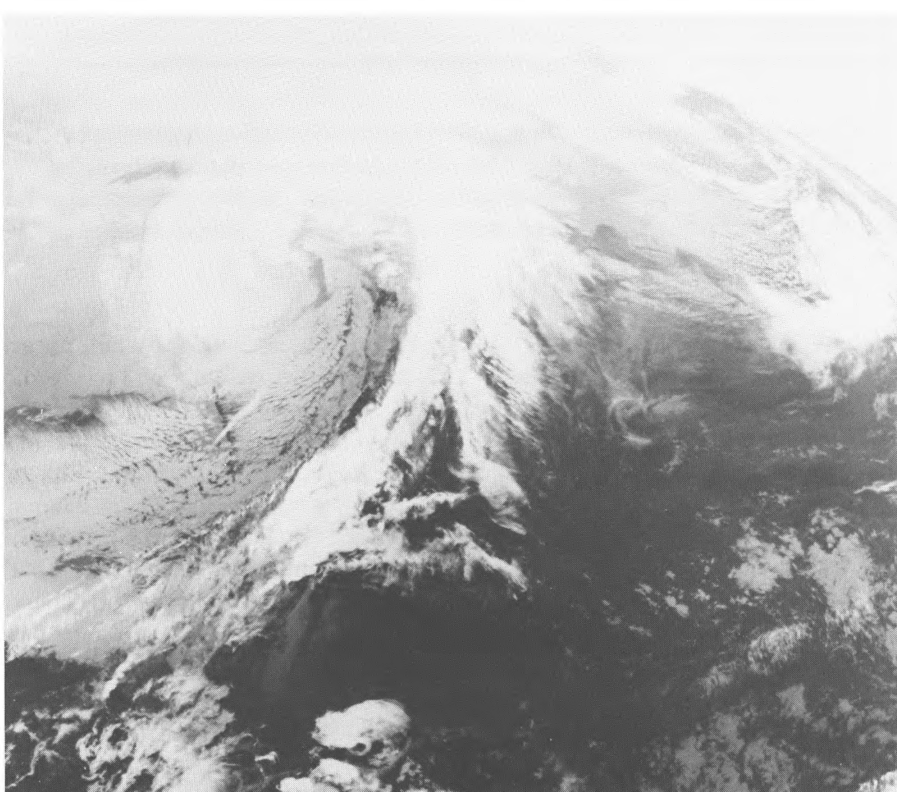
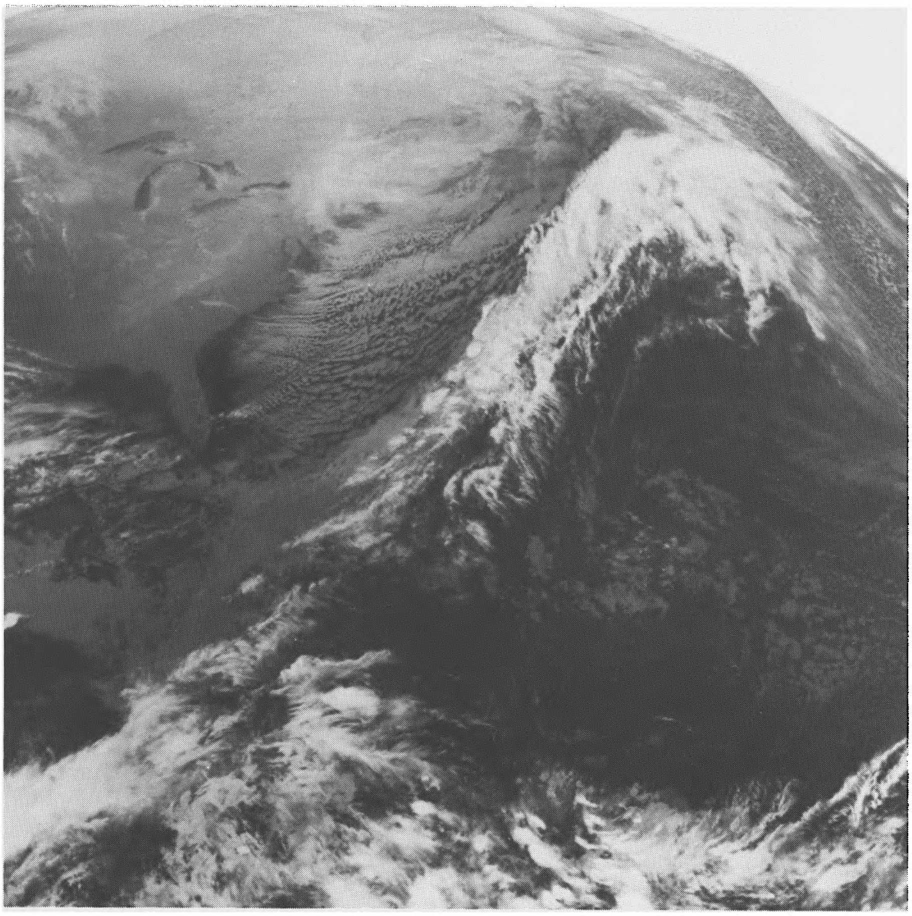


Figure 1. (a) Working chart from the Central Forecasting Office of the UKMO for 0600 UTC on 14 March 1993, (b) Meteosat image of the storm at 2355 UTC on 13 March 1993, and (c) as (b) but 24 hours later.

(c)



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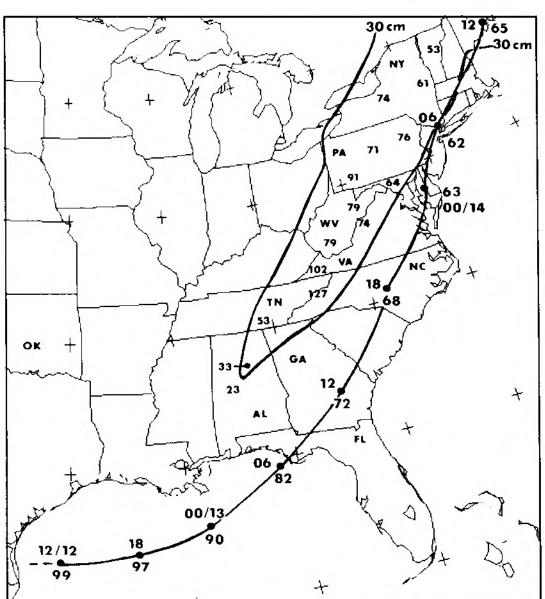


Figure 2. Track of the low-pressure centre and swath of heaviest snow accumulation in the storm of 12–14 March 1993. Storm track is depicted by heavy line with dots at 6-hour positions. Times are depicted along the track with pairs of numbers; e.g. 18/12 indicates 1800 UTC on 12 March 1993. Numbers to the right of the storm track indicate central pressure at 6-hour intervals (99 indicates 999 hPa; 82 indicates 982 hPa). Other heavy line outlines area receiving snowfall accumulations of at least 30 cm, with small numbers indicating selected points of maximum reported snowfall (cm). Letter pairs refer to States mentioned in the text (e.g. AL = Alabama).

Eighteen homes on coastal Long Island, New York reportedly toppled into the sea. Damage was reported to many shore-front homes in other states. Melting of the snow pack contributed to flooding in the mid-Atlantic States and New England about two weeks later.

The storm drew much of its energy from a strong thermal contrast, with many stations across the northern United States (and to the north in Canada) experiencing a 500 hPa temperature of −40 °C or colder on the morning of 12 March, while the Gulf Coast states had just experienced a period of near-record warmth. A massive cluster of convection developed over the northern Gulf of Mexico, and an impressive squall line developed rapidly across the Gulf. This is illustrated by the Meteosat 3 IR images in Fig. 3 and by the lightning activity detected from the other side of the Atlantic by the UKMO's ATD system. As shown in Fig. 4, the first flickers were observed off New Orleans at about 1800 UTC on the 12th and developed steadily to a peak at about 0500 UTC on the 13th and then dissipated by about 2000 UTC. (The storms over the Atlantic shown in Fig. 4(b) were discarded later as the ATD system adjusted itself to increased activity elsewhere.) The greatest activity came just as the line started to cross Florida and Cuba. The squall line produced tornadoes and wind damage across Florida; Cuba seems to have escaped tornadoes but had winds gusting to 90 kn (see 'World weather notes' in the June

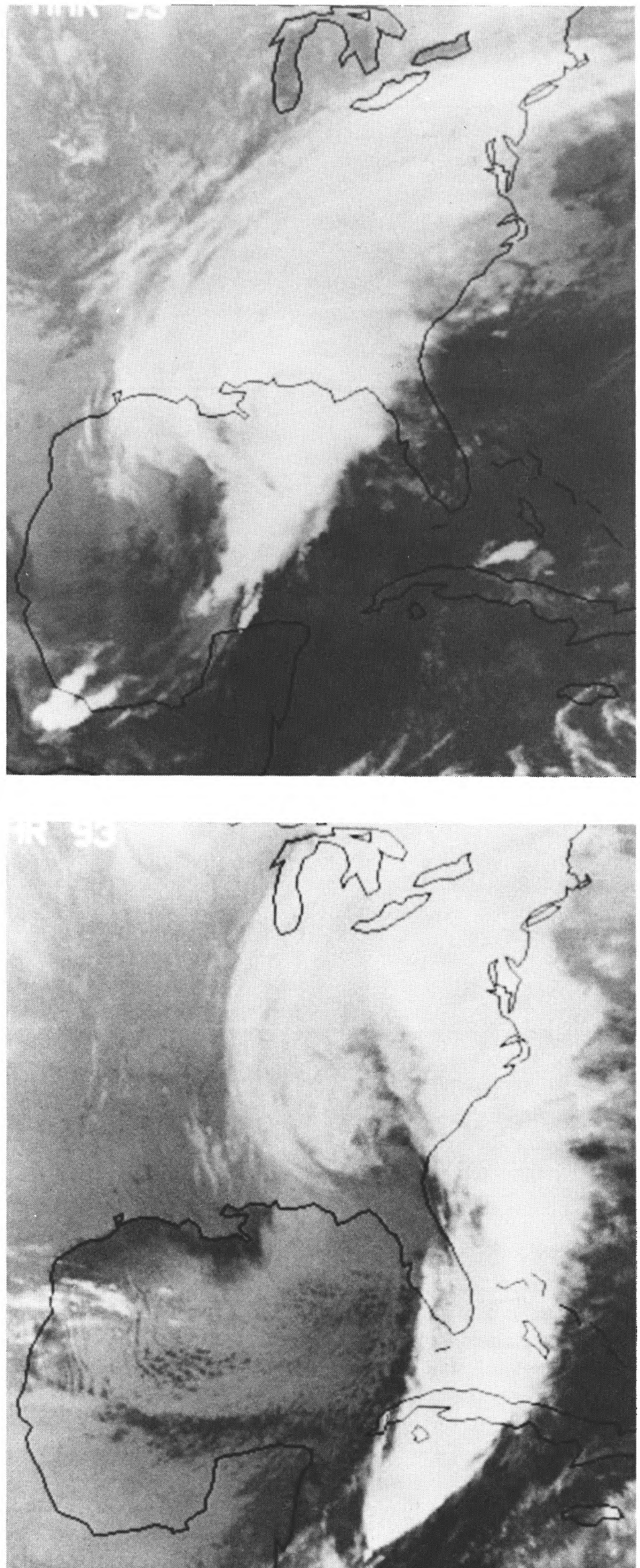
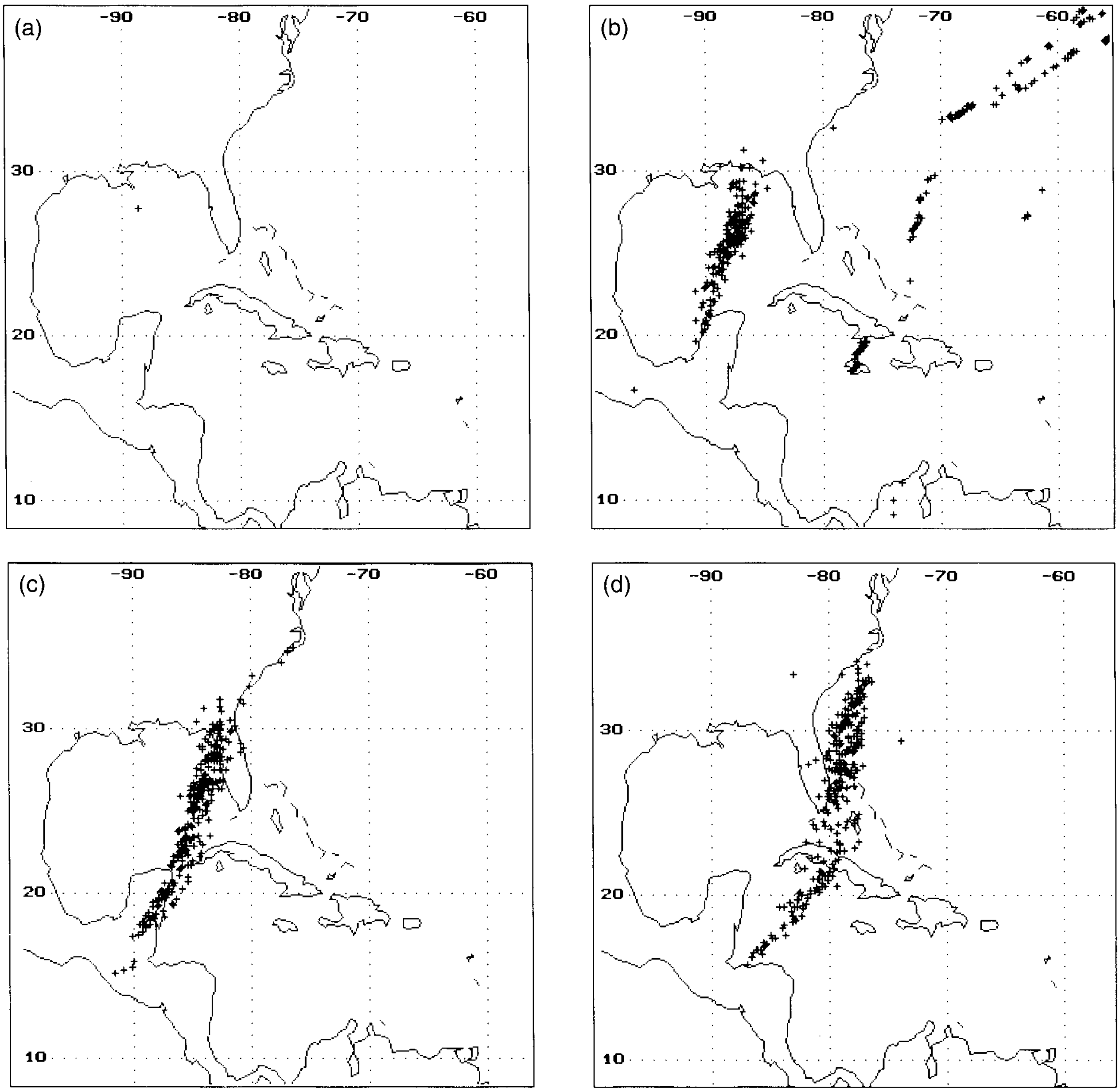


Figure 3. Meteosat 3 IR images taken on 13 March 1993 at (top) 0000 UTC and (bottom) 1200 UTC.



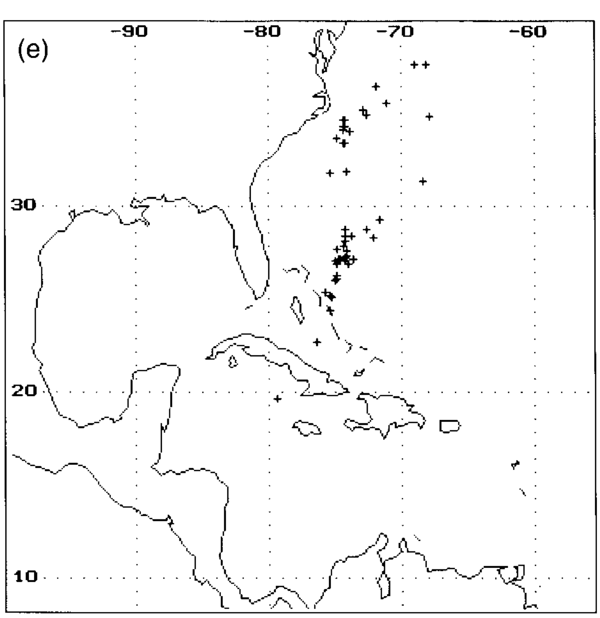


Figure 4. The development of electrical activity on the squall line as gathered by the UKMO ATD system for 2-hour periods. (a) 12th 1700 to 1900, (b) 12th 2300 to 13th 0100, (c) 13th 0500 to 0700, (d) 13th 1100 to 1300, and (e) 13th 1700 to 1900 (all times are UTC). Each '+' represents one or more lightning strikes in a 1/20 degree square.

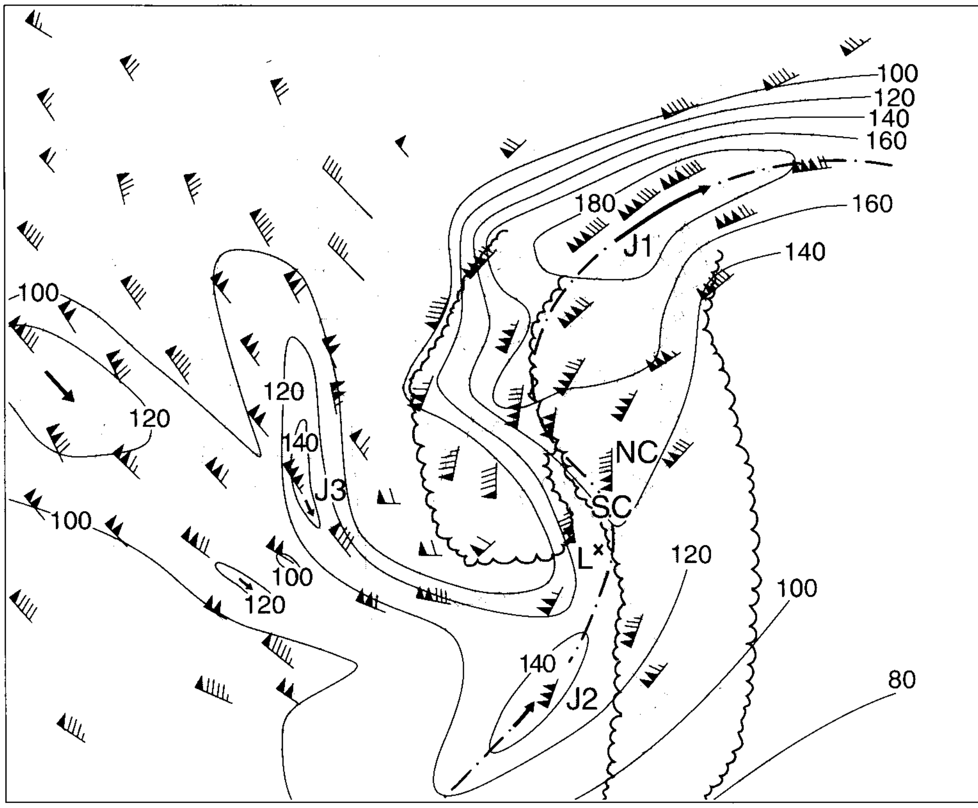


Figure 5. Maximum reported upper-tropospheric winds (kn) at 1200 UTC on 13 March 1993. The dash–dot line is the axis of maximum winds, and the scalloped line is the edge of the high cloud from Fig. 3 (bottom). J1, J2 and J3 are jet streaks, NC and SC are North Carolina and South Carolina states and L is the surface low centre.

1993 issue of *Meteorological Magazine*). The cyclone deepened from about 999 hPa to about 982 hPa while accompanying the trailing edge of the squall line across the Gulf of Mexico, making it seem likely that latent heat release within the widespread convection also contributed to cyclone intensification.

The major thermal contrast was accompanied by very strong jet stream winds, measured as high as 90 kn over northern Maine at 1200 UTC on 13 March in the upper troposphere, and exceeding 160 kn at many stations across the north-eastern United States. Winds of 200 kn were reported over north-eastern Canada at 0000 UTC on 14 March.

Fig. 5 depicts the upper-tropospheric wind pattern at 1200 UTC on 13 March. The strong winds over New England and north-eastern Canada were affiliated with the confluence of several branches of the polar jet stream, resulting in a jet streak entering Maine at 1200 UTC. Also shown in Fig. 5 is a subtropical jet streak located over the Gulf of Mexico. The cyclone intensifying over south-eastern Georgia at this time was, therefore, in the entrance region of the polar jet streak and the exit region of the subtropical jet streak. Uccellini and Kocin (1987) have shown that this type of positioning is dynamically favourable for, and common in, east coast heavy snowstorms. Divergence was present at 250 hPa throughout the region between the jet streaks, with values as large as $6 \times 10^{-5}\ s^{-1}$ near the North Carolina/South Carolina border. The branch of the jet stream and embedded streak heading south over Oklahoma were affiliated with mid-tropospheric cold advection which was helping amplify the mid and upper-tropospheric trough centred over the Mississippi River Valley.

Strong winds were observed at all levels, with gusts exceeding 86 kn reported on mountain tops in North Carolina and New Hampshire. Strong surface winds created snow drifts more than 3 m deep in places.

Fig. 6 depicts key features of the surface chart at 1200 UTC on 13 March 1993. In detailed surface analyses, the beginning of a 'bent-back' warm or occluded front or 'T-bone' front (Shapiro and Keyser 1990) can be seen to the south-west of the cyclone centre. The warm front shown along the Atlantic coast is collocated with a coastal front moving slowly inland, common in major east coast snowstorms (Kocin and Uccellini 1990). Temperatures decreased by 10 °C over about 65 km to the west of the coastal front. The storm centre tracked north-eastward along the coastal front during the day.

Perhaps the most striking aspect of this storm was the broad expanse of the east experiencing moderate or heavy snowfall rates simultaneously: 1500 km long by up to 300 km wide (Fig. 6). The snow extended well to the north of the surface low-pressure centre in a belt parallel to the coastal/warm front, and to the south-west of the cyclone centre in the region of strong low-level cyclonic

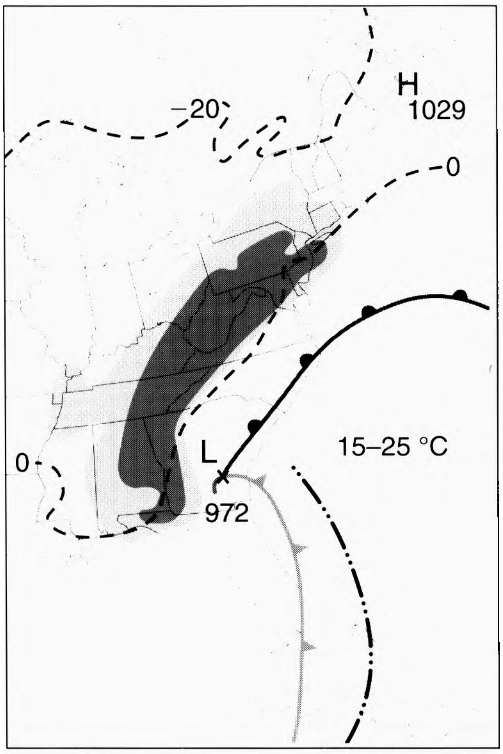


Figure 6. Surface chart for 1200 UTC on 13 March 1993. The dash–dot line is a squall line, and heavy dashed lines are are isotherms (°C). Light shading indicates falling snow and darker shading indicates moderate or heavy snowfall. Temperatures in the warm sector ranged from 15 °C near the warm front to 25 °C in the south-east of the figure.

curvature. The snow in the latter portion of the storm may have also been enhanced by upward vertical velocities in the left exit region of the approaching Oklahoma jet streak (Fig. 5). The snow ahead of the cyclone is attributed to moist south-easterly winds at low levels ascending the coastal/warm front and veering toward the north-east. This region was also experiencing positive vorticity advection (Fig. 7).

A moderate high pressure centre is located over Nova Scotia on Fig. 6. Unlike many north-east heavy snowstorms, this anticyclone had not been in residence over New England well in advance of the snowstorm, but had developed there since 1200 UTC on 12 March. Much of the anticyclogenesis is consistent with the New England region being under the influence of a strong large-scale confluence zone in the upper troposphere during the period. The development of a coastal front along the New England coast by this time (not shown) is linked to the anticyclogenesis. The coastal front forms in the confluence between onshore (easterly) gradient winds over the ocean south of the anticyclone centre and frictionally backed and orographically blocked (north-easterly) flow along the east slopes of mountains inland.

Fig. 7 shows the 500 hPa pattern at the time when the storm had just completed its period of most rapid deepening. The cyclone centre is located at the trailing (south-west) edge of a zone of strong cyclonic absolute vorticity advection that is producing rapid pressure falls over the

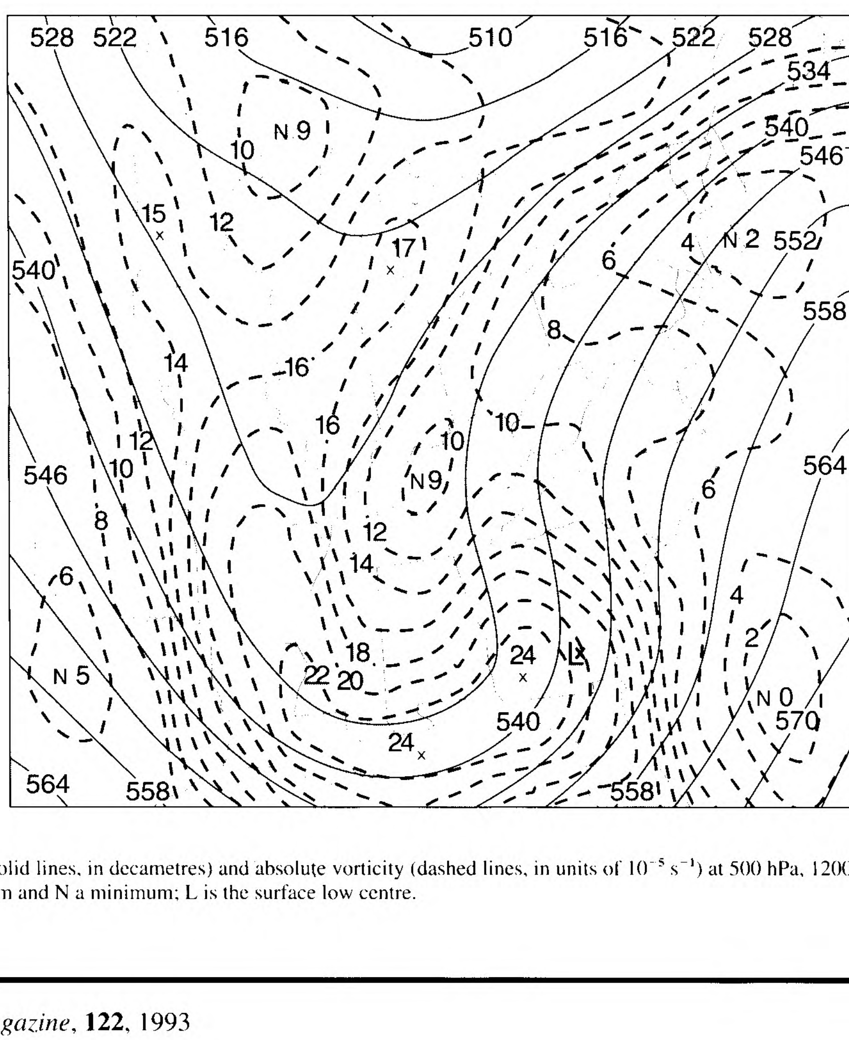


Figure 7. Heights (solid lines, in decametres) and absolute vorticity (dashed lines, in units of 10^{-5} s^{-1}) at 500 hPa, 1200 UTC on 13 March 1993. X is a vorticity maximum and N a minimum; L is the surface low centre.

region toward which the cyclone is moving. Of course, by quasi-geostrophic theory, vorticity advection must increase with height to contribute to upward motion. Fig. 8 shows the region where cyclonic vorticity advection increases with height in the layer from 850 to 400 hPa. Heavier stippling indicates larger implied upward motions. The pattern correlates fairly well to the belt of moderate to heavy precipitation. Warm advection aloft over the same region is also contributing to surface pressure falls.

Fig. 9 shows the contribution of thermal advection to vertical velocity through use of isentropic analyses on the 293 K surface. Fig. 9(a) shows the pressure levels at which 293 K potential temperature is found, and the winds relative to the isentropic surface. The surface is assumed to be moving toward the west/north-west at 9 kn, the observed velocity of the coastal/warm front. Strong upward motion is implied, as relative winds are crossing strongly toward lower pressures, overrunning the frontal surface. Thus, air from near the surface at HAT ascends the frontal zone and precipitates, reaches IAD at about 725 hPa, and then veers off to the north-east as it continues to ascend.

Fig. 9(b) shows the observed winds on the 293 K isentropic surface. The streamlines clearly show the distinction between the moist conveyor belt heading north-westward off the Atlantic Ocean and rising over the coastal/warm front, versus the polar westerlies to the west of the cyclone. This limiting streamline agrees fairly well with the western limit of the precipitation. Also shown are relative isentropic vertical velocities calculated through use of Fig. 9(a). Two corridors of strong upward motion can be seen: one just west of the surface position of the coastal/warm front, and one farther to the west near the crest of the Appalachian mountains. Upward vertical velocities as large as 21 microbars s^{-1} were computed in the corridor near the coastal front.

Fig. 10 shows soundings from along the Atlantic coast at Cape Hatteras, NC (HAT) and within the belt of moderate to heavy snow at Washington, DC Dulles International Airport (IAD). The frontal inversion can easily be seen over IAD, which separates the warm conveyor belt aloft from the cold conveyor belt beneath the inversion (Carlson 1980). The isentropic charts of Fig. 9 crossed IAD at about 725 hPa, just beneath the top of the inversion layer. Winds at this level were from the south-south-east at about 50 kn, but increased to 62 kn and veered to southerly within the base of the warm conveyor belt near 650 hPa. Thus, warm air from near the Atlantic coastline flows north-westwards, overruns the frontal surface and cools moist adiabatically. In the process, precipitation occurs first as moderate rain, then ice pellets, and finally moderate to heavy snow as the initially warm air is progressively cooled during its ascent.

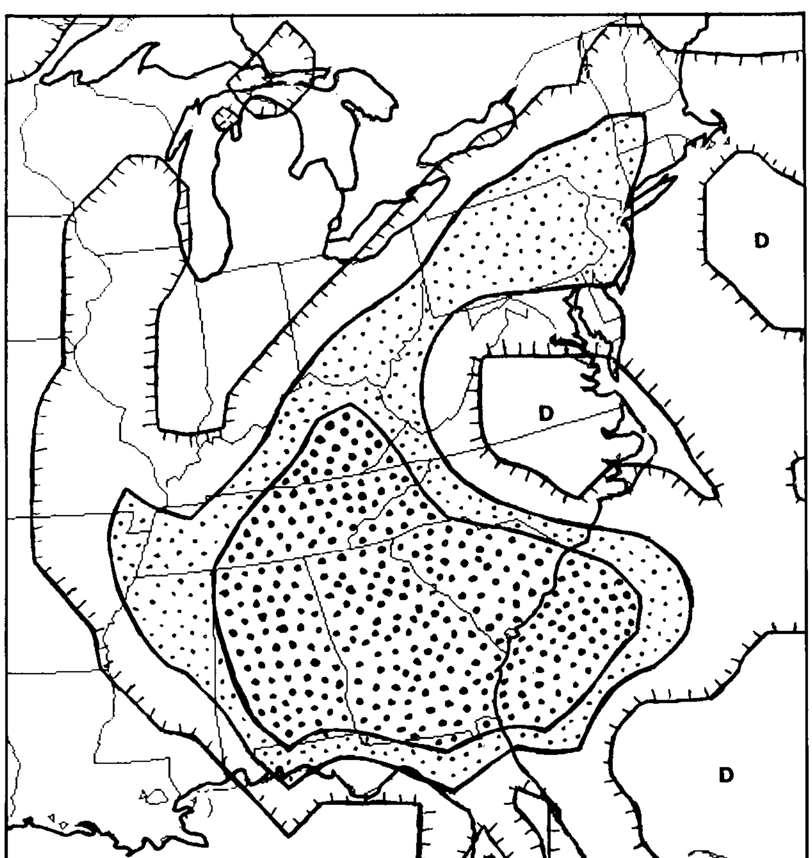


Figure 8. Differential advection of absolute vorticity in the layer from 850 to 400 hPa at 1200 UTC 13 March 1993. Areas within the hatched line but without stippling represent weak contribution to upward motion from differential vorticity advection. Light and heavy stippled areas represent moderate and strong upward motion contributions. Areas labelled with D have a decrease of vorticity advection with height, contributing to downward motion.

(a)

(b)

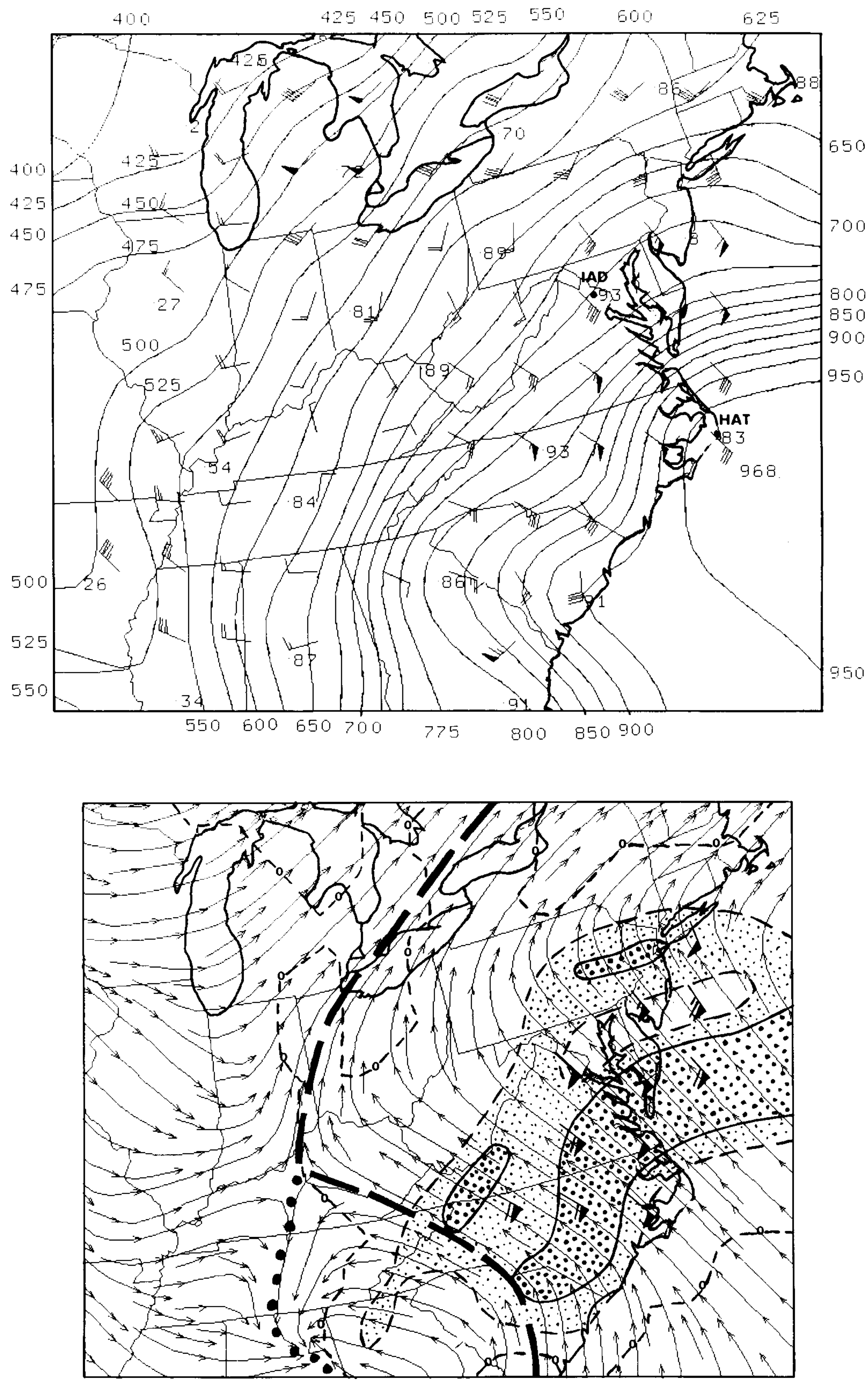


Figure 9. Isentropic analyses on the 293 K surface at 1200 UTC on 13 March 1993. (a) Pressures and relative winds. A movement of the isentropic surface from the ESE at 9 kn has been subtracted from the observed winds, representing the speed of movement of the coastal/warm front. Numbers indicate relative humidities with respect to liquid water at rawinsonde sites. (b) Streamlines of the observed winds, and wind barbs showing the area with wind speeds in excess of 50 kn. Areas with upward vertical velocity are shown, with light stippling where vertical velocities are 5–10 microbars s^{-1}, and heavy stippling where greater then 10 microbars s^{-1}. Heavy dashed line depicts limiting streamline separating moist flow off the Atlantic from dry continental polar air. Heavy dotted line represents deformation zone near the cyclone centre where bent-back warm/occluded front or frontal 'T-bone' is forming aloft.

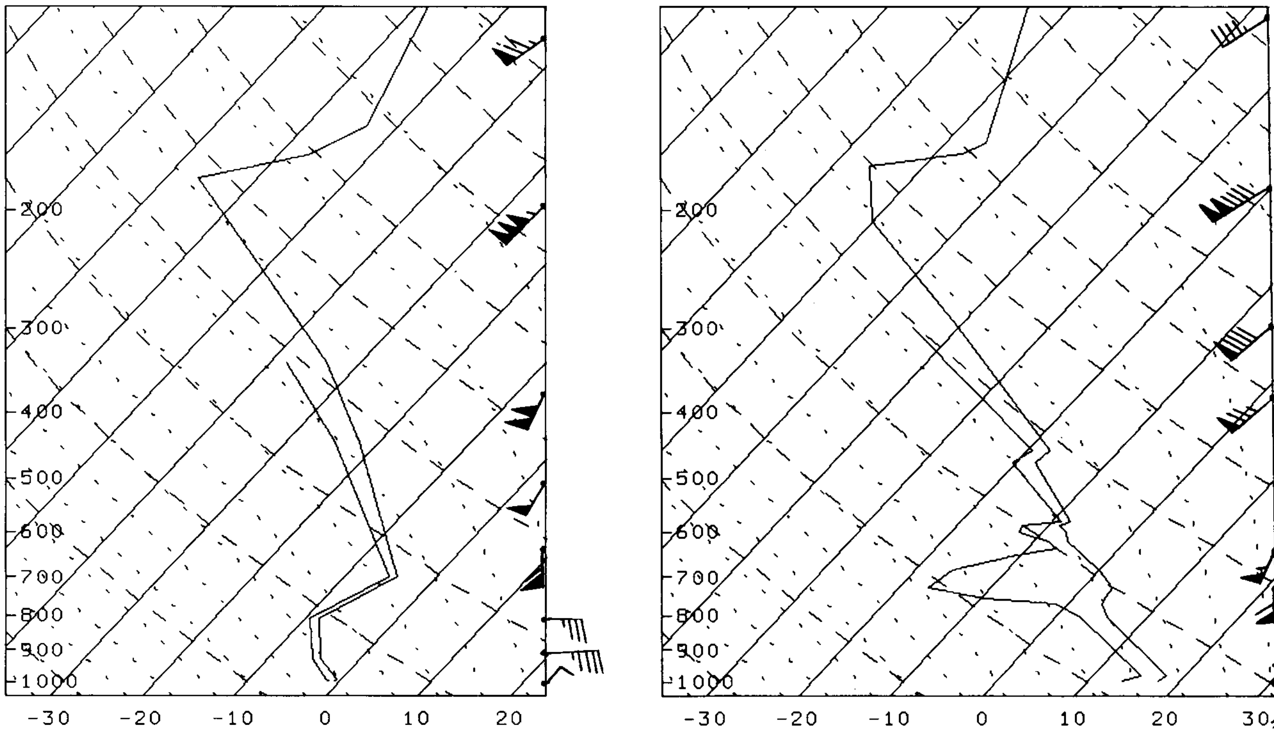


Figure 10. Soundings, skew T-log$P$, from (left) Cape Hatteras, North Carolina (HAT on Fig. 9(a)) and (right) Washington, DC Dulles International Airport (IAD on Fig. 9(a)) at 1200 UTC on 13 March 1993.

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Understanding the North Sea System

Preface

On 4 and 5 November 1992 a scientific meeting on 'Understanding the North Sea System' was organized by, and held at, The Royal Society. What follows was prepared after the meeting by The Royal Society and The Association of British Science Writers, to summarize key issues raised by the speakers. I am indebted to Dr S.J. Foreman of the Meteorological Office for contributing additional comments and explanations and to Valerie Doodson of the Proudman Oceanographic Laboratory for the chart and trapping a few residual errors.

This is the first of what I hope will be a series on ocean–atmosphere interactions: papers on sea-ice, wave modelling, and sea-level are being prepared for later this year.

Introduction

The North Sea is but a puddle compared to the world's mighty oceans. But to the countries around it, and Britain in particular, it is a source of food, energy and recreation as well as a sink for all manner of waste. It was therefore appropriate that scientists embarked, in 1988, on a project to understand the North Sea more thoroughly and in more detail than any large sea has been understood before.

The North Sea is a shelf sea — that is to say it lies not over the thin crust of the deep ocean but what is essentially a submerged continuation of the European continent. It is possible that convection in the Earth's mantle at about the time that the North Atlantic opened almost caused an ocean to open up where the North Sea now is. The result was a stretching of the earth's crust so that the upper surface sagged and filled with sediment and the underside rose bringing heat up to bake the sediments, maturing reserves of oil and gas in the process.

Today, an emerging realization of the practical and economic importance of the Sea is coupled with concern about the health of the environment of these waters. In order to understand the interactions of both aspects, scientists are faced with the challenge of discovering the processes which control that environment. The 'North Sea Project', a major research initiative managed by Britain's Natural Environment Research Council, aimed to gather enough information to be able to set up a model of the North Sea through which to reveal the impacts of agriculture and industry as well as natural processes, and to understand the consequences of our actions in the future. What has resulted is not a physical model of the sea but a numerical model in a supercomputer. All the processes are represented by calculations and by changing the numbers it should eventually be possible to work out the real changes that could arise as a result of political action or inaction.

Motivation for the North Sea Project thus came about both from strategic necessity and from a need for fundamental science. No sea, and particularly no sea so closely linked with land and human activity, can be considered in isolation. There are constant interactions through rivers and coastal discharges, from the air, from the underlying sediments and within the water column itself. Such processes were very poorly understood and the North Sea offered the possibility of combining new and fundamental scientific research with something that has a high profile in the public mind.

Inputs and outputs

The North Sea is an environment under pressure. It receives a huge input of what, to man, is waste but, to marine algae are nutrients: human and animal sewage and nitrates washed from well-fertilized fields. The River Rhine alone contributes about a million tons of nitrate every year and until recently that output has been doubling every fifteen years. The result is often good news for the marine algae or phytoplankton that use nitrate as food. With the summer sun to aid their photosynthesis they can multiply on a tremendous scale and sometimes, particularly along the Dutch and German coasts, produce great foaming blooms reminiscent of pollution by detergent. In theory these might consume all the oxygen from the water, leaving it anoxic. In practice, so far at least, the blooms are very localized and only slight oxygen depletion has been observed around the Dogger Bank and the German Bight, and that does not last long.

Algae in their turn are food for marine animals. They are grazed upon by microscopic zooplankton which in turn are consumed by tiny predators and so on, up the food chain to fish. But fish have been removed from the North Sea at a phenomenal rate. At present one fish out of three is caught every year (*poor thing! Ed*). The long-term result of that has not only been a decline in all fish, but also a change in the balance of species, from herring and halibut to fish such as sandling that are usually processed industrially into animal feed.

In 1988 the plight of the North Sea was given widespread publicity as a result of the death of hundreds of seals around its shores. Ironically, this was almost certainly due to an epidemic of viral infection and not directly to pollution, but it placed the North Sea Project, which began in the same year, centre stage.

The North Sea Project

For fifteen months between August 1988 and October 1989, the Royal Research Ship *Challenger* (Fig. 1) worked exclusively on the North Sea Project, sailing a 3200 km course around the southern North Sea every month. Each circuit lasted for twelve days and RRS *Challenger* was able to visit up to 120 separate sampling stations. At each, instruments were lowered over the side and data were recovered from moored instruments. For the other half of each month, the floating laboratory concentrated her attention on studying specific processes in more detail: the physics and chemistry of the sea, the interactions between air, sea and sediment and the biology of the waters.

A series of special instruments was developed to accomplish this. Principal among them was a structure weighing a quarter of a ton and including sensors for temperature, salinity, dissolved oxygen, the chlorophyll in plankton and the clarity of the water, together with ultra-clean sample bottles that could be filled at different depths beneath the ship. It is a tribute to the crew of RRS *Challenger* that they deployed this at most stations, even in gale-force winds.

Another essential instrument was Seasoar, a device resembling a small, stubby-winged aircraft that could be towed behind RRS *Challenger*. Thanks to special hydrodynamic faring on the towing cable, Seasoar could be used whilst the ship was cruising between sampling stations at her full, if leisurely, speed of 9.8 knots. By angling the 'wings', it was possible to steer Seasoar up and down to take measurements at different depths. Perhaps most valuable of all, though less obvious, was the simple fact that all the measurements were carried out from the same ship with the same instruments calibrated to the highest standards, so the results could easily be combined into a single comprehensive database on the North Sea. Those processed data are now available internationally on a compact disc.

The dynamic sea

In the south, the North Sea is typically no more than 40 metres deep. In the north it can be deeper than 100 metres. That is deep enough to cause complex problems for divers and oil companies installing offshore production platforms, but to an oceanographer it is shallow indeed. The North Sea is also almost entirely surrounded on three sides by land. Yet into that enclosed basin comes a huge input of energy. The tides supply about 50 gigaWatts. That is roughly the total electricity

Photograph by Terence Soames (Cardiff) Ltd

Figure 1. RRS *Challenger.*

consumption of the whole of the United Kingdom. It is manifested not only as the twice daily rise and fall of sea level but also as a powerful stirring force. It lifts sediments and mixes chemicals through the water column. At the same time, the sea surface is also stirred by the wind.

Energy also comes from above as the sun warms the surface, particularly in the summer. That tends to make a layer of warm water develop at the surface. Because this warm water is less dense than the body of the sea below, it stays there. This kind of layering is known as thermal stratification. Further stratification can arise from salinity. In the North Sea, there is a constant battle between the sun's energy causing stratification and tidal energy mixing the water up. In the north, the sun wins and the surface of the sea remains comparatively warm and unmixed. In the south, tidal energy mixes the entire water column so the sun must heat more water and surface waters are cooler. The mixing in the south also stirs up more sediment so the water is less clear. That stirring process, together with input from rivers in the south, makes more nutrients available to stimulate algal growth.

Where the stratified northern waters and the mixed southern waters meet, they form a front, a region of sharp horizontal temperature gradients similar to fronts in the atmosphere. During the North Sea Project, RRS *Challenger* sailed to and fro across one of these fronts which typically runs down the Yorkshire coast and then across from Flamborough Head towards The Netherlands. Complex eddies can develop along it and biological activity in the form of plankton rises and falls depending on the temperature, clarity and availability of nutrients. In some places warm, clear water from the north and nutrients from the south provide just the right conditions for a bloom of phytoplankton such as coccolithophores.

The tidal rise and fall in the North Sea due to astronomical effects was predicted last century by Lord Kelvin and is one of the easiest things to model numerically. More recent models include the effects of the wind and are accurate to less than half a metre and regular predictions (from a model developed by the Proudman Oceanographic Laboratory (P.O.L.)) are issued by the UK Meteorological Office. Such models are also useful for tackling the harder problem of the fate of pollutants.

There is an overall anticlockwise circulation in the North Sea (see Fig. 2). Currents are fastest along the Norwegian coast where the maximum is about 13 km per day, but typically the flow is only a few kilometres per day and pollution can remain in the confines of the Sea for up to three years. During the North Sea Project, current measurements were taken from the ship, from moored instruments and by tracking free-floating buoys using satellite or radio navigation systems. There were mechanical current meters, acoustic Doppler current meters and radar current meters. Traces of radioactive caesium discharged from the nuclear reprocessing plant at Sellafield were tracked rounding Scotland and entering

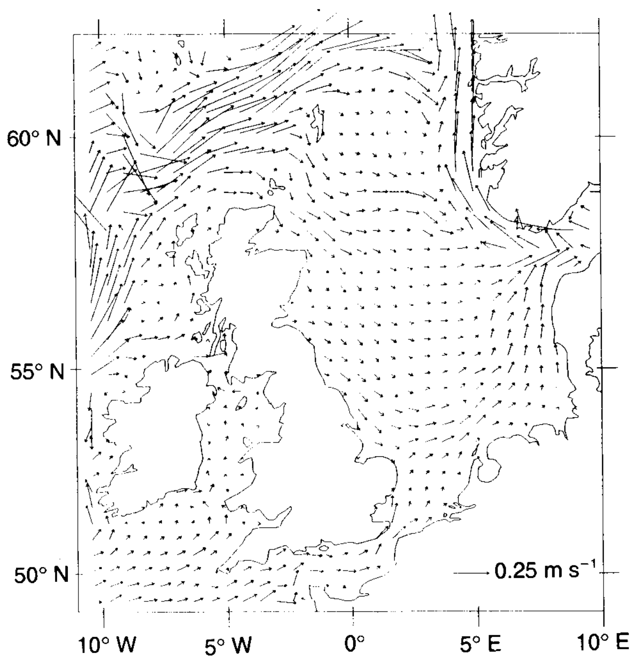

Figure 2. Mean surface currents (0–10 m depth) for January from a 3-D numerical model.

the North Sea. The flow through the Strait of Dover was monitored by radar from May 1990 to August 1991.

Vanishing sediments

The North Sea is muddy. It is not simply mud washed down in rivers. A large amount is stirred back into suspension from the sea floor or eroded from coasts. It provides a major constraint on the biological productivity of the waters by clouding them so that sunlight cannot reach algae far below the surface. The mud particles also perform important roles in absorbing chemicals such as metals and pesticide residues and thus remove pollutants from the water column. The sediments also store and release nutrients, continually recycling them into the marine environment.

One of the major surprises in the North Sea Project was the scale of sediment transport. At any one time in the summer there is about a hundred million tons of sediment suspended in the North Sea. In the winter, as gales whip up the waves and tides scour the bottom, the suspended sediment rises fourfold (the organic component remains roughly constant, the change is basically due to mud). The nett loser in this process is the British coast between Suffolk and Yorkshire, particularly the Holderness coast. Between them, they lose 6 million tons every year, most of which is transported across the sea towards the German Bight where it is deposited around the Friesian Islands. A lot of the pollutants are probably deposited here also, locked up in the sediments.

Interactions with the air

Rivers may supply most of the chemicals that enter the North Sea but a substantial quantity also comes from the air. The shallow sea with a large surface area, its waves and roughness, plus wind and rain all conspire to transfer soluble gases into the sea. If it were just a physical process, it would soon reach equilibrium with as much gas coming out of the sea as goes into it. But chemical changes take place which remove some of the dissolved gases from the balancing mechanism.

Carbon dioxide, for example, is taken out of solution by plankton which use it through photosynthesis to build their cells. They die, sink and decompose or are eaten by larger organisms. Eventually, a lot of the carbon gets recycled back to the atmosphere but some sinks to the bottom and is removed from circulation. During the North Sea Project, the scientists attempted to measure the rate at which carbon dioxide is removed from circulation. Before humans started burning fossil fuels and felling forests in large quantities, it is probable that the carbon cycle balanced. Now, we are releasing billions of tons of extra carbon dioxide every year. But it is not all remaining in the atmosphere and adding to the greenhouse effect. About half of the extra is somehow removed and it was assumed that the principal mechanism for this was through the microscopic plants in marine plankton. Measurements during the North Sea Project showed that this route only accounts for about 30% of the excess carbon dioxide. So perhaps processes on land, and in particular in forests, may account for more than anyone realised, making their destruction all the more serious.

The atmosphere supplies oxygen too; the oxygen that fish and other animals require, and the oxygen used as organic material decomposes. A fear that is frequently expressed in connection with the North Sea is that nutrients, such as nitrates and phosphates, washing into the sea from human activities, will stimulate the growth of plankton which will in turn die, sink to the bottom of the sea and decompose, using up oxygen from the water. In theory, that could lead to what is known as eutrophication — the water might become so starved of oxygen, at least at depth, that it becomes stagnant and smelly, changing the chemistry of its interaction with the sediments on the bottom.

That is already happening in parts of the Baltic where, each spring, organic material from the plankton blooms builds up below the surface and uses up all the oxygen. Since they cannot oxidise further, the nutrients remain suspended or dissolved in the water and if they were stirred up again by storms and brought back into the sunlight near the surface, they might not only create a stink but also produce a slime near the surface.*

During the North Sea Project, the scientists found that oxygen depletion was indeed occurring in the North Sea, on either side of the Dogger Bank and close to the coast of The Netherlands. But they doubt that a larger eutrophic zone is likely to develop because of the powerful tidal mixing which brings fresh oxygen throughout the water column.

* Readers wishing to learn more about air–alage–ocean interations are recommended the article in *New Scientist* of 21 August 1993.

The North Sea gives out gases as well as soaking them up. On the top deck of RRS *Challenger,* well forward of any contamination from the ship, was equipment from the University of East Anglia consisting essentially of lengths of plastic drainpipe connected to a vacuum cleaner. What it was actually doing was drawing the sea air in through a series of physical and chemical filters so that researchers could study traces of organic chemicals, metals and acid gases. Chemicals dissolved in rainwater were also analysed. One of the more surprising findings of this project was that the North Sea makes a considerable contribution to the problem of acid rain.

The phytoplankton breathe out dimethyl sulphide, a sulphur-containing gas which easily breaks down in the air into a variety of other gases, such as sulphur dioxide, and eventually gives rise to cloud condensation nuclei. These can dissolve in rainwater and fall as acid rain. The North Sea scientists calculated that the sea contributes as much as 25% of the sulphur that falls over Europe as acid rain. That still leaves three times as much coming from land, mostly from power station chimneys, so does not absolve humans of responsibility for acid rain. But it does mean that, however strict the curbs on man-made emissions, a residue will persist.

The dimethyl sulphide production is strongly seasonal, following the spring phytoplankton blooms. These are encouraged by nitrates washed out with sewage and agricultural run-off. So ultimately, human activity is at least partly responsible for this source of acid rain too. It illustrates how complex the interactions are both within the North Sea and between mankind's various activities.

A model for the future

The wealth of data from the North Sea Project has been fed into a Cray supercomputer by scientists at the P.O.L. The numerical model of the North Sea developed by P.O.L. now fits the observed facts with considerable precision. The horizontal currents, the vertical mixing, temperature, salinity, air and sediments are all represented. The aim is that, for any set of starting conditions, the computer will calculate how the real sea will develop. Once that is achieved, the scientists will have what they call a water-quality model. They will be able to program in various different political scenarios such as curbs on the use of nitrates or the discharge of sewage and see what their impact will be at sea.

The North Sea has a vast capacity for absorbing and treating the wastes we discharge into it, but that capacity cannot be infinite. At present, the great saviour is the natural stirring of the sea. It disperses pollutants and stirs up sediments so that light does not penetrate very deep, limiting phytoplankton to the surface. Thus they do not normally grow out of control in spite of abundant nutrients. The slimy froth of Phaeocystis plankton washing up on the shores of The Netherlands , and the eutrophication of water sheltered by the Dogger Bank are warnings that limits cannot be safely exceeded. Just what those limits are, and how the resources of our local sea can best be managed, should emerge from the computer models in the years to come.

The pioneering work performed on the North Sea will have applications far beyond our shores. Canada's Gulf of Maine, the Patagonian Shelf off Argentina and China's Yellow Sea are all examples of shelf seas to which many of the lessons learned in the North Sea will apply. Ultimately, even the best science will have to be supported with the political will to preserve the quality of such waters.

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Black south-easter havoc in Cape Town

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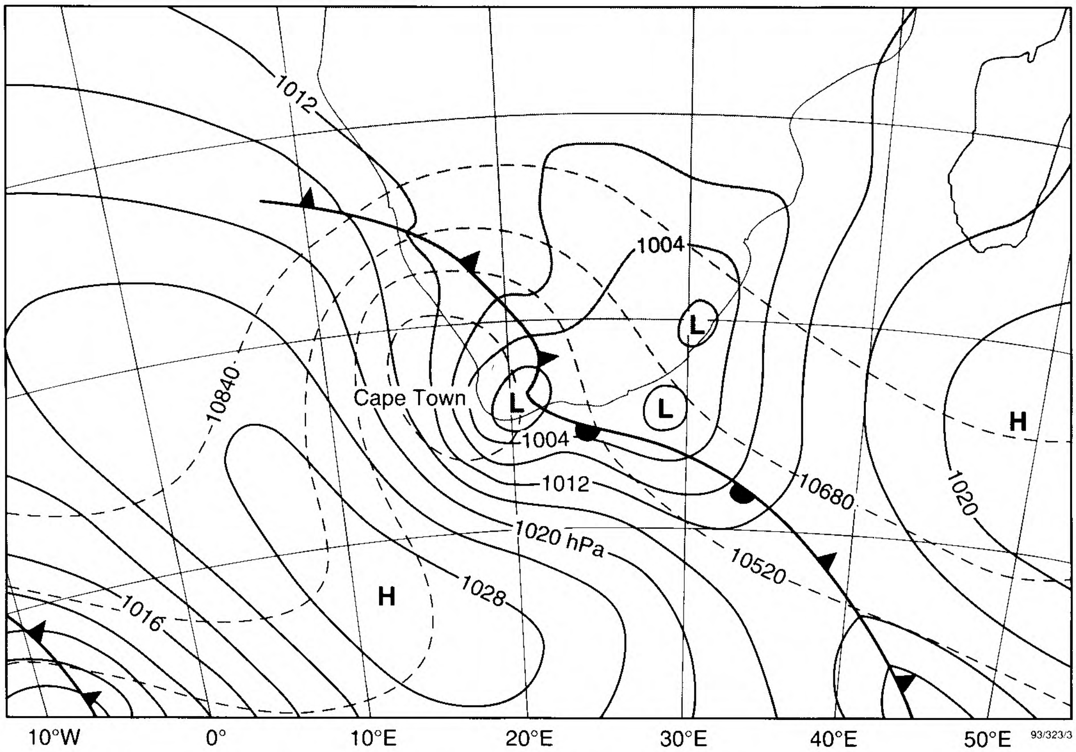
The extraordinary wind and rain condition that battered the Cape Town area during Easter 1993 was caused by the passage of a well developed cut-off low pressure system, locally termed a 'Black south-easter'. The prevailing summer 'south-easter' being a shallow wind associated with sunny weather.

A high (1016 hPa) in the area between Gough Island and South Georgia during 8 April started moving eastwards and a large amplitude trough approached Gough on the 10th setting up a strong meridional flow west of the high which in turn developed to a peak value of 1034 hPa late on the 10th.

Cold sub-polar air sourced in the Bouvet Island area was advected northward towards Cape Town and into a low (1002 hPa) off the South African west coast. This low was spawned and was well reflected passing an automatic weather station (AWS) in the Tristan Island group on the 9th.



Surface chart showing situation on 11 April 1993 at 1200 UTC. Dashed lines are contours (m) at 250 hPa.

The picture above, kindly donated by *The Argus* shows a wave breaking over the Kalk Bay harbour wall. Damage to the breakwater later allowed the waves to get into the harbour itself, and this led to the destruction of the wooden quay in the foreground.

The necessary energy became available to modify this benign low into a deep, cold-cored cut-off low. The low crossed the coast close to 32° S latitude early on 11 April and moved rapidly southward to exit off shore east of Cape Town in the Cape Agulhas area, during the afternoon of the same day with a central pressure of 999 hPa. Strong gale force SSEly winds spread rapidly over the area from the south. One coastal AWS close to Cape Town showed a jump of 22 knots between hourly averaged speeds.

Large topographically induced differences in wind speeds around the Cape Peninsula are well described (Jury 1980). The Port Captain's log noted a gust of 94 knots late on the 11th in the Table Bay Harbour area (anemometer atop a 14-storey building). Under deep SSEly wind conditions the harbour coincides with an area of extreme turbulence where a mountain wave returns to the surface downwind of Table Mountain. Press reports naturally latched onto this sensational value. At the D.F. Malan Airport, hourly averaged winds reached 39 knots gusting to 58 knots.

Cut-off low pressure systems of this intensity are well known to deliver localized extreme amounts of rainfall over the sub-continent. Taljaard describes 11 systems per annum with 1 in 5 causing flooding (Taljaar 1985). The rainfall is induced by vertical motions associated with surface convergence and upper divergence. Local orographic uplift was also a major contributory factor in this case.

Rainfall measured at the airport showed the highest 24-hour total on record on the 11th, namely 96 mm. The previous record standing at 65 mm in May 1974. Two of our rainfall stations situated close to the Franschloek Mountain range recorded 24-hour totals of 150 mm.

A wave-rider buoy on the western side of the Cape Peninsula recorded an increase of 5.5 m in wave height in 9 hours to 1500 UTC on the 11th, to peak at 7.76 m (Hmo), 13.5 sec.

False Bay is a traditionally safe refuge from the winter NWly gales but this abnormal wind driven sea wrecked many fishing and pleasure craft. A wooden quay and part of the sea wall in the Kalk Bay fishing harbour were very badly damaged. The rapid onset of wind caught a fleet of dinghies unprepared in Saldanha Bay. Their regatta was abandoned while rescue craft were kept very busy.

One Cape Town morning newspaper ascribed 12 deaths to this storm, the other, 6. Flooding and road wash-aways were the order of the day while electrical power lines were cut in many areas. At the airport, wind-driven rain from this quarter penetrated the instrument landing system and caused it to malfunction. Air traffic was halted for the night. Local press reported this as the first airport closure in 26 years which resulted in 27 aircraft diversions and 2400 delayed and irate passengers.

Computer model predictions gave ample warning of the excessive wind and rain early on the 10th (Saturday). Local forecasters were most concerned with the possible disruption of home-coming Easter weekend road traffic which is traditionally very heavy. The worst of the storm, however, passed during Easter Sunday afternoon and evening and it was only mopping-up operations which hindered home coming holiday makers.

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Noctilucent clouds over western Europe during 1992

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Summary

Noctilucent cloud observations by professional and amateur observers in the British Isles, Denmark and the Netherlands indicate a very low incidence in 1992.

Table I summarizes the noctilucent cloud (NLC) reported to the Aurora Section of the British Astronomical Association (BAA) during 1992. The times (UT) are the reported sightings limits; not necessarily the durations of the displays. 'Negative' nights (Table II) are based on the judgement of two or more experienced observers north of 54° N with clear or nearly clear sky conditions over the period of the night when NLC is likely to occur.

Only 12 definite NLCs were reported with four 'suspect'. Only one, on 21/22 June, was a major display: from simultaneous parallactic photography by Dr Simmons (Milngavie, Glasgow) and Dr Gavine (Joppa, Edinburgh), Dr Gadsden calculated a height of 81.9±1.0 km. Contributions were received from 15 voluntary observers and three meteorological stations in the British Isles, five excellent observers in Denmark and two stations of the Royal Netherlands Meteorological Institute, but there is still a shortage of observers in the rest of Europe. The Finnish–Estonian NLC sightings continue to be published annually in the journal *Ursa Minor* of the URSA Astronomical Association, Helsinki. Details of individual nights, and observing instructions, are available from the author, but all NLC data up to 1990 are held in the Balfour Stewart Archive at the University of Aberdeen. To avoid confusion it would be appreciated if observers use the 'double date', e.g. 21/22 June, the night of the 21st and morning of the 22nd, and log all times in UT. It would also be useful for more observers to log 'negative' nights.

Our thanks to all observers, amateur and professional, and to the following for their support and co-operation: Mr Ron Livesey (BAA Aurora Section Director), Mr Tom McEwan (Junior Astronomical Society Aurora Section Director), Mr Veikko Makela (URSA, Finland), Dr Balthus Zwart (Netherlands), Mr Mark Zalcik (USA–Canada Network) and Dr Michael Gadsden (University of Aberdeen).

Table I. Displays of noctilucent clouds over western Europe during 1992

Date — night of	Time UT	Notes
2/3 June	2227, 0200	NLC band suspected at Aberdeen and a possible pale horizontal form in a poor sky at Witham, Essex, at 0200, but no NLC visible in clear skies in Stirling, Ayrshire and Denmark.
9/10	2315–0152	White opalescent veil up to elev. 20° at Kinloss, brighter 0045; very faint bands up to 15° at Alness, suspected faint veil at Witham. No NLC visible in Denmark up to 2245 then faint bands at Tisvildelege at 2315.
10/11	2325–0150	Mr Fraser at Alness observed faint bands in NE up to 25°, Kinloss met. station saw faint 'silvery streaks' up to 20°. No NLC visible at Morpeth or S of Scotland, nor Denmark.
14/15	0100–0200	Bands and billows noted by a single observer at Kemnay near Aberdeen but no NLC visible in clearing sky in Ayrshire 0045–0140.
16/17	2345–0115	Suspect diffuse bands in haze in Ayrshire but negative reports from Alness, Milngavie, Morpeth and Denmark.
18/19	0130–0200	Possible NLC in trop. cloud breaks at Glengarnock, Ayr, 0130, definite bands above cloud bank at 25° from 0145.
19/20	2330–0050	No NLC at Vildbjerg (Denmark) up to 2300, moderately bright billows up to 20° at Greve at 2330, bright bands up to 40° at Copenhagen 2345–0050.
20/21	2330	Mr Olesen at Rønne (Bornholm) detected bands up to 15° in a moonlit sky. No NLC at Morpeth but sky conditions deteriorating.
21/22	2130–0245	Bright and extensive display, all forms, reported and photographed from Moray Firth to Isle of Man whose observer noted that it was the brightest he had ever seen. Blue-green colour reported at Milngavie. NLC visible in zenith at Vildbjerg (Denmark) 0100, Morpeth 0200, and in Ayrshire reached altitude 120° at 0215.
26/27	2250–0100	Moderately bright bands observed from North Wales, Isle of Man, Whithorn and Morpeth. At 0005 Mr Young in Dundee saw billows and whirls, white and gold, up to at least 20° in trop. cloud gaps. No NLC visible at Witham and Bornholm.
2/3 July	2230–0035	Mr Andersen at Vildbjerg photographed veil and bands up to 18°. No NLC visible at Stirling, Copenhagen and Bornholm.
3/4	0220–0235	Bright billows in trop. cloud gaps at Glengarnock. No NLC in broken trop. cloud at Bornholm 2115.
8/9	0000	Suspect faint band very low at Stirling. No NLC in clear sky at Milngavie or Glengarnock 2230–0215.
20/21	2110–2340	Veil, bands and billows up to 10° in trop. cloud gaps with bright moon, photographed at Bornholm. No NLC in mainland Denmark. Fair Isle met. station reported one okta of billows up to 20°.
21/22	2155–0130	Bands up to 20° observed at Morpeth and St Andrews, photographed by Mr Whipps at Consett.
22/23	2150–2325	Fairly bright display of bands with some billows and whirls up to 10°, observed at Bornholm and Vildbjerg. No NLC visible in deteriorating sky at Morpeth.

Table II. Negative nights (British Isles and Denmark) north of latitude 54° N

May 25/26, 26/27, 27/28, 28/29; June 1/2, 3/4, 5/6, 6/7, 7/8, 8/9, 11/12, 15/16, 23/24, 24/25; July 4/5, 5/6, 6/7, 7/8, 10/11, 14/15, 25/26, 26/27, 28/29, 29/30, 30/31; August 3/4, 4/5 .

The management of change. Case-study — the commercialization of the UK Meteorological Office

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Summary

This paper presents a case-study of the management of the change towards commercialization by the United Kingdom Meteorological Office during the period 1984 to 1992.

1. Introduction

The UK Meteorological Office successfully integrates a broad range of meteorological activities, research and operational tasks, as well as the provision of services to a very wide range of users. These include the armed forces, national and international civil aviation, universities, institutions, organizations in both the public and private sectors, as well as the general public. On 31 March 1991, it employed 2490 staff, and had an annual expenditure in 1990/91 of £107 million. The present-day Meteorological Office, a part of the Ministry of Defence, is modern, effective, and in the forefront of world meteorology. Forecasts are consistently accurate to well above the 80% level, and it speaks with authority on major issues concerning the environment — the ozone layer, pollution and global warming.

In 1984, an independent review (called the Resource Control Review) recommended greater commercialization of existing services of the Meteorological Office as a way of improving the use of its resources. As part of this, marketing disciplines were developed and applied to the Office's revenue-earning activities. This commercialization process advanced steadily until the present day. In April 1990, the Meteorological Office became an Executive Agency. As both owner and principal customer of the Meteorological Office, the Ministry of Defence has now given the new Agency much more challenging targets than in the past, and a far greater emphasis on developing its customer–supplier relationships.

2. First steps

Services attracting payment have been offered to parts of commerce and industry for many years. Initially they were forecasts or climatological data summaries that were priced at levels which have now come to be regarded in the United Kingdom as very low. The background of the organization as a public service created a widespread and even passionately held belief among staff that all users of meteorological services should be given the best possible information even where the price charged was below cost. Thus the quality of service was seen to be measured almost entirely by the accuracy of the data supplied; little effort was given to enhancing the presentation or delivery of the services. The needs of customers were generally assumed to match this view, and customers, knowing little better, tended to accept what was offered.

Following the recommendations of the Resource Control Review in 1984, the Office established a Marketing Branch, and a Steering Group was set up to direct the development of commercial activities in the Office. Little clear guidance was available about how to develop from a public service into a commercial organization, and there was only partial commitment at the most senior levels. This was reflected in a general reluctance to adopt new business practices and marketing disciplines, and a tendency to rely upon the established wisdom that we already knew what customers wanted.

There was an initial burst of undirected market research and opportunistic development of commercial activities. This period was very valuable in gaining experience and understanding about markets, and in testing the theoretical marketing models offered in training courses. However, it led to several failures and little real market development. Several marketing consultants were brought in to assist with the problem; their advice was very variable in quality. The best advice was to base a market development strategy on information from an initial in-depth interview survey of a range of existing users, together with the information about customers that was already available within the Office. Much of this information was qualitative, but it provided a workable basis for identifying the major market opportunities at that time. The strategy created was to develop each market opportunity in turn, starting with the one most likely to achieve success. As each of these came to fruition, great care was taken to give the success to other involved management areas and not the Marketing Branch, even where it was initially responsible for the development. If successful, this would not only provide credibility within the Meteorological Office for marketing techniques, but would also help to encourage managers to address the organizational problems of commercialism.

3. Development

Up to 1990, when the Meteorological Office was made an Executive Agency, the commercial development was slow, but it followed the proposed strategy. However, the subjective day-to-day experience of many staff seemed very different. Enthusiasm for a more commercial way of doing things was very patchy, often found in individuals rather than in groups, and it often had little clear direction. New products were invented and launched without any reference to the customers they were supposed to reach, and market research was conducted in an *ad hoc* manner, with little attempt to put the results into some overall context. Customers were fitted into functional categories ('customers for forecasts', 'customers for climatological services'), so that many of them had to get the information they wanted from different parts of the Office. Commercial procedures were not consistent across the organization — some customers would contact several weather centres in order to get the cheapest price for a service.

Despite all this, two fundamentally important points emerged.

(1) People began to learn through their own experience and the experience of others. Even negative experiences were incorporated into the corporate body of thinking as examples of 'how not to do something'. This learning process was at the heart of the change in culture that has been observed, and was an absolute precondition for the rapid changes that followed the creation of the Executive Agency.

(2) The major part of the early growth in commercial revenues came from the simple process of telling people about the Meteorological Office and its services. This was done in many different ways, but with little overall coordination. Newspaper articles, television interviews, talks and lectures, information sheets and brochures, telephone conversations and face-to-face meetings occurred, often initiated by enthusiastic individuals, but all were characterized by an excitement with, and belief in, the services being offered by the Office.

4. Organizational changes

As the credibility of the commercial approach improved within the Meteorological Office, so it was possible to implement changes to improve the organization of commercial activities. A programme of commercial training for all staff was developed. This was aimed not only at improving skills, but also at creating a commitment to a commercial philosophy and to identify commercially oriented staff who could be moved into more influential positions. Financial and information systems were gradually modified to match the segmentation of customers that had been developed, and to link the revenue generated by a service, or by a group of customers, with the associated costs. In this way there was a gradual change away from maximizing revenue as the principal commercial objective towards the objective of maximizing profit.

Before 1990 the most significant structural development was the introduction of two Business Units. These were created in response to market information that showed that many customers needed services from more than one functional area in the Meteorological Office, they wanted to deal with only one point of contact and they wanted to speak to staff who understood their problems and who spoke in terms they could understand. Business Units were set up to serve the Retail Industry and the Television Industry.

5. Developing a commercial culture

The fundamental problem of commercialization of the Meteorological Office has been the creation of a commercially oriented culture. When the Meteorological Office started to develop its commercial activities, there was a general suspicion that such a culture was in some way 'immoral' and that it would cause standards of quality to drop. Feeding these suspicions was the possible threat of job losses in the future.

Managing such a radical culture change requires leadership skill and considerable patience; people cannot readily be programmed, and they take time to change their views. In essence, it involves encouraging staff to change their viewpoint in a positive manner, and removing obstacles to such changes.

Several methods used to encourage staff to change their views.

(a) *Involvement in the commercial process.* Staff who felt they were a part of a new initiative, and whose ideas were listened to invariably were among the first converts.

(b) *Conferring success.* Although most of the early successful developments were initiated within the Marketing Branch, great trouble was taken to confer the success to other managers in other sections. A good example is the launch of the new 'OpenRoad' package of services to the highways departments of local government where, following about two years of Market Research and product development, the Weather Centres were assisted in selling the new service. Sales materials and marketing consultants were provided. The success of the venture was a great boost to the pride and motivation of staff in the outfield.

(c) *Training.* Training courses were aimed at improving the skills and motivation of all staff.

(d) *Leadership.* Leadership within the commercial sections of the Meteorological Office tended to occur spontaneously in a few individuals, and was not treated by senior directors as a particularly important factor in the development of a commercial culture.

Management has now developed leadership teams in each business area.

(e) *Having a clear mission.* Coupled with the lack of concerted leadership was the initial absence of any clearly understood and accepted mission statement, which expressed the basic purpose of the organization and the values that the organization expected every member of staff to share. This shortcoming has now been rectified with the Chief Executive's Charter Statement, published in 1993. It is headed:

Our purpose is to excel
in providing meteorological services
that meet our customers' present and future requirements.

6. Maturation

Following a long period of development, the change to Executive Agency was relatively straightforward; all that was needed was to organize and direct the changes that had already taken place. A restructuring occurred to bring all of the commercial activities under one director, and organized in a conventional business structure: Marketing, Sales, Production, Product Development and Administration. Within the Sales Division, each major market sector is served by a Business Unit, responsible for serving the complete range of needs of their customers. The old, functional divisions have mostly disappeared.

The success of this strategic approach to the management of change can be seen in the rapid growth in revenue from services to the major market sectors: land transport, premium-rated telephone services, services to Television and so on. In the five-year period from 1984 to 1988 commercial revenues doubled (from about £4 million to £8 million), and it is predicted to double again (to £16 million) by 1993.

7. Conclusion

The development of commercialization within the UK Meteorological Office has taken place over a period of nine years, and the process continues. There is, however, a long way still to go.

Change has not come quickly. Those made responsible for the changes were advised that it would take years, not months. It has been a long and frustrating process for all involved, and there were mistakes made in the earlier years that may have caused the changes to be even slower in maturing.

However, despite the mistakes and false starts, the Meteorological Office has been profoundly successful in its change to commercialization, and the Commercial Services Division now enjoys an equal status with the other major divisions, and plays a vital part in securing funds for the continuing operation of the Office as a whole.

Books received

Inverse methods in physical oceanography, by A.F. Bennett (Cambridge University Press, 1992, £35.00, $59.95) explores the potential for inverse theory in oceanography, emphasizing possibilities rather than expedient or rudimentary applications. Ocean models considered range from linear, finite-dimensional systems of equality and inequality constraints to non-linear, regional primitive-equation models. Exercises of varying difficulty rehearse technical skills and supplement the central theoretic development. ISBN 0 521 38568 7.

Climate system modeling, edited by K.E. Trenberth (Cambridge University Press, 1992, £35.00) provides a thorough grounding in climate dynamics and the issues involved in predicting climate change. It not only discusses the primary concepts involved but also the mathematical, physical, chemical and biological basis for the component models and the sources of uncertainty, the assumptions made and the approximations introduced. This is a comprehensive text which will appeal to students and researchers concerned with any aspect of climate and the study of related topics in the earth and environmental science. ISBN 0 521 43231 6.

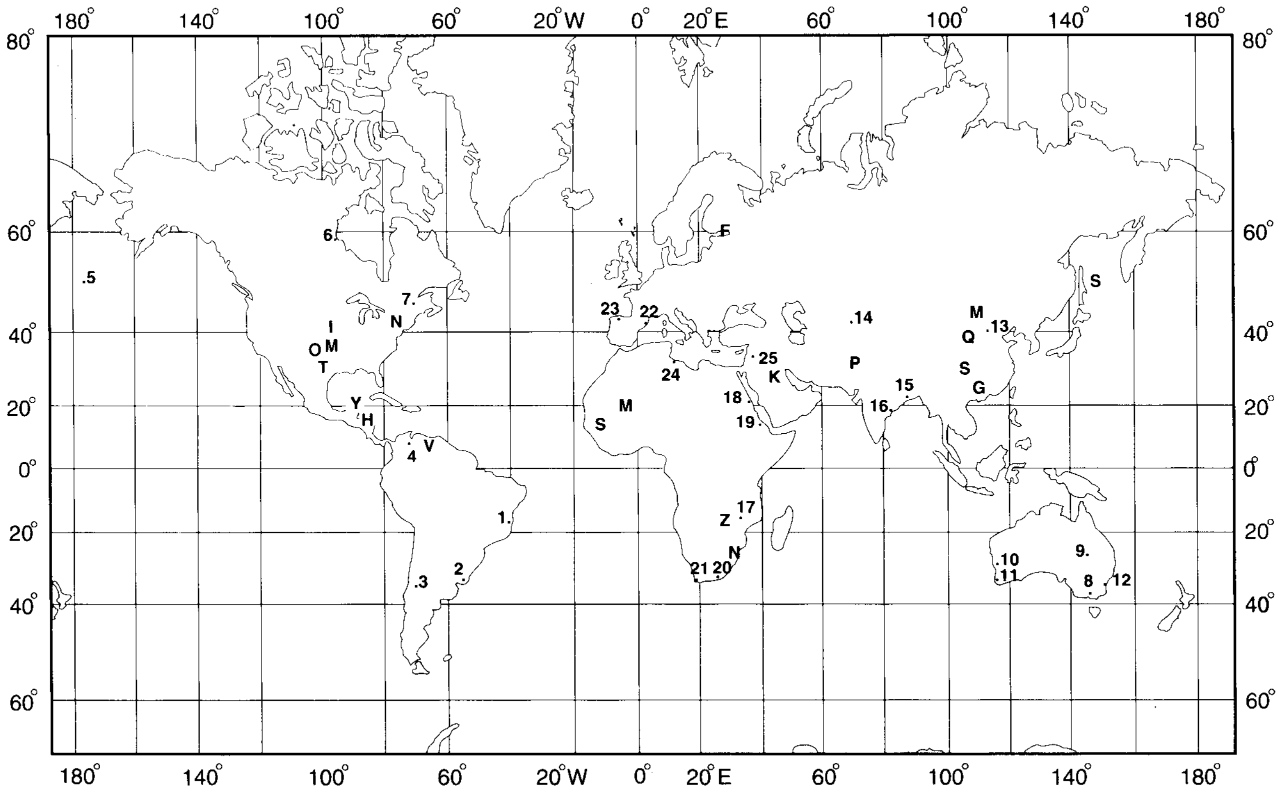
El Niño — historical and Paleoclimatic aspects of the Southern Oscillation, edited by H.F. Diaz and V. Markgraf (Cambridge University Press, 1992, £40.00) examines for the first time different approaches to reconstructing ENSO based on a variety of proxy sources, ranging from high-resolution environmental indicators such as tree rings etc. to records on the impact of ENSO on fisheries and marine and lacustrine sediments, to a long record of vegetation changes in the southern hemisphere. This book will be of importance to all professional scientists and researchers in climatology, meteorology and the earth and environmental sciences, while graduate students will also find this book a useful reference source. ISBN 0 521 43042 9.

The atmospheric boundary layer, by J.R. Garrett (Cambridge University Press, 1992. £50.00, $79.95) is intended to be an advanced graduate level text and a reference book for practising meteorologists and atmospheric scientists. The emphasis is placed on surface processes and the application of atmospheric boundary-layer problems to the modelling of climate. ISBN 0 521 38052 9.

World weather news — April 1993

This is a monthly round-up of some of the more outstanding weather events the month, three preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and press reports. Naturally they are heavily biased towards areas with a good cover of reliable surface observations. Places followed by bracketed numbers, or areas followed by letters, in the text are identified on the accompanying map. Spellings are those used in The Times Atlas.



Location of places mentioned in text

South America

Linhares (1) in Brazil is our first report of heavy rain — 110 mm in a thunderstorm on the 3rd: Santa Vitoria do Palmar, near Montevideo (2), followed with 168 mm on the 3rd/4th with 86 mm in a 6-hour period (the April average is 74 mm). A depression crossing Uruguay over the period 3rd to 7th deposited 161 mm in Montevideo (April average 99 mm) and well over 50 mm elsewhere. Santiago (3), Chile, broke its half-year drought on the 13th when 15 mm fell; by the 20th the total had reached 77 mm (the April average is 13 mm).

The heat around the Gulf of Mexico reached Colombia on the 16th when Cucuta (4) broke its April record in getting to 37 °C. The country suffered flash flooding on the 26th with between 50 and 100 feared drowned in Los Andes 75 miles from Medellin, and along a 220 km stretch of the river Cauca. In three days starting the 25th Quibdo measured 152 mm; further east at Villavicencio, south-east of Bogota, got 238 mm.

North and Central America

On the 6th a Chinese Eastern Airlines MD-11 aircraft encountered severe turbulence over the Bering Sea, one passenger was killed and 50 injured, and the aircraft was forced to make an emergency landing at Shemya (5) in the Aleutian Islands.

Spring arrived with April in the Canadian province of Manitoba; Churchill (6) recorded +6 °C on the 4th, about 13 °C above the average.

Flooding occurred at the beginning of the month in Iowa (I) as 50 cm of snow pack started to melt in heavy rain. These floods gradually spread south, and by the 12th the Mid-West was reporting problems as the upper reaches of the rivers Mississippi and Missouri flooded over wide areas. Waterway traffic was badly affected by strong currents and locks being closed to control the flow. Problems reached their worst about the 23rd and started to ease at the very end of the month.

There was a stream of reports of high temperatures from around the Gulf of Mexico, one of the first was Campeche, Yucatan (Y), with 37.7 °C on the 7th (April average is 31 °C). Choluteca in southern Honduras (H) reported 40.0·°C on the 8th and many observers in north-west Venezuela (V) were reporting 35–40 °C on the 10th. Merida, Yucatan, had 37.8 °C on the 14th; on the 25th a new record was set when 39.5 °C was reached.

On the 19th there was a 'a catastrophic' storm of wind and hail in Texas (T) and Missouri (M) with tornadoes. Details are scarce but insurance claims are running at $60m due to damage to skylights, roofs and cars. Something similar happened five days later on the 24th in Tulsa, Oklahoma (O), ten were killed by tornadoes that struck late in the day, funnel clouds skipped but touched down to obliterate two truck stops on Interstate 44, seven miles of which were closed for a time while debris was cleared. Sirens were only able to give a few minutes warning and 140 homes were damaged.

An ordinary winter storm occurred on the 22nd and dumped 15 cm of wet snow on Pennsylvania and New York State (N) at low levels: over the maritime provinces of Canada about 30 mm of rain fell. A secondary low to this system brought strong northerlies on the 25th and caused a storm surge on Lake Champlain, south of Montreal (7), putting a metre of water into the shore towns.

Australasia

This information is largely based on that kindly given by the Australian Bureau of Meteorology.

Persistent high pressure systems near south-eastern Australia in the second half of the month produced very warm and dry weather over the eastern half of the continent except the tropical coast of Queensland (QLD) and the south coast of New South Wales (NSW). In many places it was the warmest and driest April on record. Among the new record mean maxima were Melbourne (8) with 23.1 °C (previously 22.9 °C set in 1865) and nearby White Cliffs 30.0 °C (29.8 °C in 1922) and Windorah, QLD, 33.1 °C (32.8 °C in 1953). Although it was not the first rainless April for many stations, there were some that had not had one since 1923. At the other extreme, Geraldton (10) in Western Australia (WA) equalled its previous lowest April maximum with 18.9 °C on the 30th. In the rainfall stakes Cape Leewin (11), WA, took the palm with a new April daily record of 88.4 mm on the 30th (previously 68.8 set in 1913). The most notable thunderstorm of the month occurred on the other side of the continent when late on the 5th, Canberra (12) got 18 mm of rain and hail in 20 min with a gust to 56 kn: this caused much damage to property, trees and power lines.

Asia

During the first week of April Sakhalin Island (S) had a 'cyclone' which is quoted to have dumped two months' rain and snow on the island and brought most transport to a stop. Possibly related, on the 3rd, the town of Zhangjiakou 100 miles north-west of Beijing (13), found the previous day's maximum of 16.2 °C had been followed by a minimum of −0.2 °C with snow. The Chinese province of Quinghai (Q) had 'severe snow storms that have buried an area the size of Norway since January'. This is a sparsely populated area but thousands of head of livestock died and many thousands of people suffered frostbite and snow blindness and expeditions were dispatched to help out. In Mongolia (M) there were reports of devastating snow storms on the 15th which had killed more than 13 humans and more than half a million livestock. The storms are said to have been the worst for 30 years with huge drifts in mountainous areas, help was required to dig people out. In contrast Beijing broke its April record when the temperature reached 32.1 °C. A few days later on the 24th, in the Chinese province of Sichuan (S) there were reports of hail and gales which combined to kill 31 people and injure 379, destroying 30 000 houses in 11 cities: the cause of this disaster is not clear. Further heavy thunderstorms, with hail, were reported to have caused widespread damage on the 25th throughout Guangxi (G) province. They killed 18 and injured 300. The rain lasted for two days and about 400 homes were destroyed. It seems likely that this mayhem was connected with the collapse of a heat-wave that had been affecting much of central Asia up till then. As a single example, Tashkent (14) had a maximum of 28 °C on the 23rd but only 6.5 °C on the 24th.

On the 22nd Mount Sheveluch in Kamchatka erupted spectacularly after being dormant since 1964. However I have no reports of how high the dust was ejected. Japan had problems on the 29th when heavy rain fell on the sides of the active volcano Mount Unzen, and the resulting debris and mud (lahar) washed into nearby rivers, causing a lot of flooding.

Indian subcontinent

West Bengal suffered tornadoes on the 10th when more than 100 were killed in Murshidabad, 100 miles north of Calcutta. Apparently this is quite a rare occurrence in India. The casualties seem to have included some 2000 head of cattle and reports speak of two lorries and a van load of people being hurled hundreds of metres into the middle of a rice paddy and drowned. Many newly installed power lines were blown down and trees uprooted. Ponds became contaminated by bodies and carcasses of cattle. The 12th and 13th gave some thunderstorms in Orissa, the town of Bhubaneswar (16) got 62 mm (monthly average 41 mm) and Jamshedpur 40 mm (average 25 mm). As the month wore on temperatures rose (on the 28th Hissar in the Punjab (P) reported 45.7 °C) but a sinister development was heavy, thundery rain in north-east India and Bangladesh with falls of nearly 100 mm in several places over the last day or two of the month (see this space for June).

Africa except the Mediterranean coast

We open on a hot note: in Senegal (S) temperatures were near record values on the 9th when 43.6 °C was reached. On the 12th 42.5 °C was reached at Segou on the banks of the Niger in Mali (M), that night some cloud moved in and the minimum was 30.4 °C! For much of the rest of the month maxima in western sub-Saharan Africa were between 40 and 45 °C. Further south in Zambia (Z) the rainy season is supposed to have been over, but a thunderstorm at Mongou dropped 106 mm (monthly average is 39 mm). A couple of days later, on the 14th, Bukoba on the shores of Lake Victoria collected 132 mm; Harare's (17) 54 mm (April average 39 mm) showed that the Zimbabwean rains had not yet ended.

In Sudan there seems to have been an unusually violent cold front around the middle of the month. The unusually heavy rain led to flooding which caused the deaths of up to 21 around Port Sudan (18) and put out of action a bridge on the vital highway to Khartoum; it also endangered the fresh water supply. About the same time thunderstorms were causing some damage further south in Eritrea rendering thousands homeless. Reports say that at noon on the 15th in Massawa (19) winds suddenly reached 70 kn from the north for 45 minutes and this was followed by heavy rain for another 45 minutes. The town was flooded, the port installations damaged. Dockside cranes were blown along their rails at more than their maximum design speed, this caused gearing to overheat and burn out clutches.

The month came to a hot close in Niger; N'Guimi raised its April record by one and a half degrees to 45.6 °C; in the Sudan a new April record was set at Karima with 47.0 °C.

The following notes are kindly supplied but the South African Weather Bureau.

In the first week a persistent trough in the west spread scattered showers eastward into Natal (N) on the 4th with some good falls of rain (75 mm at Underberg). A fast moving depression on the 5th/6th generated strong coastal winds with some damage to buildings and trees in Port Elizabeth (20). On the 11th one of the worst storms in 30 years crossed the south-west Cape with exceptionally heavy rainfall (153 mm at Villersdorp): at least eleven people were drowned in the subsequent flooding. The railway from Simonstown (21) to Fishoek was closed and the N1 was closed when a dam wall collapsed with considerable damage to the main breakwater jetty and many small vessels. (The meteorological background to this storm occurs elsewhere in this issue.) The cold front brought frost to the interior and light snow to the Drakensburg. Another deep low skimmed the southern Cape on the 16th/17th with gale force winds, showers over Cape Province, and hail damage near Colesburg. The second half of the month brought some settled weather in which Alexander Bay managed a maximum of 40.0 °C on the 21st but with ground frost in Orange Free State. The last cold front of the month on the 27th was followed by the coldest night when −1.6 °C was recorded at Buffelsfontein. April rainfall records were broken in Cape Town, Cape Agulhas and Port Nolloth. Although the rainfall was welcome, there was some damage to crops, and few surface water reservoirs were replenished.

Europe, North Africa and Arabia

Much of the month was cyclonic, with a tendency for many smaller lows rather than single monsters. The overall trend was for the south-west to be cool and wet, the south-east to be hot and the north averagely mixed. For a change a UK station starts the list of notable events; Middle Wallop weighed in with 40 mm on the morning of the 1st (monthly average is 54 mm); many other southern gauges followed suit with 30 mm or more. A different low was giving similar amounts of rain along the south coast of France along with a brisk mistral, Cap Béar (22) reached 55 kn with gusts to 62 kn. On the 5th the Swiss had their turn when over a two-day period high-level stations collected 70 mm and the lowlands more than 20 mm. The Easter holiday brought a real stinker to Aberdeen; an almost stationary front caused hours of gloomy south-east wind off the North Sea, a maximum temperature of 6 °C and 40 mm of rain.

The Gulf of Finland (F) was the scene of some excitement on the 8th when an unusually cold spell caused the formation of new ice flows just as the ice breaker returned to port for refuelling, Then on the 12th the vessel Vishva Mohini with a cargo of 1200 tons of heavy machinery had problems when heavy seas caused its cargo to shift in a force 7 easterly in the Bay of Biscay. The ship sank suddenly, but 16 of the 48 crew were rescued about 48 miles north of Cape Penas (23). A couple of the days later on the 14th there was a report of a tornado in San Tropez, yachts were sunk and trees were blown down and about £2m of damage was done.

Among the hot spots were Tripoli (24) 36.4 °C on the 11th, Iraklion, Crete, with 35 °C on the 13th, Tel Aviv 35.0 °C on the 14th; Damashq (25) 34 °C on the 16th (1 °C short of the record). Cairo's minimum of 29.2 °C on the 18th was 1 °C above the normal daytime value.

The cool, wet spots included the thunder-struck Balearics on the 14th where Mahon collected 23 mm. Calamocha in eastern Spain measured −3.5 °C and Majorca +2.8 °C on the very chilly morning of the 18th: in the narrows of the Strait of Gibraltar Tarifa was having a easterly gale with gusts to 43 kn (and 72 mm of rain on the 28th). The prize has to go the Mount Aigoual north of Nîmes, for 48 hours of the 26th and 27th they had persistent fog with thunder, hail, rain, sleet, snow and a gale with gusts to over 80 kn.

On the fringe of this area Arabia had a hot month, but most notable were the thunderstorms that swept south on the 26th from Iran to Bahrain and Riyadh. Compare Kuwait's (K) 26 mm with the average of 13 mm, and Abadan (average 20 mm) had 34 mm on the 25th; next day another 24 mm fell accompanied by a squall to 52 kn.

Antarctica

On the 3rd McMurdo Sound collected snow to a rainfall equivalent of 15 mm (April average 25 mm) with a temperature of about −12 °C. On the 10th an AWS near the Pole reported a temperature of −67.9 °C, the Russians at Vostok managed −70.7 °C!

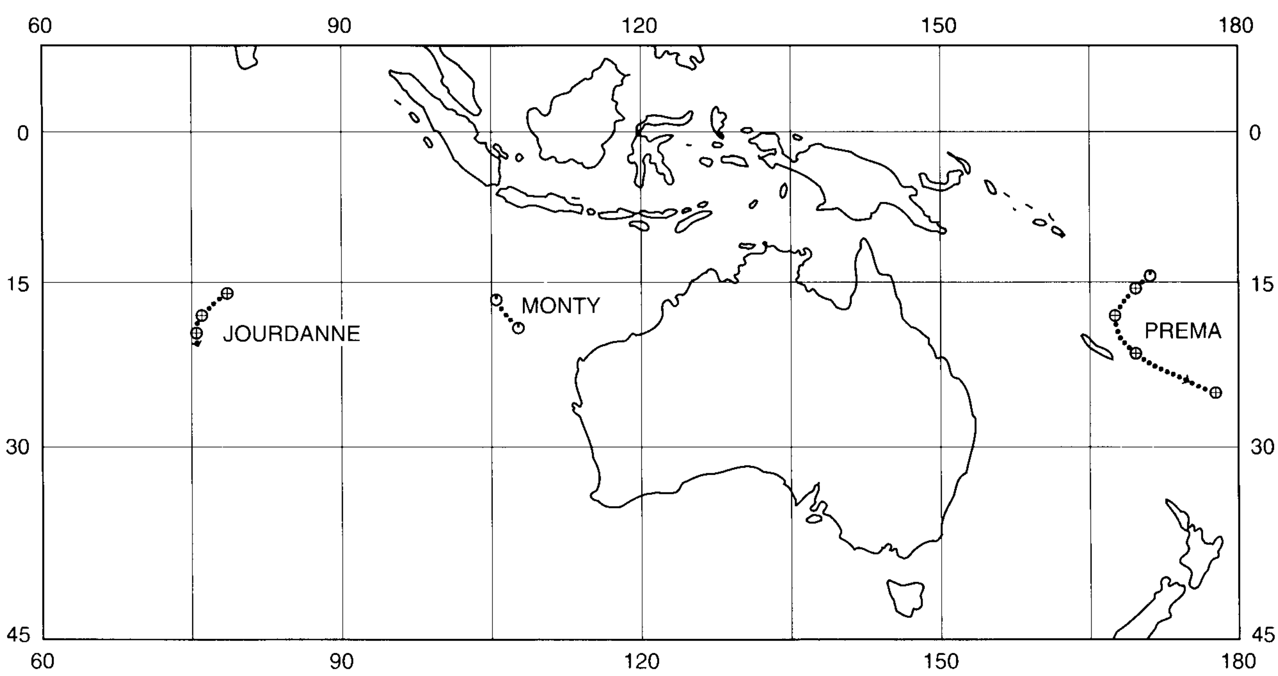
April tropical storms

This is a list of tropical storms, cyclones, typhoons and hurricanes active during April 1993. The dates are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during this month. The maps show 0000 UTC positions: for these I must thank Julian Heming and Susan Coulter of the Data Monitoring group of the Central Forecasting Office.

No	Name	Basin	Start	End	Max. (kn)
1	Prema	AUS	27/03	01/04	120 (in March)
2	Jourdanne	SWI	03/04	09/04	120
3	Monty	AUS	10/04	12/04	50

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific; I — Indian Ocean; WI — west Indian Ocean; AUS — Australasia.

Notes: None of these storms affected land during this month.



Your Editorial Board announces that the Meteorological Office Board has decided that the publication of the *Meteorological Magazine* will cease with the issue for December 1993.

As one of the leading European establishments for research into meteorology our publications should be subject to external peer review: this is already the case for much Meteorological Office work. The publication of a new international and European quarterly journal by the Royal Meteorological Society (to be called *Meteorological Applications*) is expected to provide a suitable vehicle for the kind of articles that now appear in *Met Mag*, namely on research, practice, measurements, reviews, applications of meteorology, book reviews, etc.

The first edition of the *Meteorological Magazine* was published in 1920 by HMSO. It took over from *Symons's Meteorological Magazine* which started in 1866. This decision therefore brings to an end a continuous publishing record of 129 years (except for the duration of World War II). It is understood that legal obligations accepted when *Symons's Meteorological Magazine* was adopted are fulfilled by the continuing production of the *Monthly Weather Report* and *Rainfall 19XX* and our internal journal mentioned below.

The December 1993 issue of *The Meteorological Magazine* will be a bumper one of about 40 pages celebrating the Magazine's contribution to the development and dissemination of meteorological knowledge. It will contain a selection of highlights from 1866 up to around 1986.

The United Kingdom Meteorological Office (UKMO) Annual Scientific and Technical Review

This Review describes the major developments in science and technology within the UKMO over the year and is produced as part of the Meteorological Office Annual Report and becomes available in July each year. If you wish to be put on the mailing list please write to:

The News Desk,
Publications (room 709),
Meteorological Office,
London Road,
Bracknell,
Berks
RG12 2SZ.

Informal communications

The UKMO has instituted an in-house periodical for informal and rapid dissemination of the latest relevant science and technology news to its staff and outside collaborators. Most contributions come from UKMO staff, but offers of material from outside will be welcome — though there is no guarantee of publication.

Back numbers: Full-size reprints of Vols 1–75 (1866–1940) are available from Johnson Reprint Co. Ltd., 24–28 Oval Road, London NW1 7DX. Complete volumes of *Meteorological Magazine* commencing with volume 54 are available on microfilm from University Microfilms International, 18 Bedford Row, London WC1R 4EJ. Information on microfiche issues is available from Kraus Microfiche, Rte 100, Milwood, NY 10546, USA.

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Severe thunderstorms over western Germany — a case-study of the weather situation on 20 August 1992

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1. Introduction

In the relatively warm summer of 1992 there were several occasions of heavy convective overturnings with hazardous weather in central Europe. On one of these occasions — the 20th of August — gusts of 90 and 70 kn were recorded in Saarbrücken and Frankfurt/M. respectively during the passage of a squall line accompanied by hail and heavy rain. The course and development of this weather situation will be described in the following. The description is partly based on an internal report by Liebetruth (1992) from the Regional Forecasting Centre Frankfurt.

2. Large-scale weather development

The surface charts for 19–21 August 1992 (Fig. 1) show, typically for late summer, an initially slack pressure gradient over central Europe with an area of high pressure extending from the North Sea towards Poland, and a shallow depression over Biscay moving slowly north-eastwards.

A poorly defined surface front, separating moist and hot tropical air in the south from cooler and drier air in the north, runs along 50° N before curving south, behind the Biscay low, towards Iberia. The position of this front is well reflected in the distribution of the equivalent-potential temperature (θ_e) at 850 hPa (Fig. 2). Analyses of that temperature are generally used in the DWD for fixing surface fronts. However, the temperature distribution in the tropical air is not uniform. In the θ_e field as well as in the pure temperature at 850 hPa (Fig. 2) a zone of high values exists which extends from Spain over the Alps up to the Balkans.

During the 20th the originally shallow depression experienced some intensification and arrived over the German Bight at 0000 UTC on the 21st with a central pressure near 1000 hPa. As a consequence of the increase of the pressure gradient, together with the deepening, the cold front pushed eastwards more quickly and reached the western parts of Germany on the night of the 20th/21st. Meanwhile widespread thunderstorms were released ahead of the front, which strongly influenced the temperature distribution near the ground through their cold air production, and the front became barely recognizable at the surface. Instead, a new convergence line with cold front characteristics developed at the fore part of the area with thunderstorms on the evening of the 20th and cleared most of Germany by the end of the day. This process is also reflected in the θ_e field which shows a cold inlet just over Germany ahead of the original front.

Corresponding to the above air-mass distribution, there was a west to south-west current in the middle and upper troposphere over western and central Europe starting in a trough west of the Iberia (Fig. 2). Stronger, wavy winds blew north of 50° N and it is interesting to note that the baroclinicity in the middle troposphere was smaller than in the lower levels.

The upper trough swung slowly north-eastwards, to a position over Biscay at 0000 UTC on 20th, and subsequently crossed France to reach the southern parts of the North Sea and western Germany during the following

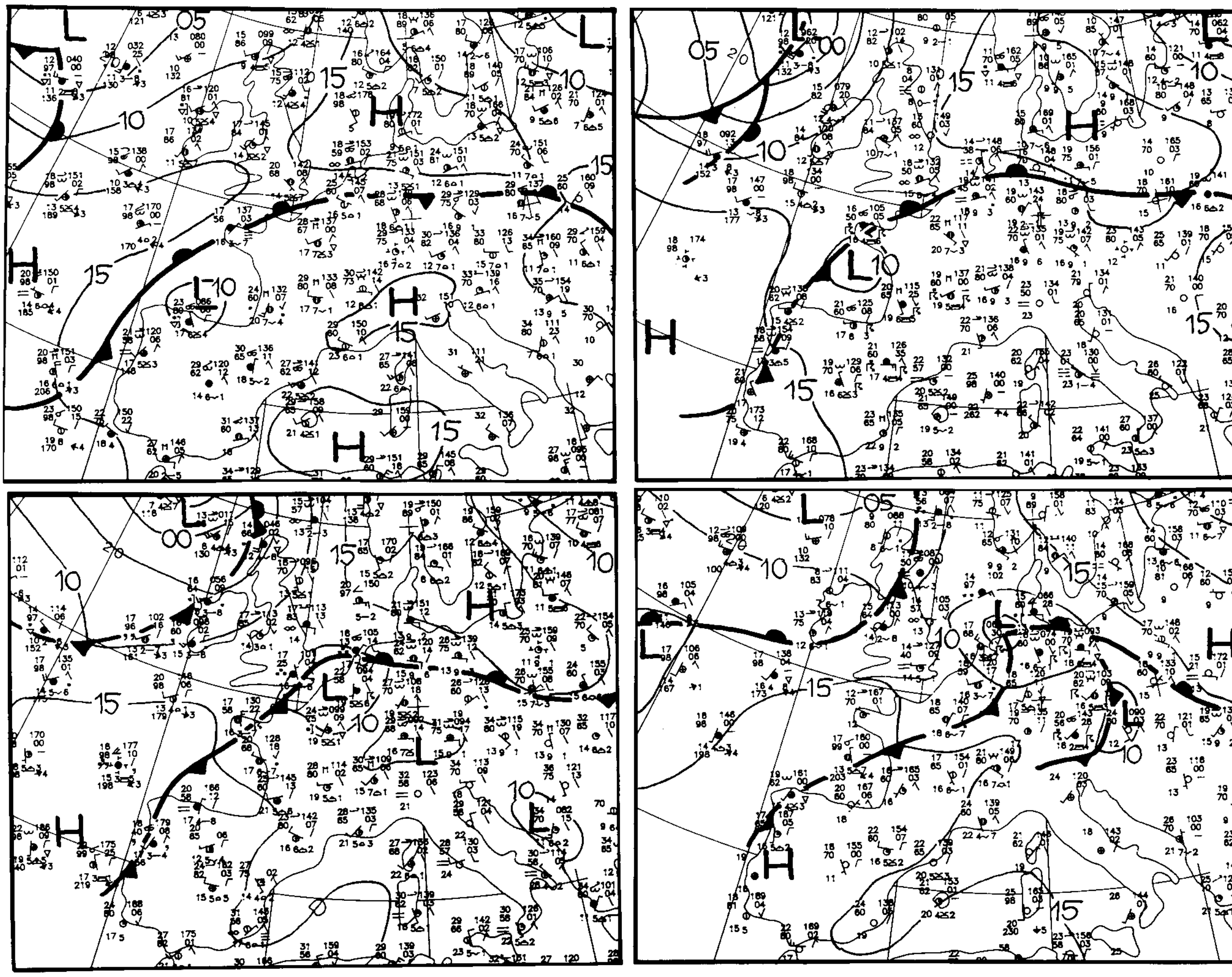


Figure 1. Surface isobars and fronts at1200 UTC on 19 August (top left), 0000 UTC on 20 August (top right), 1200 UTC on 21 August (bottom left) and 0000 UTC on 21 August (bottom right).

night. The surface low deepened ahead of it. Another important aspect is that the trough had already overtaken the surface front towards the warm air early on and remained there relative to the front. That was decisive for the release of the convective overturnings, since the ascending motion ahead of the trough could fully catch the tropical air south of the front (see section 4).

3. Weather events

3.1 First convective overturnings

Light rain or drizzle was often observed near the front in western and central Europe during this time. As regards convective activity, the first thunderstorms had already developed over eastern France in the afternoon hours of the 18th moving quickly north-eastwards and crossing southern Germany. Their intensity was rather low judging from the measurements in the synoptic network of the DWD.

A small circular convective cell formed north-west of Frankfurt about 0000 UTC on the 19th and intensified while moving eastwards. Gusts of up to 31 kn with 8 mm precipitation were recorded during its passage of the eastern part of the Erzgebirge (Saxony). This cell subsequently crossed Poland and the Ukraine and was north of the Black Sea at noon on 20th.

Likewise in the second half of the 18th many thunderstorms developed over the Iberia and encroached on the Pyrenees and south-western France during the following night as the cloud slowly spread out north-eastwards. A nearly circular convective cell formed at its leading edge, and again over eastern France at noon on the 19th. It broke loose from the main cloud and crossed the centre of Germany by the next morning. Its activity was significantly stronger than its forerunners. Frankfurt/M. (10637) had a gust of 45 kn and 26 mm of precipitation; 53 kn was registered at Tholey (10706). That cell moved further eastwards while weakening, and disappeared over the Ukraine during the afternoon of the 20th.

3.2. The main event

Meanwhile the main cloud area had been displaced north-eastwards and covered western Germany, the Low Countries, northern France, England and the southern

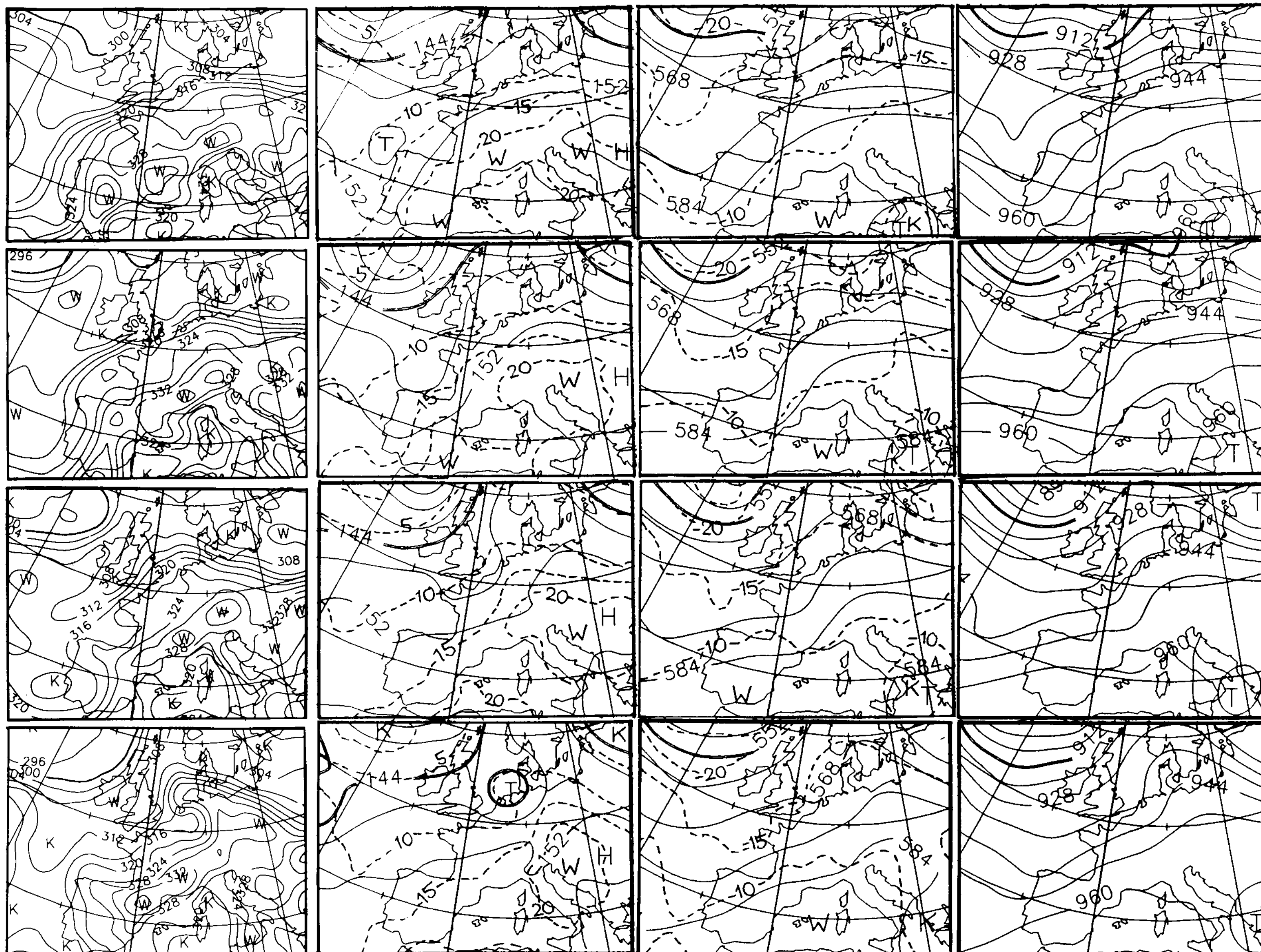


Figure 2. (Columns, left to right) analyses of θ_e equivalent potential temperature at 850 hPa, and geopotential (solid lines, in gpdam) at 850, 500 and 300 hPa at 12 UTC on 19 August (row 1), 00 UTC on 20 August (row 2), 12 UTC on 20 August (row 3) and 00 UTC on 21 August (row 4).

North Sea at noon on the 20th. Rainfall was observed at many places in its domain, partly accompanied by thundery outbreaks in Belgium and northern France. However, very intense thunderstorms developed at the southern edge of this cloud area after it reached eastern France at noon. The satellite images (Figs 3(a) and 3(b)) show very impressively, how a shield formed out of some thunderstorm cells in a very short time. The shield, with a diameter of nearly 500 km, covered the whole of central Germany at 1800 UTC (Fig. 3(c)). The temperature at the top was −68 °C corresponding to a height of nearly 45 000 ft. The shield soon merged with the clouds from powerful cells that developed further south. A broad, deep comma-like cloud zone had formed by 0000 UTC on the 21st, stretching from the North Sea over Denmark, eastern Germany, Poland and the CSFR to the eastern Alps.

Contrary to the impression conveyed by the explosive spread of cirrus shields, the radar measurements (Fig. 4) demonstrate, together with the surface observations, that the main thunderstorm activity was organized first of all in the form of a typical squall-line and later on in the form of a line-like elongated zone. The line came into the range of the Frankfurt radar after 1330 UTC and had a length of about 150 km and a width of 30 km at that time. It moved north-eastwards at roughly 40 kn and passed Saarbrücken Airport between 1432 and 1455 UTC with heavy hail and a gust of up to 90 kn from the north-west. This was the highest wind speed ever recorded at this site. The observed hail fall tallied with the strength of the radar reflectivity exceeding 55 dBZ in the core of the line.

During the next hour the line merged with cells developing ahead of it and at its eastern flank. It therefore lost its original character and became more of an elongated zone of convective activity moving further north-eastwards with a speed of 45–50 kn. The zone reached the Frankfurt area at around 1600 UTC causing gusts to 70 kn, torrential rain (60 mm within 2 hours) and hail with a diameter of up to 5 cm.

Fig. 5 allows a comparison between the NOAA-12 IR image for 1814 UTC, the radar measurements of the DWD network and of the COST network to the west. The precipitation detected by the radar is confined to the western half of the big cloud shield, and the zone of strongest echoes running along the River Weser is 350 km long by 50 km wide.

3.3 Effect of the convective overturnings

As demonstrated by Fig. 6(a), most of the stations in the climatological network of the DWD reported thunderstorms in the course of the 20th. Only in north-western and northern Germany and in some parts of the south-west was no thundery activity recorded. The main activity was concentrated in the middle parts of Germany where precipitation totals generally exceeded 10 mm: the highest total was 59.6 mm at Gross-Auheim east of Frankfurt. The structure of the precipitation field (Fig. 6(b)) shows a large and some smaller strips of large amounts orientated from south-west to north-east.

It is interesting to note that hail was only reported in the southern half of Germany and sometimes in areas with relatively small amounts of precipitation. Hail and heavy rain was only observed at the squall-line in the Federal States of Saarland, Rhineland-Palatinate and Hesse.

The most striking effect of the convective overturnings were the extremely strong gusts registered in Saarbrücken, Frankfurt and other places. As shown by Fig. 7, the gust of 90 kn in Saarbrücken had to be estimated since the registration form only went up to 80 kn! There were no marked wind shifts connected with the gust but a more or less steady veering from south-west to north-west. After the gust the wind rapidly decreased and turned to an easterly direction clearly indicating the backward direction of the cold air outflow of the squall-line.

Simultaneously with the gust, the surface pressure made a jump of nearly 7 hPa upwards immediately followed by a fall of around 4 hPa. A few minutes later heavy hail set in lasting more than a quarter of an hour. The diameter of the hail was between 2 and 4 cm. The temperature dropped from 28 °C to 14 °C whereas the relative humidity rose from 50 to 95%. The observer at the Saarbrücken Airport characterized the event with the words "minutes of horror and stress, but possibly unique in an observer's life!"

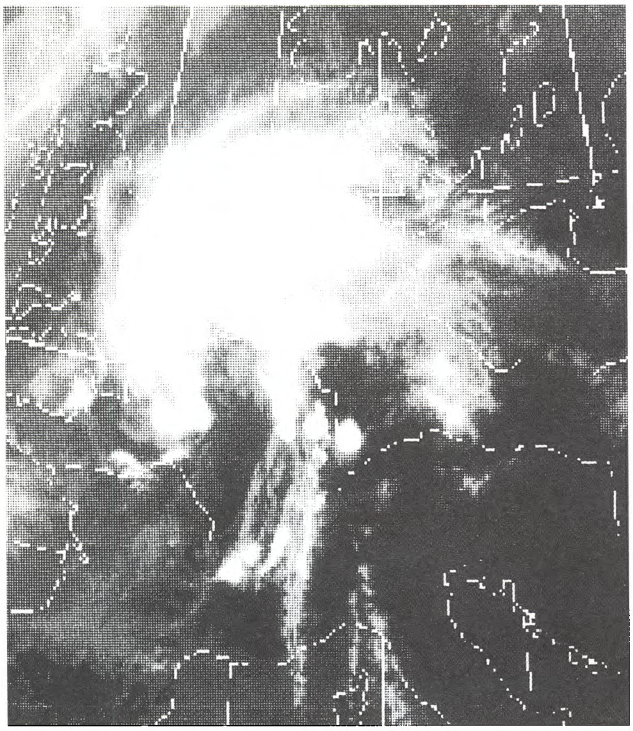
Many trees were overturned by the gusty winds, causing great damage and dangerous obstacles for traffic. At places with heavy rain, as, for example, in the Frankfurt area, many streets were flooded and the fire brigades were very busy pumping out flooded cellars. In Frankfurt it was the second night of uninterrupted operation for the police and fire brigades.

4. Physical aspects of the release of the convective overturnings

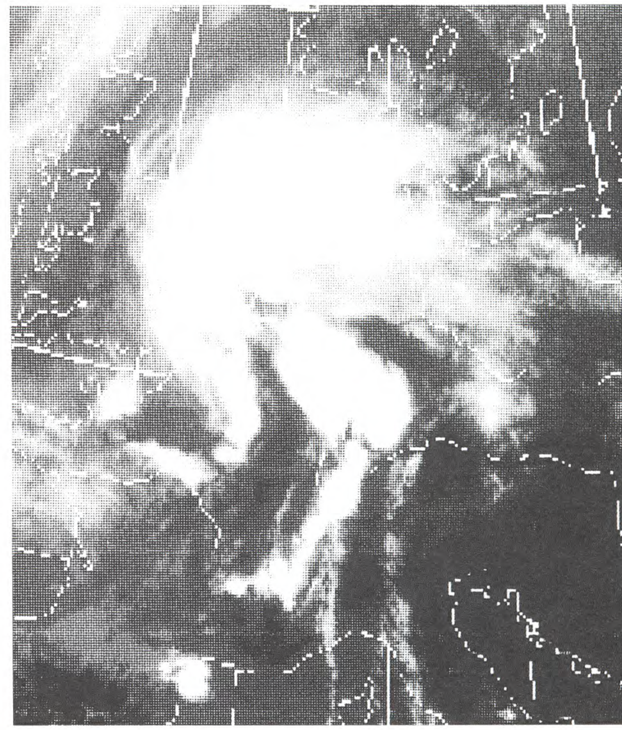
4.1 Vertical stability

As is typical for air masses of tropical origin, the lapse rate in the warm, moist air south of the surface front was conditionally as well as potentially unstable. However, as demonstrated by the ascents from Nancy (07180) at noon on 19th and 20th in Fig. 8, the release of the conditional instability was hindered by stable layers at 850 and 800 hPa, respectively, and surface heating to 32–34 °C was needed to cause deep convection. (Nancy is the upper-air station nearest to the origin of the thunderstorms during those afternoons.)

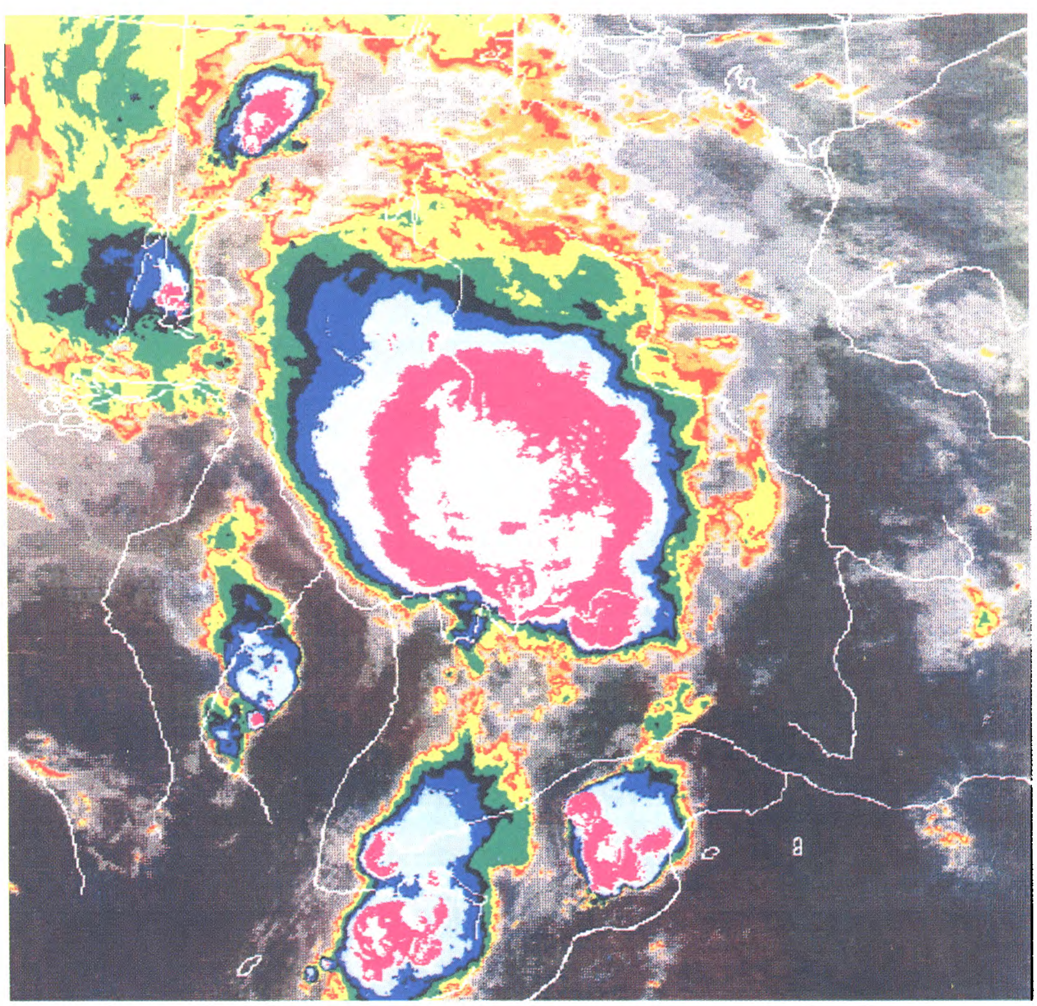
On the 19th the required temperatures had been partly reached in the area concerned, so that the development of the thunderstorms which formed on the leading edge of the main cloud area that day, and moved towards Germany, could be traced back to the heating from the ground in course of the day. This explanation is, however, not valid for the next day and the formation of



(a)



(b)



(c)

Figure 3. Meteosat images at (a) 1400 UTC and (b) 1600 UTC on 20 August, and (c) NOAA-12 image at 1814 UTC on 20 August.

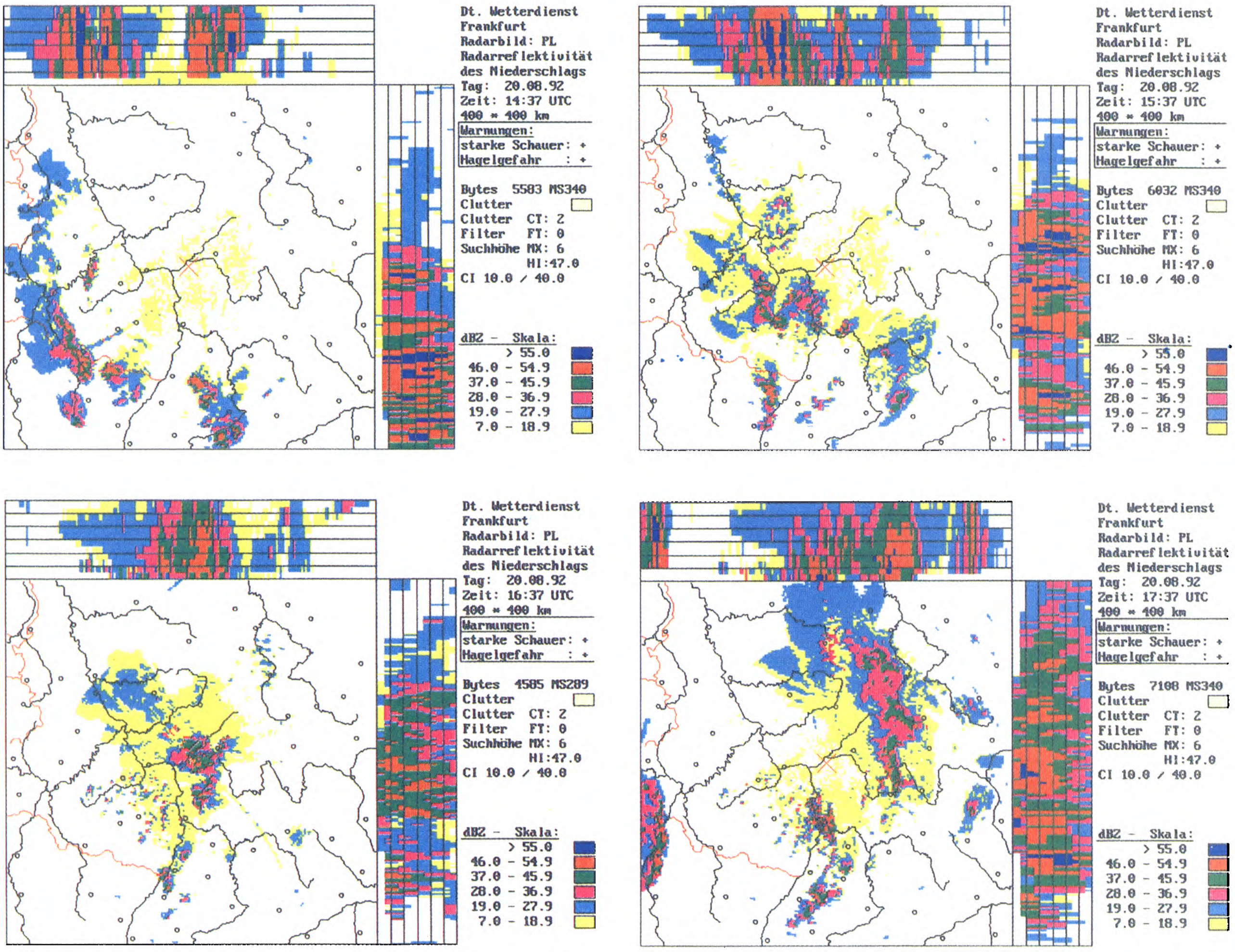


Figure 4. DWD weather radar images from Frankfurt at 1437 UTC (top left), 1537 UTC (top right), 1637 UTC (bottom left) and 1737 UTC (bottom right). The cross-sections show the vertical distribution of the strongest echoes in east–west and south–north directions.

the squall line. The temperature had only risen to about 28 °C in the area of origin by noon and the new threshold of 30 °C was only reached later in smaller areas further east and south. That means that another process must have been effective in releasing the convective overturnings in addition to warming from the ground. A characteristic of the formation of mesoscale convective systems is widespread ascent as an additional trigger.

The vertical stretching below the level of the strongest ascent leads to an increase of the vertical temperature gradient. If enough latent heat is released through condensation in the lower levels, the threshold to moist or even absolute instability can eventually be crossed. The prerequiste for this is a potentially unstable lapse rate of the ascending air mass. It is indicated by a decrease of the equivalent potential temperature in the vertical.

Such conditions could be found between the surface layers and the middle troposphere in the soundings at Nancy on both days. The equivalent potential temperature decreased from values between 60–70 °C near the surface, down to 50 °C or less between 500 and 600 hPa. However, very low values of θ_e were reached as low as 850 hPa on the 19th.

For the presentation of the horizontal distribution of the potential instability the so-called KO-Index (developed in the DWD) can be used: it is defined as

$$KO = \tfrac{1}{2}(\theta_{e500} + \theta_{e700}) - \tfrac{1}{2}(\theta_{e850} + \theta_{e950}).$$

The index reflects approximately the vertical gradient of the equivalent potential temperature. The distribution of KO, derived from the numerical analyses and given in Fig. 9, shows negative values (corresponding to a decrease of θ_e between the lower and the middle troposphere) in the area covered by tropical air, and values below -10 K.

4.2 Release of the instability through superimposed ascent

The widespread ascent necessary for the release of the potential instability can come as large-scale forcing in baroclinic waves or as a mesoscale process — with its typical form of transverse circulations — at well defined fronts. Since the front in the situation under consideration was only poorly defined and not subjected to

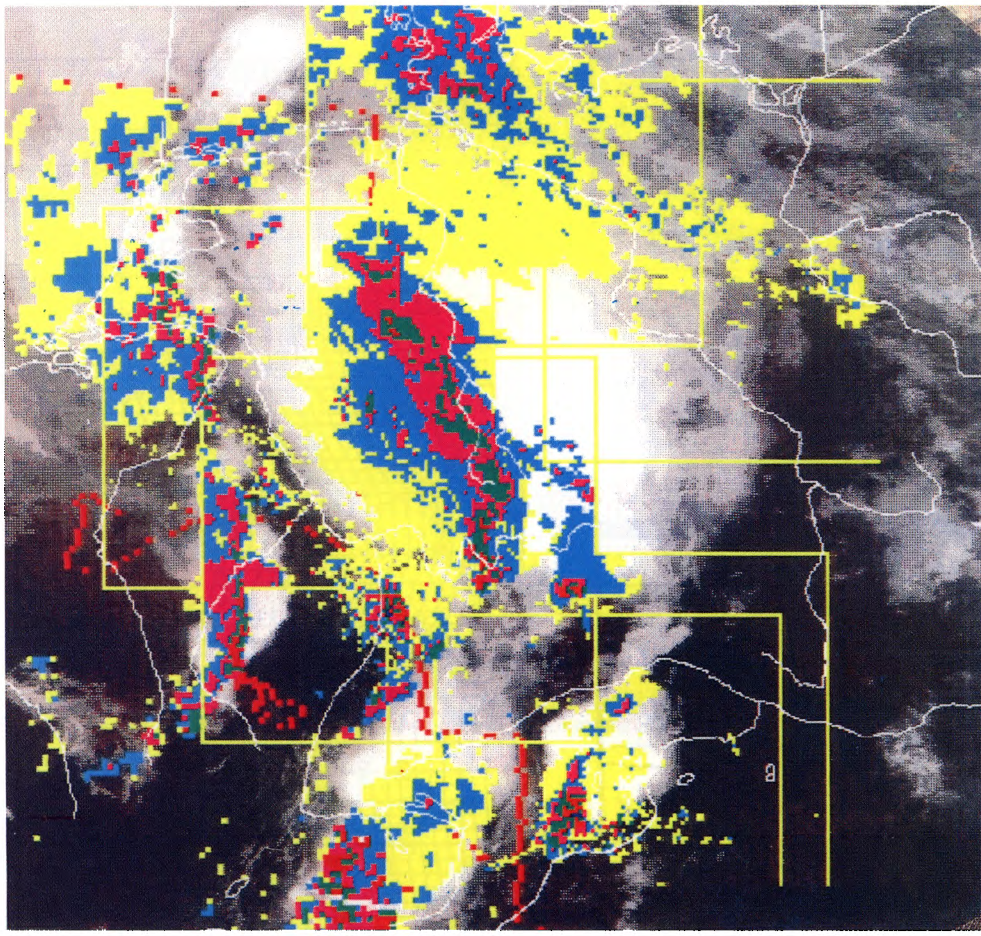


Figure 5. NOAA-12 infrared image at 1814 UTC on 20 August with radar data for 1800 UTC (green 37–45.9, violet 28–36.9, blue 19–27.9 and yellow 7–18.9 dBZ radar reflectivity).

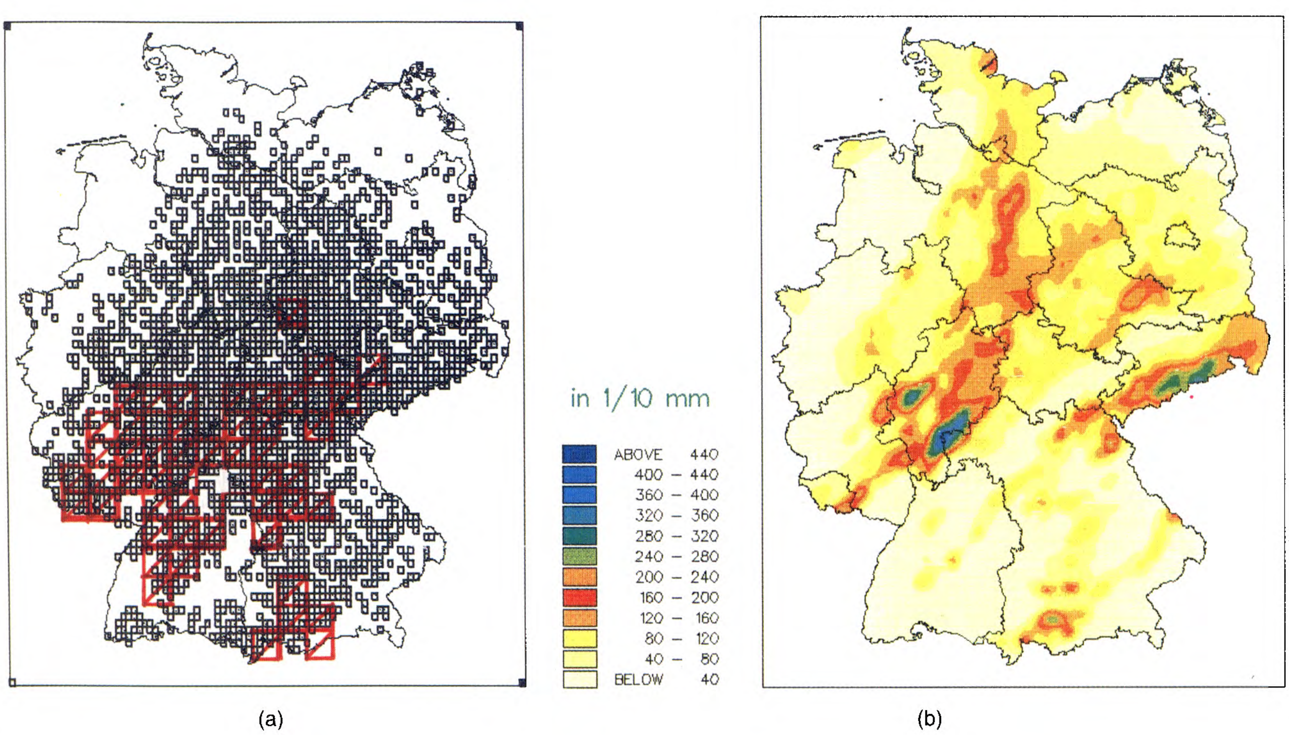


Figure 6. (a) Stations of the DWD reporting thunderstorms (black squares) and areas reporting hail (red squares) on 20 August, and (b) total precipitation from 0500 UTC on 20 August to 0500 UTC on 21 August.

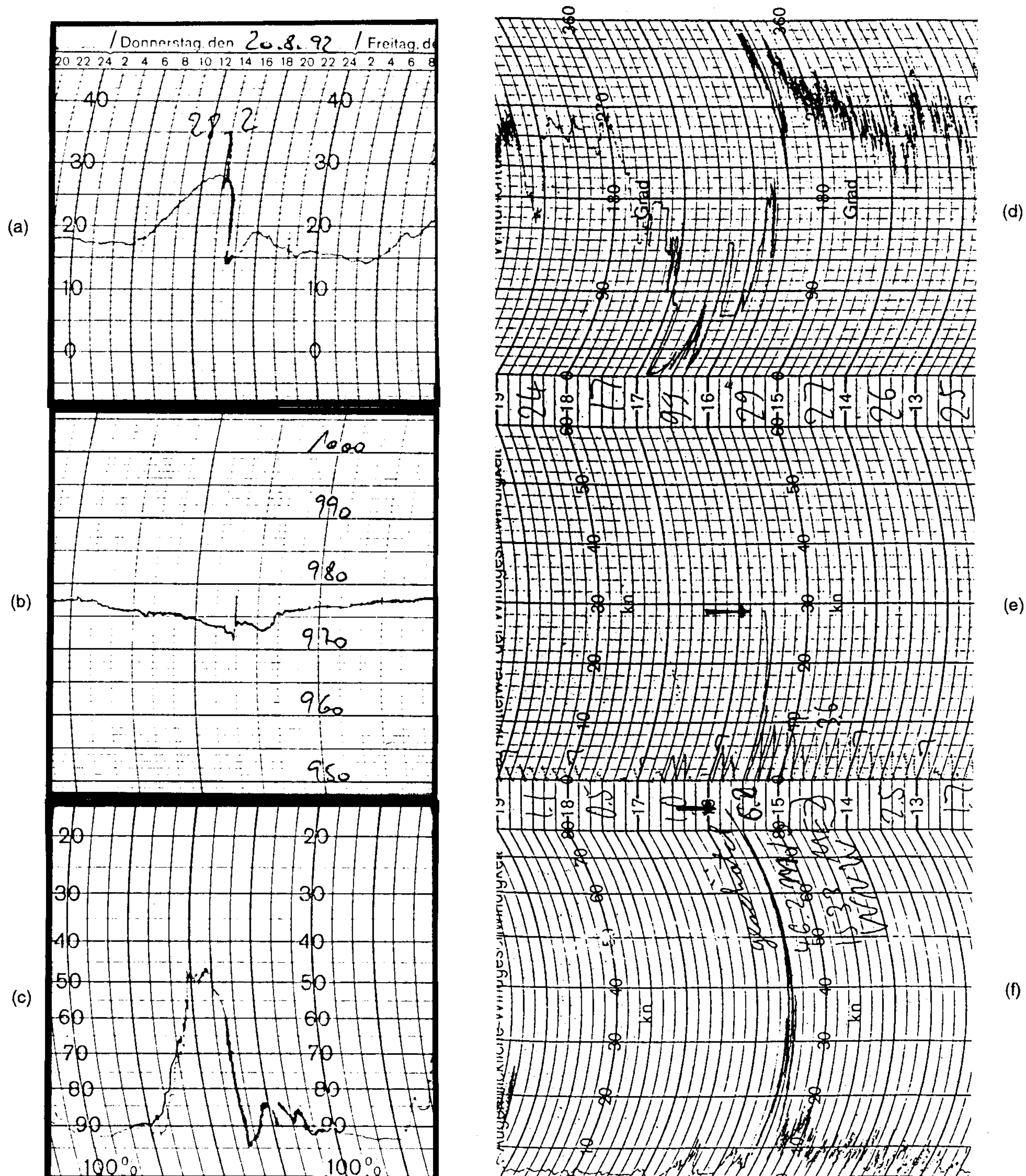


Figure 7. Autographic records from Saarbrücken Airport on 20 August 1992 showing (a) temperature, (b) pressure (hPa), and (c) relative humidity. Note the reversed time-scale of the anemogram in which (d) is direction, (e) is the 10-minute mean and (f) is the instantaneous speed. Arrows mark the peak speeds in (e) and (f).

frontogenetic effects, at least in the beginning, we have to look for large-scale ascending motions.

The distribution of large-scale vertical motions is described by the well known omega equation which contains in its simplest, quasi-geostrophic form, two forcing functions — the vertical gradient of vorticity advection and the horizontal distribution of temperature advection. Ascent is to be expected in areas with vertically increasing positive vorticity advection and/or maximized warm air advection. For example, the former works ahead of mobile short-wave upper troughs, the latter ahead of warm fronts. When ascent causes condensation the vertical motion can be boosted by the release of latent heat.

In terms of looking at the forcing at a particular level, it is advantageous to use an alternative form of the omega equation containing only one forcing function.

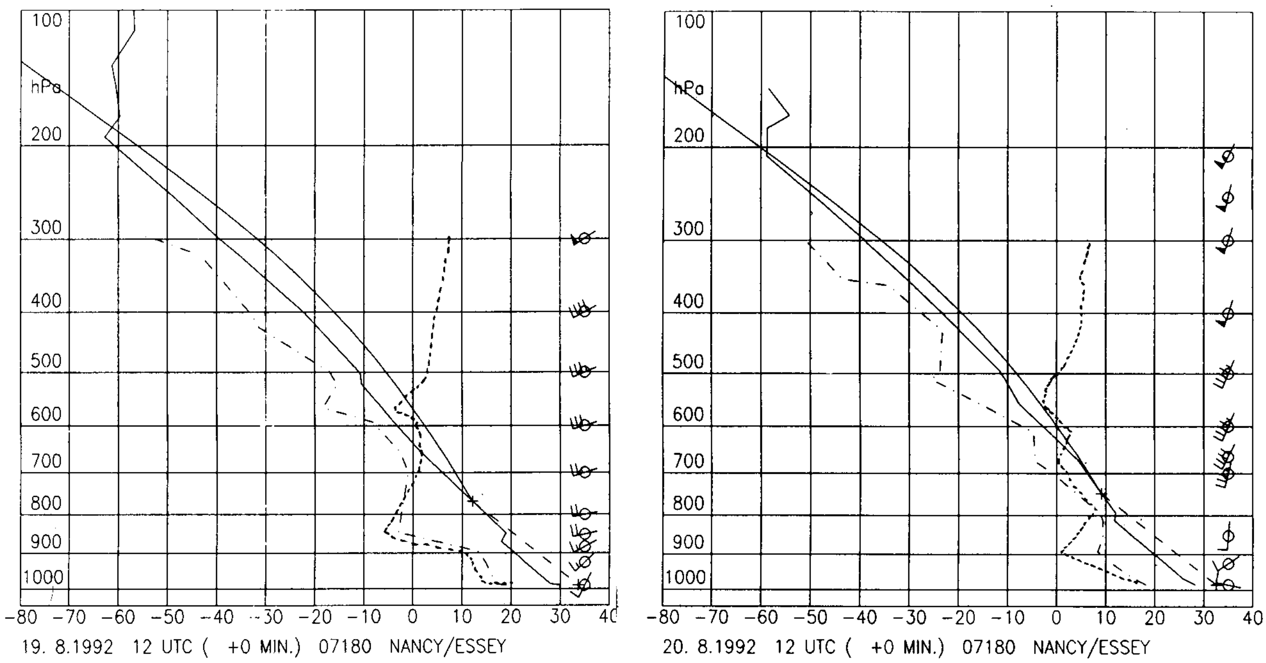


Figure 8. Radiosonde ascents from Nancy at (left) 12 UTC on 19 August and (right) 12 UTC on 20 August, showing temperature and dew-point, adiabatic through cumulus condensation level and, dotted, equivalent potential temperature (50 subtracted).

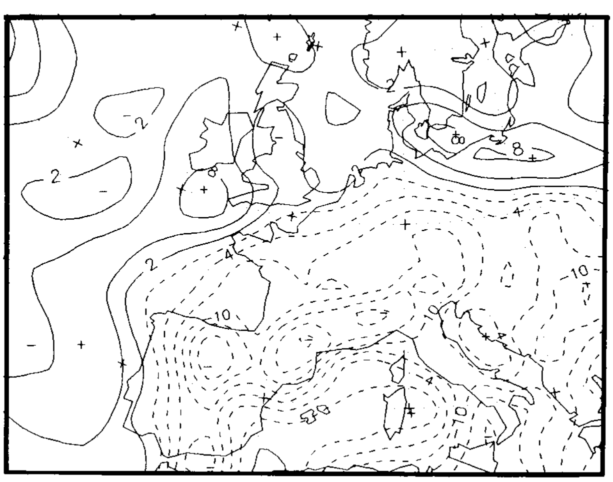


Figure 9. Analysis of the KO-index for 0000 UTC on 20 August.

That form results by using the Q-vector defined by Hoskins *et al.* as

$$\mathbf{Q} \equiv \mathrm{d}g/\mathrm{d}t.\nabla_p.\theta = (-\partial \mathbf{v}_g/\partial x.\nabla_p.\theta - \partial \mathbf{v}_g/\partial y.\nabla_p.\theta),$$

where subscript g denotes geostrophic.

It describes the total time rate of change of the gradient of the potential temperature θ within a geostrophic current at a pressure surface. The forcing of vertical motion is given by

$$2h.\nabla_p.\mathbf{Q} \qquad (h = R/p_o(p_o/p)^{c_v/c_p}.$$

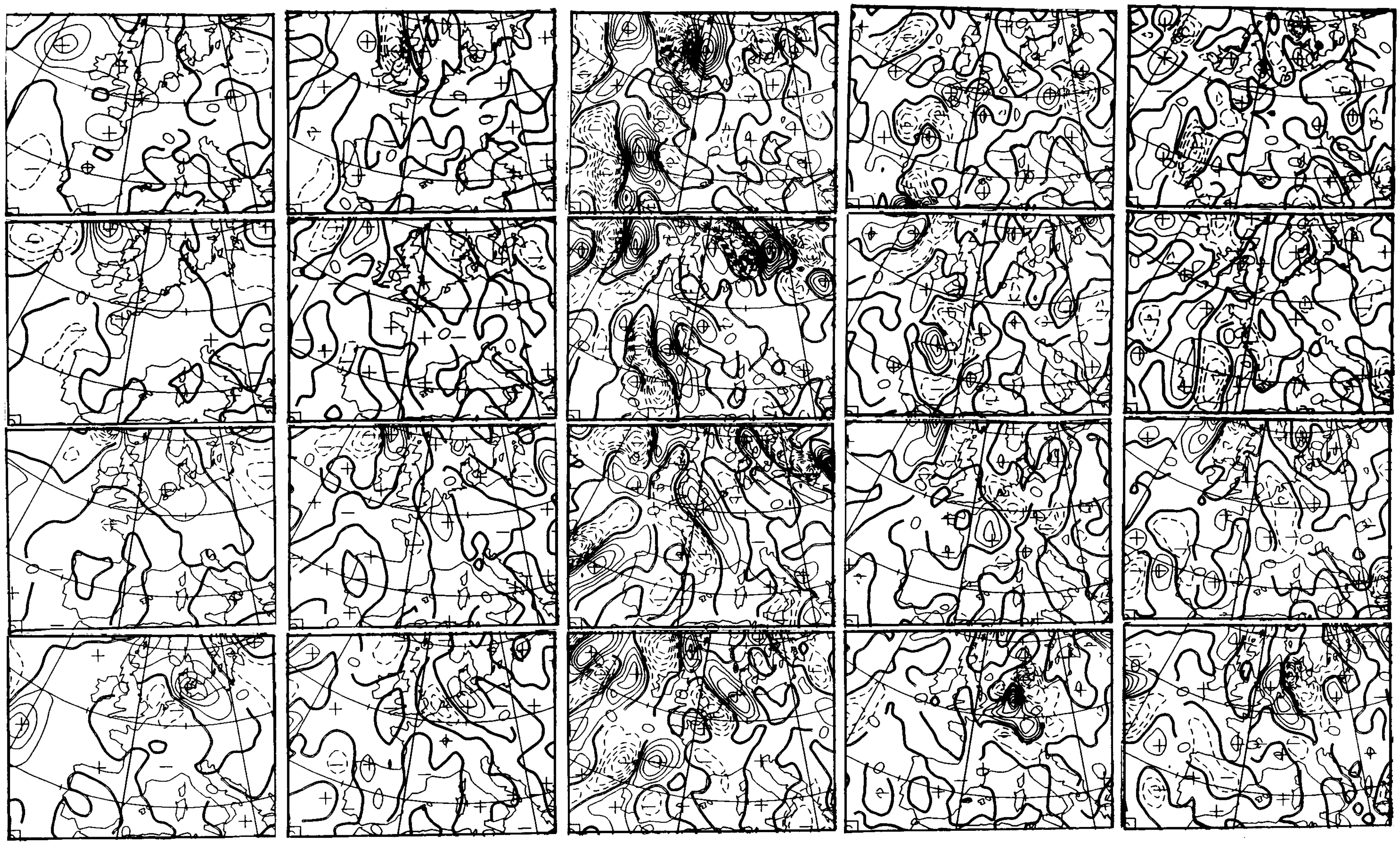
This can reasonably be assumed to be directly proportional to omega. Ascent is therefore to be expected in regions with a convergence of the Q-vector whereas descent occurs in areas with a divergence of **Q**.

To use these correlations for synoptic diagnosis, maps, containing the vorticity advection 500 hPa, the thickness advection for 500–1000 hPa and the Q-vector divergence at 700 hPa derived from numerical analyses, are distributed in the fax programme of the DWD (DCF 54). These maps, supplemented by some other fields are reproduced in Fig. 10.

By comparing the position of the individual thunderstorm areas with these analyses, an amazing correspondence can be found in most cases. This is already the case for the first thunderstorms moving from Germany towards Poland on the 19th which correlated with an area of forced ascent at 700 hPa mainly caused by maximized warm-air advection in the area concerned. The convective overturnings taking place over the Iberian Peninsula at the same time, and encroaching on western France, were released, or at least supported in their development, by large-scale lifting ahead of the upper trough approaching from the west.

The correlation was weaker for the formation of the thunderstorm cell over eastern France during the afternoon of the 19th. Forced ascent was only indicated there by the Q-vector-convergence analysed at 850 hPa.

The ascending motion over western France during the night of the 19th/20th had its origin partly in warm air advection, and partly in the positive vorticity advection ahead of the upper trough. It produced the large cloud-field with embedded thunderstorms in that area. It also led to convergence in lower levels and therefore to the production of cyclonic vorticity which became visible in the formation of the surface low pressure centre. The



(a) (b) (c) (d) (e)

Figure 10. (a) Thickness advection 1000–500 hPa (2×10^{-7} m^3 kg^{-1} s^{-1}), (b) vorticity advection at 500 hPa (2×10^{-9} s^{-2}), (c) vorticity advection at 300 hPa (2×10^{-9} s^{-2}), (d) Q-vector divergence at 850 hPa (5×10^{-18} m kg^{-1} s^{-1}), and (c) Q-vector divergence at 700 hPa (5×10^{-18} m kg^{-1} s^{-1}), at 12 UTC on 19 August (row 1), 00 UTC on 20 August (row 2), 12 UTC on 20 August (row 3) and 00 UTC on 21 August (row 4).

somewhat noisy structure of the distribution of vorticity advection on that date (Fig. 11) was possibly not fully realistic since the numerical analysis did not exactly catch the position of the upper trough.

The correspondence between thunderstorm development and large-scale forced ascent is striking at noon on the 20th. Precisely there where the line of thunderstorms formed over eastern France forced ascent is indicated at 700 hPa which can be again traced back partly to warm air advection and partly to positive vorticity advection ahead of the upper trough. Therefore deep convection was possible without the need for high temperatures near the ground, rather the release was due to a superimposed large-scale ascending motion typical for most strong convective overturnings.

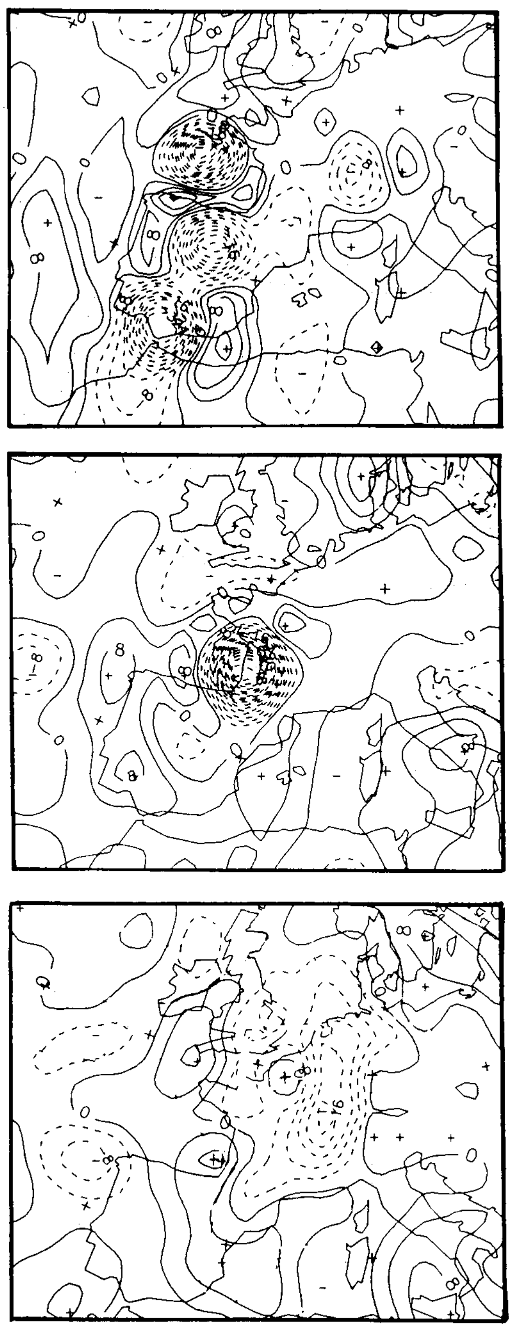


Figure 11. DWD analyses of omega at 500 hPa (hPa h^{-1}) at 1200 UTC on 19 August (top), 0000 UTC on 20 August (centre) and 1200 UTC on 20 August (bottom).

Besides containing the zone of ascent over the North Sea and eastern central Europe (which corresponds well with the cloud configuration) the distribution of the Q-vector divergences for the 21st at 0000 UTC has an area with strong forced descent due to the combined effect of cold air advection and negative vorticity advection behind the trough. The cold air advection works in the lower levels not only at the rear of the original cold front but also ahead of it too, namely behind the newly formed front at the forward edge of the thunderstorm area.

It is of great interest to compare these results with the vertical motions produced by a numerical model. They contain not only the large-scale forcing, but also the convection simulated within the model physics. Fig. 12 shows analyses of the vertical motion at 500 hPa from the DWD operational T+106 model. The comparison shows a qualitative correspondence with the quasi-geostrophic estimated forcing in many areas on the one hand, and on the other a good correlation with the development of cloud and hydrometeors in most cases. That is especially true for the Iberian Peninsula and Biscay on the 19th and the night of the 20th, as well as for the release of the thunderstorms at noon and in the afternoon of the 20th over eastern France.

In order to have a chance of forecasting the release of potential instability by superimposed lifting, 12-hourly forecasts of KO-Index and omega at 500 hPa are distributed twice a day in the DWD facsimile broadcast. The relevant forecast maps from 19–20 August 1992 are reproduced in Fig. 11. They clearly indicate the highly potentially unstable conditions south of the air mass boundary throughout the whole period. The forecast ascent at 500 hPa was generally in agreement with the analyses just described and the quasi-geostrophic reasoning with aid of the Q-vector divergences. In particular, the strong upward motion predicted for noon on the 20th over eastern France, was a significant hint that

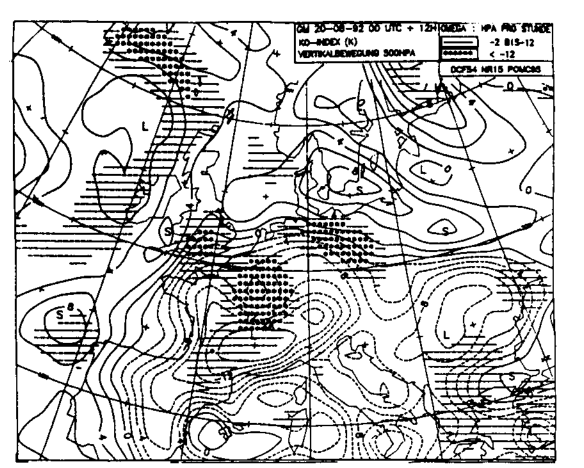


Figure 12. KO-index at 0000 UTC on 20 August with areas of ascent ($\omega \leq -2$ hPa h^{-1}).

corresponding intense convective overturnings could be expected in that area. The use of these maps tailored for very-short-range forecasting can therefore be strongly recommended.

5. Conclusions

The described weather situation was characterized by a sequence of convective systems developing over eastern France and crossing Germany eastwards or north-eastwards. The size and intensity of the convective overturnings increased from day to day and culminated in the passage of the line-like thunderstorm zone with hail, severe squalls and torrential rain in the afternoon and evening of the 20th.

The convective overturnings were released in conditionally and potentially unstable tropical air masses south of a poorly defined surface front which did not play any role in the release of the deep convection. Nor was the daily heating due to insolation enough to explain the convective development on all days. That is especially true for the main event on the 20th. The release of the instability on that day can be definitely traced back to large-scale ascent ahead of an upper trough swinging north-eastwards.

That reasoning is corroborated by diagnoses of the quasi-geostrophic forcing of vertical motions using vorticity and temperature advection functions on the one hand and Q-vector divergences as direct indicators of the forcing on the other. A comparison with the vertical motion simulated by a numerical model shows a qualitative correspondence with the quasi-geostrophic forcing in many areas.

In order to forecast the release of potential instability by superimposed ascent, 12-hourly prognoses of a stability index and the model omega at 500 hPa are produced and distributed twice a day in the DWD facsimile broadcast. For the main event this map gave a clear indication for the release of strong convective overturnings over eastern France exactly in the area where the development of the line-like thunderstorm zone started.

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A message from the Editor

I am very aware that, with only a few issues of *The Meteorological Magazine* left, I shall not be able to publish all the papers that have been submitted to me in the past year or so. When the November issue has been made-up I will write to authors whose work has not been used, offering to return it or to pass it on to another publication. I am also aware that many of the unused papers will be from overseas, and that these papers are important to remind UK readers that there are meteorological services elsewhere that do research work. I therefore hope to use some of these papers in the *Meteorological Office Science & Technology Review* (*MOST*): being of restricted circulation, publication in *MOST* should not preclude publication of the same work in a 'learned' journal where more kudos may be earned.

Meanwhile, I am anxious to build up a network of correspondents outside the UK, who will let me know of interesting developments in meteorological methods and instrumentation in their part of the world. Although I get to read about many of the more exciting weather events in the British press, accounts are often incomplete and inaccurate. So accounts, or local newspaper cuttings will be welcome. Because space will be limited (and reproduction will be by photocopier) lengthy items with colour illustrations will be inappropriate during 1994. Items for *MOST* should be more like Hisscott (February 1993) and Moir (July 1993) than Forbes (July 1993) and Kurz (this issue). Articles of a more general nature (such as the history of weather forecasting at London Airport) may be longer, but subject to serialization.

Editors of other journals will be encouraged to reprint items from *MOST* in their own language.

Because it seems likely that 1994 will arrive before the next issue of the Magazine, I would like to take this chance to wish all our loyal readers greetings appropriate to their celebrations of Christmas and the New Year.

Rodney Blackall
17 November 1993

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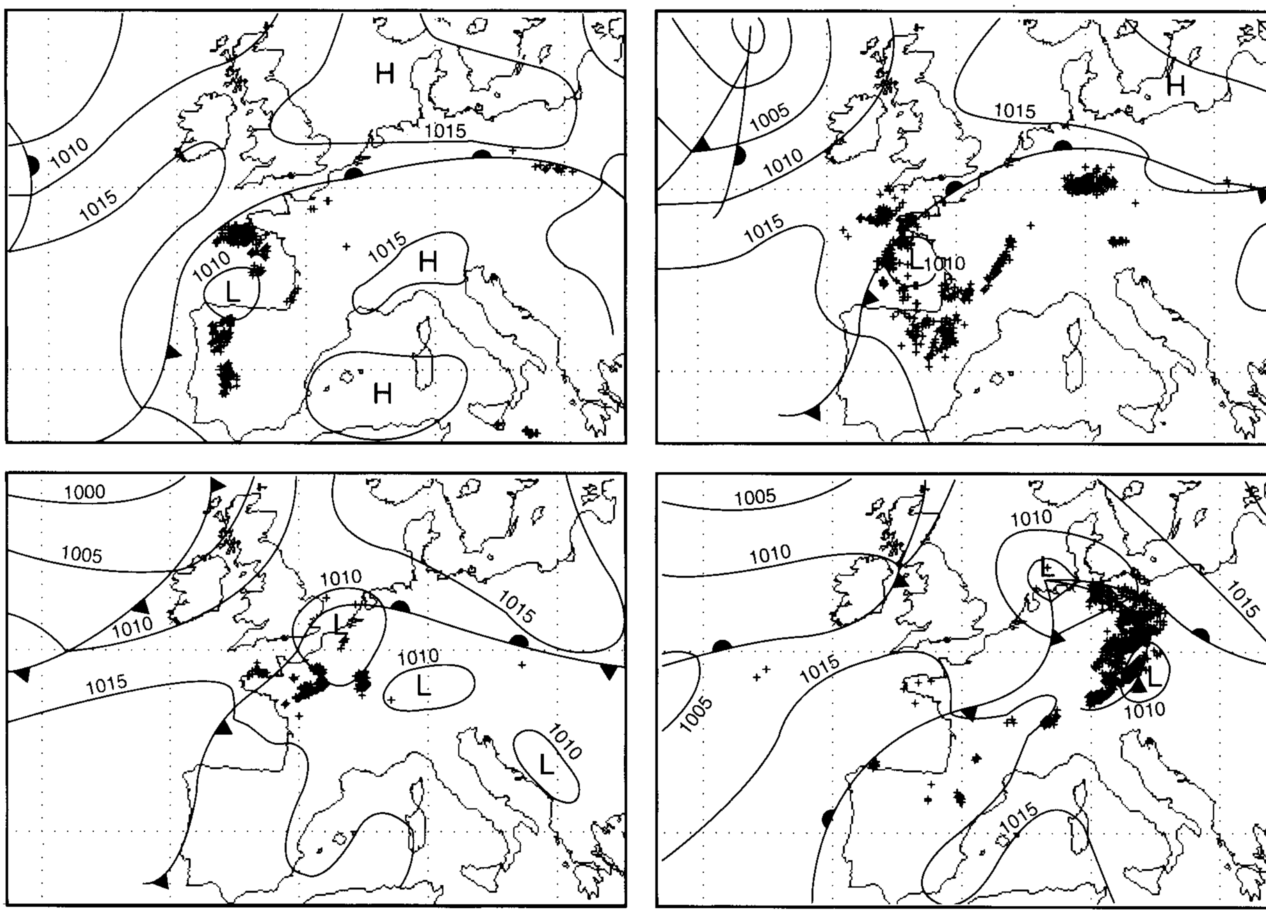
The thunderstorms of 19/20 August 1992 — a view from the United Kingdom

R.M. Blackall and P.L. Taylor
Meteorological Office, Bracknell

The article by Dr Kurz gives a very good description of the main event. However, I thought readers would be interested to see what the UK Meteorological Office ATD system detected. The four charts are for the same time as Kurz's Fig. 1. The surface analysis has been redrawn on the projection of the ATD charts. Taylor asked his system to print a '+' for each report in the four hours preceding the surface analysis time. Naturally there is a lot of overlap, but this makes the main clusters show up more clearly than any written description.



UK Meteorological Office ATD reports combined with DWD surface analyses for 1200 UTC on 19 August (top left), 0000 UTC (top right) and 1200 UTC (bottom left) on 20 August, and 0000 UTC on 21 August (bottom right).

Editor's note — what follows has been extracted from the transcript of a talk given at a Meteorological Office colloquium in September 1992. With the rise of climate modelling as a science, it behoves us all to be more knowledgeable about the behaviour of the large ice fields. This also is the second in our series on marine subjects (the North Sea was described last month).

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Sea Ice — a view from the Ice Bench

A.P. Maytham
Meteorological Office Sea Ice Office with Metroute

1. Introduction

The essential requirement of any ice service is the dissemination of sea ice data, and those from the Meteorological Office are largely collated from external sources. A watch is maintained on the seasonal variations in the mass balance of the cryosphere as these variations are an essential part of the seasonal global pattern.

2. The formation of ice

When cold air passes over water it removes heat from the surface, the cooled water is denser than the warmer water underneath, and so it sinks — being replaced by that warmer water from below. This process would continue until the whole column of water had cooled to zero; then a change of state, from liquid to solid, would talk place. The Arctic, being between 1000 m and 2000 m deep, with a maximum of 3800 m, would never have any sea ice at all. Firstly the winter season would not be long enough to freeze it all. Secondly the North Atlantic Drift, passing vast volumes of temperate water into the Arctic basin via the Fram Strait, would ensure that the Arctic column always remained well above freezing, and therefore liquid. Most substances contract when cooled, one of the facts of physics. However, fresh water behaves anomalously and expands when cooled below +4 °C. This expansion gives the coldest water more volume and less density, so instead of sinking, it creates a stable layer at the surface, which can now be cooled to freezing if the air is cold enough. This stable surface layer is usually about five centimetres deep, but is dependent upon the severity of the frost. The mixing will carry on as normal below this level until the next 5 cm layer is at 4 °C, and becomes stable and ice can form. The ice will grow further as the layers underneath cool and become stable.

Sea water usually has a salt concentration of about 35 parts per 1000 and has to be cooled to about −1.8 °C before ice forms. Sea ice has a large temperature gradient from top to bottom and consists of pure water ice with pockets of more concentrated brine within. The brine has a still lower freezing point and gravity pulls it downwards towards the higher temperature. This process continues until the salts are eventually expelled back into the sea, and within two years the sea ice is pure. This process creates areas of very cold dense saline water which sink. The maximum growth of sea ice is about 2 m in a winter. We do not normally get more than this, because the degree-days of frost for further downward growth would require air temperatures to fall much below −60 °C, and this is rare.

3. Some characteristics of the North polar region

(a) The Arctic ice sheet is free-floating but surrounded by land which naturally inhibits seasonal spread.
(b) The ice sheet is one seventh the size of the Antarctic and contains one eighth of the ice.
(c) The ice is mainly 2 m thick, with one eighth above and seven eighths floating below sea level. (The Greenland ice sheets are separate from Polar as far as the Ice Bench is concerned.)
(d) The average winter extent of sea ice is 15 million km^2 (msk). The average summer extent of sea ice is 8 msk giving an annual range for the Arctic of only 7 msk
(e) The ice grows in the Arctic for four months of the year, from November to February. The Arctic has a four-month decay period from March to May. The seasonal change is called the ice pulse. Because snow has a very high albedo, most of the sun's heat is reflected and the surrounding snow-covered land encourages ice formation in Winter. The land assists in warming the sea in Summer, but when the spring thaw starts, fresh water coming from the land flows under the ice, protecting it from the warmer, saltier water below.

From the Ice Bench point of view, we divide the cryosphere into five parts. Each is a distinct system, differing not only by seasonal fluctuations, but in the forces and ice dynamics which control the systems. There are four systems in the northern hemisphere, and one in the southern hemisphere. All are so different that they have to be independently discussed.

In the north, three of the four systems are shown in Fig. 1.

1 — The North Atlantic with access to the Pole; and major outflow of ice from the polar region.
2 — The North Atlantic without access to the Pole (Baffin Bay, Hudson Bay and Davis Strait, etc.).
3 — The north Pacific area, with access to Pole, but no forced outflow, only seasonal ice growth, and unaffected by the polar gyre.

4 — Freshwater sea ice areas of the Baltic and enclosed Black Sea.

For the fifth, The Antarctic, there is not enough space here. The reader is advised to read the fuller version published in *The Marine Observer* (Maytham 1993, 1994).

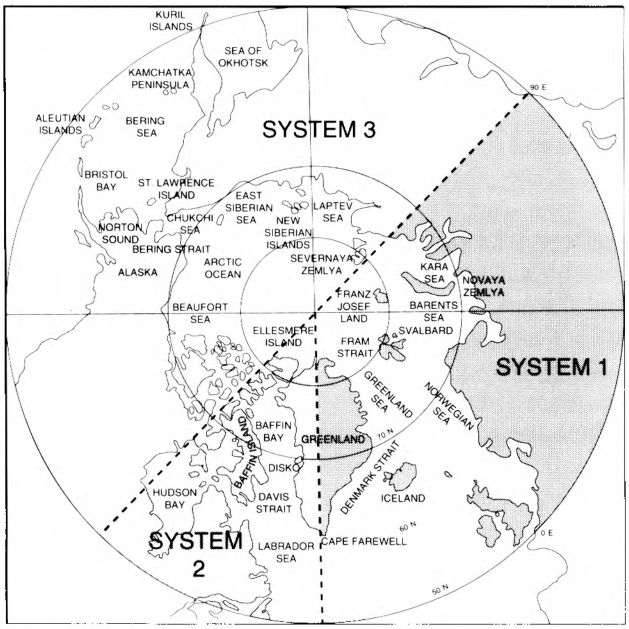

Figure 1. The Arctic, showing Systems 1 to 3.

4. Systems

System 1

The main factors here are the Polar Gyre and the Trans-Polar Drift. Although the weather patterns over the pole are varied, the polar region as a whole enjoys a degree of stability: a cold high tends to dominate the area. However, one special feature of the north is the Beaufort Sea low. This is formed by the upwelling from currents in the Beaufort Sea area clearing the ice; the exposed warm water generates a low. The winds, blowing anticlockwise around the low, move the ice, which is nearer the pole, in a clockwise gyre. The low is not always present, and the gyre may be maintained, even started — by the dominant polar high. It is however, known as the Beaufort Gyre even if it is not started by the Beaufort Low. We will refer to it hence forward as the Polar Gyre to avoid confusion.

The Polar Gyre, is the main influence moving the ice around and this has been shown in the main drift patterns of ships that have gone into and through the ice. Their tracks around the Arctic Ocean are well documented, and they all tend, in the long term, to the Fram Strait. However, the currents also influence the Polar region, but not until the gyre is stopped; and then the ice cap can be literally pulled apart by them. The sub-surface currents, which cause upwelling and 'downwelling' bear no resemblance at all to the surface currents (Fig, 2), or the actual gyration of the ice cap, but they do play a part in

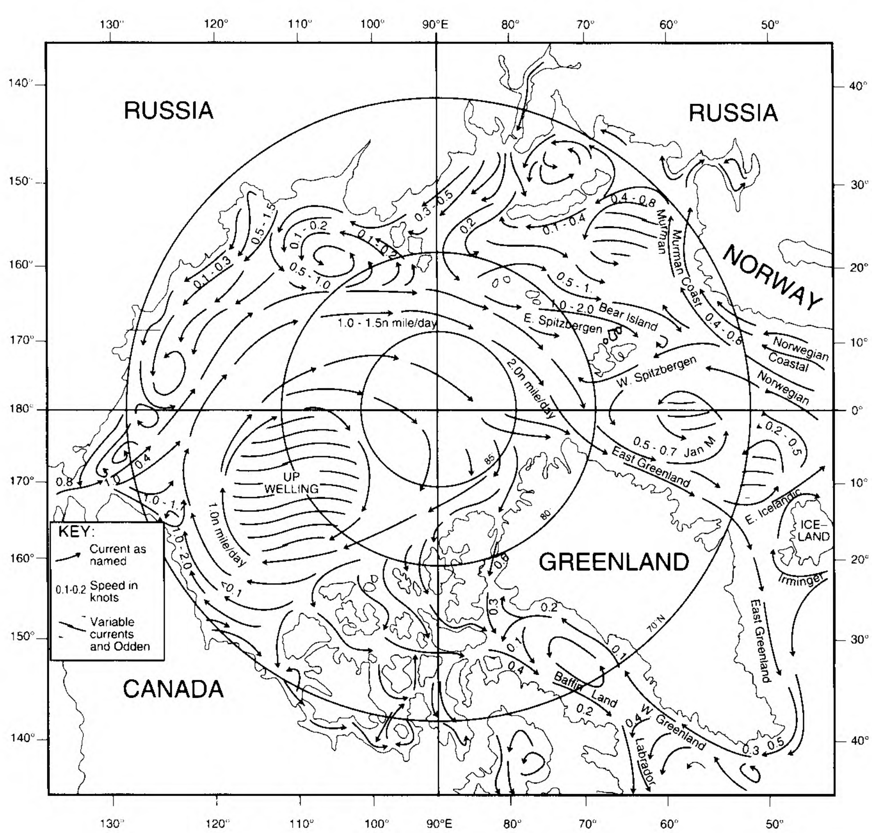

Figure 2. The Arctic. General surface currents (speed in knots, except where shown).

the starting off of the Beaufort Low. The sub-surface current at depths of up to 150 m brings warm water to the Beaufort Sea area. *Note that the ice is mainly driven by the winds.*

There have been occasions when explorers walking to the pole have encountered vast areas of open water, entirely unexpectedly. (See the section on Odden below.)

Sea ice in the Arctic can only ever develop to about two metres thick. But by the time it has spent up to five years in circling the Arctic, pressure from the polar gyre and polar drift, rafting, ridging, hummocking and various impacts, its thickness could be four, or in extreme cases, five metres. By this time it is heading through the Fram Strait and comes into what is known as the marginal ice zone (MIZ), The Fram Strait is the only feeder of ice that influences this system. The ice tracks down the east Greenland coast with the East Greenland Current to Cape Farewell — the southernmost point of Greenland (Fig. 3).

The rate that ice, as heavy, medium and light floes, moves out through Fram Strait follows a similar pattern every year. However, the gyre does vary in strength, and the volume of ice passing out can be predicted from it. The stronger the Polar Gyre, the more ice flows out. The Fram Strait monthly flow does have a consistency worth monitoring. Torna Vinje, who is the head of the Norwegian Polar Research Institute, has done a vast amount of research on the Fram Strait. Vinje has shown, by flow meters across the Strait, that in fact the inflow equals the outflow, which is not shown from the charts of surface currents. The currents play a large part in the flow of the ice along this coast. The charts show the main current down the coast of Greenland, and the main strength. This main strength follows the continental shelf, and this is fairly consistent with the maximum flow of ice. This main flow of ice is along the marginal ice zone, and this is where the main mixing and the melting take place. After the Fram Strait, there are various features in the topography that divert the current, and the ice. The eddies in the Gulf Stream drift also affect the mixing areas.

From the Ice Bench point of view, the mixing areas are quite interesting as they do have various features. Where there is mixing, there are little vortices. These show fairly clearly on satellite pictures taken by NOAA Advanced Very High Resolution Radiometers (AVHRR).

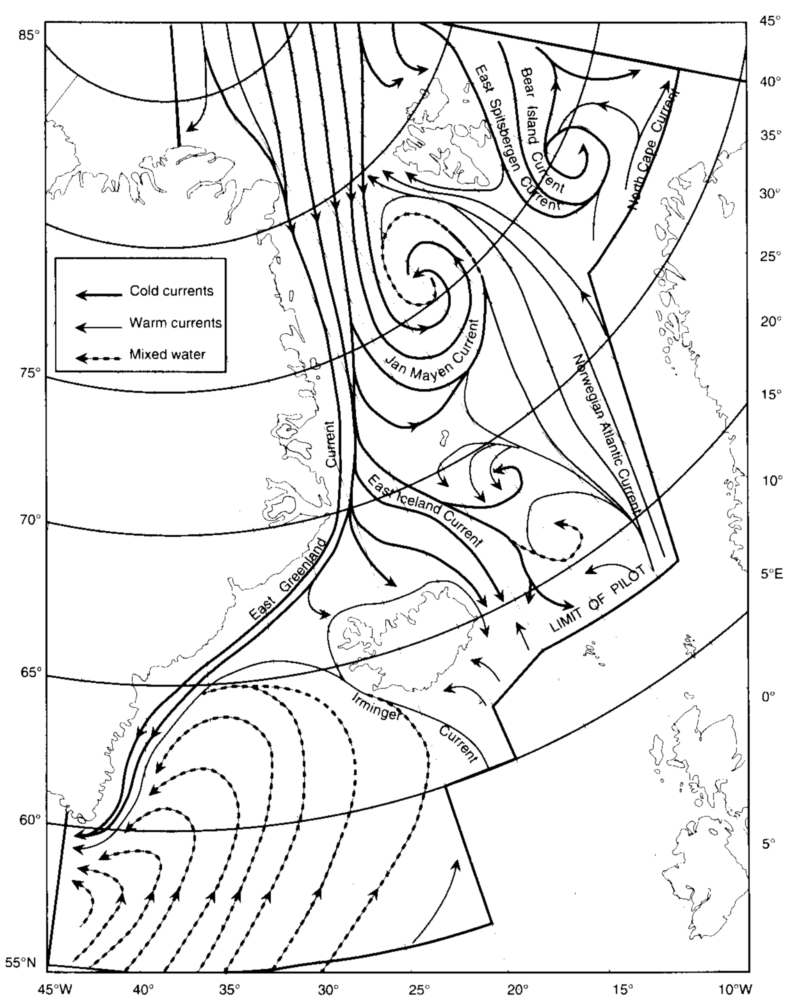

Figure 3. Norwegian Sea and Fram Strait; general surface circulation (extracted from Admiralty Pilot NP11, *The Arctic*, published by the Hydrographer of the Navy).å

These give a good overall picture, but on some channels the footprint is small. The Synthetic Aperture Radar (SAR) microwave scanner of ERS-1 is best for showing actual ice concentrations because it has the right size footprint and shows the mixing and the vortices along the MIZ.

The large melt in this area generates vertical frontal systems in the water. The main currents do not mix, as the cold melt water flowing south is stable and as dense as the warmer water flowing north. The resulting front can be seen on a bathygram of the various areas. There are some areas that are virtually stable fresh water, and there are others of mixed water both stable and unstable. It is the areas of mixed water that create the fog problems in this particular region; but cold, stable water will refreeze as soon as there is cold air above.

The topography of the area shows why we get certain currents. The East Icelandic Current, The Irminger Current, the Jan Mayen Current, and all the eddies associated with these, follow the main ridges and shelves. These divert the ice away from the continental shelf flow and it then melts rapidly.

One notable feature of System 1, is the scarcity of icebergs of land origin. Most are calved from the Siberian glaciers and are mainly trapped in the New Siberian Islands by the pressure of the Trans-Polar drift, so they do not actually pass into the gyratory system. They do not become a major feature; in fact the reverse, the lack of bergs is the interesting feature.

System 2 (Baffin Bay, Hudson Bay and the area to the St Lawrence Seaway and the Grand Banks)

The main feature of our System 2 is bergs. There is no access to the polar gyre, and the region is not influenced by the trans-polar drift. Surrounded by land and islands, it is an entirely independent system. The predominant feature which governs the berg flow, is a warm current passing up the west coast of Greenland. This plays an important part in the ecology of the area, and controls the ice melt/growth in the seasonal pulse. The importance of the current, which begins at Cape Farewell, can be seen from the actions of the bergs. They are all taken by the current northwards to Baffin Bay, to circulate for up to three years, before drifting southwards to the Grand Banks — which area they have made famous.

Ice coming down from the Arctic Ocean will, in Winter and extreme conditions, reach Cape Farewell. And although this is not normal, some ice may round the Cape and travel into our System 2. (To all intents and purposes, System 1 ends at Cape Farewell, where System 2 starts.)

The warm current going up the west Greenland coast collects the bergs as it tracks northwards. There are small bergs calved south of Disko Island, but the main calving grounds for the larger bergs are further north where there are about 100 main tidal fjords which maintain a heavy flow of bergs. The sea ice is never more than about four metres thick — from rafting and ridging. However, the bergs are land ice, and are up to the depth of the glacier, usually soon breaking up into smaller pieces. As a norm, sea ice is usually present for most of the year, very light and coastal only — caused by land cooling. Even in mid-Summer there are still bits of sea ice about. They are never of great depth or in heavy concentrations. Most is light sea ice which has drifted out of the fjords, with bits of land ice from small glaciers. The current, although it plays a large part in keeping this little system moving, keeps the Davis Strait and Baffin Bay mainly free of sea ice in Summer. This is because the current brings water with temperatures of up to 8 °C. In water this warm, a normal berg of flawed land ice will melt in about 5 or 6 days. They do not survive long south of Disko Island.

The bergs are brought south with the vast amounts of soil, rocks and debris that glaciers gouge out of the land under normal circumstances. Normally sea ice, in salt water is 1/7th above the water line: freshwater ice, in fresh water is 1/8th above. But with ice of land origin there is no way of estimating the keel depths, because it has the rocks and various other debris within, and the mass balance is entirely changed. Gravity will pull much from the berg as they come down east of Baffin Island and into the Labrador Current: then down to the Grand Banks, where they greatly influence commerce. The Ice Bench is always particularly interested in the icebergs in this region.

The Labrador Current divides over the Grand Banks, and carries smaller bergs along the coast, or grounds them on the banks. A display of the topography over the banks, which is mostly mud, shows great grooves covering almost the entire surface. As the bergs melt, they change shape and may capsize, changing their draught. A berg may initially clear the banks on a high tide only to ground later. Drift will continue with the next high tide, or after some melt has taken place. The debris that is retained on arrival at the banks, will be released, and will help the bergs to split into smaller pieces. It also reduces the depth of water. Much of the silt settles between the boulders, and gives a flat appearance, scared by bergs grounding.

The main flow of the bergs is with the currents around the Grand Banks, and with the tides. There are little vortices and eddies which bring the bergs south of Newfoundland. Although the main southbound current flow stops at about 43 °N, there have been bergs much further south; and bergs have been reported as far south as Bermuda and as far east as the Azores: these must be considered.

In Winter the sea ice along the Labrador current is mixed with bergs. There are some bergs on the outer limits, but not many. The current, being cold, ensures that bergs within survive, but those outside the main flow soon encounter eddies and warm water mixing which destroys them.

As a result of the sinking of *Titanic* on 15 April 1912 the International Ice Patrol (IIP) (based in Groton, Connecticut) was set up in 1914. This body reports on the extent of the icebergs while the main bergs are drifting southwards. This occurs as the sea ice recedes and releases the bergs to the currents during June and July. Of all bergs, 94% appear between March and June, but 64% between April and May.

The lesser Bays, Basins, Gulfs and Inlets are all usually sea ice free in Summer, and follow the seasonally adjustable patterns. The Hudson Bay area does not have glaciers, so there are no icebergs. The seasonal pulse is greatly influenced by the heat budgets of a particular season. The heat budget for Hudson Bay is huge, and can prevent the early growth of sea ice, even though the land mass may be forming coastal ice. (It has been reported that sufficient heat is absorbed in one season to light the entire country of Canada.) The heat that is absorbed, and retained, is quite sufficient to prevent the ice from growing to any great depth and sometimes from forming at all.

System 3

There are three main features of System 3, peculiar to this area. First, although it is exposed to the pole, it is not influenced in any way by either the polar gyre or the Trans-Polar drift. The sea ice follows a fairly constant seasonal pattern of growth and decay. The current in the Bering Strait is in a northerly direction, and therefore has no effect on outflow of ice. The second feature is that all the ice is new ice, there is never any second or multi-year ice in the Pacific area, although some may be wind driven out of the Bering Strait. The third feature, peculiar to this area, is lack of icebergs. There are no glaciers which feed the Pacific area, and none flow out from the Arctic basin into the Pacific.

The air temperatures in Japan give severe winters: they get a lot of snow, but sea ice only grows as far south as Hokkaido Island in north Japan. The ice never grows further south because the currents moving north inhibit the growth. Currents along the west coast of Canada keeps that coast ice-free also. Due to the northbound currents, the mean concentrations of sea ice are fairly high.

System 3 has no pressure, no main outflow, and no current driven pattern. The sea ice will seasonally grow and recede through the Bering Straits, and will have a maximum keel depth of one or two metres depending on its history.

System 4

Our other ice systems in the north are the Baltic and the Black Sea. The Crimean ice grows because it is in very shallow water, and it cools and freezes rapidly. Never growing to any great depth because of time (or lack of it); it decays rapidly as the air temperature rises. The ice season is very dependent upon air temperatures, and, when ice does form, it is usually between February and March.

The Baltic ice is a major influence on shipping concerns in our area. On average it will grow to cover the Gulf of Bothnia. The northern part is known as the Bay, and the southern part the Sea; the whole being the Gulf. On average it will always freeze. The Gulf of Leningrad usually freezes, but not always the Baltic Sea, either North or South. Because it is fresh water, between 1.002 and 1.006 density, it starts to freeze as soon as the air temperature cools it to 0 °C. The sea ice does not often reach the North Sea, and when it does, is usually Baltic ice tide-drifted out.

The ice in the Arctic Ocean has only ever been measured to about 5 or 6 metres, and that from heavy ridging and rafting. However, in the Baltic, hummocking, rafting and pressure ridging, can generate keel depths down to 28 metres, which — from a sea ice point of view — is phenomenal.

5. Features

5.1 Polynya

These are areas of open water in a ice field. There are three types of polynya. The 'shore polynya', the 'flaw polynya', and the 'reoccurring polynya'. A shore polynya occurs between the shore and the ice, a flaw polynya is a crack opened up by current, tide or upwelling. A reoccurring polynya is largely self explanatory, and an example is the Beaufort Sea Polynya. A land/shore polynya is not always opened up by tides or current — wind may create an opening. There is also upwelling which can start a shore polynya to be maintained by the wind.

The polynya are not unusual, they can occur anywhere and everywhere; and frequently do. The only recurring one is the Beaufort Sea Polynya. The others are usually wind generated on the southern part of the east Greenland coast, and current generated on the northern part of the east Greenland coast. Polynya are very easily seen from satellites. In the north there are many small currents which all play a part in packing the ice/bringing warm surface water/bringing warm sub-surface water for upwelling melt/clearing ice/packing ice — and many other small influences like eddies and small vortices. Some are peculiar to Summer only. The main currents are the Jan Mayen Current, The Irminger Current, the East Iceland Current and the Norwegian Current (remnants of the Gulf Stream Drift).

5.2 Odden

'Odden' is Norwegian for tongue; they occur when cold air passes over cold stable water. Ice forms, probably 9 or 10 tenths coverage, but only a few centimetres thick. The ice will last only as long as the cold air is above it, as sub-surface currents and warm air soon cause its decay. The only odden are the Jan Mayen Odden, the Bear Island Odden and the North-East Odden. All are associated with currents in the area. Some mixing with sub-surface currents in the area may keep the odden ice very thin and even inhibit development. The North-East Odden and the Bear Island Odden are not actually discernible, because the current brings ice anyway. The Jan

Mayen current does not carry ice far from the continental shelf barrier, so this odden is the most conspicuous.

5.3 Whalers' Bay

Warm water from the North Atlantic Drift, becomes the West Spitzbergen Current, and flows into the Arctic basin. This warm water causes the ice to decay, and a vast area of open water develops north of Spitzbergen. This has a bay-like shape, and can last for some considerable time. The warm water can be seen passing Iceland, and takes about two weeks to arrive at 80 °N and start the Bay forming.

5.4 Fronts

The fronts are persistent interfaces between cold and warm water. The south-flowing cold water has much the same density as the warm northerly flow because it is mainly fresh melt, less saline, and colder. The volumes of water have a vertical contrast of salinities and temperature, rather than the normal horizontal divisions. Along the fronts there is upwelling of warm saline water and the cold denser water sinking. these movements are known as funnels, and the effect known as the 'chimney effect'. These chimneys don't only occur in this part of the world, they do occur throughout the globe where there is, for whatever reason, mixing taking place. By and large, in the open oceans, the layers are fairly well defined in a horizontal pattern. But along the east coast of Greenland they are not.

The front that is most noteworthy is the 'Norwegian Coastal Front' as it changes character twice a year. In the summer the land heats coastal waters, these become much warmer than the Gulf Stream drift, so a front forms with warm water landward and cold to sea. In the winter the land cools the coastal waters, while the warm water of the Gulf Stream drift is largely unchanged; this puts cool water to landward, reversing the front.

Graphs of salinity and temperature comparison show the fronts well. The very concentrated cold salt water excluded from the sea ice naturally sinks, and is replaced by warmer water which gives a fairly clear-cut level under the ice. As this is continually mixing at the MIZ the expectation is for a continuous front. It does not follow these lines. The 35 parts per 1000 average salt water does not vary much in any of this area. Graphs show 35 or 34.9. But where the salts are being pulled through the ice it can go up to 40 parts, but this usually sinks so rapidly that it is not seen for long. There are places that have recorded 50 parts per 1000 but this is unusual.

5.5 Icing

One of the worst features of sea ice areas is the icing of ships. The main problem with it is that it can be seen happening, but the extent of the danger is not known. The ice seals the doors and the windows and all exits, so it can become impossible to get out. Radio aerials become iced over, and can break, leaving no means of communicating the distress or the problem in the area.

5.6 Satellites

Guidance in using meteorological satellite data to distinguish between clouds, ice and snow will be found in Chapters 1 and 8 of *Images in weather forecasting* to be published by Cambridge University Press early in 1994.

The Farnborough research centre produces a seven-day mean isotherm chart. We also get satellite data. We receive very useful data in real time from the Norwegians, who can do no wrong in our eyes.

We generate our own SXNT ice chart on Tuesdays from the Norwegian and Canadian data, on Thursday we use data from NOAA and the Joint Ice Centre. We also produce our AXXX sea isotherm chart. The ice bench charts are distributed mainly to CFO, and to the search and rescue centre at Chivenor, Devon, who disseminate to various authorities that require this information.

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Maytham, A.P., 1993: The Cryosphere — a view from the Ice Bench. *Mar Obs*, **63**, 178–189.

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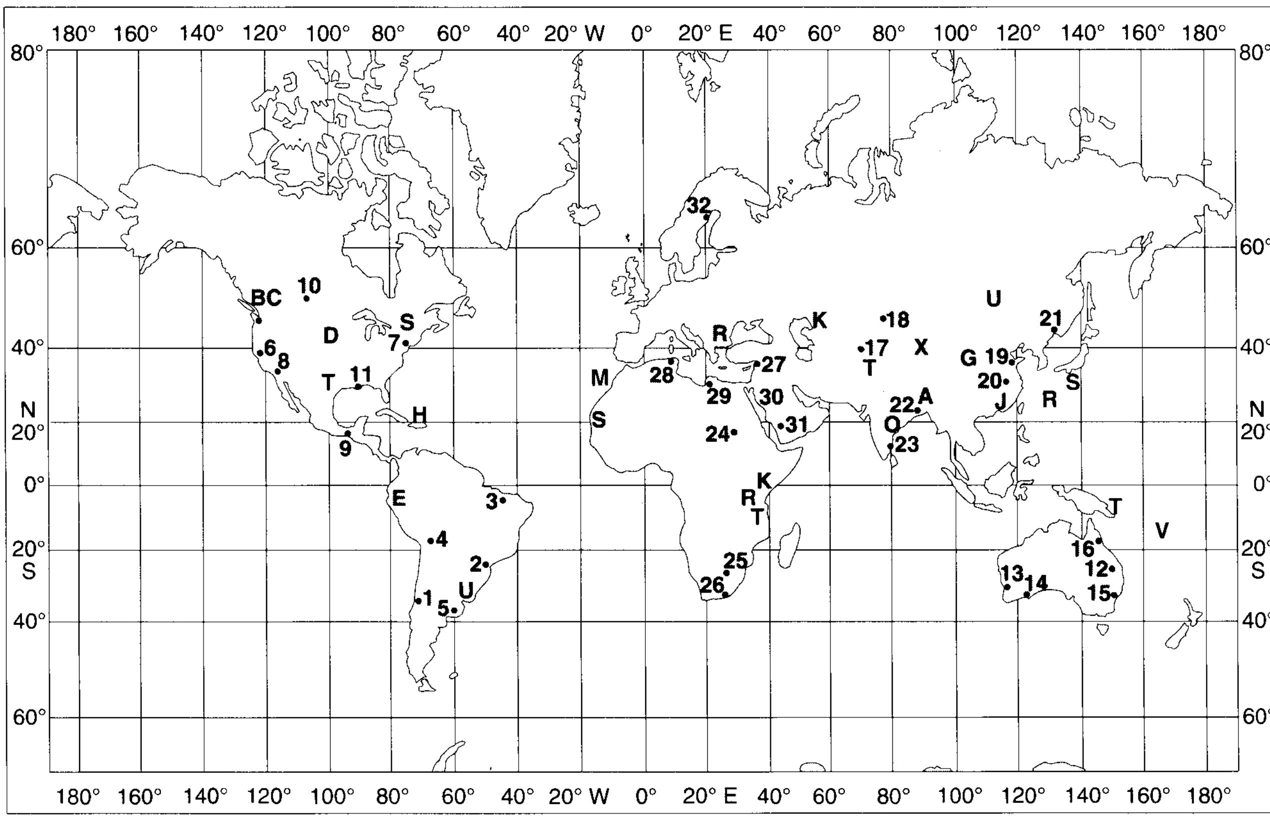
World weather news — May 1993

This is a monthly round-up of some of the more outstanding weather events of the month, three preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and press reports. Naturally they are heavily biased towards areas with a good cover of reliable surface observations. Places followed by bracketed numbers, or areas followed by letters, in the text are identified on the accompanying map. Spellings are those used in The Times Atlas.



Location of places mentioned in text

South America

Heavy rain at the beginning of the month led to landslides and much flooding around Santiago (1), Chile, on the 4th with a death toll of 11. Ecuador (E) suffered a calamity on the 9th when an earth tremor coincided with heavy rain near the Peruvian border, a cliff honeycombed with gold miners' tunnels collapsed with a heavy toll of life as 64 bodies were recovered and more than 200 were reported missing. Earlier in the month, heavy rain had caused the river Paute to flood in rural Ecuador with the loss of 20 lives. On the 8th, Artigas in Uruguay (U) found there had been 158 mm of rain in the previous 24 hours; this is about 50 mm more than the average for the whole month: to prove this was not a fluke, Salto next day beat its average by a similar amount when they measured 137 mm. Not to be outdone the Argentinian town of Concordia managed 155 mm in the week to the 10th, which is double the average for the month. The result of these remarkable rainfalls which had been occurring on and off since April was $400m of flood damage to Argentina's farm belt but no deaths. The Salado river was at its highest ever and flooded four million hectares.

Irati, near Curitiba (2) in southern Brazil had falls of 58 mm and 118 mm on the 13th and 14th respectively — their monthly average is 115 mm. On a different note, the eastern Brazilian town of Teresina (3), where the record temperature for May used to be 35 °C, had a hot spell starting on the 14th; maxima reported were 36.0, 35.6 and 36.0 °C. This is winter down south and La Paz, Bolivia (4), had a night minimum of −5 °C on the 18th, 2 °C lower than the previous record. In Patagonia −10 °C was quite common on the 26th breaking some records. Returning to the rainy theme, Tandil (5), 200 miles south of Buenos Aires, had 86 mm of rain on the 24th, their monthly average is 63 mm.

North America (and Gulf of Mexico)

A cold front crossing Texas (T) early in the month brought warm, wet air up from the Gulf and converted it to heavy rain; on the 6th San Antonio had 159 mm, nearly double the normal for the whole month; not far away Victoria had 194 mm while around Houston there were reports of tornados and baseball-sized hail. On the 9th there was a tornado near Dallas which killed one and injured 30: the same day brought news of high temperatures with the news with 33 °C in San Francisco (6) and 31 °C in New York (7) though the hottest was Monrovia (8), California, with 38 °C. The heatwave extended as far south as Salina Cruz (9) on the Pacific coast of Mexico where the 40.0 °C on the 10th was just above the old record. At the other end of the continent Edmonton (10) in north-west Canada managed 32.6 °C on the 12th which is 2.6 °C above the previous record: records were still being broken in British Columbia (BC) on the 18th.

In mid-month news came of a week of heavy rain over Hispaniola (H) and eastern Jamaica causing damage to crops, flooding and landslides. Twelve were killed in the Dominican Republic and traffic was severely disrupted in Santo Domingo. The period 18th/19th was probably the worst in Jamaica when 96 mm (the average for the whole month) fell, but no one was killed.

Rather imprecise information on the 22nd spoke of violent storms in South Dakota (D) and Texas with high winds, hail up to an inch in diameter and 150 mm of rain in two hours. The 26th brought heavy thunderstorms to the Mississippi delta flooding New Orleans (11) with 75 mm (May normal of 112 mm). On a general note, after analysing VHRR scans at the end of April, NOAA announced that 'In the USA the area with well developed vegetation is much smaller than in any of the last five years. Development is three to five weeks behind schedule except in south Florida, California and Texas.' On a more sinister note: after a record wet April Lake Ontario was 20 cm above flood level. The St. Lawrence Seaway (S) was being used to relieve the situation. It was closed to shipping two days a week so that locks could be left open. Watch this section next month.

Australasia

This information is largely based on that kindly given by the Australian Bureau of Meteorology. The month seems to have been uneventful over much of Australia with only Surat (12) in Queensland being picked out for mention — its mean maximum temperature of 26.8 °C was the highest in the 44 years of record. All the news seems to be reserved for Western Australia where wind and rain were the dominant features. The 1st brought heavy thunderstorms around Perth (13). In the country there were losses of newly shorn sheep and damage to roads and property: in the city electrical failures upset traffic lights and computers and one strike ignited a petrol pump. One man escaped unhurt when his umbrella was destroyed by lightning! Several places had their lowest May maxima for more than 30 years because of rain. The rapid deepening of a low near Esperance (14) on the evening of the 28th lead to them recording a new record gust of 82 kn (mean speed 59 kn) just before a power failure cut off the anemometer. At least six widely spaced gauges collected new May monthly record rainfalls of around 130 mm: Perth got half the month's normal rainfall in 48 hours from the 27th to 29th as 67 mm fell.

There were some notable storms elsewhere, Ulladulla (15), about 100 mile south of Sydney, had 101 mm on the rain day ending the 9th, and 91 mm of that fell in six hours. Innisfail, near Cairns (16) had 77 mm on the 22nd at the end of a week that brought 231 mm (the month's average is 305 mm).

Further afield the short-lived cyclone Adele developed near the island of Bougainville on the 14th and caused havoc in the Trobriand Islands (T) before crossing the extreme south-east of Papua New Guinea. No deaths were reported but a high proportion of the buildings on the Trobriands were destroyed. Sola in the Vanuatu (V) group attracted attention on the 22nd when 275 mm fell in 12 hours.

Asia

The southern Japanese island of Shikoku (S) started by getting half the usual month's rainfall almost at once with 117 mm in 24 hours to midday on the 2nd. However, the dominant feature seems to have been an especially potent cold front. The news from China on the 5th was dramatic! A 'cataclysmic' sandstorm in the north-west Chinese province of Gansu (G) lasting about two hours and laden with sand and pebbles killed 47, most of these were children swept into watercourses where they drowned: power lines and trees were blown down of course. Crops were buried or blown away and at the time the story emerged, 25 were still missing and 153 were injured. Further west, in Xinjiang Province (X), hurricane force winds created a violent sandstorm that blocked the main railway line in seven places stranding 48 trains, 10 000 people and damaging seven locomotives. These stories are probably related to the events further north in Mongolia. A depression moved east, and in Ulaanbaatar (U) the balmy 19 °C of the 5th (well above normal) was replaced by −6 °C, snow and sandstorms killing at least 16 people. A comparable change occurred in Tashkent (17) soon after when their maxima fell sharply: 7th, 26 °C (average); 8th, 21 °C; 9th, 7 °C. Alma Ata (18) reached 22 °C on the 7th, 8 °C on the 8th and 3 °C with heavy snow showers on the 9th. Tajikistan (T) was pounded by torrential rain on the 8th which brought flooding and destroyed 3000 homes, a dam and half the power supply system of the capital Dushanbe. The capital of China's Shandong Province, Jinan (19), had torrential rain at the end of this period when 84 mm fell in the second half of the 11th, this is 48 mm more than their daily record and monthly average. A little later Wuhan (20) on the Yangtze river just set a new record with a fall of 96 mm. In Jiangxi Province (J) the heavy rain and hail killed eleven and caused the river Gan to flood. The big change reached Japan on the 13th when Tokyo's maximum of 30.7 °C (near the May record) was rapidly followed by 21 mm of rain and a maximum of only 13.9 °C next day.

Severe contrasts were noticed again in Mongolia on the 19th with daytime maxima ranging from near 20 °C to continuous snow and night minima between −5 °C and −10 °C. Reports emerged of severe flooding in Khazakhstan (K) in mid-month as a result of torrential rain and heavy snowfalls. The worst effects were said to have been along the banks of the River Ural which rose more than 8 m. Our customary report of heavy rain in the islands comes from Cilacap on the south side of Jawa, here on the 19th, they managed 189 mm, 167 of which fell between 1200 and 1800 UTC. Daily totals well in excess of 100 mm were then reported from China on the 25th and 26th on the Ryuku Islands (R) on the 27th: out of all these 90 mm at Wutai-Shan, 200 miles south-west of Beijing, was perhaps the most impressive; their monthly normal is only 11 mm!

Sometime on the 24th or 25th one of the worst hailstorms for eight years hit eastern Iran; violent thunderstorms accompanied by hailstones weighing 150 g caused extensive damage to crops. To finish as we began, Vladivostok (21) had a maximum of 27 °C on the 27th, a new record by more than 3 °C, after the passage of a cold front the best next day was a mere 10 °C.

Indian subcontinent

'It was winter. We were of Kipling's 'hosts of tourists who travel up and down India in the cold weather showing how things ought to be managed'. It is a common expression there 'the cold weather,' and the people think there is such a thing. It is because they have lived there half a lifetime, and their perceptions have become blunted. When a person is accustomed to 138 °F in the shade, his ideas about cold weather are not valuable. I had read, in the histories, that the June marches made between Lucknow and Cawnpore by the British forces in the time of the Mutiny were made in that kind of weather — 138 °F in the shade — and had taken it for historical embroidery. I had read it again in Sergeant-major Forbes-Mitchell's account of his military experiences in the Mutiny — at least I thought I had — and in Calcutta I asked him if it was true, and he said it was. An officer of high rank who had been in the thick of the Mutiny said the same. As long as these men were talking about what they knew, they were trustworthy, and I believed them; but when they said it was now 'cold weather,' I saw that they had travelled outside their sphere of knowledge and were floundering. I believe that in India 'cold weather' is merely a conventional phrase and has come into use through the necessity of having some way to distinguish between weather which will melt a brass door-knob and weather which will only make it mushy. It was observable that the brass ones were still in use while I was in Calcutta, showing that it was not yet time to change to porcelain. I was told that the change to porcelain was not usually made until May.' From Mark Twain in chapter LVII of *More Tramps Abroad*. 138 °F = 59 °C.

To prove the above is not totally unfounded, the 2nd brought maxima in excess of 46 °C in east Pakistan and Orissa (O). The month opened with heavy rain in Assam (A) and Tripura which caused flash-flooding and made tens of thousands homeless. About the same time Dhaka (22), Bangladesh, was struck by a 45-minute storm of great violence. Nine were killed and 250 injured as gale force winds flung debris around. Shortly afterwards there were heavy hailstorms in surrounding areas. Three major rivers then broke their banks under the weight of water flowing from the Himalayan foothills. The Ganges delta had a 'tornado' on the 14th with wind speeds of about 100 kn that killed 25, injured 2000 and razed 15 000 bamboo huts. Madras (23) was rudely awakened on the 15th when a thunderstorm deposited 72 mm in three hours before local noon (this about three times the monthly average).

Storms in the north of Afghanistan between the 14th and 16th were said to have killed at least ten humans and 200 animals. Far away to the south-east, Comilla near Dhaka, suffered a period of 'seasonal storms' on the 16th and 17th: the heavy rain and tornados killed 8 and made 5000 homeless and in surrounding areas 100 000 were marooned by flooding. The last week of the month brought heavy rain and widespread flooding to much of Sri Lanka, killing five and making 150 000 homeless.

Africa (except the north coast)

Northern parts of Tanzania (T) were hit by a five-hour rainstorm on the 2nd which brought flooding and extensive damage to crops. Nearby on the shore of Lake Malawi, Nkhata Bay measured 145 mm on the morning of the 1st and a further 114 mm on the morning of the 2nd. Early on the 3rd Nyere, Kenya (K) followed suit with 108 mm (average for the month is 120 mm). Mwanza on the south shore of Lake Victoria had just over half its usual monthly fall on the 4th with 58 mm. It was not all rain in this part of the world, Nairobi's 28.6 °C on the 9th was a near record and followed eight days of above average warmth. Further north the heat triggered thunderstorms and Mandera's 125 mm was about five times the average for the whole month and Meru's 114 mm was nearly four times the average.

Over on the west coast Senegal (S) fairly sizzled on the 11th when Matam broke its May record by nearly a degree in reaching 48.0 °C. Back in the wetter east, Rwanda's (R) capital Kigali just managed a new May 24 hr rainfall record on the 16th when 69 mm fell: Dzaoudzi in the Comoros (north-west of Madagascar) normally only has 36 mm of rain in May; they had 99 mm in 30 hours to 1200 UTC on the 17th. The rains spread further north into the Sudan than usual when on the 23rd El Obeid (24) got 23 mm compared with the monthly average of about 18 mm. In contrast to the frost in South Africa (e.g. −4 °C in Bloemfontein (25) and −3 °C at Tsabong, Botswana) Zimbabwe and Kenya had near record maxima of 28 °C on the 28th and 29th respectively.

The following notes are kindly supplied but the South African Weather Bureau. While the south-west coast was wet most other areas were having about 25% of normal rain and Port Shepstone's 0.1 mm was a new record. At the other extreme Vredendal's 80.8 mm was also a record. The 1st brought heavy rain and flooding to the Cape Peninsula, 55 mm at Goodwood, and on the 16th a deep low to the south brought gales. Out at sea, off Port Elizabeth (26), storm force winds and an 11 m swell brought about the loss of the *Nagos* when a hatch cover blew off: half the crew was rescued but the weather was too bad to pick up the remaining 17.

Europe, North Africa and Arabia

A low developed over Syria on the 5th producing heavy rain and thunderstorms on its western side. Hama's (27) 32 mm on the 4th/5th was the wettest and 11 mm above the average for the whole month. Meanwhile at the other end of the Mediterranean a low had drifted from Madeira into the Alboran Channel, so on the 5th Gibraltar got 26 mm of rain in 12 hours instead of taking a month over it. Across the Strait, Tangiers (May average 39 mm) had 27 mm on the 3rd and 51 mm on the 4th. The heavy rains spread along the north African coast and Annaba (28) in north-east Algeria had 46 mm in the 24 hours to 0600 on the 6th (the 38 mm that fell in one 6-hour spell equalled the usual total for the whole month) and Ajdabiya (29) in eastern Libya got 13 mm in a thunderstorm on the 6th (their May average is about 6 mm). By the 7th the low was just south-east of Sicily, and although Malta's 15 mm exceeded the monthly normal of 11 mm they got off lightly — 67 mm fell on the south coast of Sicily and 55 mm on Tunis. Two days later it was the turn of Souda, Crete to get three times its month's rainfall in one day when 43 mm fell. By the 10th this low had lost its identity over Turkey but still gave Antalya, on the south coast, their average month's rain, 33 mm, in one day. The moist air hung around a bit till the 12th when at Iskenderum (27), near the Syrian border, 132 mm thundered down in twelve hours.While all this had been going on another low had given Madeira (M) heavy thunderstorms on the 9th; Funchal had a record 56 mm in six hours (the previous record was 41 mm in 24 hours, the average for the whole month is 18 mm).

Violent thunderstorms struck many parts of France on the 11th leading to some soil erosion and hail damage as well as flooding; although there were no human casualties there were fears that champagne grapes might have been affected. Your editor had avoided the steamy heat of Bracknell (the maximum of 25.1 °C on the 12th was above that in Madrid, Malaga or Rome) and fled to the Lake District and on the 13th and 14th saw a cold front stalled over north-west England and south-west Scotland; prolonged rain through the cold air behind it lowered temperatures further to give significant snow to quite low levels — the Kirkstone Pass in the Lake District was blocked for a while. There was more snow the next day (22 cm on Lowther Hill, midway between Carlisle and Glasgow, and the large rainfall totals on the windward slopes leading to flooding in Northumberland with 52 mm in 18 hours at Newcastle upon Tyne and 75 mm in 30 hours at Ballypatrick Forest in Northern Ireland. (On the 14th May 1992 Edinburgh's maximum temperature was 29 °C; this year it was 4 °C.) The cold air and warm sun led to some strong convection: there was heavy hail and violent rain in Bracknell on the 15th. In south-west England on the 17th a soldier was killed on Dartmoor when the aerial of his radio was struck by lightning. In Wales, five miles north of Rhyader, a tornado is reported to have carried a flock of sheep over five stone-walled fields and a river, killing at least six but with twenty survivors: some farm outbuildings were flattened and ten vehicles and caravans badly damaged.

At the far corner of this region all had not been quiet as sharp troughs moved east. Riyadh (30), Saudi Arabia had a burst of heavy rain on the 12th when 25 mm fell to break their previous daily record fall of 18 mm: Libya had a ghibli on the 12th with 35 kn southeast winds bringing temperatures of 36 °C and 500 m visibilities in desert dust: Corfu had thundery rain on the 13th and 14th totalling 72 mm. More heavy rain was reported from Saudi Arabia on the 15th when 44 mm fell at Khamis Mushait (31): Hail, on the edge of the Nafud Desert, found 24 mm in the gauge at the end of the 18th.

By the 20th a cold front was slow moving from Algeria to Iceland and ripples running northwards along it gave more than 30 mm of rain to much of the south of France. In the south-easterly flow ahead of it Trondheim, being in the lee of the Norwegian mountains for a change, had a maximum of 28 °C on the 19th which was 3 °C above the previous record. The 20th saw a similar pattern, this time the 30 mm of rain was over central southern England and the warmth continuing over Scandinavia (an interesting point here was that Lulea (32) at the north end of the Gulf of Bothnia had temperatures of around 20 °C inland with ice floes at sea).

The 23rd brought news of a well documented lucky escape. A parachutist jumping from 4000 feet near Toulouse had fallen to 1000 feet when he entered the updraught of a Cb and was lifted to at least 25 000 feet (the limit of his altimeter) and held there for nearly two hours at −30 °C before the canopy suddenly collapsed. On the way down he retained consciousness long enough to open his reserve parachute and land senseless in a farm yard 30 miles from his target.

Violent thunderstorms and torrential rain struck Romania (R) on the 24th and 25th, in the resultant floods six were killed and four missed, hundreds of head of livestock lost and hundreds of homes destroyed. On the 25th a complex area of low pressure covered Biscay and Iberia and this triggered some big thunderstorms: Guadalajara came top with 68 mm, Soria had 60 mm, there was 39 mm in Madrid and Toledo. England's turn came on the 26th when the village of Faringdon, Oxfordshire, had a violent storm. Local flooding temporarily isolated it and left the market square with a thick layer of mud. The nearest synoptic gauge was at Wootton Bassett, Wiltshire, where 50 mm fell in three hours. The storms also affected Ireland where 30 mm seems to have been common in the south-east quarter of the country. When the storms got to Switzerland, Comprovasco, on a windward slope in Ticino canton, collected 127 mm in the 24 hours to 0600 UTC on the 28th.

The Antarctic
Vostok started the month with near normal temperatures, i.e. about −64 °C; after that it got colder and by the 7th it was down to −79.4 °C. After a mini heatwave mid-month when temperatures soared to −61 °C they fell back to −81 °C by the 22nd.

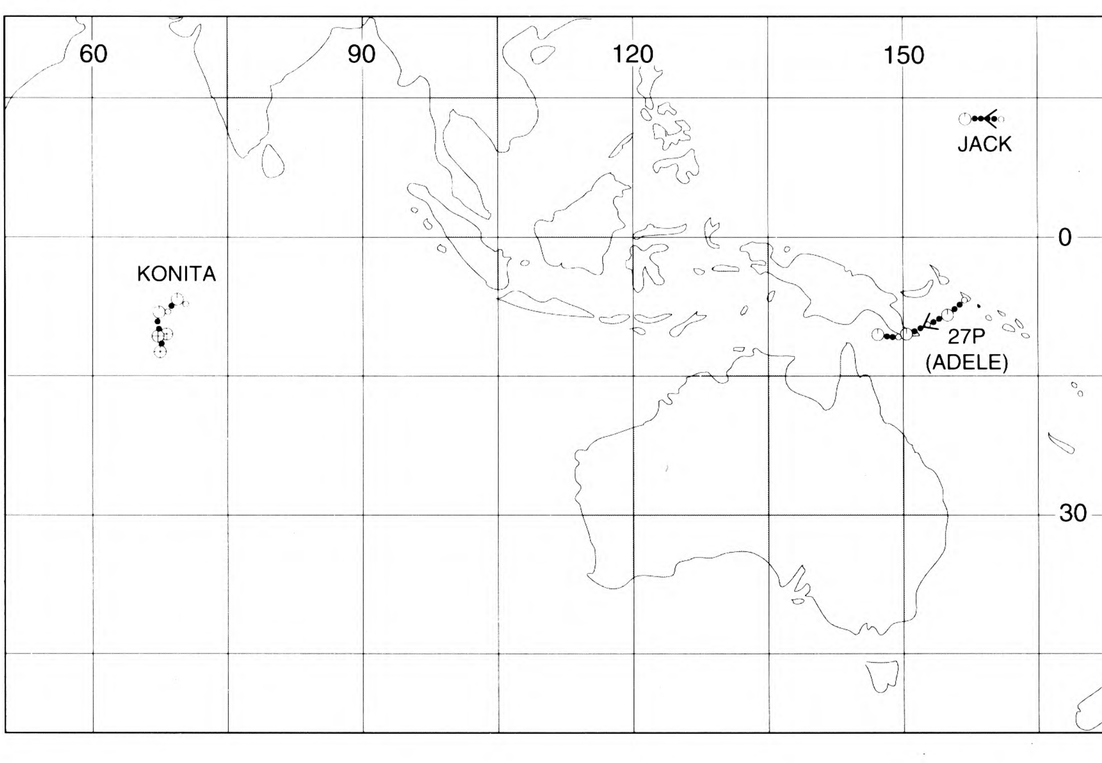
May tropical storms

This is a list of tropical storms, cyclones, typhoons and hurricanes active during May 1993. The date are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during this month. The maps show 0000 UTC positions: for these I must thank Julian Heming and Susan Coulter of the Data Monitoring group of the Central Forecasting Office.

No	Name	Basin	Start	End	Max. (kn)
1	Konita	SWI	02/05	07/05	85
2	27P (also called Adele)	AUS	13/05	16/05	45
3	Jack	NWP	17/05	22/05	35

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific; I — Indian Ocean; WI — west Indian Ocean; AUS — Australasia.

Cyclone Konita followed a hook-shaped course to SW, S and finally NNE. Adele did a lot of damage on the Trobriand Islands off New Guinea.



Your Editorial Board announces that the Meteorological Office Board has decided that the publication of the *Meteorological Magazine* will cease with the issue for December 1993.

As one of the leading European establishments for research into meteorology our publications should be subject to external peer review: this is already the case for much Meteorological Office work. The publication of a new international and European quarterly journal by the Royal Meteorological Society (to be called *Meteorological Applications*) is expected to provide a suitable vehicle for the kind of articles that now appear in *Met Mag*, namely on research, practice, measurements, reviews, applications of meteorology, book reviews, etc.

The first edition of the *Meteorological Magazine* was published in 1920 by HMSO. It took over from *Symons's Meteorological Magazine* which started in 1866. This decision therefore brings to an end a continuous publishing record of 129 years (except for the duration of World War II). It is understood that legal obligations accepted when *Symons's Meteorological Magazine* was adopted are fulfilled by the continuing production of the *Monthly Weather Report* and *Rainfall 19XX* and our internal journal mentioned below.

The December 1993 issue of *The Meteorological Magazine* will be a bumper one of about 40 pages celebrating the Magazine's contribution to the development and dissemination of meteorological knowledge. It will contain a selection of highlights from 1866 up to around 1986.

The United Kingdom Meteorological Office (UKMO) Annual Scientific and Technical Review

This Review describes the major developments in science and technology within the UKMO over the year and is produced as part of the Meteorological Office Annual Report and becomes available in July each year. If you wish to be put on the mailing list please write to:

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Informal communications

The UKMO has instituted an in-house periodical for informal and rapid dissemination of the latest relevant science and technology news to its staff and outside collaborators. Most contributions come from UKMO staff, but offers of material from outside will be welcome — though there is no guarantee of publication.

Back numbers: Full-size reprints of Vols 1–75 (1866–1940) are available from Johnson Reprint Co. Ltd., 24–28 Oval Road, London NW1 7DX. Complete volumes of *Meteorological Magazine* commencing with volume 54 are available on microfilm from University Microfilms International, 18 Bedford Row, London WC1R 4EJ. Information on microfiche issues is available from Kraus Microfiche, Rte 100, Milwood, NY 10546, USA.

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Smoke plume features
June storms in British Isles
World weather news — June 1993

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The heavy rainfalls of 22–23 September 1992

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Summary

The extent and limits of the heavy rainfalls occurring during 22–23 September 1992 are investigated. The last comparable historical precedent was found to have been 14–15 September 1968 in south-eastern England.

1. Introduction

After residual outbreaks of thundery rain had died out over East Anglia by mid-morning on 22 September 1992, much of the south-eastern half of England remained overcast and misty in potentially very unstable warm sector conditions. Slow-moving heavy showers and thunderstorms began to develop during the early afternoon, and a wet night ahead was forecast for the South-East. In this account all times are UTC.

2. Synoptic developments

A double cold-frontal structure was being followed on 22 September 1992, and this was moving steadily eastwards over northern England (Fig. 1). The second cold front was being disrupted by orography further south, particularly over Wales. Dashed lines indicate where minor troughs had formed, or sea-breezes were initiating convergence lines.

Although indistinct in the south, analysis of the eastern frontal system could be arbitrarily drawn (in Figs 1(a) and 1(b)) between the 15 °C dew-point temperatures on the surface in the warm sector, and the slightly cooler, less-oppressive air to the west and south. The instability of the air over the south of the United Kingdom is shown in Fig. 2(a). At this time the centre of low pressure was ill-defined at about 1006 hPa. It deepened slowly at a modest 1 hPa per 3 hours during the evening and overnight as an upper cut-off low approached from the south-west (Fig. 2(b)).

The surface depression became double-centred near The Wash from 0100 on the 23rd, with a triple-point depression moving northwards, while the other centre prolonged in the rain as it drifted over East Anglia (Figs 1(d)–1(f)). By 0600 the 500 hPa low was also over East Anglia and in the process of becoming complex.

The onset of a moderate north-north-easterly surface wind at Wittering and Bedford by 2100 on the 22nd suggests that development of the (thundery) back-bent occlusion could first be included in Fig. 1(c). Thundery activity associated with this feature was last reported as far south-west as south Oxfordshire between 2300 and midnight, with radar imagery revealing that, thereafter, heavy rain marked its passage south-eastwards to the Sussex coast by 0600 on the 23rd.

3. Radar study

Fig. 3 is a three-hourly sequence of UK Weather Radar Network 'modified composite pictures' produced by FRONTIERS, which may be compared with the surface synoptic charts of Fig. 1. Coloured pixels represent precipitation intensities averaged over 5 km × 5 km squares, as shown in the caption.

At first, there was little evidence of a definite frontal structure, the precipitation pattern (in Fig. 3(a)) showing convective development of heavy showers and thunderstorms as the afternoon progressed. In Fig. 1(a), the development of a mesoscale warm-frontal wave was

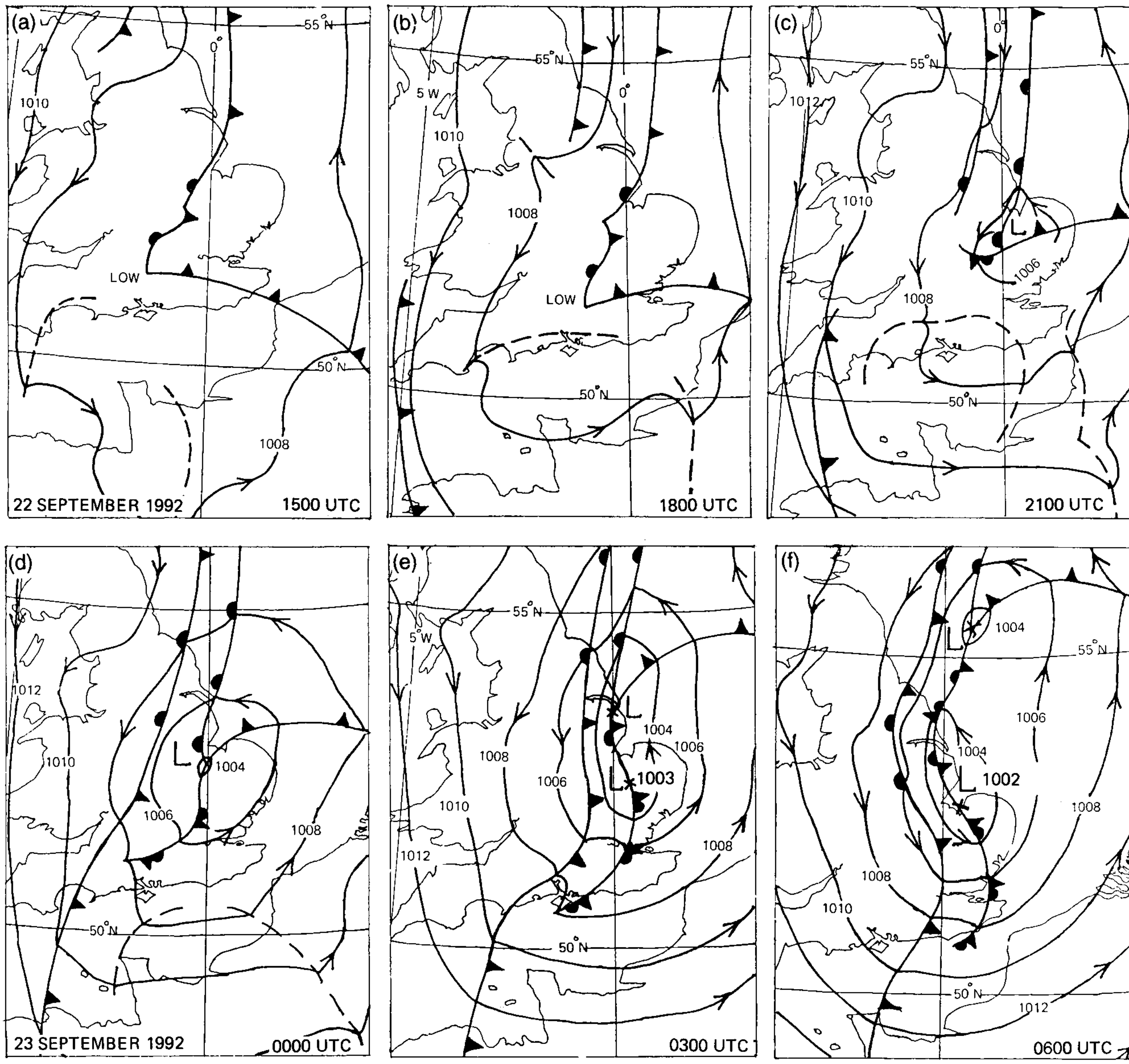

Figure 1. Surface synoptic charts at 3-hour intervals from 1500 on the 22nd to 0600 on 23 September 1992.

indicated (by surface wind and temperature observations) just to the north of Bedford, where the very heavy rain reported at DRA Bedford and Riseley was probably falling from slow moving embedded cumulonimbus. Fig. 3(b) indicates that precipitation areas had generally increased in size and intensity by 1800 on the 22nd, when returns from the warm frontal ripple had become more marked and intense (a remarkable fall of 54mm was recorded in two hours between 1700 and 1900 at Rutland Water).

Where a south-westerly sea-breeze opposed the northerly gradient wind near the south-east coast of Devon, a notable convergence line formed and, by 1800, had lengthened considerably near the south coast (Figs 3(a) and 3(b)). Heavy showers and thunderstorms developed in a slow-moving band along this line through southern Somerset (where Yeovilton had a noteworthy fall of 42.2 mm in the two hours between 1600 and 1800) and Dorset; lighter showers formed as far east as Sussex.

Fig. 3(c) shows the general expansion and intensification of precipitation areas continuing at 2100 over most counties south-east of a line from the Humber to the Severn. The warm-frontal wave was being absorbed by the deepening surface depression at this time, but an area of very heavy rain which had formed in its vicinity was affecting a considerable area between Grantham and Peterborough. During the evening of the 22nd noteworthy falls were recorded at the National Rivers Authority (NRA) gauges at Manthorpe (56 mm in 3 hours of which 37 mm fell between 1800 and 2000) and Chesterton Reservoir (31 mm between 2000 and 2200).

The merger of precipitation lines and areas continued during the late evening, and by midnight the transformation from a convective to a frontal precipitation pattern

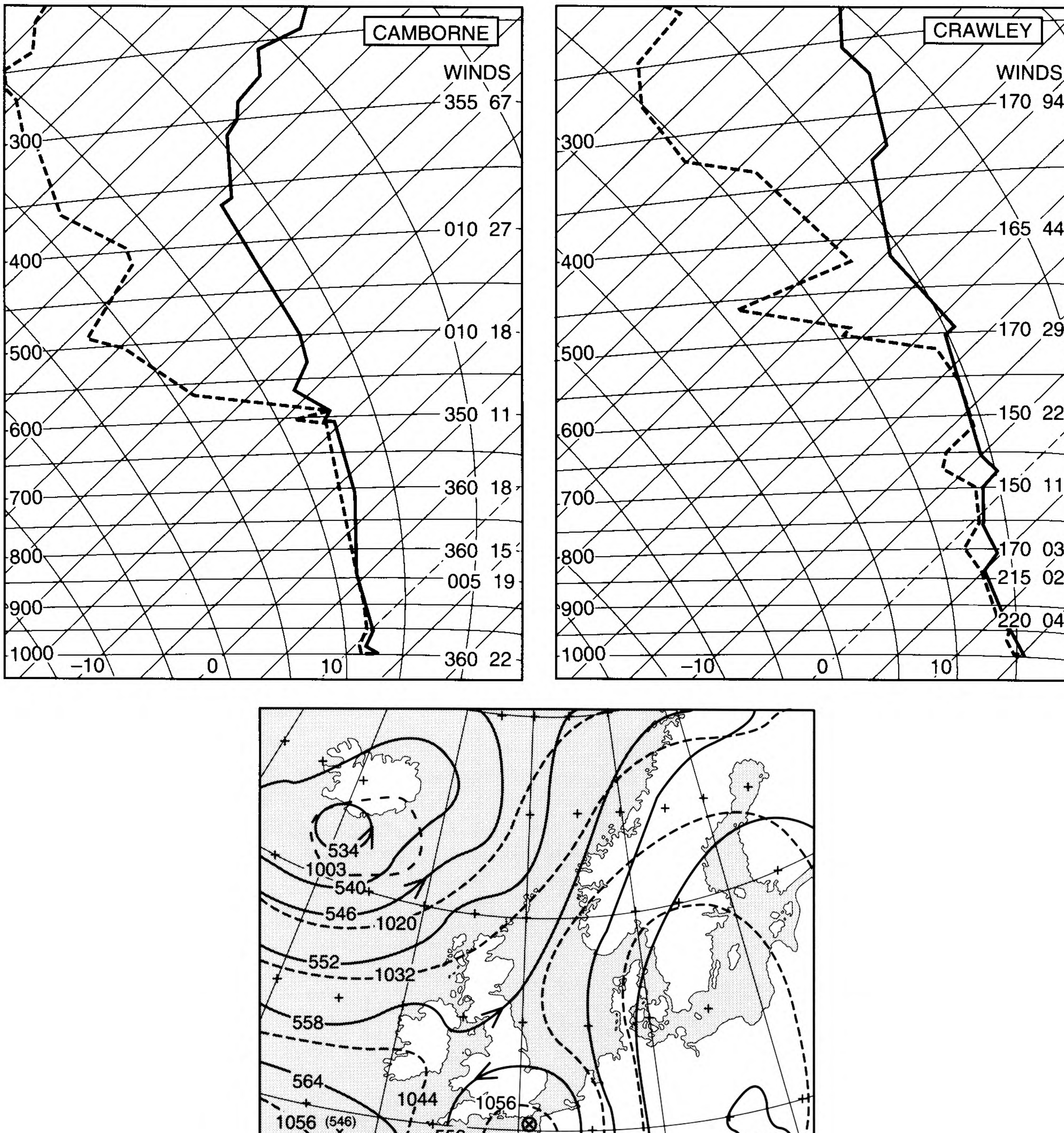

Figure 2. Tephigrams showing the unstable air over southern England at 1200 on 22 September 1992, and upper-air charts for midnight on 22/23 September 1992: 500 hPa streamlines in solid lines, 250 hPa in dashed lines (heights in decametres). 12-hour continuity of centres given by lines of dots (crosses represent the 500 hPa centre continuity).

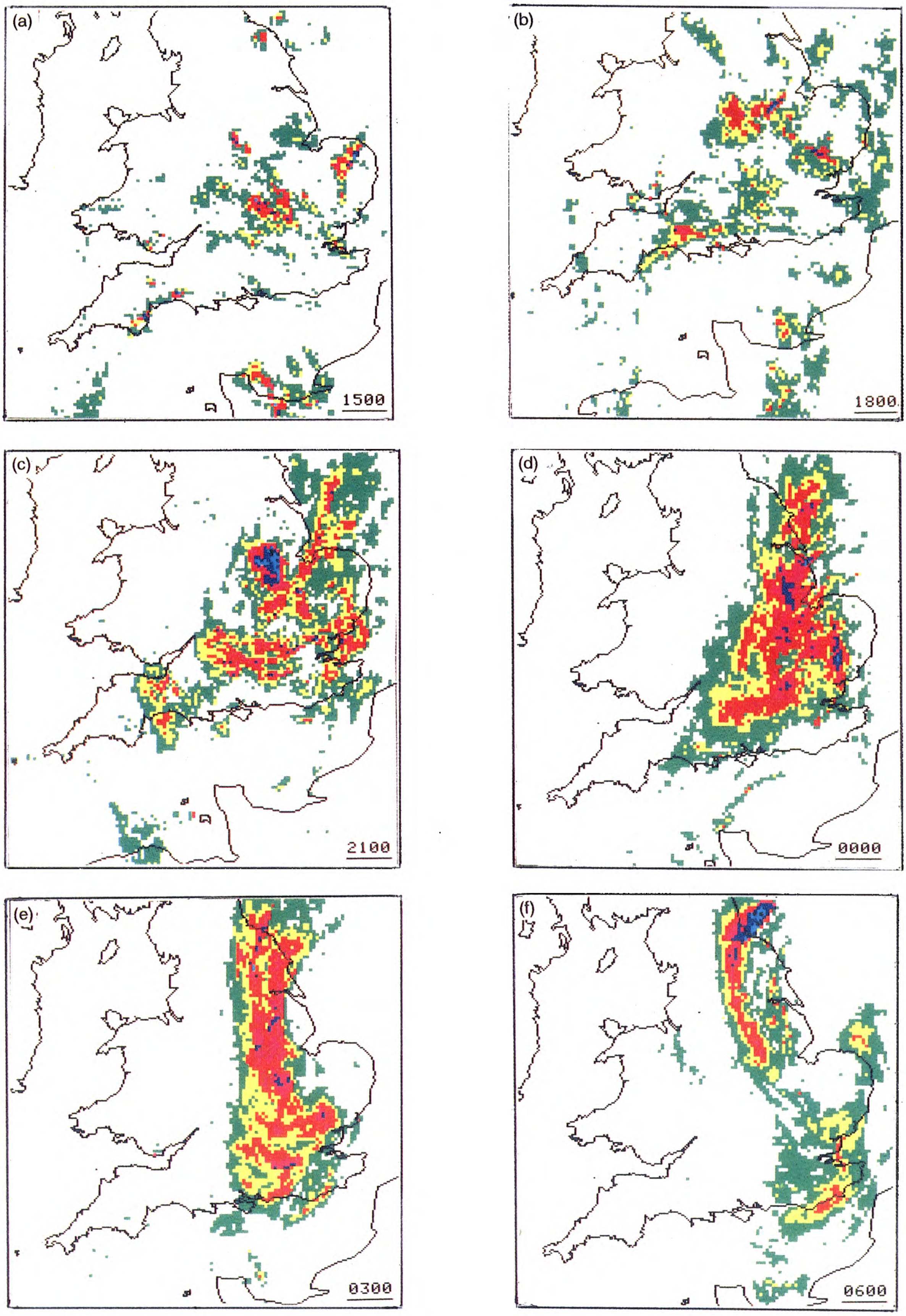

Figure 3. UK weather radar network 'modified composite' precipitation intensity data at 3-hour intervals comparable to Fig. 1. Colours represent intensities: green, less than 2 mm h^{-1}; yellow, 2–4 mm h^{-1}; red, 4–8 mm h^{-1}; pink, 8–16 mm h^{-1}; purple, 16–32 mm h^{-1}; cyan, 32–64 mm h^{-1} black, over 64 mm h^{-1}. Pixels represent 5 km × 5 km squares.

was more or less complete. Fig. 1(d) suggests that the second front had become an integral feature at the western edge of the precipitation, which was returning westwards over Humberside.

Nine main synoptic stations* in the rain area were reporting continuous heavy rain at 0200. By 0300 on the 23rd (Fig. 3(e)) a 'dry slot' appears over the Ely area of Cambridgeshire, and this is echoed in the 24-hour total rainfall distribution chart (Fig. 4), suggesting that the heavy rain further west and south over the county had remained slow moving for several hours.

The depressions were beginning to transfer northwards by 0600 (Figs 1(f) and 3(f)) with rain becoming concentrated on the leading front (i.e, warm front in the north, occlusion in the south), with heaviest rainfall over Teesside. Precipitation was at last beginning to die out over Peterborough and Cambridgeshire, although drizzle continued there for several hours, falling from low cloud below the radar scan.

* Wittering, Bedford, Wyton, Coningsby, Benson, Stansted, Odiham, Heathrow and London Weather Centre.

4. Rainfall analysis and flooding

Fig. 4 gives the 24-hour rainfall distribution chart for 22–23 September 1992, with gauge readings (standardized where possible) at 0900 on the 23rd. In many places, a general background overnight fall of 50 mm was added to the 25–50 mm which had fallen in showers or thunderstorms on the 22nd, giving the wettest 24 hours in some stations' history.

Probably not since the 14–15 September 1968 episode has such a large area of heavy rainfall occurred in September over the south-eastern half of England. Then, around the Thames Estuary, 125 mm fell in 24 hours over north-west Kent, with 200 mm in 48 hours over extreme southern Essex. Flooding was rather more widespread on that occasion, especially in Surrey (see Salter

Figure 4. Twenty-four-hour rainfall totals read at 0900 on 23 September 1992. Isohyets; thick lines at 25 mm intervals; thin lines at intermediate 12.5 mm intervals.

and Richards (1974)). Other recent notable falls of 100 mm or more have occurred in recent years in connection with summertime thundery situations. Firstly, an area from Raunds (Northamptonshire) to Fosdyke (Lincolnshire) was affected on 10 July 1968 (Salter 1969) and a small area of Northamptonshire was cited again as receiving 100 mm on 26 July 1980 (by Waterfall (1982)). Flooding associated with the 'Hampstead Storm' of 14 August 1975 in parts of north-west London (described in Keers and Wescott (1976)) was equally if not more damaging than that which affected the Edgware area on 22–23 September 1992.

The Times (of 24 September 1992) carried pictures of people in Edgware (where the Silkstream had overflowed) being rowed to safety in boats over streets flooded 'with up to four feet of water'. The report continued that 'Edgware General Hospital was flooded with two inches of water, and the casualty department had to be closed. Firefighters tried throughout the night to stem the flood which swept through four wards'. The NRA's Harrow Weald gauge recorded 80.2 mm — a listing of fifteen gauges with greater 24-hour readings is given in Table I, as are other reports of over 70 mm.

Because of long-term ground moisture deficits, rainfall totals in excess of 2 inches (128 locations reported falls of 50.8 mm or more over a considerable area shown in Fig. 4) appear to have been needed to end the drought. Certainly, reservoirs and rivers which had either dried up or had been running in a depleted state for many months were now, at least, partially filled. A typical 'periodic' chalk downland stream, the River Pang at Frilsham, was found to have 'two feet of murky water' in it on the 23 September, according to Peter Bloodworth in *Newbury Weekly News* of Thursday the 24th. However, 70–75 mm appears to have been the real threshold for more serious or longer-term flooding to have occurred near overburdened streams and rivers where, in western Fenland and other clay vale areas, flooding lasted several days in places. The River Great Ouse flood levels had reached 40 cm on the 23rd but were still running near

Table I. Rainfall totals in excess of 70 mm for the 24 hours ending 0900 on 23 September 1992

	Station	Total (mm)	Nat Grid Ref.	Met. Office ref. or other source
1.	Lodge Farm, Walcot, Nr Sleaford, Lincs	113.3	TF 060351	147674
2.	Rutland Water	109.0	SK 946081	NRA, Lincoln
3.	Grimsthorpe, Lincs	106.1	TF 047231	NRA, Lincoln
4.	Riseley, Beds	106.0	TL 042628	COL
5.	Old Somerby, Grantham, Lincs	99.0	SK 964339	154818
6.	Yaxley, Nr Peterborough	99.0	TL 196934	196776
7.	Manthorpe, Lincs	96.5	TF 067164	NRA, Lincoln
8.	Warmington, Nr Peterborough	92.4	TL 082913	163388
9.	Carlby, Nr Stamford, Lincs	91.6	TF 049142	156000
10.	Culverthorpe, Nr Grantham, Lincs	89.6	TF 025402	148248
11.	DRA Bedford (Thurleigh)	89.0	TL 037587	The Met. Office
12.	Corby Glen, Lincs	85.0	SK 992246	NRA, Lincoln
13.	Chesterton Reservoir, Nr Peterborough	84.0	TL 128946	NRA, Lincoln
14.	Litchborough St Martin, Northants	83.6	SP 633542	158714
15.	Radnage, Bucks	83.3	SU 791952	274267
16.	Harrow Weald (Cemetery), Gtr London	80.2	TQ 153920	NRA, Reading
17.	Warboys, Cambs	79.9	TL 303801	196001
18.	Rickmansworth, Herts	79.3	TQ 052948	COL
19.	RAF Wittering, Nr Stamford	79.2	TF 039031	The Met. Office
20.	Castle Bytham, Grantham	78.6	SK 985174	155271
21.	Oundle STW, Northants	78.5	TL 038897	NRA, Lincoln
22.	Royston, Herts	78.1	TL 346402	182578
23.	Lodge Cottage, Pilton, Peterborough	77.6	TL 014849	162865
24.	University of Reading, Berks	76.3	SU 743717	University of Reading
25.	Bourne End STW, Bucks	76.2	SU 892881	274134
26.	Towcester STW, Northants	76.0	SP 695487	170809
27.	Northwood, Gtr London	75.1	TQ 094916	COL
28.	Windsor (Royal Gardens) Berks	74.5	SU 979754	275574
29.	London NW2	74.2	TQ 240849	COL
30.	Brook Farm, Swineshead, Beds	74.1	TL 061658	177833
31.	Ufford, Nr Stamford, Lincs	73.1	TF 094044	153908
32.	Saltersford Weir, Nr Grantham, Lincs	73.0	SK 926335	NRA, Lincoln
33.	Birkholme, Lincs	72.8	SK 969235	155011
34.	Caversham, Berks	72.4	SU 720740	265922
35.	Great Stukeley, Huntingdon	70.9	TL 217745	179264
36.	Gunthorpe Hall, Nr Oakham	70.4	SK 869057	153244

STW = Sewage Treatment Works
COL = Climatological Observers' Link

Table II. Bilham (1935) Classifiable 'remarkable' and 'noteworthy' rainfalls on 22 September 1992

A. Remarkable fall:			
1.	Rutland Water. (SK 946081)	54 mm in 120 min (1700–1859; 31.5 mm in first hour).	NRA, Lincoln
B. Noteworthy falls:			
1.	DRA Bedford* (TL 037587)	27 mm in 57 min (1453–1550)	The Met. Office
2.	Litchborough STW (SP 624551)	26 mm in 60 min (1600–1659)	NRA, Lincoln
3.	Yeovilton, Somerset	42.2 mm in 120 min (1600–1800)	The Met. Office
4.	Manthorpe, Lincs (TF 067164)	56 mm in 180 min (1800–2100) (25.0 mm, 1800–1859; 12.0 mm, 1900–1959; +16.0 mm, 2000–2059)	NRA, Lincoln
5.	Chesterton Res.(TL 128946)	31 mm in 120 min (2000–2259;	NRA, Lincoln

* See Figure 5

30 cm on the 26th. The *Rutland and Stamford Mercury* of Friday the 25th reported the B1177 Billingborough to Horbling road still 'impassible to motorists'. This is in a low-lying Fenland location just 9 kilometres from where the maximum 113.3 mm 24-hour rainfall (see Fig. 4) had occurred.

Table II lists those classifiable 'heavy falls in short periods' (Bilham 1935) that were recorded by tilting-siphon or tipping-bucket rate-of-rainfall gauges. Several have been mentioned in Section 3, but it may be added that the locations of Manthorpe and Chesterton are similar to that of Walcot, i.e. on the first rising ground immediately west of the relatively flat Fenland. This could point to orographic enhancement as being an ingredient of some particularly heavy falls in both Tables here.

In addition to the officially recognized records in Table II, there were two further reports of noteworthy falls during the afternoon storms of Tuesday the 22nd from keen volunteer Thunderstorm Census Organisation (TCO) observers. Mr R. Peverall at Stony Stratford, Bucks, measured 28 mm in 70 mins (1450–1600) during a thunderstorm. At Wappenham (Northants, NGR SP623457, 16 km away to the west-north-west) 25 mm fell in 40 mins (1450–1520) but before the thunder and lightning, which occurred from 1525–1630 with a further 8 mm of rainfall, according to local publican, Mr R.L. Mobbs. As a 'postscript', he reported that the difficulties experienced by his customers travelling by road (due to local flooding of the River Tove system) lasted for 48 hours following the heavy overnight rain of 22/23 September.

With electrical activity lasting 70 minutes at Stony Stratford and 65 minutes at Wappenham, given light to moderate south-easterly cloud-steering winds backing from SSE to ESE with time on Crawley and Hemsby by ascent, it is quite probable that the same thunderstorm was involved, albeit in a decaying state, arriving at Wappenham some 40 minutes later, after the deluge-producing cell which had developed ahead. Other TCO observers in central East Anglia reported thunderstorms moving slowly from south-east to north-west.

Fig. 5 shows three traces from tilting-siphon rate-of-rainfall recorders for the 24 hours ending 0900 on the 23rd. All three show a long period of heavy rain. The University of Reading had its wettest 24-hour period since records began in 1921. The basic design of the tilting-siphon rain recorder has not changed much since its invention by Dines (1920), who reported its 'satisfactory' use at Benson Observatory 'since January 1915'. Once correctly installed and adjusted, the only problems he encountered were foreign objects (earwigs) blocking the siphon tube, but he later found that storm debris obstructing the collecting funnel also produced untrustworthy rates of rainfall on the records. Over the years, Met. Office development has improved the speed of the siphoning process by introducing a double siphon tube, but apart from refining the collection method somewhat, the essential mechanism has remained largely unaltered, a testament to its sound original conception.

Usually, between 0.2 and 0.5 mm are lost during the mechanical siphoning process, depending on the intensity of the rainfall. The instrument at Wyton needs a slight adjustment to correct its zero setting, but otherwise the record is a good one. Unfortunately, there is no record at all from Wittering where adequate drainage was a problem, the instrument siphoning only once before being flooded out. Hourly records show heaviest rain occurring at Wittering between 2000 and 2200 on the 22nd (when 23.5 mm fell) and again between 0100 and 0200 on the 23rd (with a further 12.3 mm).

Fig. 5 gives a clear picture of the noteworthy fall at Bedford, showing the initial torrential rainfall tailing off in intensity with time from its onset at 1453 to cessation at 1550. The trace appears to be typical of convective rainfall coming from a cumulonimbus cloud. Thunder was not observed at Bedford until mid-evening, however, reports from adjacent counties indicate that showers and thunderstorms were occurring by mid afternoon.

5. Conclusions

The heavy rainfall of 22–23 September 1992 will probably be most memorable for 'ending the drought' over a wide area of the south-eastern counties of

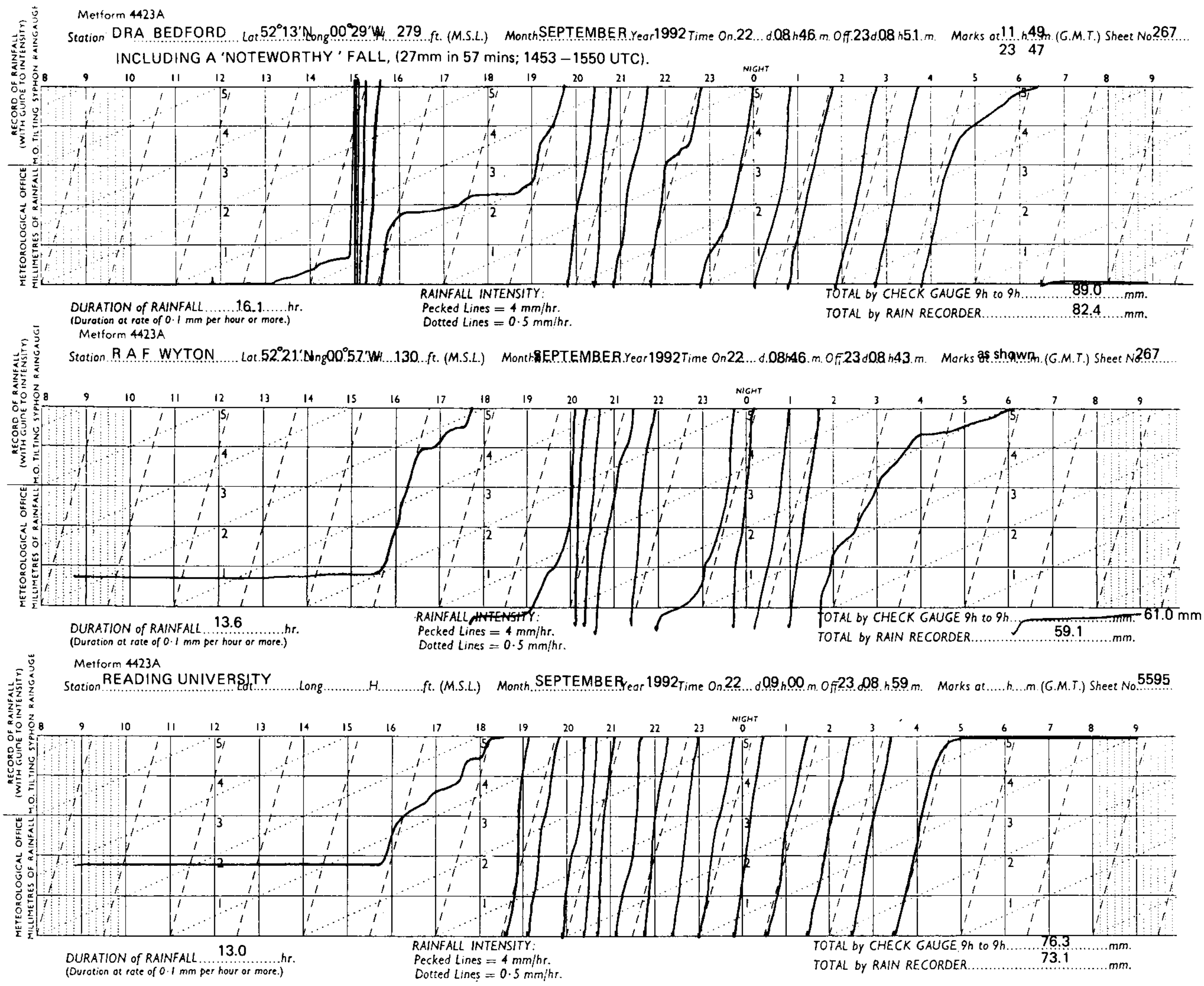

Figure 5. Tilting-siphon rate-of-rainfall records for the 24-hour period ending 0900 on the 23 September 1992 from (1) DRA Bedford (top), (2) RAF Wyton (centre) and (3) University of Reading (bottom).

England: 50 mm or more fell in 24 hours over approximately 1160 square kilometres, with more than 75 mm over 125 square kilometres. The heaviest rain was mainly over modestly rising ground to the west of the Fens.

Parts of Buckinghamshire, Hertfordshire and Berkshire also had totals over 70 mm. Over the relatively dry ground at that time this appears to have been the threshold for flooding, locally severe around the Silkstream in Edgware, or long-lasting flooding, notably the River Great Ouse around Bedford.

According to the Bilham classification of heavy precipitation in short periods, there was one remarkable fall and several noteworthy ones during convective activity on 22 September. Some evidence for orographic enhancement of these showers and thunderstorms was found. Other factors believed to have been ingredients responsible for intensification of precipitation were:

(1) Formation of a mesoscale warm-frontal wave which moved northwards over western Fenland during the afternoon and evening of Tuesday the 22nd.

(2) Formation of convergence lines later in the afternoon of the 22nd (particularly one near the Somerset–Dorset border).

(3) Arrival of an upper level low from the south-west.

Not since 14–15 September 1968 has such a large area of heavy rainfall occurred over the south-eastern half of England in September.

Acknowledgements

At the Met. Office, Bracknell (HQ), special thanks to Pete Newcomb and Steve Barker for the radar imagery used for Fig. 3; also to Mick Wood and Staff of Archives in Scott Building for supplying data upon which Figs 1 and 2 have been drawn; also especially for use of the A2 copier which enabled data from several hundred raingauges to be compiled on a large-scale OS NGR British Isles chart used as a step towards Fig. 4.

Additional rainfall reports came from Met. Office Data Services, Johnson House, Bracknell; and more numerously from the National Rivers Authority Anglian and

Thames Regions (thanks to Allan Bond, Lincoln; Diana Butcher, Reading, and Bob Hillier, Brampton).

I am indebted to the Senior Met. Officers at Bedford, Wittering, Wyton and Yeovilton for sending their rainfall data, particularly forms F4423A where available, for use in Fig. 5.

I am also very grateful to K. Spiers, met. observer at The University of Reading, for sending his F4423 (which was 'worked up' on an F4423A to complete Fig. 5). Thanks also go to Malcolm Wickenden (East Malling) and to Andrew Lee (Institute of Hydrology, Wallingford) for their additional F4423s not included in this article, they were much appreciated.

Additional rainfall data came from the Climatological Observers' Link September Bulletin, also from Terence Meaden and Jonathan Webb (TORRO), and thunderstorm reports were freely made available by Keith Mortimore (Director of TCO at Corsham).

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551.515.43(410.1)

Location of frequent ground strokes

W.S. Pike

19 Inholmes Common, Woodlands St Mary, Newbury, Berkshire RG16 7SX

Thunderstorms of the 8–9 August 1992. *It was originally my intention to run a long article by Mr. Pike on these storms but time and lack of space has prevented that. Instead, he will present that work at the Royal Meteorological Society meeting on Saturday 22 October 1994 in the meeting he is organising called 'Thunder, lightning, hail and tornadoes'. However there is room this month to print his supplement on the electrical activity and a technical note on the system with which gathered the data he mentions.*

Despite reports that much of the lightning activity over the southern United Kingdom during the storms of 8–9 August 1992 was inter- or intra-cloud, over 85 000 strikes to ground ('ground strokes') were detected by the Electricity Association (EA)'s lightning location system over that 48-hour period. The EA system is described later.

The current (*1992 — Ed.*) network (Fig. 1) consists of five ground stations (Melbury, Thetford, Churton, Harwood and Rhynie) and is capable of storing up to 40 strikes per second for later analysis. Information on strikes (up to 4 hours old) is displayed graphically as coloured dots on a VDU map, although currently, the screen only has a capacity to display 1000 strokes, with all earlier discharges being removed.

Fig. 2(a) shows a rather persistent storm having passed from south-east Devon to the Severn Estuary during the past 4 hours; with a new storm over central southern England. This was the beginning of 'Storm Area 1' (after Hewson (1993)) that was soon to be responsible for causing £23 000 worth of damage to a house at Hampstead Norreys (just to the north-east of Newbury, Berkshire) which was struck at 2105 UTC (personal correspondence with Mr R. Chapman).

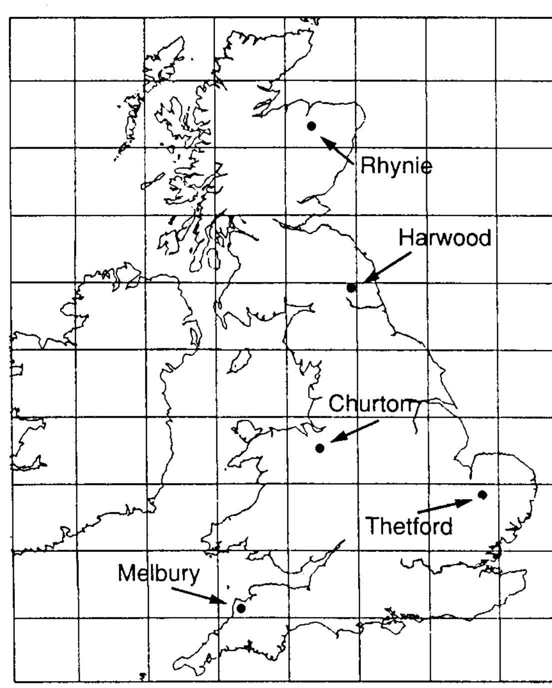

Figure 1. Location of the current direction finding stations. The area of coverage approximates to the area shown. Western Eire is not fully covered.

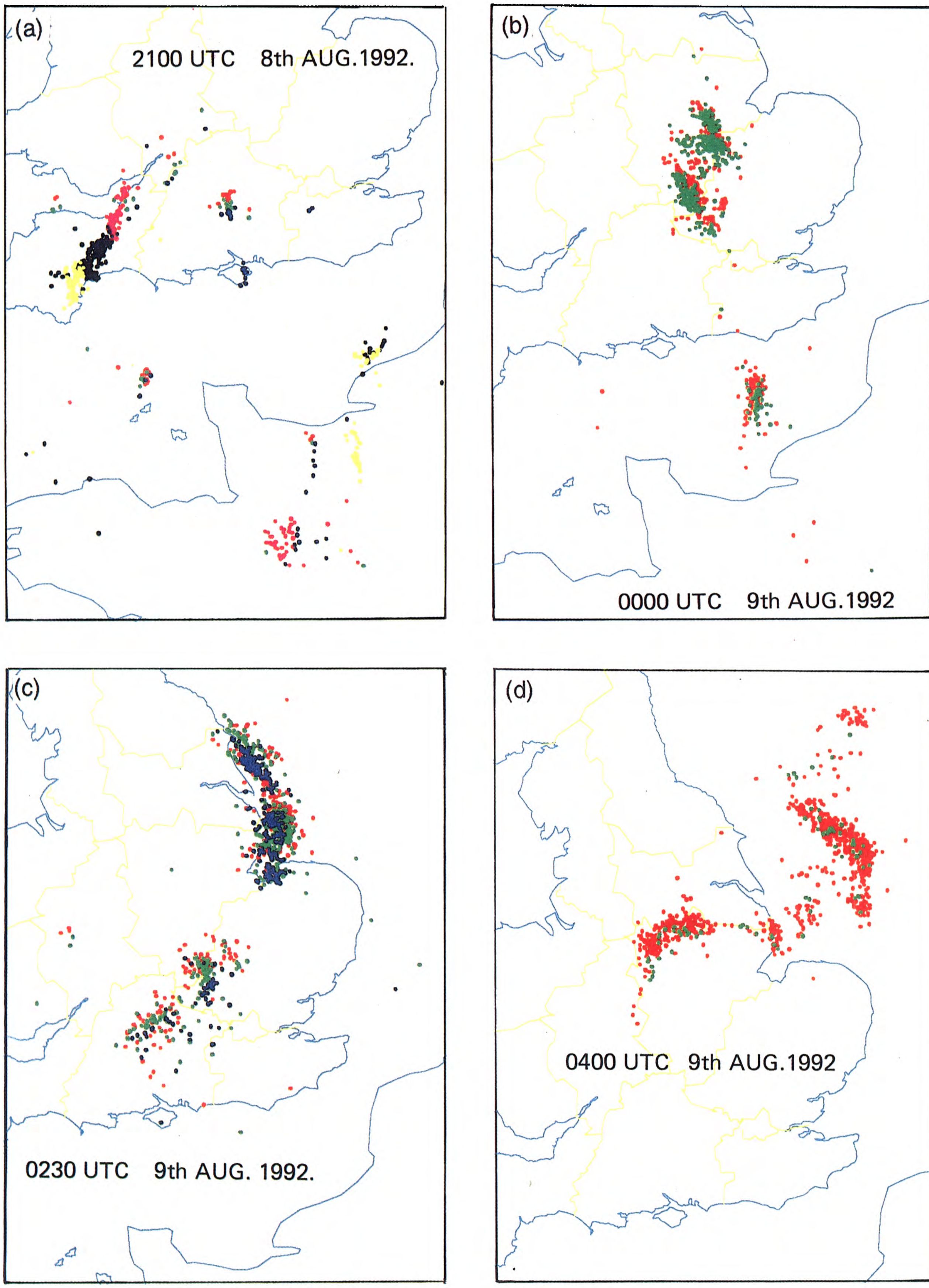

Figure 2. Ground strokes registered by the EA Technology lightning location system. Times are shown within Figures. Key — Strikes in the last 10 minutes, red: 10–20 minutes, green: 20–60 minutes, magenta: 1–2 hours, blue: 2–3 hours, black, and 3–4 hours, yellow.

Fig. 2(b) shows 'Storm Area 1' over Northamptonshire at 0000 UTC on the 9th, with a new 'Storm Area 2' (after Hewson (1993)) moving northwards from the Le Havre area of France. Note that even with 1000 ground strokes displayed, nothing over 20 minutes old appears on the screen! Fig. 2(c) shows a temporary diminution in lightning frequency with 'Area 1' leaving the Lincolnshire–Yorkshire coastline and 'Area 2', having formed a line of activity, moving north-north-westwards over central southern England and northwards into the east Midlands.

Fig. 2(d) shows storm 'Area 1' moving away north-eastwards over the North Sea, with storm 'Area 2' continuing northwards as a dinstinct line (the discharges being particularly numerous at this time in the Sheffield–Doncaster area of South Yorkshire). Note that most of these ground strokes registered over just the past 10 minutes, indicating the extreme intensity of these two storms combined. In moving some thirty degrees to the right of 'steering' winds, storm 'Area 1' was behaving like a 'supercell' (after Browning (1962, p. 349)).

Acknowledgment

Images were kindly supplied by Terry Morgan at EA Technology, Capenhurst, Chester.

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Lightning flash location

T. Morgan

EA Technology, Capenhurst, Chester

1. Uses

Lightning damage of the distribution system is believed to cost the Electricity Companies in the UK some £4m annually. However, until recently the position, severity and influence of individual strikes has been virtually unquantified.

The National Lightning Flash Location System, developed by EA Technology, has not only made the collection of such data possible, but also provides near 'real-time' presentation of the information on the VDU of a personal computer.

2. Benefits

— Early warning of the approach of a storm enables control staff to prepare for the storm in good time, before problems occur.

— Strike information is received within seconds of the occurrence, making it possible to follow the progress of a storm as it moves across the country and assisting in the management of overhead line working, increasing both the safety of personnel and the efficiency of such operations.

— Faster re-establishment of lost supplies following a storm is possible as personnel can be moved into the path of a storm ready to repair the damage, rather than having to wait for notification of the damage before moving to its location.

— As well as 'live' use of the system, the data is stored for later replay and analysis. This will be used in the longer term to relate equipment failures to lightning occurrence. The effectiveness of protection equipment can be better assessed, by comparing the performance of the network before and after protection equipment was fitted, with a knowledge of the incidence and severity of lightning activity.

— Ground strike density and stress maps are being built up by EA Technology to assist in deciding where protection equipment would be best utilized.

3. Technology

Damage to the electricity distribution network, and to other earth-based structures, is caused by cloud-to-ground strikes These make up a third of all lightning strikes: the remaining two thirds occur within clouds or between clouds. It is important to differentiate between these types, since often lightning may be seen but no damage occurs. For this reason, the EA Technology system has been designed to locate only cloud-to-ground strikes, because its primary purpose is for assessing, locating and to some extent predicting damage.

EA Technology's system uses radio direction finding techniques to locate the lightning strikes. At the frequencies commonly used for direction finding, the radiation from the lightning strike can be regarded as propagating as two waves — one which follows the ground ('ground wave' — vertically polarized) and one which is reflected from the ionosphere ('sky wave'). This 'sky wave' (horizontally polarized) is superposed on the ground wave and can result in the direction finding station reporting an erroneous bearing. In order to avoid this effect, the EA Technology system uses an extra-low frequency (ELF) of 1.1 kHz with a bandwidth of 350 Hz. At this frequency the earth's surface and the ionosphere act as conducting shells separated by an insulating gap of between 50 and 100 km. This is less than half the wavelength range of 235 km to 325 km which can be 'seen' by the EA Technology direction finders. The cut-off frequency of the waveguide for horizontally polarized waves (sky waves') is above 1.3 kHz, and therefore these do not propagate to any significant extent.

The ELF waves generated in the gap and propagated around the earth in this two plate waveguide are only the 'ground waves'. As there is no 'sky wave' at the operating frequencies, the bearings produced are more accurate than conventional systems.

Because inter- and intra-cloud strikes mainly produce horizontally polarized radiation, a further advantage of using this frequency is that they are not registered by the system unless they are very close (within 30 km) to a direction finding station.

A number of direction finding aerials around the UK report 'sight' of a lightning strike to a central computer at EA Technology. The strike reports are processed and then reported to on-line subscribers at a rate of up to 5 strikes per second. Up to 40 strikes per second can be accepted and stored or later analysis.

4. Specification and outputs

Users of the system can receive on-line information on the location, time and strength of lightning strikes within the United Kingdom and the north-west coastal regions of continental Europe. The information is stored by the user's personal computer and the strike is instantly displayed graphically on a VDU map. Stored data can be replayed at accelerated speed over any chosen time period, colour prints of the display map showing all strikes within a given period and area can be produced, alternatively a list of strike information within a given period can be printed. The data may also be used for more-detailed analyses of lightning trends, or for assessing the suitability of protection schemes.

The display software runs on an IBM compatible PC within the Microsoft 'Windows' environment. The program is menu driven. It is controlled using a 'mouse' to position a cursor on the screen and select a command or item. Flashes are displayed within seconds of their occurrence on an outline map of the British Isles and the north-west coast of continental Europe. Pan and zoom of the display is provided, varying the vertical dimension of the screen from 50 km to 1600 km. Various overlays are available displaying the 400 kV, 275 kV and 132 kV network, power stations and substations. User-defined overlays are easy to produce and can be included in the display.

The strike position indicators are colour coded, representing the time of the strike. Data on any specific strike an be extracted by positioning cross hairs over the strike using the 'mouse' and clicking the 'mouse' button. A window opens which shows the details of the strike including the latitude, longitude and Ordnance Survey National Grid reference of the strike position, the uncertainty in the fix, the current of the strike, the date and time to the nearest hundredth of a second. In addition a multiplicity counter is reported for restrikes. A colour printer provides hard copy of both the screen display and details of strikes within a given time period.

5. EA Technology services

Although the system was initially developed and installed for the UK electricity companies, services are now available from EA Technology which would be of value to any organization whose operations and profitability could be affected by lightning activity.

Services are customised to suit an individual organization's needs. They range from full on-line display of lightning activity to the occasional provision of historic data, and can include analysis by EA Technology's team of lightning specialists if required.

For further information about the Lightning Flash Location system, how it has developed since September 1992, and the services available, please contact:

Terry Morgan
Technology Transfer Executive
EA Technology
Capenhurst, Chester
CH1 6ES
UK

Direct dial: 051-347 2554
Direct fax: 051-347 2305
Telex: 627124 RESELEC G

Postscript

The storms did not pass unnoticed at sea; below is a report printed in The Marine Observer, *Volume 63, No. 321, July 1993. the* Marine Observer *is published quarterly for the Meteorological Office by HMSO for £5, annual subscription £19 including postage.*

Passage of a squall — North Sea

m.v. *Drupa*. Captain A.J. Howe. At anchor, Dogger Bank. Observers: the Master and Mr J. M. Bastone, 2nd Officer.

9 August 1992. At 0445 UTC whilst awaiting orders weather and sea conditions were noted as: pressure 1009.7 hPa, wind E'ly, force 4, sky cloudy but not overcast, light sea with no swell. Shortly afterwards occasional thunder was heard and lightning was seen astern (the vessel's heading being 054°) and at 0455 the wind was noted to veer and increase to force 6 with gusts to 30 knots. The cloud cover changed to 8 oktas of stratus, the pressure rose vertically, being 1010.1 hPa at 0500, there was constant heavy rain which severely restricted visibility while continuous thunder and lightning (sheet and forked) was observed. These conditions lasted for 15–20 minutes and at 0518 the rain ceased, the wind decreased to W'ly, force 3–4 while the thunder and lightning became distant and sporadic. The sea was till light, but the vessel was now rolling slightly to a moderate south-westerly swell.

During the heaviest rain the radars showed a dense cloud running in a north/south direction; it was 4–5 n mile wide and about 25 n mile long, completely engulfing the vessel (good old *Drupa*, right in the wrong place again). At 0540 the pressure was falling vertically, reading 1008.9 hPa at 0545 and behaving like a yo-yo, the wind was N'ly, force 3, and there was moderate rain falling from 8 oktas of cloud. Thunder was again present at and around the vessel as lightning was observed to strike the sea 120–150 m away from it, rather too close for comfort.

Apart from the observers, the ship's company apparently slept through the entire event.

Position of ship: 54° 30'N, 02° 18'E.

Images in Weather Forecasting

A practical Guide for interpreting Satellite and Radar Imagery

Edited by M.J. Bader, UK Meteorological Office
G.S. Forbes, Pennsylvania State University, U.S.A.
J.R. Grant, UK Meteorological Office
R.B.E. Lilley, UK Meteorological Office
A.J. Waters, UK Meteorological Office

The aim of this manual is to present the meteorology student and operational forecaster with the current techniques for interpreting satellite and radar images of weather systems in mid-latitudes. The focus of the book is the large number of illustrations, many of them in colour. Images are matched with conceptual models and weather charts. Written in an image-led mode, rather than in the style of a standard textbook on meteorology, the presentation allows the user to identify and interpret patterns on the images as easily and quickly as possible. Patterns observed in satellite and radar images are explained in terms of basic airflows. Examples are presented showing variations on the basic patterns.

Material for the book has been provided by experts from North America and Europe, and reviewed by people from universities, training establishments of meteorological services and operational forecasters.

The project has been backed by Eumetsat and WMO and will be published later this year by Cambridge University Press.

Contents

Introduction to satellite and radar images — basic principles and simple interpretation. Interpretation of synoptic-scale cloud and moisture patterns. Fronts and waves. Depressions in mid-latitudes. Convective cloud patterns. Fog and low clouds. Orographic and polar phenomena. A Glossary of common terms and abbreviations.

For further information about the manual, please phone Joann Motherwell, Science Marketing Controller on 0223 325781, or write to Science Publicity at Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge, CB2 2RU, UK.

It is not usual for this journal to print reports by those with no meteorological knowledge! However the events of this night were unusual on two counts. First, the event took place very close to an official meteorological observing site (03693), one with a radiosonde unit no less! More remarkably, of the few witnesses there were, most were police, trained to observe and record, and these included one whose standard of English is of the simple, straightforward type I am always hoping to find. It should be noted that all times in the witnesses' statements are BST which is UTC+1; meteorological data is UTC as normal.

Credit is also due to Robert Holborn *at the Shoeburyness meteorological office for collecting the reports and photographs. To me, an unusual aspect of the storm is list of casualties amongst the bird population. Although it seems obvious that such a storm should kill practically every bird in its path, this is either rare or goes unremarked. It may be that they were roosting and missed the signals that normally save them; on the other hand, about the only shelter on Foulness is designed to protect humans from straying artillery shells. Thanks to the presence of mind of some Churchend villagers some hailstones were refrigerated. On measurement the approximate average size was 25 mm diameter, with the largest measuring 48 by 42 mm.*

The surface charts show a small low drifting eastwards over the western English Channel with a cold front moving north-eastwards over south-east England.

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Hailstorm at Foulness — eyewitness accounts of the storm on Friday 18 September 1992

Sergeant G1091 V. Thicke MDP and Constable G725 I. Bailey MDP

It seems inappropriate to label the weather conditions on the night of Friday 18 September 1992 as simply a thunderstorm because they were of such epic proportions. In my view it could only to be equalled by the gale force winds of a couple of years ago when Michael Fish assured us that there was NOT going to be a hurricane, only to wake up the next morning to find such devastation.

Only twice in my life has the weather been so bad that it numbed my mind. The first was waking up the morning of the hurricane and wandering the streets in a daze, unable to comprehend the damage caused. The second was on the night of 18 September 1992.

Together with Constables Ian Bailey, Terry Turner, Martin Warwick and Ken Holland, I was on night shift at AWE Foulness. The night was much the same as any other night, although there was a thunderstorm rumbling around the other side of the estuary in Kent. Storms at night are generally spectacular when viewed from almost anywhere on Foulness and that night was no exception.

About 0200 on Friday morning the storm reached us and it was fairly obvious that this one was going to be really spectacular. The lightning was so frequent that it was almost like daylight. From Shelford Gate it was possible to see all of Havengore and down as far as Churchend. Ian Bailey was out on foot patrol and he said that from where he was in the middle of the Establishment he could quite clearly see the AWE perimeter fence. The frequency of the lightning was unsettling both Ian and his police-dog so he decided, fortunately as it turned out, to return to Shelford Gate for a break. In Ian's own words, the lightning was like staring into the strobe lights at a disco, it was making me feel giddy and affecting my balance, and the thunder was as if the whole range had opened with activity at every battery.

At about 0235 the rain became torrential. The road outside the Police office at Shelford Gate suddenly had so much water on it that the gutters couldn't manage and there was a lake of water 2 inches deep threatening to come through the doors.

At 0250 Martin Warwick and I heard the first hailstones tapping on the windows. At that point it was just the occasional one and did not seem very ominous, but suddenly it sounded as though there were a thousand people outside throwing stones at the windows. Visibility was cut to only a matter of about 50 feet and I honestly thought that the window were going to crash in. I got up from my desk and stood in the middle of the room so that any breaking glass, hopefully, would not reach me. The noise was so great that it was almost impossible to hold a conversation, and in a matter of minutes the road outside was covered with hailstones the size of golf balls. It looked as if it had been snowing steadily for a couple of hours and the snow had settled.

At this time Ian Bailey was about half a mile from the office. He said afterwards that there was suddenly a very loud rumbling noise off to his right. He could not make out what it was, and knew it had not been there earlier in the night. He thought that maybe there had been a lightning strike and the lightning had somehow started up a large generator. Suddenly he felt as if he were being stoned to death. He held his cap against the side of his head to stop the stones hitting him and headed for the office.

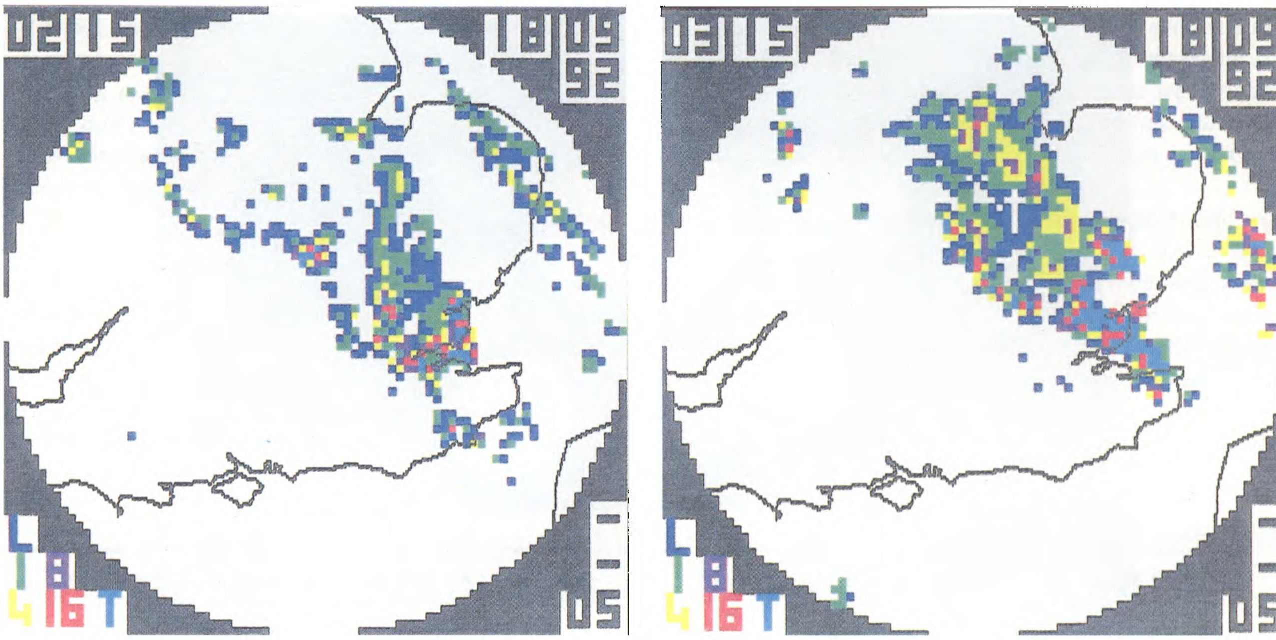
Back in the office I was trying to contact him by radio to see if he was all right. I could not get through. All of a sudden he stumbled through the doorway and just stood

(Top) a typical sample of hailstones which fell on Foulness Island, and (bottom) indentations caused by hailstones on a villager's car during the storm.

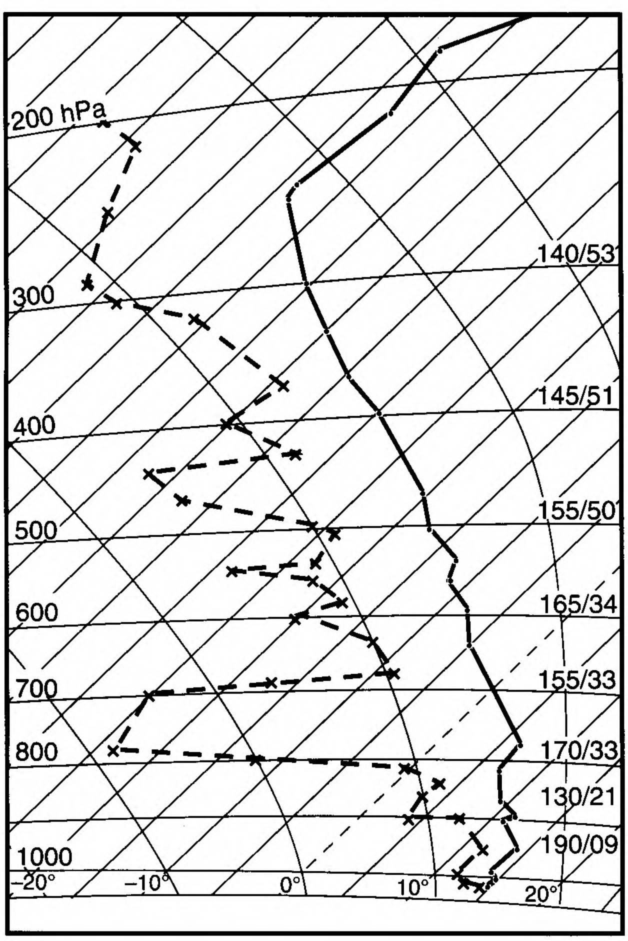
there. He said that he had never been so frightened in all his life and had really thought that he would not make it back. From the look on his face that night I can believe it. At this time hail was coming from a southerly direction.

At about 0305 the hail stopped, and within a matter of seconds the building was engulfed in dense smoke drifting in from the north-north-west. We thought that there had been a lightning strike somewhere and that something was on fire so Ian Bailey and Martin Warwick went out in the landrover to check. The road outside the office was still flooded with water and they both got very wet feet getting to the vehicle. As it turned out there was no fire and the smoke was in fact a very thick mist which had appeared from almost nowhere.

When they got to the vehicle they called me out of the office because the landrover had been badly damaged. Almost every panel on the landrover was covered with dozens of dents caused by hailstones striking it. It was at this point that we realised that our private cars were also parked there, a quick inspection showed that all our private cars had also been extensively damaged. One



Chenies radar data on 18 September at (left) 0215 and (right) 0315 UTC. Colour code is shown at bottom left. L = trace, 1 = >1 mm h^{-1}, 4 = >4 mm h^{-1}, etc. and T is <16 mm h^{-1}.



Shoeburyness tephigram for 0700 UTC on 18 September 1992.

private car had a broken windscreen, and the blue light on the landrover had been smashed.

Shortly after this there was another downpour of hailstones for about 5 minutes, but these appeared to be coming from the north. The area of the hailstorm covered the whole of the AWE site area.

At 0530, over 2 hours after the storm, when I handed over to my relief, the area outside the office was still covered with hailstones, and they had not noticeably diminished in size.

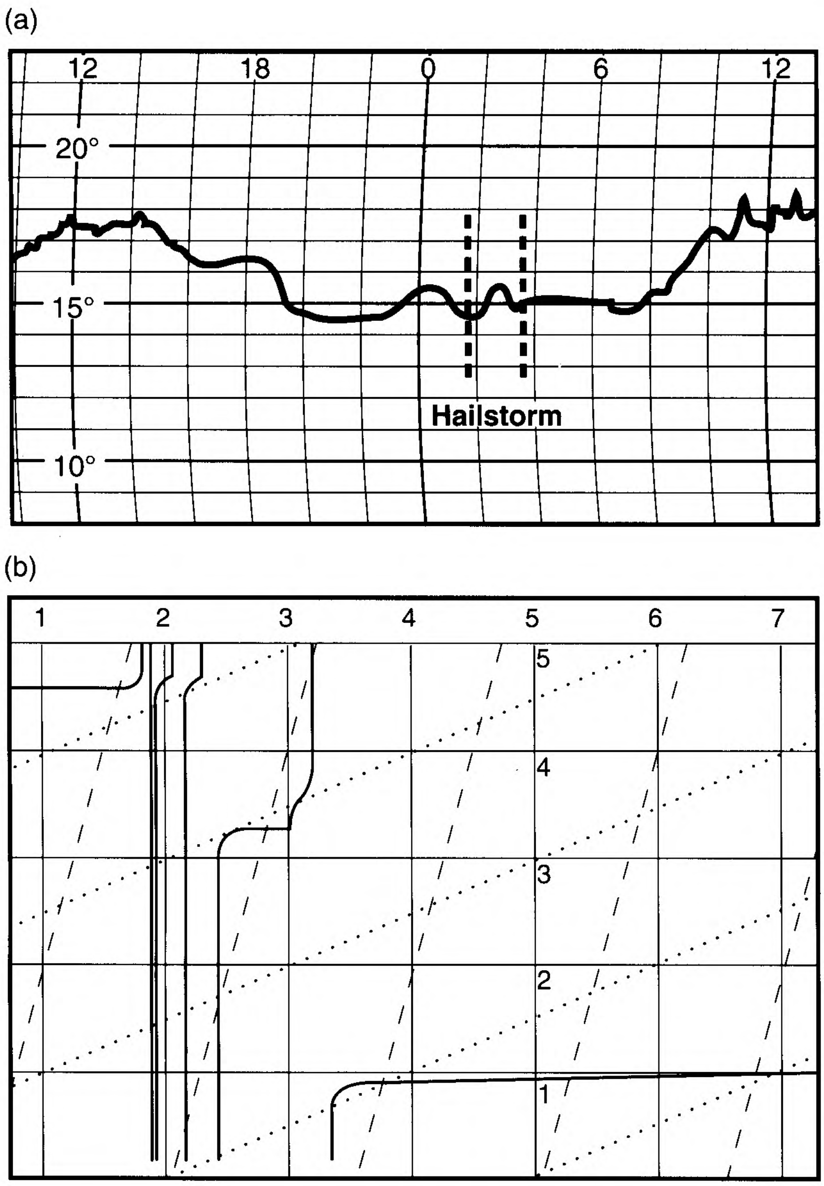
The road between AWE and Landwick was still flooded in places, and scattered with debris from the trees where the hailstones had broken small branches and almost denuded the trees of leaves.

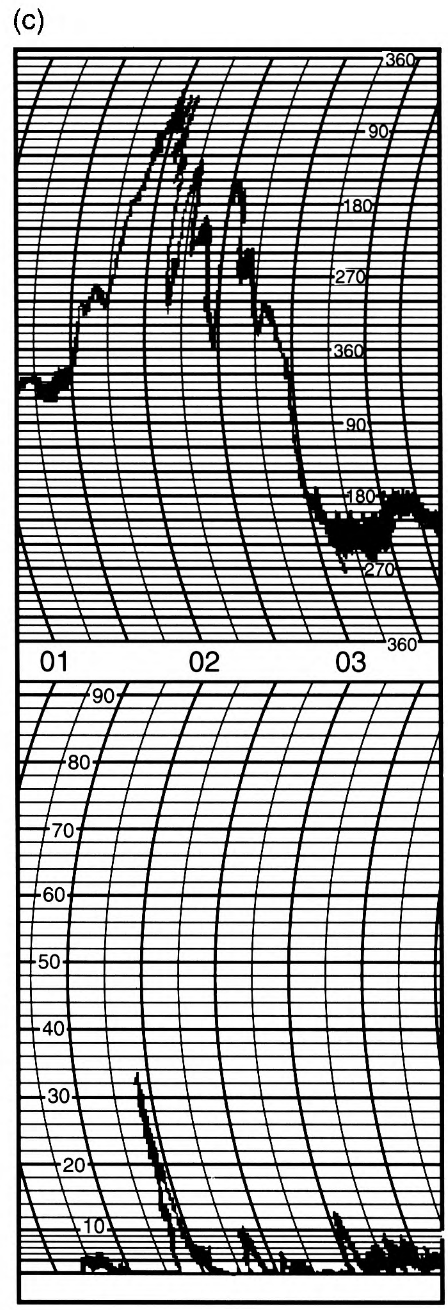
During the height of the storm we were waiting with baited breath for the phones to ring for we knew that if the hailstones were very widespread we should all have our wives calling to say that our homes had been damaged. Fortunately that was not the case and if it had not been for the damage to our private vehicles, they would probably not have believed us.

The next day when I took my car to the garage to have the damage estimated for repair, the estimator was amazed at the damage and said "I live in Great Wakering, and I heard the thunderstorm last night, but we never had any hailstones at all".

Eyewitness account of the storm by M. Hume

I live at 32, Churchend and was woken by the thunder at about 3 a.m. on 18 September. At about 3.15 I was standing in our conservatory when there was a bang on the corrugated perspex roof, which was the first of the hailstones. The next one came straight through the roof in





Shoeburyness autographic instrument records for the night of 17/18 September 1992 (a) thermogram, (b) hyetogram, and (c) anemogram. The hyetogram suggests that little hail fell in it; it certainly does not seem to have been blocked, and the melt water is only just over 0.1 mm between 0320 and 0700 UTC.

front of me. This one was about one inch in diameter. The hailstorm lasted for about 15 minutes. The largest hailstone I saw was about the size of a large chicken egg. The noise of the storm was deafening, even drowning out the sound of the thunder.

The storm totally destroyed our conservatory roof, greenhouse roof and punched holes in the guttering around the house and garage, also breaking and cracking slates on the house roof. The ground was completely covered by the hailstones after the storm and these lasted for quite a few hours. The next morning I was amazed to see dents 5 mm on the cars in the village that had been left outside during the storm.

Wildlife casualties compiled by Mr Adcock

Table I is a list of dead birds found after the hailstorm. The exact number was probably higher as many were washed out to sea. Many suffered broken bills, wings, legs and smashed skulls. RSPCA inspectors were called in to help dispatch the badly injured. High tide on that morning was at 0435 and by 0230 waders were already beginning to congregate towards the high water mark. It was this factor that probably resulted in the large number of waders being killed. Pheasants and partridges are bred at Rugwood Farm. It was this grouping that accounted for the high number of game bird fatalities. One sheep and eight hares were also victims of this storm.

Table I. Bird casualties in the Foulness hailstorm

Cormorant	2	Blackheaded Gull	817
Grey Heron	3	Common Gull	195
Wigeon	1	Lesser Black-backed Gull	7
Tufted Duck	1	Herring Gull	53
Sparrowhawk	2	Great Black-backed Gull	7
Partridge sp.	3	Gull sp.	42
Grey Partridge	142	Sandwich Tern	3
Red-legged Partridge	526	Common Tern	3
Pheasant	107	Black Tern	2
Oystercatcher	267	Guillemot	1
Ringed Plover	2	Stock Dove	10
Golden Plover	14	Woodpigeon	30
Grey Plover	140	Collared Dove	2
Lapwing	1	Turtle Dove	4
Knot	9	Barn Owl	3
Curlew Sandpiper	1	Skylark	5
Dunlin	93	Meadow Pipit	3
Bar-tailed Godwit	210	Blackbird	1
Curlew	43	Magpie	5
Redshank	260	Starling	211
Turnstone	6	House Sparrow	1

551.556.42:77

Features of a smoke plume determined from successive photographs

L.G. Hidalgo
Universidad Central de Venezuela, Facultad de Ingenieria, Caracas, Venezuela

Two pairs of successive photographs of a combustion-generated smoke plume taken during a tropical land-breeze episode were analyzed to determine some geometric (horizontal and vertical extensions) and kinetic (velocities of inner masses) features of the plume. The times between photographs were 3.5 s (first pair) and 6.1 s (second pair).

In the tropics, information concerned with smoke plumes and local winds is important for many petrochemical industries, but surface wind data from only a few coastal land stations are available. Here, I am reporting a successful attempt to get information about a combustion-generated smoke plume during a land-breeze (low-speed) episode using successive photographs taken in a tropical bay (Ocumar Bay) on 30 March 1991. I have followed basic ideas by Sutton (1953) on smoke photographs and Smith (1967) on airborne tracers in agricultural meteorology, but using two pairs of successive photographs and plume inner masses as airborne tracers. The time between the photographs of each pair is less than 10 seconds and the time between pairs is nearly a minute. The use of plume photographs has also been reported by Hanna and Perry (1973). Rickel *et al.* (1990) and Templeman *et al.* (1990) have reported the use of video digitization. Smith (1992) has pointed out the importance of low wind-speed meteorology.

The pairs of photographs were taken and the prints were analyzed to determine some geometric (horizontal and vertical extensions) and kinetic features (velocity of inner masses) of the plume. See the first photograph of the first pair in Fig. 1. A land breeze and an inversion above the top of the plume may be inferred by visual inspection of Fig. 1. The photographs, with the smoke source near their centre, were taken toward the ESE from

Figure 1. First photograph of the smoke plume taken on 30 March 1991 (0721 LT (1152 UTC) 10° 29′N, 67° 46′W, 5 m AMSL, Ocumare Bay, Venezuela, southern coast of the Caribbean Sea).

a distance of 1350 m, at right angles to the plume which was pointing to the NNE, toward the sea. The time between photographs were 3.5 s (first pair) and 6.1 s (second pair). Figs 2(a) and 3(a) show outlines of a 314 m sector of the plume.

The analysis combines visual inspection and measurements of distances on the prints (in millimetres) that are transformed into true distances (in metres) using a photograph scale determined by the following procedure. Photographs of pipelines and buildings were taken of a petrochemical industrial area, After comparing those photographs with maps, it was found that the field of view of the camera is 38° wide. A similar procedure was used for Ocumare Bay obtaining a similar angle. That angle gives a view of 930 m wide and 628 m high for a photo taken from 1350 m when the print is 148 mm wide and 100 mm high. Those values lead to a 1:6280 photographic scale on a virtual vertical plane containing the plume centre line, assuming minimum optical distortions. Using a print with those sizes and the above scale, it is possible to obtain a horizontal plume extension of 434 m for Fig. 1, measured downwind from the smoke source centre.

For the determination of velocities five masses were marked in the first pair of prints (A–E) and six masses in the second pair (F–J) and the coordinates (x, horizontal; z, vertical) were measured in millimetres of print with respect to a fixed frame. Later, by differentiation, the vertical and horizontal displacements of masses were computed in millimetres of print. Using the photographic scale, the displacements in millimetres of print were converted into true metres and these last values were converted into speeds by dividing by the time between photographs. Table I presents the speeds. Figs 2(b) and 3(b) show the composite velocity vectors. The horizontal wind speed is nearly equal to the horizontal speed of any mass.

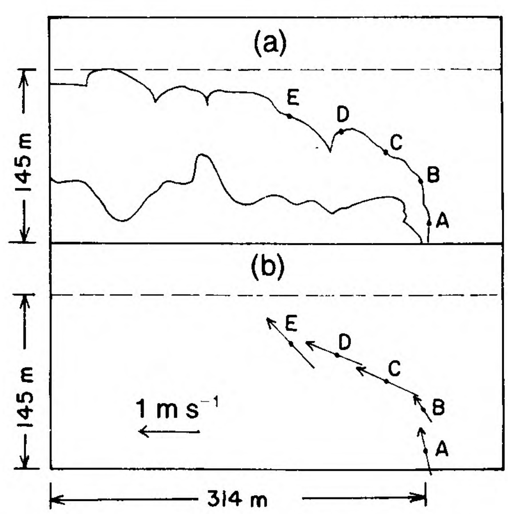


Figure 2. Outline of the plume (a) and velocity vectors of inner masses determined from the first pair of photographs (30 March 1991; 0721 LT; 3.5 seconds between photographs). Masses labelled with letters (A–E) should be interpreted as airborne tracers.

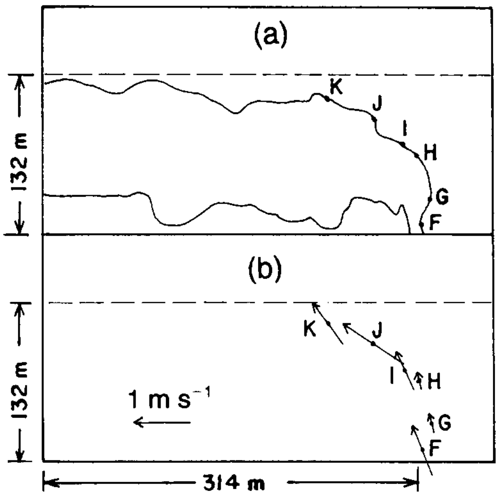


Figure 3. As Fig. 2, but for the second pair of photographs (0722 LT (1152 UTC); 6.1 seconds between photograph).

Table I. Horizontal (u, m s^{-1}), vertical (w, m s^{-1}) and composite (v, m s^{-1}) speeds determined from the photographs

Mass	u	w	v
A	0.2	0.8	0.8
B	0.3	0.4	0.5
C	1.0	0.4	1.1
D	1.0	0.4	1.1
E	0.8	0.8	1.1
F	0.3	0.8	0.9
G	0.1	0.3	0.3
H	0.1	0.3	0.3
I	0.3	0.7	0.7
J	1.0	0.7	1.2
K	0.5	0.7	0.8

$v = (u^2 + w^2)^{1/2}$

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Reviews

Advances in Bioclimatology. Part 1, by R.L. Desjardins, R.M. Gifford, T. Nilson and E.A.N. Greenwood. 158 mm × 241 mm. Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer Verlag, 1992, pp. x + 157 Price DM 118. ISBN 3 540 53483 7..

Advances in Bioclimatology. Part 2 — The bioclimatology of frost, by J.D. Kalma, G.P. Laughlin and J.M. Caprio. 158 mm × 241 mm. Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer Verlag, 1992, pp. xvii + 144. Price DM 118. ISBN 3 540 53855 0.

This new review series under the general editorship of G. Stanhill, has the aim of 'providing a common forum for those wishing to obtain an authoritative review of the latest developments in bioclimatology. The emphasis will be on advances which are soundly based on biological and physical principles rather than those describing empirical relations'. Many of the reviews have been commissioned from internationally known authors. So far two books have been produced: book 1 with four contributions on several topics, and book 2 which concentrates on the bioclimatology of frost.

Book 1 begins with a chapter on techniques to measure CO_2 flux densities using surface and airborne sensors. The aerodynamic, energy balance, Bowen Ratio and eddy correlation techniques are described for surface-based instruments and their strengths and weaknesses highlighted. Aircraft-based measurements can give better spatial averaging and the author gives a critique of the methods which draws upon his own experience of using aircraft in this way.

The CO_2 theme is continued into chapter 2 where the impact of rising CO_2 levels on the growth-limiting environmental factors such as light, water, temperature and nutrients are discussed. Starting with Liebigs (1855) 'law of the minimum', the various interactions and feedbacks between CO_2 and other limiting factors in the crop growth system are used to show that reality can be different from this hypothesis. Because light, water and nitrogen are used with greater efficiency at higher CO_2 levels there is a good prospect that the 25% rise in atmospheric CO_2 concentration in the past 100 years would be increasing net vegetation production and the storage of carbon as litter.

In chapter 3 attention is turned to the transfer of radiation in plant canopies which are not assumed to be homogeneous. Most earlier treatments of radiation extinction in plant canopies assumed spatial homogeneity. This ignored the actual growth habits of plants such as the clumping of leaves, or a row structure which is typical of farm crops. The more recent treatments consider the distribution of foliage within a canopy and a theoretical method is developed whereby the spatial non-randomness of foliage can be explained using models which group the foliage into sub-canopies. Within the sub-canopies a random dispersion of foliage elements is assumed.

The final chapter, which occupies nearly one-half of the book is about deforestation, revegetation, water balance and climate. This is a wide-ranging review of the issues involved in calculating water balance which discusses the assumptions made and the likely sources of error in the component parts such as precipitation, evaporation, run-off, subsurface flow, infiltration and soil water storage. The bulk of the review is concerned with the reported effects of deforestation and revegetation on the water balance. The general thrust supports the view that the replacement of trees by short-season arable crops can increase the water yield of a catchment because less water is used in evaporation. However, the reduced evaporation can cause reductions in rainfall in areas (e.g. Amazonia) which have a rapid evaporation–precipitation cycling of water. It has also been observed that clear-felling can increase the peak discharge of rivers and increase soil erosion. Another unfavourable effect of the removal of trees is to raise the level of groundwater. If this process should mobilise salt deposits, such as has happened in parts of Australia, then conditions may become unfavourable for the crops which have been planted instead. The writer of this chapter is optimistic that the challenge to hydrologists to change vegetation patterns without substantially altering the components of the water balance can now be adequately met.

The four chapters in book 1 are without doubt authoritative and provide a good update on the topics chosen. To this reviewer the second and fourth chapters are the better ones because they are entertaining as well as informative with hardly an equation in sight. The third chapter on radiation transfer is more difficult to follow and is really for those who are nearly expert in this area already.

Book 2 is about frost and it is aimed at researchers, engineers, extension officers and students as an aid in understanding the physical aspects of frost occurrence and distribution as well as the biological and phenological aspects of frost damage. An overview is also provided of direct and indirect methods of frost protection and prevention. The book attempts to : (1) provide a comprehensive review of advances in the past 10 years, (2) to draw together the wide range of physical, biological and engineering aspects, and (3) to draw on examples worldwide. The emphasis is on short duration frosts which would be of importance to agriculture and horticulture. Topics are restricted to the aerial parts of plants and aspects such as soil freezing for example are not considered.

The book has three parts: Part 1 (chapters 2–6) discuss the physical aspects of frost occurrence and distribution. Chapter 2 identifies the types of frost and describes the worldwide distribution of frost. There is some discussion of the impact of climate change on frost distribution and a short section on frost protection methods. The physics of night-time cooling of near surface air, ground and plant surfaces is discussed in chapter 3 and the relevant mesoscale processes such as katabatic drainage are reviewed and illustrated by a case study in chapter 4.

In chapter 5 there is a review of the techniques available for frost-risk mapping at the regional scale. The section ends with a review of the use of remote sensing in frost-risk mapping.

Part 2 (chapters 7 and 8) emphasises the relationships between frost (and other weather factors), crop growth and crop development. Topics such as plant hardiness, plant stress, frost resistance, chilling and plant rest requirement appear. Chapter 8 is devoted to a case-study of the factors which affect the winterkill of wheat in Montana (USA).

Part 3 of the book (chapters 9–11) is about frost protection methods. Frost amelioration can be active or passive. Active methods include the use of heaters, wind machines or by freezing water which is sprinkled on the crop. In chapter 10 a model to estimate the required rates of water application in sprinkler systems is described. Passive methods, which are described in chapter 11, include various management techniques such as increasing soil moisture (to raise the soil heat conductivity), growing taller plants (to raise susceptible plant parts out of the coldest air) and delaying the blooming of fruit trees by growth regulator sprays or by the chilling of flower buds using water sprays over a long period. The book ends with 15 pages of references from the past 30 years and a subject index.

This is a wide ranging and authoritative review with information on many topics. Particularly helpful are chapter 3 (microscale processes) which includes a model to estimate leaf temperature, chapter 4 on the mesoscale and chapter 5. In chapter 5 there is a comparison of two statistical methods (linear regression and spline fitting) which can be used to relate minimum temperatures to location and hence lead to mapping of frost prone areas. The role of local terrain on minimum temperature at a point is shown to be explainable in terms of the land area which could contribute to cold-air drainage to the point. Other topics are treated more briefly, but there are plenty of references to follow points of interest.

This pair of books is a good start to the series, though this reviewer found the book on frost rather the better of the two because of the unifying theme. Others in the series are eagerly awaited.

M.N. Hough

The atmospheric boundary layer, by J.R. Garratt. 177 mm × 253 mm, pp. xviii + 316, illus. Cambridge University Press, 1992. Price £50.00, $79.95. ISBN 0 521 38052 9.

To the uninitiated, boundary-layer meteorology presents if not a jungle, then a fairly dense canopy. Many students lose their way *en route* from Ekman pumping to the Penman–Monteith equation. It is sad if boundary layers remain an esoteric mystery, because of course a lot of practical weather forecasting (e.g. the difference between air-frost and ground-frost) is just boundary layer meteorology by another name. Now, too, climate research has focused attention especially on boundary-layer interactions with clouds and surface processes.

With an enviable combination of experimental and modelling experience, John Garratt is well placed to be a guide. This textbook is aimed at 'the experienced researcher or teacher working in the atmospheric or related sciences'. It forms part of the new 'Cambridge Atmospheric and Space Science Series', (editors include Sir John Houghton) — at present a fascinating collection of six titles including two on plasma physics.

In terms of Royal Meteorological Society journals the style is mostly '*QJ*' rather than *Weather*, but long mathematical derivations are avoided. Both descriptive and mathematical parts are exceptionally lucid. Some readers of *Meteorological Magazine* will find parts quite difficult, but will still gain real insight into current boundary-layer research issues if they persevere.

Deliberately, and I think rightly, the author ignores experimental and numerical techniques; a superficial discussion of these highly technical issues would not be useful. Similarly, and wisely, the very important and closely related issues of air pollution are not covered. Instead, the slant is towards climate or forecast modelling.

The introductory chapters (1 and 2) give both a descriptive summary of boundary layers and turbulence and a fairly thorough account of mean-flow and second-order budget equations. Classical similarity theory (3; always a delicate subject) is well handled, though the devil's advocate might argue that the Coriolis parameter is overrated in boundary-layer scaling. I particularly enjoyed the chapters (4 and 5) on surface and radiative processes. The thermally stratified boundary layer (6; somewhat neglected in 'dynamics' books) has a good airing. Cloud-topped boundary layers (7) represent a fast-moving and important sub-field; Garratt perceptively notes that the current theories of stratocumulus break-up disagreed with observations. The book rounds off with modelling and parametrization (8) and climate applications (9), including 'research priorities' which seemed balanced, though I am not a climate modeller.

In assessing the up-to-dateness and accuracy of discussion of recent research, the reviewer inevitably focuses on the work of his closest contacts (in my case, physical research groups in the Meteorological Office). Work by P.J. Mason and co-workers on non-uniform or hilly terrain and on boundary layer simulation gets reasonable coverage. I found the brief summary of my own recent work fair. The cut-off date seemed to be around 1990; papers from that year on stratocumulus by MacVean and Mason and R.N.B. Smith, and also work on stable boundary-layer simulation, might rate a mention in a second edition. The author's recent affiliations are American/Australian, and the coverage of other recent work seems good also.

Now for the nit-picking. The paper quality is not glossy (environmentally sound? perhaps a good thing), and a few pages in my copy were slightly smudged. A few obvious typos in the text ('Bachelor', 'Cabaow', 'mesosphytes'), but the equations seem OK. The younger generation will enjoy a smirk at 'degrees kelvin' (p. 128), though the adherence to SI units (plus the politically correct hectopascals) is commendable. There is little else to gripe about really. The index, bibliographies and appendices are good.

The publishers seem nervous that recent textbooks might have cornered the market. They need not worry too much: despite some competition, this is the best introduction to the subject, particularly from the standpoint of modelling, that I have read. The price may put a strain on the student's bank manager, but any researcher with interests in boundary-layer meteorology should have access to a copy. I shall now try to retrieve mine from my colleagues.

S.H. Derbyshire

Books received

El Niño — historical and Paleoclimatic aspects of the Southern Oscillation, edited by H.F. Diaz and V. Markgraf (Cambridge University Press, 1992, £40.00) examines for the first time different approaches to reconstructing ENSO based on a variety of proxy sources, ranging from high-resolution environmental indicators such as tree rings etc. to records on the impact of ENSO on fisheries and marine and lacustrine sediments, to a long record of vegetation changes in the southern hemisphere. This book will be of importance to all professional scientists and researchers in climatology, meteorology and the earth and environmental sciences, while graduate students will also find this book a useful reference source. ISBN 0 521 43042 9.

June storms in the British Isles

From Plymouth Weather Centre

On Wednesday 9 June 1993 parts of south-west Cornwall experienced what has been classified as a 'rare', once in 500 years event. A total of 126.3 mm of rain fell at RNAS Culdrose (03809) between 2300 UTC on the 8th and 1000 UTC on the 9th, more than twice their mean monthly rainfall for June. This in itseif was unusual but what constituted the rare event was the 59.1 mm which fell between 0700 and 0800 UTC on the 9th (Fig. 1). The fact that this did not match the record 91.4 mm which fell in an hour at Maidenhead in 1901 was no consolation to the inhabitants of the town of Helston and the village of Porthleven, who bore the brunt of the downpour.

For several days the Met. Office Limited Area Model (LAM) had been indicating that the prevailing hot spell would degenerate into thundery outbreaks some time around 9 June. In this respect it offered good guidance, but what it did not indicate was the rapid development of the storms *in situ* over south-west England overnight.

Unstable medium-level cloud which was advected northwards from Brittany on the evening of 8 June had largely decayed by the time it reach Cornwall, though it did produce some light rain. The first indication of development taking place *in situ* was a small echo south of The Lizard on the Predannack rainfall radar in the early hours of 9 June. The echo expanded quickly accompanied by a marked increase in its intensity; the ascent for Camborne at 09/0000 UTC supported Cb tops to over 40 000 feet. Although only 7 miles north of Culdrose, Camborne escaped relatively lightly as illustrated by their hyetogram (Fig. 2).

As with the Lynmouth flood of August 1952, to which this event has been likened, there is probably little that the authorities could have done to alleviate the flooding. Fortunately in this instance there were no reports of injuries or deaths.

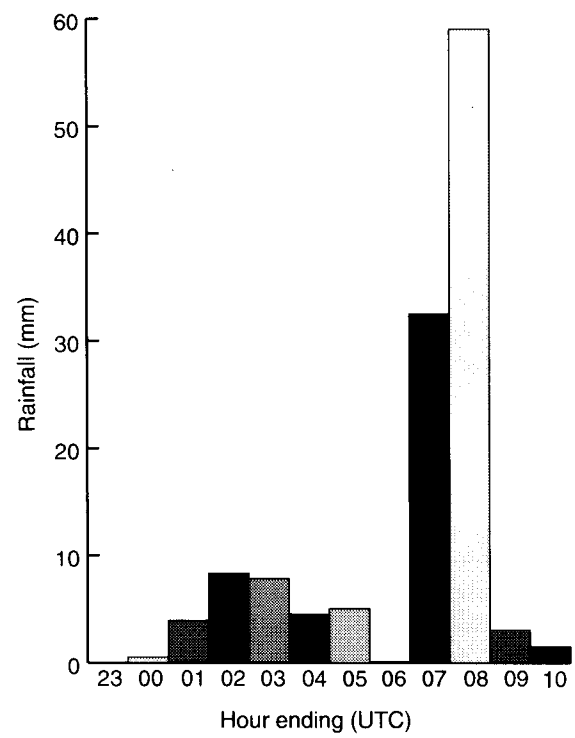


Figure 1. Hourly rainfall at Culdrose on 9 June 1993.

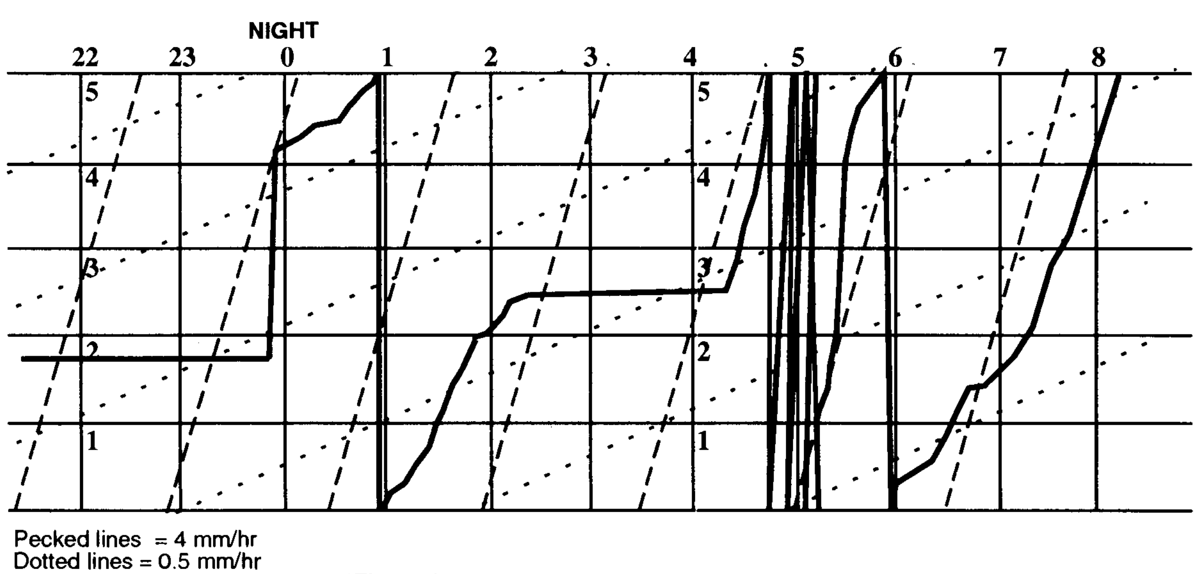


Figure 2. Hyetogram for Camborne on 9 June 1993.

It was reported that the Cornwall Fire Brigade received 80 calls in a short space of time and had to be reinforced by four Royal Navy fire engines from Culdrose. At Porthleven, down the valley from Helston, water poured seawards over the harbour wall instead of the more usual landwards! One newspaper article wrote of a resident being '....waste (*sic*) deep in water....', and likening the scene to something from the Dambusters.

On Friday the 11th and Saturday the 12th the centre of attraction moved further north. In the 24 hours ending 0900 UTC on the Saturday Chivenor (03707), near Barnstaple (Devon), recorded 60.4 mm of rain. Widespread flooding was reported around Bude (Cornwall), where the inshore lifeboat lived up to its title by operating three miles inland!

From Cardiff Weather Centre

A slow-moving upper vortex with areas of very heavy rain and thunderstorms within its circulation drifted east across the United Kingdom on 10 and 11 June 1993.

Rainfall totals were very large in places with flooding in parts of Wales and southern England. During the early evening of the 10th, torrential rain from a thunderstorm in the Llandudno area of North Wales coincided with high tide and swamped the storm water system. Floods up to 5 feet deep occurred in the lower part of the town and around Llandudno Junction. The main A55 expressway was closed due to flooding in the new Conwy road tunnel and there was up to 2 feet of water in Llandudno General Hospital for a time. About 2500 people were displaced by floodwater and rehoused with the help of an emergency social services plan developed after the flooding at Towyn.

A total of 137 mm of rain was recorded in the 24 hours ending midnight on the 10th at Conwy Mussel Tanks just along the coast, and it is thought a significant portion of that total fell in a 2- to 3-hour period during the early evening. Autographic rain-gauges at Colwyn Bay and Betws-y-Coed were reported to have been disabled by the intensity of the rainfall event, so unfortunately no figures are available.

The following day it was the turn of parts of southwest Wales to bear the brunt. Average June rainfall for Aberporth in Dyfed is 56 mm. In the 24 hour periods ending 0900 UTC on 10 and 11 June 1993, the Met. Office at Aberporth recorded 66.0 and 74.6 mm respectively. The previous highest 24-hour rainfall for June was 41.8 mm in 1971. Flooding occurred along the length of the Mwldan, a normally insignificant tributary of the Teifi. Caravans and cars were swept downstream and flooding occurred in many homes in Cardigan itself. The privately run Talyllyn railway had to cancel services for the first time in 42 years after the rain washed debris across the track, washed away an embankment and toppled a large oak tree onto the line.

Cleaning up the flood damage in Wales is expected to cost in excess of £12m, but no lives were lost, thanks to the excellent work of the emergency authorities and timely advice from the Met. Office.

From the Irish Meteorological Service — rainfall records of June 1993

The most notable event was the 24-hour totals in excess of 100 mm which fell in parts of the Dublin–Kildare area on the 11th. This was a most remarkable fall for lowland areas in the east, being over twice the long-term average for the whole of June. The 12-hour rainfalls had a return period of over 100 years and the 24-hour totals a return period of some 250 years at Casement Aerodrome (Baldonnel), which with 109 mm in 24 hours was typical of the worst affected areas. The 24-hour totals at some Dublin–Kildare stations were at their highest ever, exceeding even those of 'Hurricane Charlie' in August 1986 when the Wicklow mountains and much of the Dublin mountains had heavier falls than in this event. Dublin Airport, in spite of having a fall of 93 mm (return period of about 100 years) on the 11th, did have a higher June total in 1958, but 1993 was the wetter June at Casement Aerodrome.

On the 11th the band of the most active rain extended from Sligo to Wexford and was about 120 miles wide. As there were small-scale pockets of intense activity, the totals varied widely even within this band.

While rare in any given location, falls of more than 100 mm in 24 hours at lowland stations have been recorded. The most recent such occurrence in the Dublin city area was in a small-scale thunderstorm which affect the Mount Merrion area, curiously enough on 11th June 1963, when over 180 mm was recorded in 24 hours and over 75 mm fell in an hour. This storm affected an area of only about 8 km^2. The most recent event giving such rainfalls in Ireland occurred in October 1989 when, again on the western side of a slow moving depression, there were falls over 100 mm in parts of Donegal and Mayo.

World weather news — June 1993

If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and press reports. Naturally they are heavily biased towards areas with a good cover of reliable surface observations. Spellings are those used in The Times Atlas.

South America

Antarctic air streaming northwards from the Bellinghausen Sea brought biting cold on the 3rd to southern Chile. Punta Arenas had a maximum temperature of −0.3 °C, which is well below average. This was followed by a night minimum of −4.6 °C which is nearly a degree below the June record. Because this is the coffee growing season, the southern part of Brazil is usually more concerned with frost than rain, however early on the 5th thunderstorms dropped nearly 117 mm in 6 hours on Curitiba, near Sao Paulo.

The east of Argentina was very wet around the 8th with the port of Mar del Plata having 99 mm, nearly half this month's average on the 14th. The 14th was very wet with Junin, Argentina, having 54 mm in only 12 hours up to midday; this is 13 mm more than the monthly average, while across the border in Uruguay Colonia had 72 mm of rain, which is about the average for the whole month..

On the 28th the temperature fell to −5 °C, at La Paz in Bolivia, high up in the Andes, that is 6 °C below normal. (This is not to be confused with La Paz in Mexico mentioned in the next section.)

North America and Gulf of Mexico

The first day of the month saw 'tropical depression No.1' crossing Cuba; this was an ominously early opening to the season and much of Jamaica and Cuba had excessive rain.

The Koahuila region of north-east Mexico started the month with near record temperatures. Low pressure over the south-west USA drew warm air from the Yucatan Peninsula and temperatures rose steadily. At Monclova the temperature reached 43.5 °C on the 3rd. In contrast it was very cold at Las Vegas on the night of the 5/6th; the temperature dropped to 9 °C which equals the lowest ever for June, set back in 1939.

Midland in Texas had an intense thunderstorm on the 9th; in six hours from 1800 they had 78 mm of rain (around twice the average for the whole of the month) while the temperature fell from 32 °C to 18 °C. Severe thunderstorms developed over parts of central USA on the 11th; at Corpus Christi, Texas, 55 mm fell. St Mathews, Kentucky, had 64 mm in only 30 minutes: nearby Lawrenceville had 49 mm fall in one hour. The insured damage put down to hail, tornadoes and flooding was $150m.

During a heavy rainstorm in Atlanta, Georgia, on the 14th a sewer failed under a hotel car park creating a crater 60 m in diameter and very deep: several cars and people were lost, but one of the cars was found three miles away in a storm drain. A few days later there were reports of further tornadoes and flooding from New Mexico to Illinois over the period 17th to 19th leading to about $100m of damage. Further severe storms over the 23rd/24th did another $55m of damage.

Easterly winds got out of the Nevada Desert across the mountains to central California on the 16th. In San Francisco, where the June norm is 21 °C, the temperature rose to 30 °C and then on to 35 °C on the 17th. At the same time hot, thundery weather reached northern parts of the USA, with Chicago having temperatures up to 33 °C, but thunderstorms gave 68 mm of rain, two-thirds of its normal for the month.

Late in the month 'real' storms began when tropical storm *Arlene* developed the Gulf of Mexico and rapidly went aground at Padre Island, Texas, on the 20th; winds were only 35 kn but as one might expect it rained hard. There were totals of up to 375 mm over parts of southern Texas. The same day tropical storm *Beatriz* went ashore on Mexico's Pacific coast around Acapulco. Salina Cruz was fairly typical getting 286 mm of rain in 2 days, compared with the monthly average of 263 mm. Between them the two storms caused flooding and landslides in many parts of Mexico, including the capital: the death toll is thought to have been seven.

Further thunderstorms occurred over Texas on the 25th with 150 mm in one hour reported to have fallen near McGregor; Dallas had 55 mm. These falls caused extensive flooding. On the 29th/30th hail 50–75 mm in diameter was reported in Nebraska and the Dakotas with violent thunderstorms battering Iowa, and rainfalls approaching 170 mm in places: near Chicago there was about 100 mm and the heavy hail in North Dakota destroyed 2500 Airstream trailers gathered for a club outing. In Minnesota, 80% of the corn and soya bean crops were reported seriously damaged by flooding.

The Mexican city of La Paz recorded 48.6 °C on 28 June; this was a new record (see the other La Paz above). Not all that far away Acapulco had heavy rain, 150 mm in just 18 hours.

On the 12th the level of Lake Ontario had fallen enough for the flow down the St Lawrence Seaway to return to normal and allow shipping movements every day of the week. The lake had been raised to about 25 cm above flood level by the winter's rain and snow.

Towards the end of the month flood water coming down the Mississippi reached the second deepest on record at 7 ft above flood stage. The flow was so great that many locks had to be closed, stranding barge traffic from St Louis to St Paul.

Australasia

This information is largely based on that kindly given by the Australian Bureau of Meteorology. The emphasis seems to have been on coldness in Australia this month. Alice Springs did not have a temperature above 12.9 °C during the period from the 2nd to the 8th making it their coldest week in 53 years of records: further north Tennant Creek's maximum of 12.8 °C on the 15th was the lowest in 36 years of data by 1.7 °C. The north-west of Western Australia (WA) had heavy rain on the 8th and 9th giving totals of 75–88 mm and Port Hedland's 62 mm on the 9th beat the 50-year-old record by 7 mm: the flooding damaged roads in the area stranding traffic. In the north-east of the Territory, The Kimberley, had a persistent, cloudy north-westerly from the 10th to the 15th which brought unseasonal widespread rain and abnormally low temperatures, e.g. Halls Creek's maximum of 12.4 °C was its lowest ever by a whole 2 °C in a 45-year record. Before leaving WA we should note that the extreme south-west corner was unusually dry; the 55.7 mm at Manjimup comfortably beats the previous low total of 76.6 mm.

A strong cold outbreak on the weekend of the 11th/12th brought snow and damaging gales to Tasmania, Victoria and the south of South Australia. A wind of 50 kn was measured at Mt Gambier and the A$5m plus damage in Wonthaggi suggested that 67 kn could have been reached there. The heavy snow around Ballarat stopped football matches (*I did not realise that was possible! — Ed.*) and stopped traffic in parts of Tasmania for a time.

Asia

Heavy rain affected south-east China on the 4th and 5th with many places recording nearly 100 mm, about a third of their June normal rainfall. On the 6th the town of Shanwei had recorded a total of 297 mm since the beginning of the month; this is 77 mm more than the usual for the whole month. The heavy rain continued on the 8th when rainfalls of between 130–150 mm were recorded just north of Hong Kong.

There was further heavy rain on the 9th when 137 mm fell at Fogang, 200 miles north of Hong Kong, while on the coast near Hainan Island 145 mm fell. The rain reached Hong Kong on the 11th, where 145 mm fell in 36 hours, about one-third of the June normal. Across the water 71 mm fell on Macau.

During the second week of the month another 393 mm fell on Shanwei. Not far away Shenzhen has an average June rainfall of 269 mm; on the 16th, 254 mm fell and of those 157 fell in 6 hours. The same day in Hong Kong 138 mm fell with considerable local flooding. There were numerous landslides but only one death was reported, this was when a bus station was buried. In the neighbouring Chinese provinces a total of 216 had died as a result of the heavy rains throughout the month and a total of 585 mm of rain had been measured at one site in Guangdong where floods were 2 m deep. Overall more than five million were affected by the resulting floods.

Not all the heavy Chinese rain was in the south-east, Jingdezhn in Chekiang province had 183 mm of rain in the 24 hours ending on the 19th, a mixture of rain and thunderstorms gave one of the highest daily totals they have ever had, about three-quarters of the whole month's rainfall. Further large rainfalls were recorded on the 27th in the province of Szechwan; rainfalls of the order of 150 mm were noted at Zhanjiang; on the Leichou peninsula 114 mm fell as typhoon Koryn passed just south of Hong Kong where several were injured by flying debris and transport by land sea and air was severely disrupted. Meanwhile Shenwei had another 112 mm, making the total for the month 802 mm. At Qinzhou on the Gulf of Tongkin there was 288 mm in only 24 hours (the June average in 215 mm).

Up in north-east China there was a heatwave; on the 19th there were many cities with temperatures of 36 °C and above.

Strong winds and high seas around the Korean port of Busan on the first few days drove many vessels aground, some remaining fast into October.

A depression over the Sea of Japan brought heavy rain to parts of North Korea and northern Japan early in the month. At Chongjin there was a fall of 160 mm up to the 3rd and at Miyako, on the coast of Honshu, there was 125 mm, with 54 mm on the Island of Hokkaido.

The Island of Sulawesi was very wet over the night of the 6/7th when the east coast town of Kendari received 126 mm of rain. They would normally expect it to take 12 days rain to reach 194 mm: there was flooding.

Mount Unzen (near Shimabar, Japan) resumed eruptions on the 22nd; the ash output is of no direct meteorological consequence, but if mixed with significant rainfall, damaging lahars are to be expected (see April notes). On the 23rd the city of Nagasaki in the south of Japan had a lot of rain, 129 mm in all, and this was not unrepresentative of the area.

On the 21st tropical storm Koryn started cruising through the Caroline Islands and the Island of Truk collected 85 mm in just 6 hours while the winds blew around 35–40 kn. Koryn reached super-typhoon status for a while on the 24th when sustained winds of 130 kn, gusting to about 160 kn were diagnosed: the central pressure down to about 905 hPa at this time. Koryn crossed the Philippines on the 26th causing most damage on Luzon. Maximum winds of about 100 kn were accompanied by 100 mm of rain in many places (Sangley Point, Manila Bay, was the wettest with 165 mm). Flood water reached a depth of 3 m in parts of Manila and five were killed in Baguio. The lahars down the slopes of Mount

Pinatubo were anticipated and no-one was caught by them. Next day the captain and three crew of the 9000-tonne freighter *Lian Gang* were drowned when she sank 70 miles south of Hong Kong when her cargo shifted during an encounter with the typhoon.

Flooding of a different type was reported from the eastern side of the Urals. There, sometime during the month heavy rain combined with the thaw. Twelve are believed killed and a hundred missing and much damage caused near the town of Serov.

Indian Subcontinent

Sketchy reports of 27 killed by flash flooding in northern parts of Afghanistan emerged about the 11th: it was not made clear when this happened. More certain though was the catastrophe that happened during the night of the 14th/15th when heavy rain caused a landslide in part of Kabul that buried at least 115 under tons of mud and debris.

Ahead of the monsoon temperatures got higher and higher and in the Indus Valley in eastern Pakistan a temperature of 50.3 °C was recorded on the 7th and nearby at Bikaner a record 52.7 °C. Further south the monsoon was arriving with a vengeance with 207 mm of rain at Calicut on the 7th. Their total for the month at this stage was 420 mm which is half the month's average. Over in Bangladesh the monsoon rain dropped 150 mm at Tezpur in the Brahmaputra Valley.

Heavy monsoon rains had been causing flooding in north-east India and spread to Kerala on the 11th swamping huge areas of farmland. Floods cut off Tripura and parts of Assam. In adjoining Bangladesh at least 220 are believed drowned and millions were marooned by the rising waters. The submerging of a 27-mile stretch of railway line compounded the problems caused by the cutting of road links some days earlier: a service was restored on the 21st. On the 20th there was a report that one gauge had collected another 200 mm of rain.

Just south of Bombay, rainfall of 196 mm on the 15th raised the total for the week to 480 mm. Surat, 120 miles north of Bombay, also got rather more monsoon rain than usual; 212 mm fell in one day on the 24th. This compares with the average for the month of 218 mm.

Some old Met. Office hands will be interested to read that Gan in the Maldives had had 976 mm up to the 22nd, which is about three times the average.

Africa (except the Mediterranean coast)

The area around Mount Kilimanjaro in Tanzania had unusual dry season weather on the 4th. At Moshi, near the mountain, normal rainfall is 26 mm. They got 99 mm; this easily beats the previous June record of 38 mm in 24 hours. Not far away Nairobi had a fair amount of rain at the beginning of the month, the average is about 32 mm but in the two days up to the morning of the 6th there had been 37 mm.

It was very hot in Mali on 7th where the town of Kidal set a new June record with 46.5 °C. The 15th of June brought some very high temperatures to Sudan where 46.2 °C at Atbara was almost a new record.

By the 22nd summer rains were well established over west Africa with large rainfalls in Ghana, where 168 mm fell at Takoradi. Nearby in Benin 48 mm fell in 12 hours on the 21st and on the southern border of the central African Republic 134 mm fell on the 21st at Mobaye. However the most notable rainfall probably was at Tahoua in southern Niger, on the edges of the Sahara. Here 97 mm fell on the 21st; the previous June record for 24-hour fall was 68 mm and the monthly average is only 56 mm.

Algeria's town of In Salah had very high temperatures throughout the last half of June and on the 25th the day maximum was 47.6 °C. With winds blowing at around 30 kn the night minimum temperature was only 38.3 °C; however with the strong sandy wind the relative humidity was only a few per cent.

A combination of unusual rains in the east, and political problems, has allowed the desert locust unimpeded growth in Somalia and during the month the FAO estimated that four swarms were flying south from an area of 23 000 m^2.

The South African Weather Bureau reported that it had been an unremarkable month down there although there was a wide range of conditions. While much of the north was seasonably dry, Ceres near Cape Town managed 99.7 mm in one day. The hot spot was Mtunzini in northern Natal with 33.8 °C to contrast with Buffelsfontein's night minimum of −9.5 °C. On the 11th a deep low brought coastal gales to disrupt fishing, and the active cold front gave heavy rain around the Cape and along the south coast. This was followed by bitterly cold weather which gave heavy snow on the southern Drakensberg — De Aar in the Upper Karoo having its first snow for 10 years.

Europe, North Africa and Arabia

Early on the 6th heavy rain affected much of central Spain with Toledo collecting near 60 mm of rain, compared with a monthly average of only 25. Madrid also had a lot of rain with 29 mm falling in 12 hours about equal to the whole of the month's rainfall.

Something of a heatwave affected England mid-month with temperatures near 30 °C which was enough to reveal that expansion gaps on some sections of motorway were insufficient as they buckled in the heat: elsewhere extra staff were employed to cope with the demand for ice cream.

Very heavy rain fell from thunderstorms over the south-west of the United Kingdom on the 10th and 11th causing serious local flooding. Three were reported drowned as a result of flooding rivers and two died at sea in boating accidents. About the same time storms were affecting eastern Ireland where three were drowned near Dublin in the heaviest rain for seven years: at one stage all roads to the airport were cut and rail services disrupted. Casement Airport collected 103 mm in 30 hours to the morning of the 12th. Because May was very wet flooding was widespread as numerous rivers overflowed. (*These events are reported separately elsewhere in this issue.*)

Some Alpine storms hit Lakes Maggiore and Lugano areas during the 11–12th; Locarno had 91 mm and Lugano 60 mm (about one-third of the June average). Meanwhile in north-east Germany near Berlin one town collected 109 mm in 2 days of thunderstorms. This is 46 mm more than the June average.

Spain's Costa Brava had a surprise on 23rd when heavy thundery showers broke out; Gerona had 45 mm of rain, the sort of total normally expected to accumulate in the whole of the month. On the same day it was very hot at the other end of the Mediterranean, Damascus had its hottest June day on record with 39.6 °C and in Turkey Izmir's 39.7 °C was nearly 2° above the previous record.

Antarctica

Light winds and clear winter skies brought a bitterly cold 5 days to Vostok in the Antarctic when on the 17th the minimum temperature was minus 71.9 °C. This is somewhat warmer than it had been on the 15th when the minimum was minus 77.3 °C. It was cold for mid-winter for the Americans at Amundsen–Scott; night(?!) minima are normally around -61 °C but on the 23rd the temperature got down to −73 °C, close to the record; next day it was down to −75.3 °C.

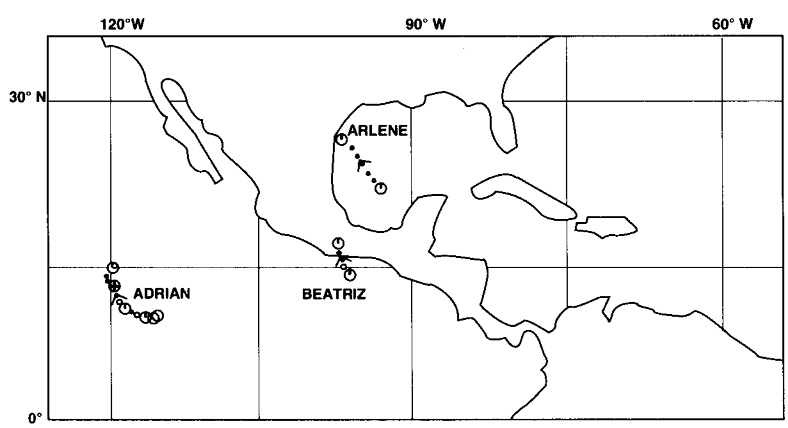
June tropical storms

This is a list of tropical storms, cyclones, typhoons and hurricanes active during June 1993. The dates are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during this month. The maps show 0000 UTC positions: for these I must thank Julian Heming and Susan Coulter of the Data Monitoring group of the Central Forecasting Office.

No	Name	Basin	Start	End	Max. (kn)
1	Adrian	NEP	15/06	19/06	75
2	Koryn	NWP	15/06	28/06	130
3	Beatriz	NEP	18/06	20/06	50
4	Arlene	NAT	18/06	21/06	35

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific: I — Indian Ocean; WI — west Indian Ocean; AUS — Australasia.

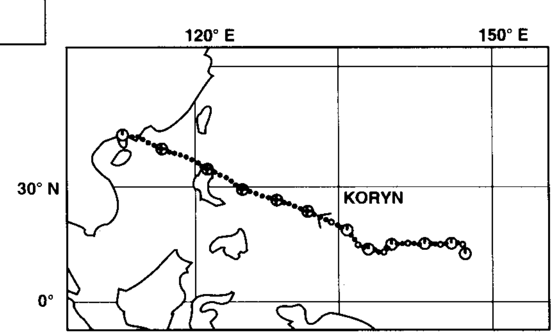
Super Typhoon Koryn affected the Philippines, Hong Kong and Korea, see under Asia above.
Tropical storm Beatriz affected western Mexico; Arlene affected eastern Mexico and Texas.



Key:

○ 30–60 kn

⊕ 60–120 kn



Your Editorial Board announces that the Meteorological Office Board has decided that the publication of the *Meteorological Magazine* will cease with the issue for December 1993.

As one of the leading European establishments for research into meteorology our publications should be subject to external peer review: this is already the case for much Meteorological Office work. The publication of a new international and European quarterly journal by the Royal Meteorological Society (to be called *Meteorological Applications*) is expected to provide a suitable vehicle for the kind of articles that now appear in *Met Mag*, namely on research, practice, measurements, reviews, applications of meteorology, book reviews, etc.

The first edition of the *Meteorological Magazine* was published in 1920 by HMSO. It took over from *Symons's Meteorological Magazine* which started in 1866. This decision therefore brings to an end a continuous publishing record of 129 years (except for the duration of World War II). It is understood that legal obligations accepted when *Symons's Meteorological Magazine* was adopted are fulfilled by the continuing production of the *Monthly Weather Report* and *Rainfall 19XX* and our internal journal mentioned below.

The December 1993 issue of *The Meteorological Magazine* will be a bumper one of about 40 pages celebrating the Magazine's contribution to the development and dissemination of meteorological knowledge. It will contain a selection of highlights from 1866 up to around 1986.

The United Kingdom Meteorological Office (UKMO) Annual Scientific and Technical Review

This Review describes the major developments in science and technology within the UKMO over the year and is produced as part of the Meteorological Office Annual Report and becomes available in July each year. If you wish to be put on the mailing list please write to:

The News Desk,
Publications (room 709),
Meteorological Office,
London Road,
Bracknell,
Berks
RG12 2SZ.

Informal communications

The UKMO has instituted an in-house periodical for informal and rapid dissemination of the latest relevant science and technology news to its staff and outside collaborators. Most contributions come from UKMO staff, but offers of material from outside will be welcome — though there is no guarantee of publication.

Back numbers: Full-size reprints of Vols 1–75 (1866–1940) are available from Johnson Reprint Co. Ltd., 24–28 Oval Road, London NW1 7DX. Complete volumes of *Meteorological Magazine* commencing with volume 54 are available on microfilm from University Microfilms International, 18 Bedford Row, London WC1R 4EJ. Information on microfiche issues is available from Kraus Microfiche, Rte 100, Milwood, NY 10546, USA.

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A Mediterranean squall

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Foreword by R.M.Blackall

I took a holiday in Calvi, Corsica, in 1992. One afternoon the ⅜ Sc drifting over on the moderate SW wind started to become more extensive and they passed by increasingly quickly as the pressure fell. At about 2130 local time there was a sudden violent squall and torrential rain that lasted for about five minutes. On my return to England I wrote to Météo-France asking if they could tell me what had happened. What follows is a précis translation of the fat report that eventually arrived: it is obvious that the forecasts from Bastia (see page 233) were not listened to by some of the locals in Calvi who had assured me there were no storms about.

I have provided an outline map of the island showing places named in the text, but an atlas should be referred to to understand the steep topography that constrains the wind direction. An example is that the 3.5 km between Calvi and Ste. Catherine airport was associated with a change of almost 90° in wind direction on 1 September.

Preface

The meteorology of the Mediterranean is characterized by two dangerous traits, violence and rapid development, of which aviators, mariners and businesses must be wary, especially during sensitive operations such has heavy lifts and oil-rig work. The natives are accustomed to the climate and notice the signs and portents, but they are not always clear enough to permit a confident forecast of developments. Météo-France tries to give the maximum notice of dangerous developments at mesoscale and synoptic scale; unfortunately it is not yet possible to do this at the small scale (e.g. waterspouts), but happily these are rare.

The situation on 31 August to 1 September 1992

At 500 hPa (Fig. 1)

A broad trough lay over the west coast of Europe at 0000 UTC on the 31st with the greatest curvature and strongest flow NNW of Coruña. The vorticity maximum (Fig. 2) moved east very close to the Mediterranean coast at 0000 UTC on the 1st bringing a strong vorticity gradient between Corsica and the continent. Cold advection was strong over the continent but weak over Corsica. The geopotential and thermal troughs sharpened during the 31st, emphasizing their passage.

At 850 hPa (Fig. 3)

A deep low was centred north of Scotland at 0000 UTC on the 31st associated with a mass of cold air, with a temperature of 0 °C over Northern Ireland. The thermal and geopotential gradients were strongest near Spain. The trough sharpened and the geopotential gradient increased with the advection of cold air. The difference was marked with the warm air at 12–14 °C and the cold at 4–6 °C. The approach of the system strengthened the SW'ly current from Spain to the Mediterranean. The effect of the Alps was to create a low over the north of Italy (Po Valley) further increasing the WSW'ly flow over the north of the Mediterranean basin (see the chart for 0000 UTC on the lst). The advection of cold air at low levels reached Corsica during the night of the 31st/1st with a temperature fall of 6 °C.

At the surface (Fig. 5)

The cold front marking the boundary of the air masses was active, the temperature contrast was obviously

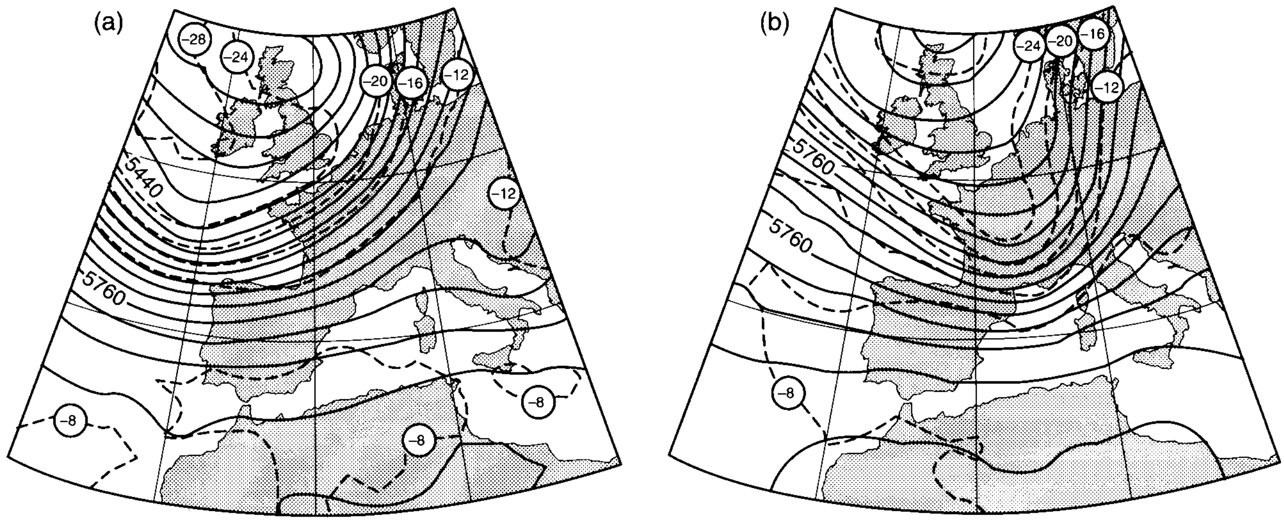


Figure 1. Charts of 500 hPa geopotential at intervals of 5 m and isotherms at intervals of 4 °C. (a) 31 August 1992 at 0000 UTC, (b) 1 September 1992 at 0000 UTC.

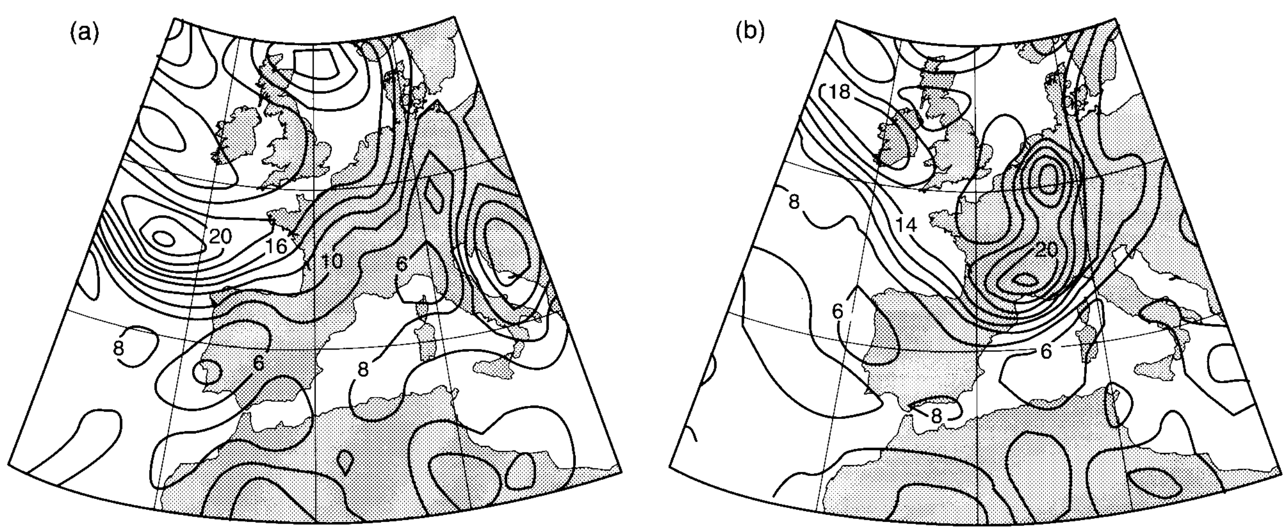


Figure 2. Charts absolute vorticity at 500 hPa at intervals of 10^{-4} s^{-1}. (a) 31 August 1992 at 0000 UTC, (b) 1 September 1992 at 0000 UTC.

important. Behind the front one can see strong subsidence on the 800 hPa vertical velocity chart (Fig. 4) for the 1st at 0000 UTC: it clearly marks the advection of cold air to low levels where it produced a well defined surface front.

Summary of these analyses

The burst of cold air, very marked at low levels, caused a significant strengthening of the gradient at all levels. This resulted in the acceleration of the low-level south-westerly flow. It was also accentuated by the creation of a dynamic trough to the east of the Alps. The strengthening of the south-westerly flow affected the whole of the western side of Corsica (see the observations at Calvi). After the passage of the cold front, the thermal wind at low levels and strong subsidence combined to strengthen the wind as it veered westerly. The northern part of the island was most strongly affected by this westerly flow (see the observations from L'Ile Rousse and Cap Corse). Despite the absence of marked cold advection at height, the passage of the cold front over Corsica produced the conditions for storm development. Essentially these are — a strong contrast in air temperature at low levels (see above) — the presence of warm sea at this season which increased the instability and supplied extra humidity — and cyclonic curvature at all levels associated with the geopotential gradient. (*Editor's comment: note also the abrupt change from weak warm advection to strong cold advection on the 850 hPa trough axis.*)

Remarks

This type of situation is classic in the Mediterranean towards the end of Summer and the beginning of Autumn when, in the absence of important cold advection aloft, low-level phenomena prevail. The

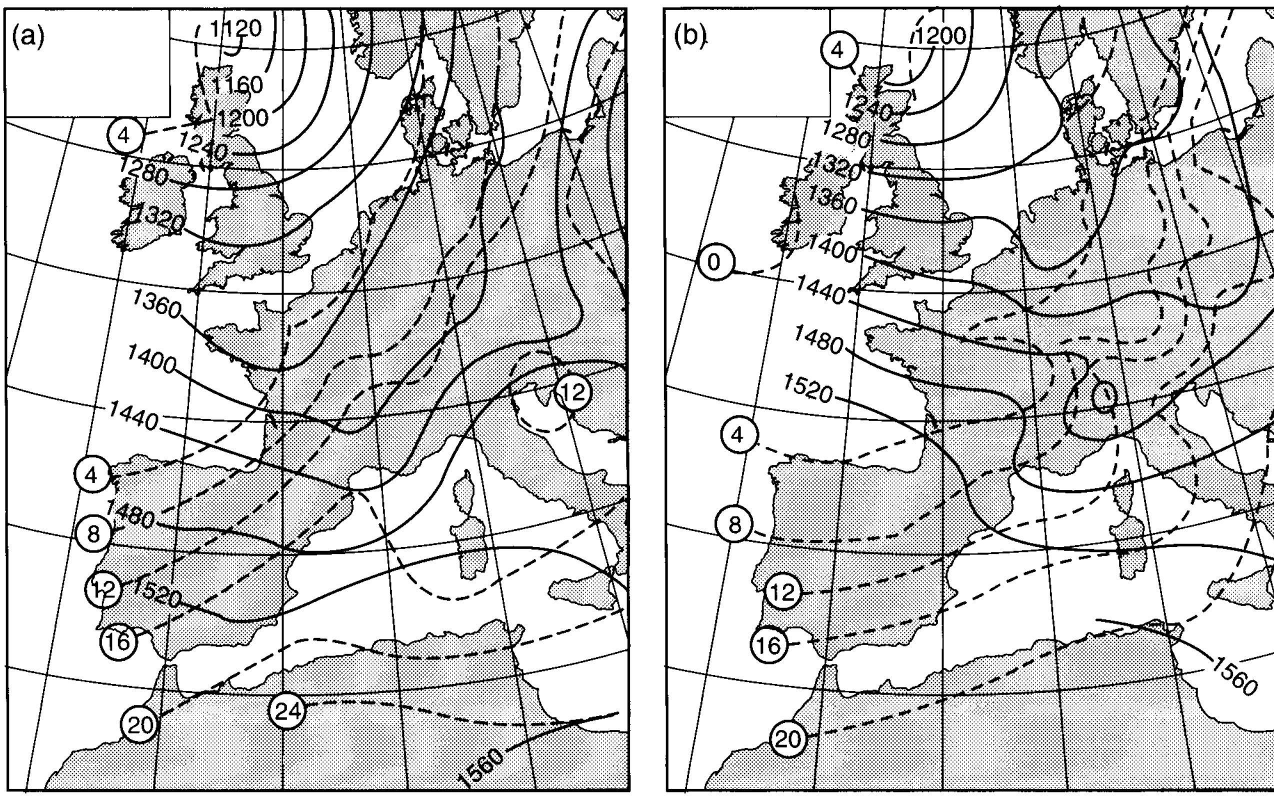


Figure 3. Charts for 850 hPa geopotential at intervals of 40 m and isotherms at intervals of 4 °C. (a) 31 August 1992 at 0000 UTC, (b) 1 September 1992 at 0000 UTC.

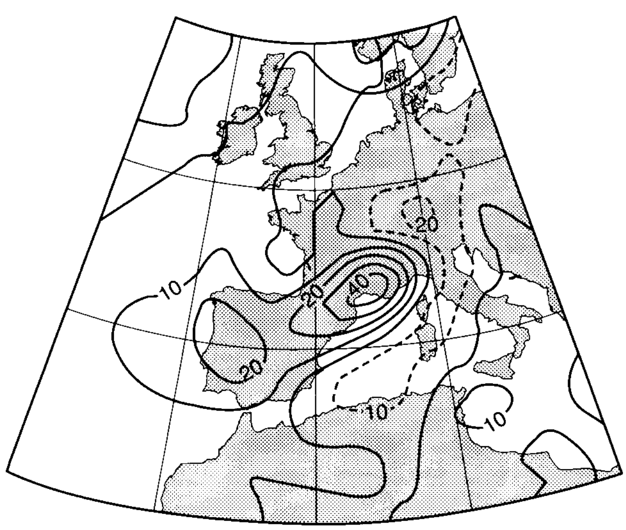


Figure 4. Vertical velocity at 800 hPa on 1 September 1992 at 0000 UTC.

absence of a strong thermal contrast aloft means the absence of thick cloud layers, except near the ground. There may be strong vertical developments with storms, violent at times, and accompanied by hail and very strong squalls. These storms can cause serious damage. Sometimes there will be cold advection aloft and this will be associated with a major reinforcement of the upper trough over the Mediterranean, leading to a marked increase in the intensity of phenomena, especially storm activity.

Study of the surface pressure field at mesoscale

A study of the pressure field at fine scale shows the local effects of relief on the wind flow. Corsica (Fig. 6) has a chain of mountains lined more or less north–south with many summits above 2000 m, the highest point, Monte Cinto, being at 2706 m. The maximum width of the island, east–west, is scarcely 80 km. The mountain chain plays a very important role in deflecting the flow of air at low levels, especially flows with a strong easterly or westerly component. In the present case the flow at low levels is well established from mainly the south-westerly direction, then veering westerly after the passage of a front. Fig. 7 shows local analyses of the pressure field at 2 hPa intervals both before the arrival of the cold air at low level (31st at 2100 UTC) and during (the 1st at 0300 UTC).

At 2100 UTC on 31 August

The formation of an orographic trough to the south-east of Corsica in the south-westerly flow is apparent; there is slack pressure gradient to the north and strong cyclonic flow south of Bastia. This cyclonic flow limits the increase in wind speed over the south-east of the island. The region around Bastia and the areas further north on the eastern side of the island are in an area of weak pressure gradient that produces a light wind. In contrast the gradient on the western side of the island is reinforced by the ridging over the south-west. Thus the south-west and north-west of the island are exposed to

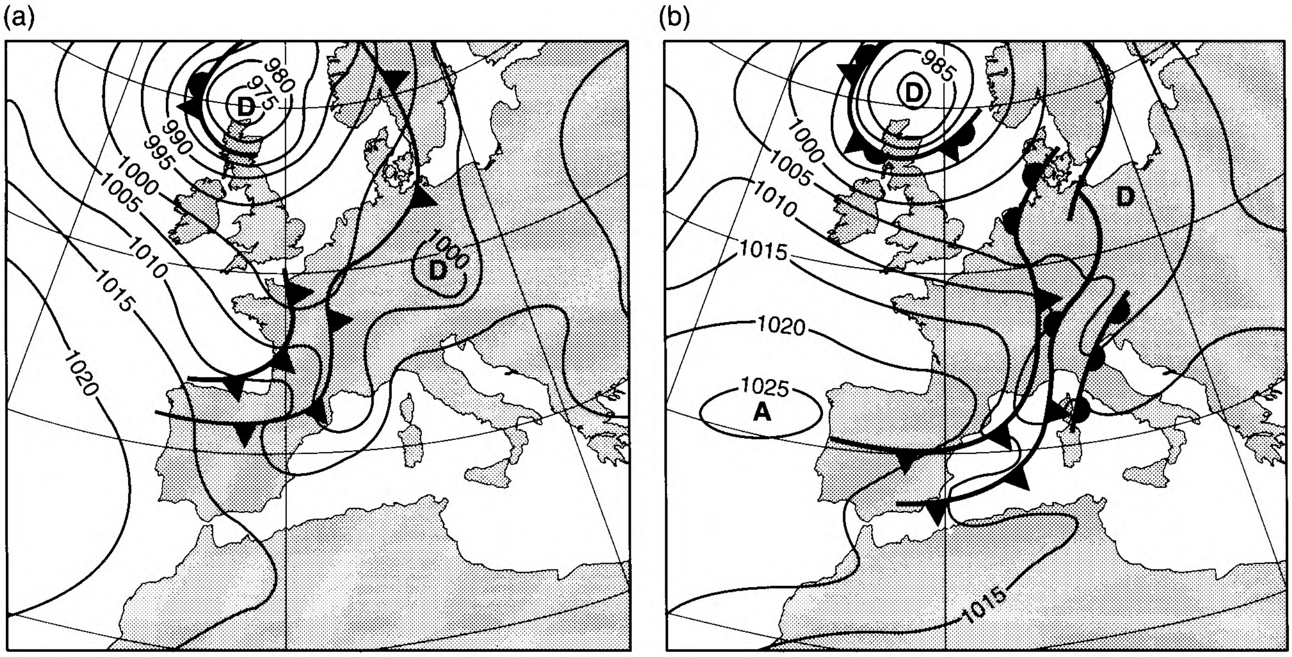


Figure 5. Surface analyses by Météo-France (with observations removed for greater clarity). Note that isobars are at intervals of 5 hPa; (a) 31 August 1992 at 0000 UTC, (b) 1 September 1992 at 0000 UTC.

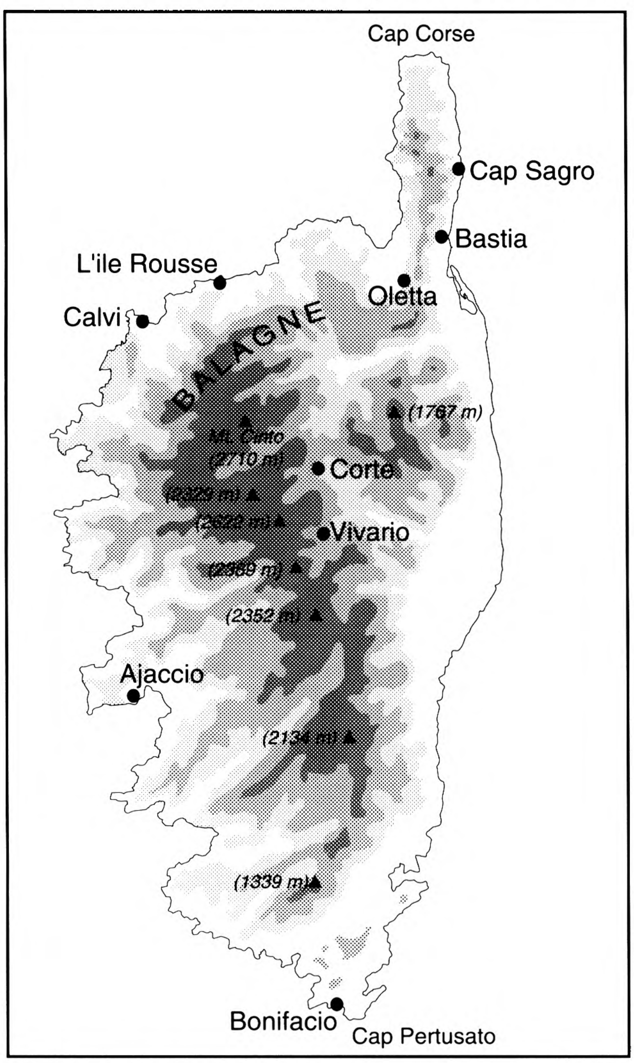


Figure 6. Sketch map of Corsica showing the locations of places mentioned in the text.

strong winds with a south-west component. The Gulf of Ajaccio is another favoured location for acceleration of the wind due to its orientation towards the south-west. The same is true at Cape Pertusato because of the funnelling through the Strait of Bonifacio between Corsica and Sardinia. The strongest winds were observed on the north-west of the island.

At 0100 UTC on 1 September

The cold air arrives. This leads to a rise in pressure, at least over the west of the island and the rise is most marked in the north-west where the pressure was lowest earlier. As well as a strong gradient the curvature has become more anticyclonic. With the turning of the gradient towards the west with the arrival of the cold air there is also a dynamic compression against the relief. The advection of cold air at low levels favours the strengthening wind and is accentuated by the curvature of the field anticyclonically. It is in this regime that we see the strongest winds. The dynamic minimum far south on the 2100 UTC chart tends to move towards the north. The most violent winds touch the north-west of the island around Cap Corse (26 m s^{-1}). We also observe strong winds in the extreme south of the island (Cape Pertusato); these are probably very local due to the configuration of the Strait of Bonifacio. The south-west of Corsica is subject to lighter winds (see Ajaccio).

The forecast

The strengthening of the wind was forecast by the services of Météo-France. A bulletin broadcast by the Centre Départmental de la Météorologie de Bastia (CDM Bastia) on 30 and 31 August is given below. The CDM at Toulon, responsible for general marine forecasts, broadcast special meteorological bulletins (BMS) to

Observations, Calvi — 31 August

Wind direction in degrees, true, speed in knots: cloud amount in oktas, height in feet

Time	Mean wind	Max	Cloud		
0900	200/11	29	1 Sc 4300	1 Ac 10 000	4 Ci 26 000
1000	240/20	33	1 Sc 4300	1 Ac 10 000	4 Ci 26 000
1100	230/17	33	1 Sc 4600	3 Ci 26 000	
1200	230/22	40	1 Sc 4600	1 Sc 6000	2 Ci 26 000
1300	230/17	35	1 Sc 4600	1 Sc 6000	5 Ci 26 000
1400	230/20	38	1 Sc 4600	1 Sc 6000	3 Ci 26 000
1500	230/22	40	1 Sc 4600	1 Sc 6000	
1600	SW/17–22 gusty		3 Sc 4600*		
1700	SW/17–22 gusty		5 Sc 4600*		
1725	230/29	42	Heavy rain shower*		

1800 to 2300 SW/17–22 gusty except around 2100 and 2300 when speeds were only 14 and 12 kn respectively. There were further showers and storms during the course of the night.

On 1 September the maximum 10-minute wind speed was 230° 29 kn at 0834 UTC. Maximum gust 200° 44 kn at 0321 UTC.

*Observed by the Editor.

Cap Corse	
1200	060/06
1500	080/04
1800	280/06
2100	260/15
0000	280/49
0300	260/58
0600	280/62
0900	280/49
1200	280/40

L'Ile-Rousse	
1200	280/13
1500	220/13
1800	040/13
2100	200/33
0000	220/26
0300	220/33
0600	220/40
0900	220/40
1200	240/33

Summary of extreme winds (kn) on 1 September

Station	Highest mean	Highest gust
Cap Corse	280/73 0450	280/91 0510
Cap Sagro	280/49 0405	320/85 0945
Ile Rousse	220/51 0320	220/67 0350
Vivario	240/33 0130	280/62 0430
Corte	310/22 0130	280/44 0730
Oletta	250/24 0900#	240/42 1100#

in hour ending at

sailors and yachtsmen on 31 August at 0000 UTC and at 1200 UTC; this is given as well. These forecasts were made on the advice and consultation with the Centre Météorological Interregional de la Region Sud-Est (CMERSE) at Marignane (transferred to Bouches-du-Rhône, Aix-en-Provence, in January 1993) and the Service Central d'Exploitation de la Météorologie (SCEM) situated in Toulouse. The CDM of Bastia broadcast their forecast widely to the public by telephone answering services, broadcast bulletins to the media, press, TV, etc. and also to the security services (firefighters etc.).

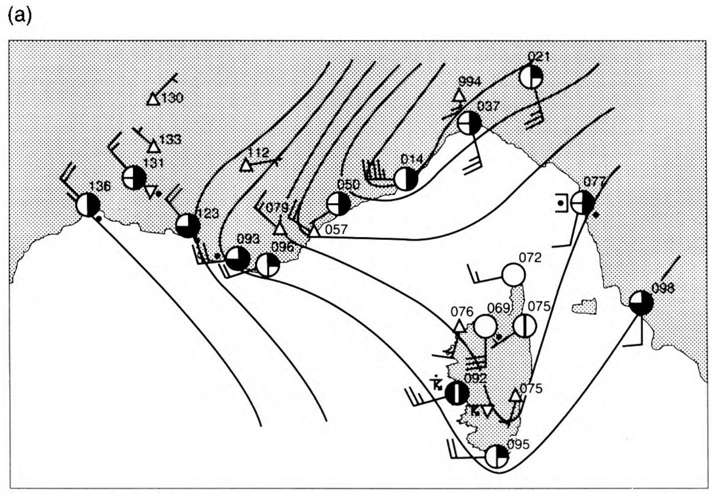
Detailed weather forecasts issued by the Centre Bastia/Poretta

Night of Monday 31 August–Tuesday 1 September. Generally cloudy, becoming rainy during the course of the night. A more stormy spell is feared during the middle of the night. The storms may be violent but of short duration. They will be accompanied by hail, thunder and violent gusts. At the beginning of the night the wind will blow from the south-east in the east at 40–50 km h^{-1}, from the south-west in the west at 50–60 km h^{-1}. NB, a sudden, violent veer of the winds to the west is expected in the second half of the night. The zones most exposed in the first place are the Balagne and Cap Corse, and also cols and peaks in the interior.

Daytime Tuesday 1 September. Generally there will be little cloud but some instability cloud may develop inland over the peaks. The westerly wind will blow violently at around 70–90 km h^{-1}. with gusts perhaps reaching 130–140 km h^{-1}. The most exposed places will continue to be the west, Cap Corse, cols and peaks. Gusts are equally likely to sweep through the Bastia region and the mouths of certain valleys (Golo, Fiumalto, Tavignano, etc.). Maximum temperatures will be around 28–30°, in the east, due to the effect of föhn, they could rise to about 33–35°. The sea will be very rough in the west, rather rough to rough in the east.

Forecast for Wednesday 2 September. Continuing sunny. Winds becoming lighter, the winds will continue to be moderate over the west and Cap Corse to 50–60 km h^{-1} and gradually veer more north-westerly.

Forecast for Thursday 3 September. Hot and sunny. Wind mainly light to moderate NE. Maximum temperature 28–30°.



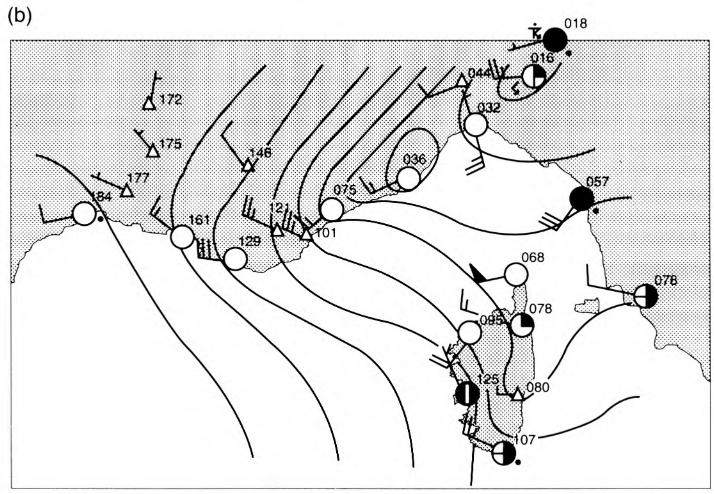


Figure 7. Simplified surface analyses using restricted plotted data with isobars at intervals of 2 hPa. (a) 31 August 1992 at 2100 UTC, (b) 1 September 1992 at 0300 UTC.

WHFX40 LFML 311200 COR
BMS MARINE DOMAINE DE LA COTE
ORIGINE METEO FRANCE TOULON NR 066
CE LUNDI 31 AOUT 1992 A 1300 UTC
DEBUT DE VALIDITE: LUNDI 31 AOUT 1992 A 1300 UTC.
FIN DE VALIDITE: MARDI 1ER SEPTEMBRE A 1300 UTC.

-ROUSSILLON LANGUEDOC:
VENT DE NORD-OUEST FRAICHISSANT FORCE 8 34/40 NOEUDS
LOCALEMENT FORCE 9 41/47 NOEUDS VERS BEAR.

-OUEST PROVENCE:
VENT DE SUD-EST FORCE 8 34/40 NOEUDS LOCALEMENT FORCE 9 41/47 NOEUDS.
VENT S'ORENTANT AU NORD-OUEST DANS LA SOIREE DU 31 AOUT.

-EST PROVENCE:
VENT DE SUD-EST ATTEIGNANT PAR ENDROITS FORCE 8 34/40 NOEUDS S'ORIENTANT OUEST DANS LA NUIT DU 31 AOUT AU 1ER SEPTEMBRE.

-OUEST CORSE LOCALEMENT EST CORSE:
VENT S'ORIENTANT OUEST A SUD-OUEST FORCE 8 34/40 NOEUDS DANS LA NUIT DU 31 AOUT AU 1ER SEPTEMBRE ET FRAICHISSANT LOCALEMENT FORCE 9 41/47 NOEUDS VERS BALAGNE ET CAP CORSE.=

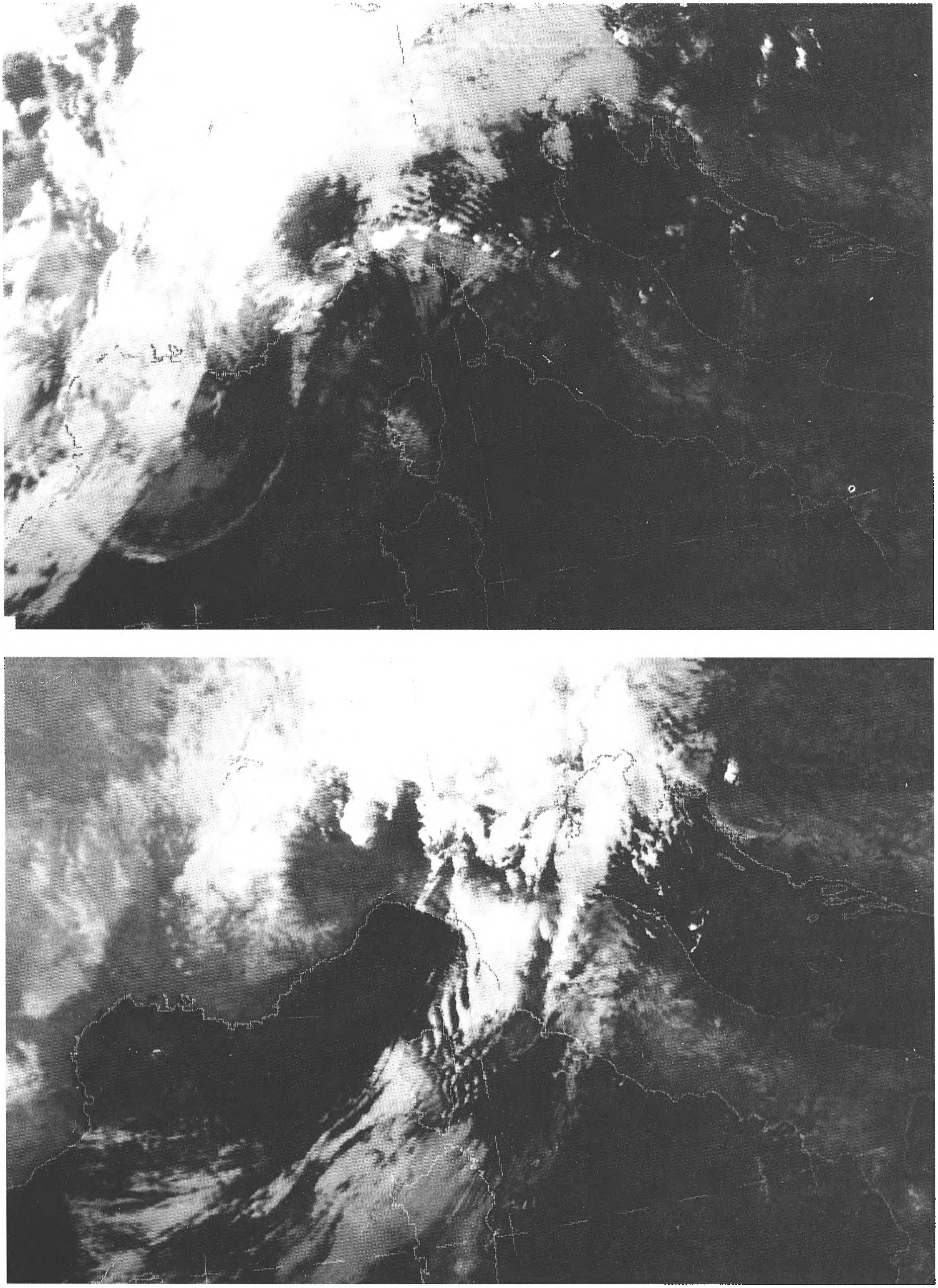


Figure 8. NOAA-11 IR images captured by Météo-France. Top, 31 August 1992 at 1745 showing cold air bursting into the Mediterranean basin. Bottom, 1 September 1992 at 0237 showing wave clouds downwind of Corsica and cumulonimbi over northern Italy.

Techniques used

The basic elements of the forecast are surface and upper-air synoptic charts and observations and forecasts. The output of the CEP (European) and ARPEGE (French) numerical models provide the main information about the medium-scale fields of humidity, the flow at various levels, absolute vorticity at 500 hPa (ARPEGE) and vertical velocities at 800 hPa (ARPEGE). The fields of vorticity and vertical motion are analyses and forecasts. We also have vital supplementary output for France from the fine-mesh model (PERIDOT) which is coupled to the ARPEGE model. These products are available in steps of six hours, up to 48 hours in advance.

Because of the broken relief this numerical model is best for the area and provides forecasts of precipitation, θ_w, wind and pressure at the surface, isotachs at 500 m, wind and temperature at 850 hPa, temperature at the surface and humidity at 700 hPa.

Low-level phenomena play an important role in the meteorology of the Mediterranean and we place much emphasis on the analysis and study of changes at low level especially those of wind (speed, convergence and divergence), vertical motion an θ_w. The most important information is available over the METEOTEL VDU system which is interactive. It provides charts and outputs from the PERIDOT model, satellite data (water vapour, infrared with cloud type and visible imagery), radar information both local and composite, sea temperature from high-resolution infrared satellite pictures and a display of lightning strikes updated every 15 minutes from the METEORAGE system. It is possible to run animations of images for satellite, radar and PERIDOT fields and to superimpose certain images; for example, a satellite picture and lightning, which is the best way of identifying probable storm cells. On the METEOTEL system it is possible to get the 700 hPa wind forecasts from PERIDOT and, using animation with the main cloud masses in satellite pictures to produce a forecast of cloud development. It is also possible to call up forecast cloudiness, certain vertical cross-sections and forecast radio soundings. METEOTEL is continually updated as new information become available.

A new version of METEOTEL, METEOTEL PC is being developed. It retains the features of the previous METEOTEL but has the advantage of a high capacity hard-disk store. This will permit animations of many more images as well as archiving a large number of fields. A fuller integration is envisaged with better imagery, summaries of observations and model forecast fields (the SYNERGIE system). Technical advances should permit zooming to a small area without loss of definition and the overlaying of fields of ones choice in different windows; all on a high-definition screen whereas the METEOTEL system has a simple TV monitor. In the new system too, updating of information will be continuous.

It should be noted that the south-east of France has a very dense network of automatic stations which allows events (mainly temperature, wind and precipitation) to be followed closely. They are an essential aid to forest-fire fighters and report several times a day, but may be interrogated at any time or continuously monitored (at one-hour intervals) if the situation requires it.

The development of the dissemination of forecasts

The 'forecaster's product' will change, thanks to the SYMPOSIUM system, in the long run the forecaster will only produce screen displays while many t .sks connected with the drafting of bulletins will disappear. The system will function in two steps, first it will load forecast information, and then automatically extract and display it according to the needs of the users outside Météo-France.

The forecasters' area will be divided into elementary zones of between a few hundred to a few thousand square kilometres and each will be treated as a single climatic region. The forecaster will load the database after each synoptic hour in the form of a chart for each parameter (or perhaps two or three), e.g. temperature, wind, cloudiness, precipitation. The value of a parameter is decided for each elementary area, and it is planned to use output from ARPEGE to initialize the database. The forecaster will then be able to control, or perhaps modify, the automatic forecast. This output can then be automatically be put into form of forecast wanted by the users (grids of data, frames of information; linguists are working at Météo-France on the automatic production of text).

Structure of the forecast service of Météo-France

The responsibility for analyses and their interpretation is pyramidal, the apex is the Service Central d'Exploitation de la Météorologie (SCEM), at Toulouse. Here at the hub of the information network, lies the computing centre permitting the most powerful techniques. SCEM provides the fundamental analyses at all levels, general advice for internal use at MétéoFrance on the evolution of fields and their interpretation, taking into account the divergences between forecasts from different models and the experience gained from their use.

SCEM has the responsibility to provide special national safety warnings of dangerous meteorological events, and provides 'ALARME' bulletins to the Sécurité Civile du Ministère de l'Interieur or special CMS bulletins to the media. In this sense, SCEM is the meteorological guardian on the national scale. There is also a supervisory and forecast role for some locations outside France; the provision of special bulletins for Atlantic shipping and protection of aviation to some international destinations such as the Caribbean and Africa. It also supports meteorological stations at airfields with international western European traffic, providing TEMSI charts of winds and temperatures for various flight levels.

A new way of providing information to airlines is being developed; this is a microcomputer with VDU and printer, connecting an airline HQ to a database fed by SCEM (the AEROMET system). This allows the companies to get on demand the information they want in form of a conventional chart. The system complements the système Interrogations Réponses Aéronautiques (IRA) which for many years has allowed airlines to obtain TAF, METAR and SIGMET data using just a simple printer connected to our database via a computer terminal.

The CDM

At the bottom of the pyramid are the forecasters of the Centres Départementaux de la Météorologie (CDM). Their role is to be the interface between Météo-France and its customers (the public, businesses, authorities). They provide the forecasts tailored to the requirements of each. The work entails elaborating on a fine-mesh forecast for a restricted area, the same as or smaller than a département. To provide a forecast on this scale naturally relies on a prior study of synoptic fields, aided by the advisories from SCEM and from the Centre Régional (see below). The CDM forecaster does an analysis at small scale taking into account climatology, topography, forestry and water features to refine the forecast.

The CDM has a responsibility for the safety of its département corresponding to the national responsibility of Météo-France. Equally it assists with forecasts with forecasts for any coastal waters in its département.

The CMIR

In the middle of the pyramid, between the SCEM and the CDM, come the seven Centres Météorologiques Interrégionaux (CMIR). Their role is essentially that of an interface, partly technical between SCEM and the CDM (distributing technical advice affecting their region and monitoring synoptic developments) and partly between Météo-France and official organizations who want information or assistance at mesoscale (an area greater than a département) or at interregional scale. They are also the logical contact for the public utilities, the Centres de Coordination Interrégionaux de la Sécurité Civile, TV networks and regional radio services.

In addition, some CDM close at night, weekends and holidays and then their responsibilities are transferred to the CMIR.

Le CMIR for the Southeast Region covers 13 départements from the Spanish frontier to the Italian, the southern Alps, Corsica and the Cevennes.

Conclusion

This study has allowed us to show several aspects of Météo-France with an illustration of a particular meteorological event in the Mediterranean. It shows the essential — fundamental — role of the forecasters at CDM for the quality of the forecasts.

The local climatologies show strong contrasts across our region, from Corsica to the Alps, the Côte d'Azur to the Cevennes, the Pyrenees to Provence. The forecasters at the CDM are able to master the understanding of local effects of wind regimes, advection of air masses, etc. in way which regional forecasters, in charge of a much larger area, and even more the SCEM, cannot hope to match.

Acknowledgements

The author thanks his colleagues, Mme Roulle and Messieurs Rivrain, Bruno, Boussious and Rambaud for their help in preparing the paper. The editor thanks the European Centre for Medium-range Weather Forecasts for their corrections to his sometimes mistaken translations.

PS. As this article was being prepared for publication I received a copy of La Météorologie, *series 8, No. 6, June 1994. Its main paper is a case-study of torrential rain over Corsica in Autumn 1993. Although in French it should be easy enough to follow given some knowledge of that language and a dictionary. There will be another article in issue No. 7. — Ed.*

551.466.2

Modelling ocean waves

M.W. Holt
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This is an edited transcript of a talk given at the Meteorological Office on 16 December 1992. A more formal and detailed paper describing the assimilation of ERS-1 data will be published in *Journal of Atmospheric and Oceanic Technology* Vol. 11, No. 5 (October 1994).

1. Introduction

I would like to start by acknowledging that although I am giving this talk there are actually three people involved in wave modelling in the Meteorological Office; Steve Foreman and Sophie Kelsall currently in Forecasting Research have had a hand in some of the work to presented. In earlier days Rachel Stratton and Rod Bromley and many other people also had quite a bit of input to some of the work actually presented here.

I thought I would start by putting into context where the wave model sits; the links we have with the other Divisions in different parts of the Office. During the course of the talk you will hopefully pick up how the wave model could be of use to the research side. On the other hand there are obvious commercial uses of the wave model output, so we will look at that later. I will start off with a review of recent progress in the wave model; in the middle section I will talk a bit about the instruments on ERS-1 of interest to the wave model, and the assimilation of satellite data (we have had over a year now to look at, and decide what to do with them). At the end I will present a short look at the idea of coupling the wave model to the atmosphere model, and getting feedback, particularly the surface stress over the ocean is wave-height dependent. And then finally some interesting plans where we think we might be going with the wave model over the next year or two.

2. Motivation

But before I get onto that I would like to give you some idea why we actually have a wave model, why we carry out wave modelling in the Met. Office and then a little idea of how a wave model actually works.

So why do we do wave modelling? Well there are really two main reasons; first is the research side and second it is commercially valuable, people actually want to buy forecasts, so we will have a look at that first. We forecast wave heights, the sea state and the wave period as well. In December 1991 a forecaster was out in the North Sea for some six weeks until a weather window could be forecast for a big job. Finally there came a spell with very low waves, but the operation was held up by swell of a particular resonant period for the lifting barge, so they could not actually do the work. Eventually a weather window was successfully forecast and the job was done. This shows it is not always the high waves that are important. Recently we have been providing the full forecast wave energy spectrum for similar operations. That is the offshore work, oil exploration, particularly in the North Sea, but it is becoming increasingly a global market. The Ship Routeing Bench in CFO looks after ships going all over the oceans, hoping to avoid the worst of the waves and so saving voyage time, and possible damage to the ship. Those two are the main commercial applications of the wave model output.

On the research side we see shall that the wave model is a very sensitive indicator of performance of the atmosphere models, I will be talking about the interaction of waves with the atmosphere. Of course the waves are at the air–sea interface, and there are obviously important details here for climate work where you need to get the fluxes of surface stress and various other quantities correct.

3. The model

So how does a numerical wave model work? First, we are not modelling individual waves. What we model is the wave energy spectrum, which is a statistical description of average sea state. If we think of the sea-state field at any particular time and place, we probably have a collection of waves of different frequencies, and travelling in different directions. Some will be swell, some will be wind–sea and directly related to the local wind. So we take that and represent the wave spectrum in terms of the energy level of the waves of a particular frequency, travelling in a particular direction. We come up with a polar plot like Fig. 1, for example, where wave frequency increases with radius. When we have represented the wave energy spectrum we evolve it according to Equation (1).

$$dE/dt + C_g.\Delta E = S_{in} + S_{diss} + S_{nl}. \qquad (1)$$

Equation (1) is the transfer equation for the evolution of the wave spectrum at each grid point. On the left-hand side we have the local rate of change and advection by the group velocity (that is frequency dependent — linear gravity waves are on the surface of the deep water, so group velocity depends on wave frequency). On the right-hand side we have various source terms. S_{in} is the

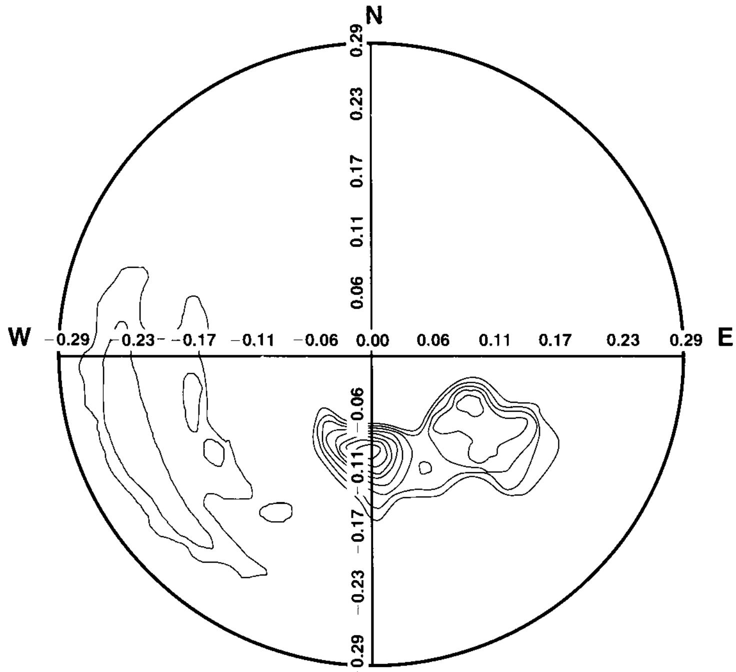

Figure 1. An example of a two-dimensional wave spectrum.

input term of energy from the wind stress to the waves; S_{diss} is the dissipation of wave energy, representing energy loss due to breaking waves and white-capping; S_{nl} is a non-linear transfer term which acts to represent wave to wave interactions and to transfer wave energy between waves of different frequencies.

Having decided what we want to do with the wave model we need to choose our wind data. As I mentioned earlier, it is very important to get the best possible wind data so we can make the best possible forecast of the waves: and we have a choice of using 10-metre winds, or the actual surface stress, or, as in our case, we use the winds from the lowest level of the atmosphere model.

Our global wave model has the same resolution as the atmosphere model and the grid coincides with the wind-data positions; we take the wind values hourly. These are considerations when you initially set up your wave model. You discretize the energy spectrum, and you have to choose the number of frequency components and choose how you want to allocate them; you have to choose the number of direction components as well. In our particular model we have 16 direction components giving an angular resolution of 22½°. The input term (S_{in}) is fairly standard, there is a common formulation used by most of the wave models in existence that is based on observations of waves. The dissipation term is a fairly standard formulation used in most of the wave models that are around and is based on an energy balance hypothesis. Where you can have a difference is in the treatment of the non-linear terms. This leads to the basic differences between one wave model and another. Our particular wave model, a so-called second generation model, parametrizes this term by forcing the growing wind–sea energy to take a particular spectral shape. We use a look up table, but it is a parametrization based on observations. As well as all that you have to choose your advection scheme and how you are going to do the time-stepping, and do you want deep or shallow water?

The next stage is to approximate these non-linear transfers and try to include some of the physics of what is actually going on. This approach is taken by the WAM (WAve Model) at the European Centre for Medium-range Weather Forecasts (ECMWF) and is called a third-generation model. The reason you have to approximate this is because the full calculation is extremely expensive in computer time, and has only been done for a single-point experimental model. The calculation can be done, but it is not practical to do so in a global model. The differences between the two simulations can become apparent particularly if you have rapidly turning wind; you can also continue the transfer of energy down to lower frequencies after the wind has fallen. The good news is that these effects, particularly the turning wind, are parametrized in our second generation model. The strategy that we have adopted for our research over the last two years or so has been, as far as we can, to concentrate on those aspects of the source terms of the formulation that are independent of whether your model is second or third generation and try to follow the work from there. At the same time we need to understand what differences there between these two approaches, because the question will come up soon when we have the computer power. Do we actually want to go towards the third-generation model, can we afford it? In the meantime we shall be using anything we discover to spin off improvements in our second-generation model.

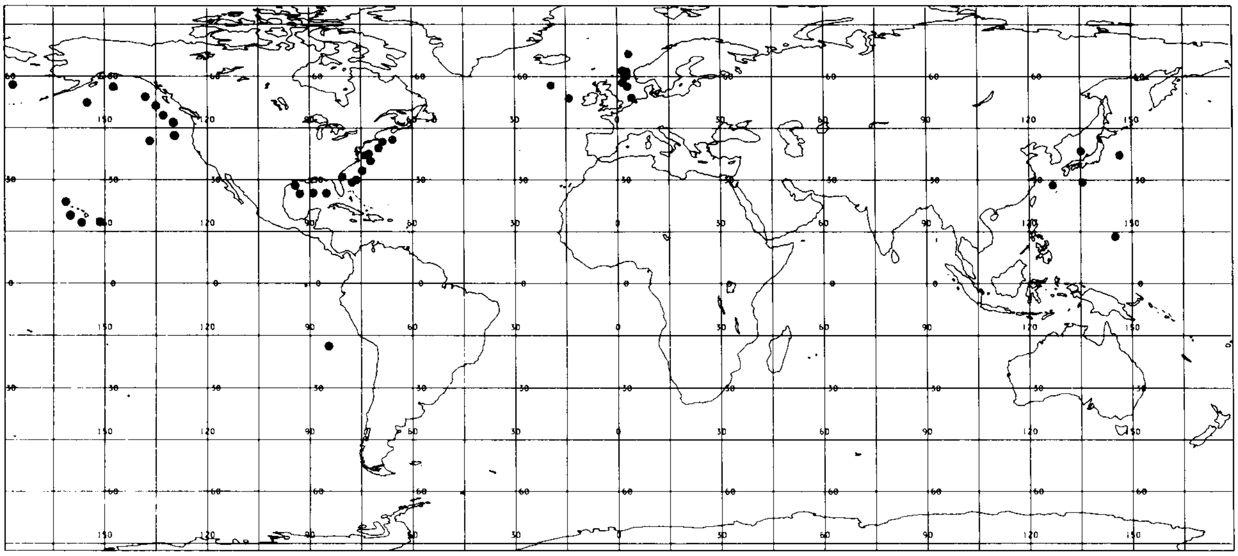

Figure 2. Locations of wave buoys and platforms.

Certainly there is a question facing us in the next couple of years, as to whether we continue with our current approach, or whether we take up the WAM.

In the global wave model we include a great circle propagation of swell. We take surface winds from the Global Model or indeed ECMWF model. The waves represented in our model range from the longest swell period of 25 seconds, which is a wavelength of almost 1 km, to the highest frequency, which is 3 seconds, waves which are 15 m long. In the Global Model, if we include coastal points as well, there are 37 322 data points on the grid and at each of these we have 13 frequencies and 16 directions. Operationally there is also the European model (which takes its wind from the Limited Area Model atmosphere) and covers the North Sea, the Mediterranean and the Continental Shelf areas; this version of the model includes shallow water effects. Before the ERS-1 satellite came along, we were not at all well off for observations. Fig. 2 shows there are a few moored buoys and many platforms in the North Sea, but there is only one buoy in the southern hemisphere. The majority are clustered on the continental shelf or close to it, and near to the USA. This has to be remembered when we look at verification figures.

4. Model intercomparison

We learned a few things from the intercomparison between our model and the ECMWF's WAM that led us to do some work to recalibrate our model. The trial was originally a four-way comparison, using Met. Office winds, ECMWF winds, our wave model and their wave model. We did it on the global grid at 3° resolution, which is what the ECMWF use. We used a direction resolution of 15° and when we did the verification we looked at the data from the model grid-point nearest to the buoy position. We ran the models for the month of November 1988, which happened to be a case already studied with detailed observations available. Initially we tried rescaling the different heights of the winds so that we ran the ECMWF model with our model's 10-metre winds and vice versa. We very quickly found out that that was not a good idea, instead we looked at runs of our model with our winds, and the ECMWF model with their winds. But the idea of the intercomparison was basically to have as much as possible in common, and for any differences to come from the model formulation rather than differences in resolution. Of course it is a further benefit to our model to be able to run at high resolution. Because of the formulation of the WAM, it actually has twice as many frequencies as ours because it has to physically resolve the transfer of wave energy. We looked at some verification figures and looked at the spectral output and all sorts of comparisons, and we eventually decided where some of the problems lay.

One of the things we found was that our model was lacking in swell in the Pacific and in the tropical areas. A time-series of wave heights from our model, WAM and one of the buoys in the central Pacific near Hawaii, showed that wave heights in both models were lower than the observed, but that our model is a bit lower than the WAM. There is also a diurnal variation in the observed wave heights and we have managed to represent this even if we do not get the height quite right; the evolution of the WAM is a lot smoother, probably because they use their winds at 6-hour intervals. We quickly found out that although the wave height was low where there was swell, it was not that bad when we also looked at cases in the north-west Atlantic. Off the coast of the USA there is a slightly different sea state regime; the conditions are dominated more by the developing depressions, and you have wave growth limited by fetch and by how long the wind is blowing, so you have far more waves which will grow into equilibrium with the local winds. We find that under these conditions both models do fairly well; if the corresponding model of the atmosphere gets the storms right, then the wave model will get the waves right.

We also looked in detail at a case of turning winds and found that in fact the parametrization in our model was doing a good job, which was useful confirmation. The conclusions from the intercomparison were that behaviour in both models was fairly similar when it came to looking at wind–sea; in our model the parametrization of turning winds was effective, but we had difficulties and problems in the handling of swell. In the Pacific, the wave heights of both models were noticeably lower than observed. When we looked in detail at the spectrum, we found problems with an energy gap in the middle of the frequency range. Our model was lacking in energy there, but we were OK at the lower frequencies. This led to various changes being tested and we finally finished in September 1992 with a set of revisions. We changed the look-up table for the spectral shape (which is the non-linear transfer parametrization), we reduced the dissipation coefficient (which altered the energy balance at equilibrium) and we made a change to the section of code where we had identified we were losing swell in falling winds.

In Fig. 3 the symbols show you where our model frequencies actually lie. At one end is the energy from long waves of low frequency (that will be swell energy going in whatever direction); at the other end, of a higher frequency (that is shorter wavelength) are waves which are closely in equilibrium with the actual wind speeds. The figure summarizes the intercomparison showing what we did and what the WAM was doing at the same time. The solid line is the observed energy distribution and the line of short dashes (joining triangles) shows you what our previous model was doing before we amended it. They do not match well and the difference corresponds to 2–3 metres of wave height. The dotted line shows the energy from the final revised model and it shows that the revision has gone some way to reduce the bias, but there is still room for improvement. By comparison the dashed line shows the spectrum coming from the WAM — there is work to do with that as well.

We looked at model verification at the buoy sites, we looked in detail at some of the spectra, but what was useful in retrospect was to look globally at where the improvement had come.

In terms of wave height, the difference between the revised model and our previous wave model shows a quite decent improvement in the model performance. This is particularly so in the central Pacific tropical areas where the revised model gives waves 60–80 cm higher than the previous one. The revised model became operational on 13 October 1992 and the verification taken one week either side of that data shows that we actually got the improvement we wanted, an increase of some 30 cm of wave height overall. However, that is not the whole story because we also have a time-series of Global Model verification going back to July 1987 and it shows (Fig. 4) a bias in the wave height. Bearing in mind that during this time there was no change in the Global Model but this was in the last days of the wave model on the Cyber before we introduced the Unified Model, you can see there is a reasonably steady downturn in the wave model performance over the years, even during the period when the model has not changed. During this time the model on the Cyber was unchanged but changes did take place in the atmosphere model. We find in particular that changes were made through the data assimilation scheme. The analysis correction scheme was introduced in 1988 and the wave model verification went down

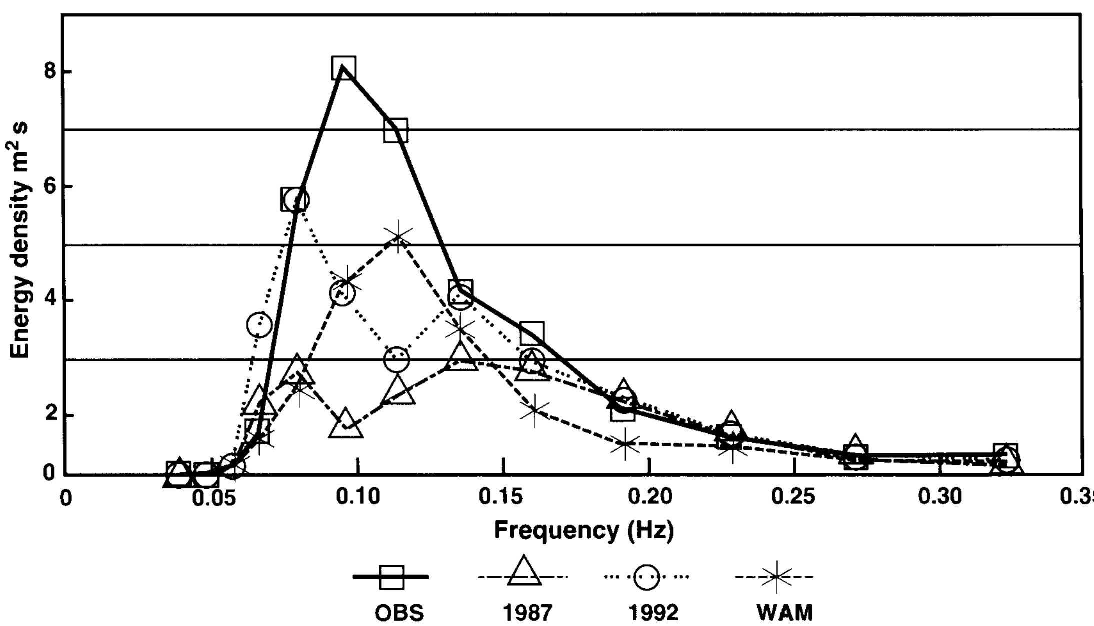

Figure 3. The distribution of energy in waves of various frequencies for the models.

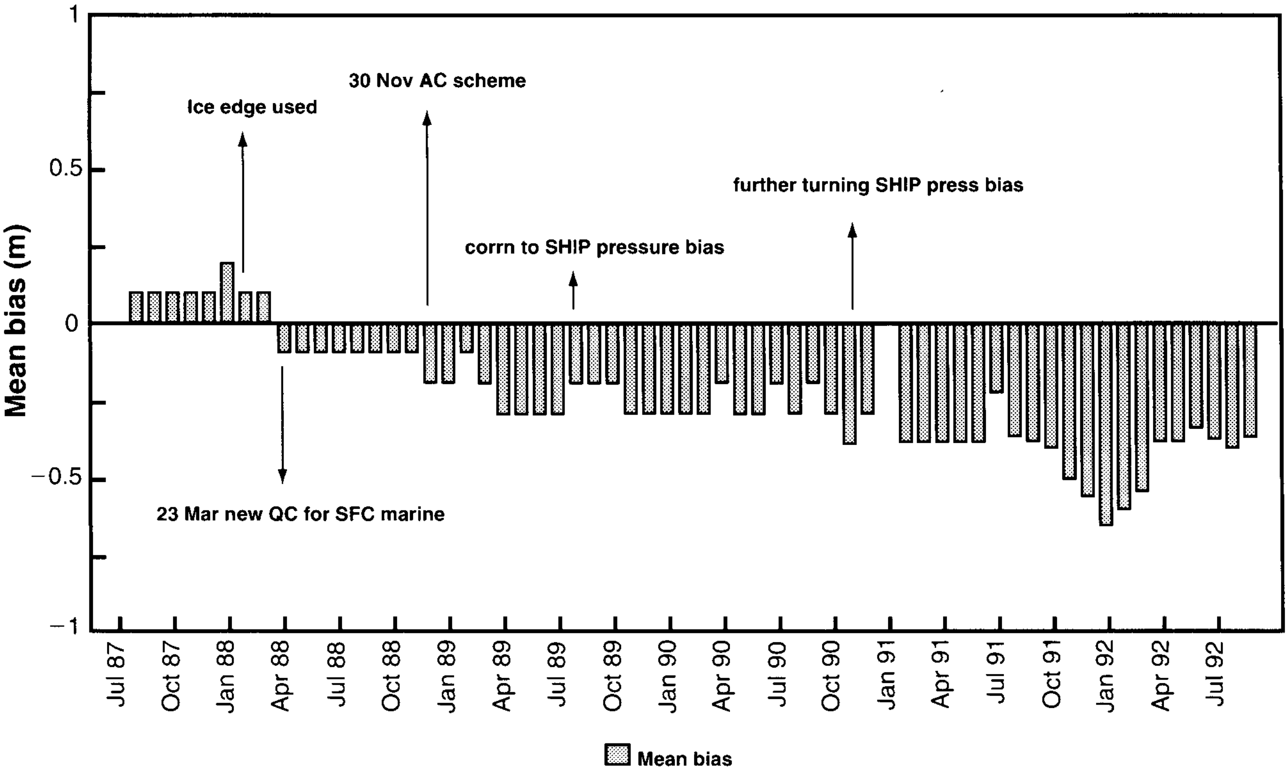

Figure 4. Changes in wave height bias in the Global Model Verification.

10 cm, due to a change in the ship observation pressure bias, and down again. So various things happened along the lines of data and changes in detail of the assimilation scheme. The wind speed verification actually looks good, verification of wind speeds against buoy stations shows a reduction in bias over the last four years, and we see the last few months match the observed very well. However, when you look more closely you realise that these wind speeds are from the lowest level of the model, at a nominal height of 25 m, and are compared with moored buoys with anemometers at a height of 5 m. We suspect that the wind speeds in the atmosphere model are a little lower than they ought to be at the surface.

Another thing we found in practice is that, because all these moored buoys have reported using SHIP code, the data is actually being put into the model at the height of 25 m. So we have learned that the performance of the wave model depends critically on the atmosphere model getting it right, and so hopefully operational changes, if they are likely to affect the surface wind speed, should consider the likely impact on the wave model, ideally before they are implemented.

5. Impact of satellite data

There are three instruments on the ERS-1 satellite directly of interest to wave modellers. The altimeter measures wave height and wind speed at the point directly below the satellite over the oceans. The scatterometer measures a swathe of surface winds which can be assimilated into the atmosphere model. The third instrument is the synthetic aperture radar (SAR), this can give very detailed information about the waves, it can give you the full frequency and direction energy spectrum at any point where the measurement is made.

We can compare the location of the buoys in Fig. 2 with the typical 12-hour coverage from the altimeter shown in Fig. 5, and you can see that now we are covering quite a lot of the ocean surface during that time. So obviously it is useful, as most satellites are in that respect. A particular feature of the development of the calibration of the satellite instruments was the use of wave models and model data right from the start. A comparison of collocated model and satellite data quickly revealed some teething troubles with the satellite values, and these were soon corrected. It also showed that our model wave heights were lower than observed over much of the oceans and also that there will be spikes in the data which occur when the instrument is crossing from land to sea because it thinks it is very high waves — so obviously we shall have to quality control data before using it.

Apart from the fact that our model wave heights are a bit lower than observed, it led to the discovery of a calibration error in the software on board the instrument, that effectively meant the minimum wave height was 2 m. By comparing a large amount of model data collocated with satellite data, this was picked up fairly early on and the model data was extremely useful in correcting large errors in both (ERS derived) wave heights and wind speeds. ECMWF was also looking in detail at the wave-height data and I am pleased to say that the wave models were useful in finding rather more subtle errors in the formulation of the models. The scattergram (Fig. 6) shows the model wave-height of the

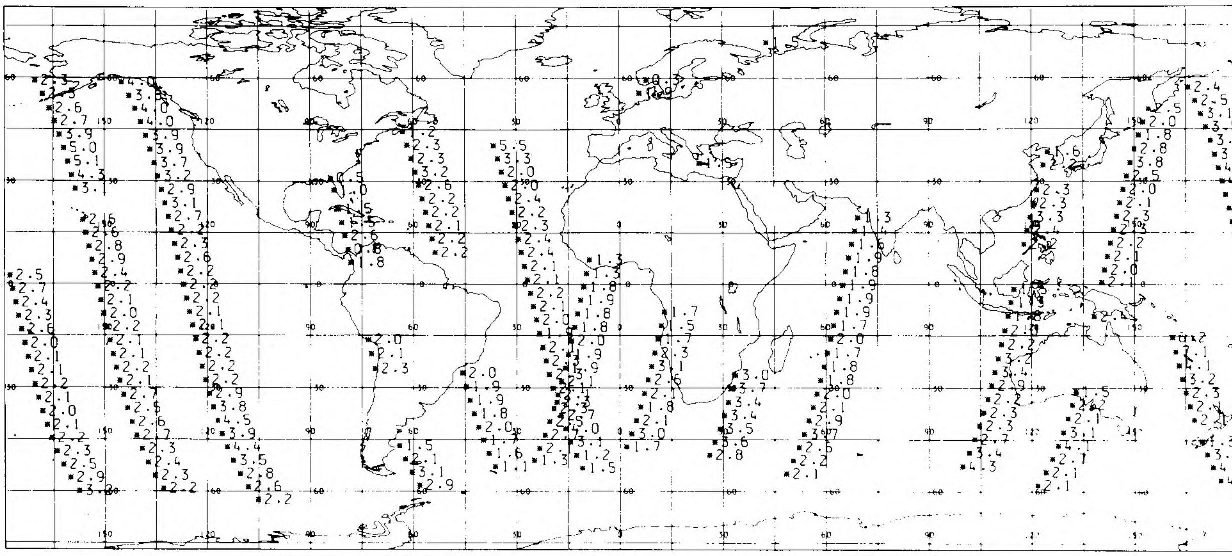

Figure 5. Typical 12-hour coverage of wave height data (m) from ERS-1.

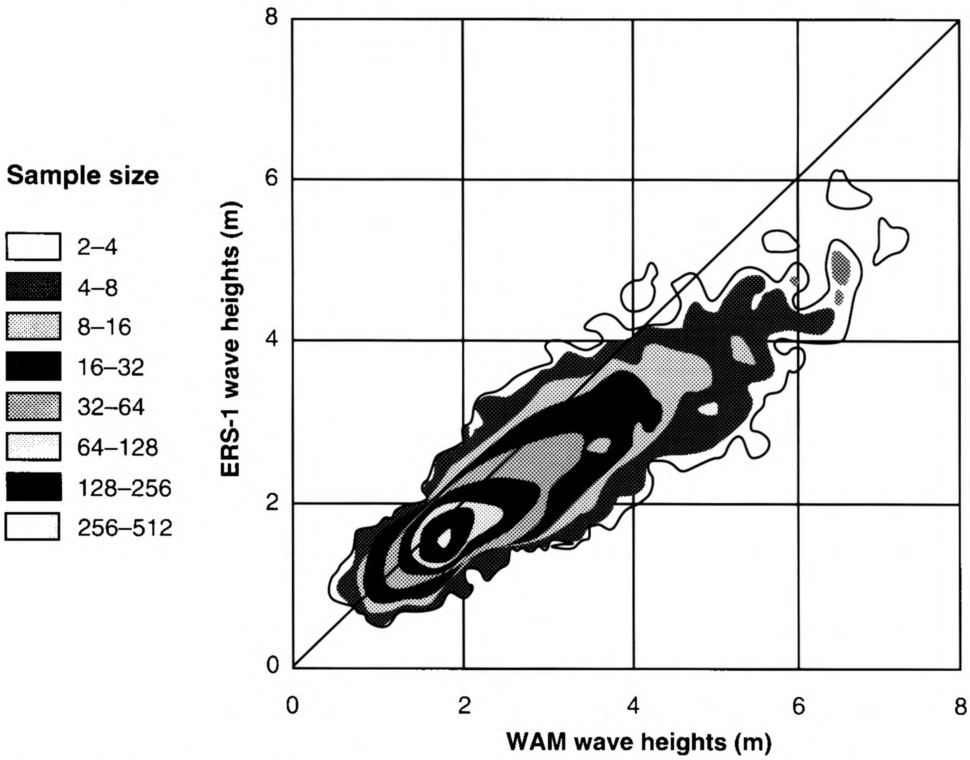

Figure 6. Scattergram of ECMWF WAM against ERS-1 wave heights for the period 6–13 October 1991.

ECMWF model against the altimeter wave height. When measured, the slope comes out to be 0.8, so they rang people at ESA who said "Of course, we have a 20% reduction in wave height, that was programmed in as a result of ground tests before take-off". That correction was soon taken out but it is difficult to see how this would have been discovered without comparison with the model data.

Having convinced ourselves that the information was useful we carried out a trial assimilation of the altimeter data of the wave height and the wind speed. The observations were processed in the normal way and spread out over an area that influenced some 300 km for the waves and some 200 km for the wind speed; so although the observation is purely at the point below the satellite, its effect is spread.

I will say a little bit now about the assimilation technique, it's magic, it really is, because we have two bits of information — wind speed and the wave height, and we go to 13 frequencies and 16 directions — 208 pieces of information — relying a great deal on what is already in the model. The basic principle is that we take the model wind speed and direction, and then split the wave energy at the point, into the swell part and the wind–sea part. We have the observed wind speed so we can get an expression for the wind–sea energy (the amount of wave energy that is directly tied in with the wind speed). The observed wave height measured by the altimeter tells us what the total wave energy should be; so knowing the wind sea energy and the total energy, we can work out the swell energy that should be there after we have done the assimilation. That then defines the ratio of the swell before, to the swell after. The wind sea is set as it would be in the main wave model (you know what the energy level is so you use the look-up table) and rescale the model swell energy. We should end up — at the point of the model where we do the assimilation — with the model wind–sea energy matching the observed wind speed and the model wave height matching the observed wave height. You start with two pieces of information and end up with 208. That is how it works in principle. Actually its not as quite as easy as that, as there are some combinations of model swell and model winds that need to be correctly handled.

Now for some results of the assimilation trial we ran from the beginning of November 1991 to the end of January 1992. There was the odd gap when things occasionally 'fell over' or communications failed. The job was run twice daily as a 12-hour hindcast run, taking the winds from the operational model run that was current at that time. When we use Fig. 7(a) to compare the verification with the previous wave model we can see

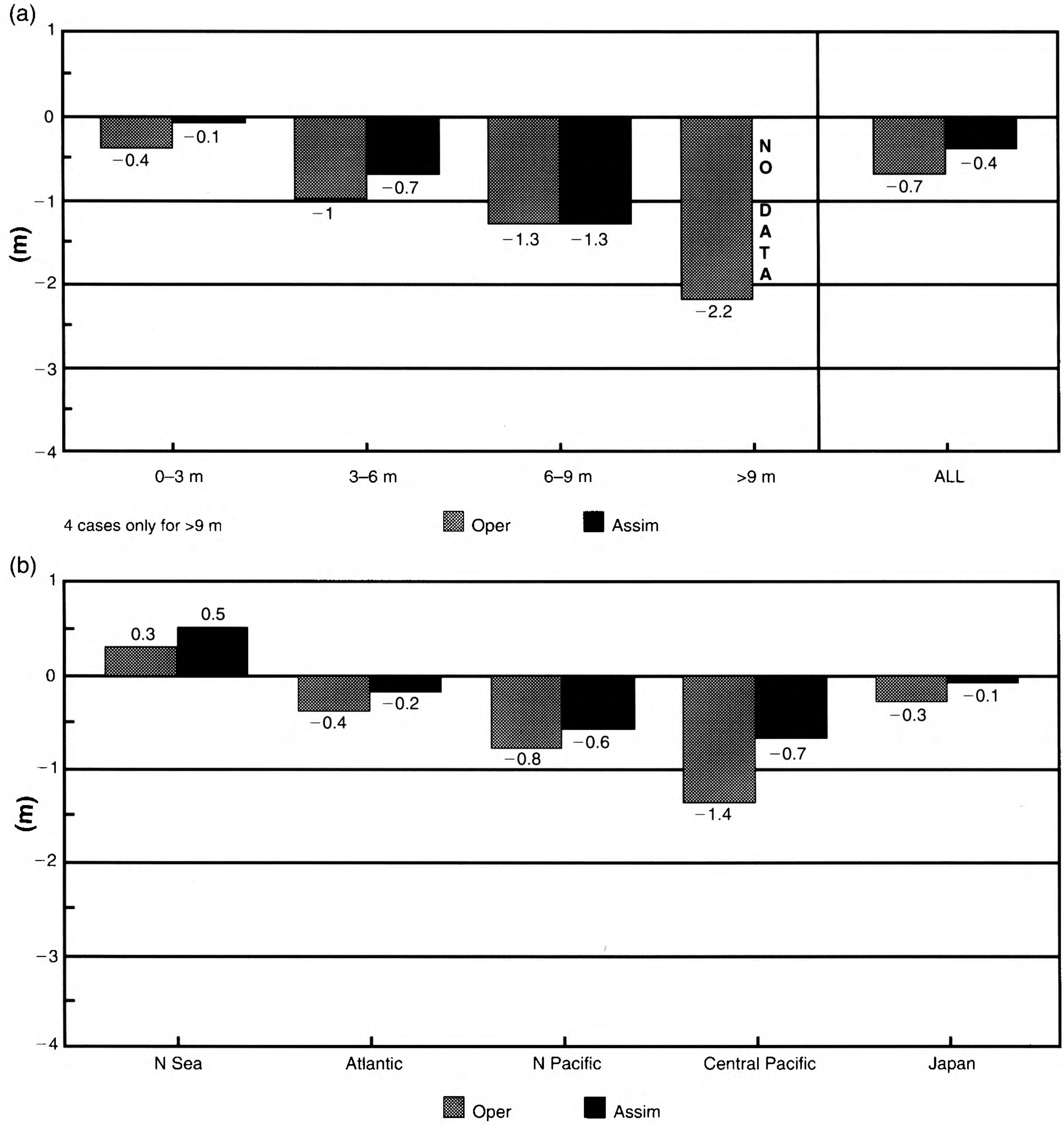

Figure 7. Comparison of verifications of the operational wave model run and with ERS-1 data assimilated (a) by wave height, and (b) by area

straight away how, for the lower ranges of wave height, we underestimate wave height in the model, and the impact of the assimilation is to bring the wave model back closer to where observed values would be, in fact by a mean of some 30 cm. If you break it down by region (Fig. 7(b)) the increases were larger than that in the tropics and central Pacific. Let us look at a time-series of all points in the Pacific. In Fig. 8 the dotted line is the observed, the dashed line is the current operational values for January 1992, and the solid line shows the run from the assimilation with the odd gap. It is obvious that the assimilation of the data has increased the wave height. We can see that when a satellite passes recently close by the information goes straight in; the wave height goes up — definitely some benefit from using the altimeter data correcting the model deficiencies in swell. If we look at one of the buoys off the east coast of the USA, because in the model the wind–sea is fairly well represented, the assimilation of the altimeter data has little effect. Occasionally we find that with because of an error in timing the swell will be increased there, but where the wave state is mostly dominated by wind-sea the assimilation has less effect.

If you look at a global map of the differences, you can see the separate satellite tracks that went in during a run and perhaps the run before, and large increases in model wave height underneath the satellite track. If you look at the difference in swell rather than total wave height you can see that the information about the swell in the sea gets spread out (an increase locally of up to 1 to 1.5 m). Information is retained and it is spread out between successive passes of the satellite. If we carry on with forecasting from the assimilated start field, we find the information in the swell is retained for two to three days into the forecast. When we rerun the assimilation trial with the revised wave model we would expect still to see an improvement in the swell height, remembering the revised model has reduced, but not entirely removed, the model bias in swell.

The second instrument was the scatterometer which measures a swathe of surface wind and here, thanks to Stuart Bell who ran the atmosphere model experiment, we did a six-day trial assimilation of the scatterometer wind in the atmosphere model, picking up the operational wave start field, and running it for six days with winds from the control run, and winds from the run using the scatterometer wind data. Looking at charts of wind speed difference at the end of that time we can see from the scatterometer data going into the atmosphere model there is really not a lot of impact. But occasionally there is, caused by the difference in position of a low centre; in one or two places you can see it actually moves the depression on. Looking at the wave height differences between the runs, again only small changes, in fact the global mean change in wave height was plus 1 cm, but there are local changes where at the end of this 6-day period the storms have changed position slightly, and this is in the northern hemisphere as well, not just confined to the southern hemisphere where we expected the greatest impact of the data. So less of an impact on waves through the atmosphere assimilation, but nevertheless a small increase in wave height.

The SAR is the third instrument, it is not straight forward to use. To get from the power spectrum as measured, back to the wave spectrum, you have to use a model's first guess spectrum. It is a non-linear inversion, and it is expensive (in computer time) and so for all these reasons, we at the Met. Office, have not been looking at data from the SAR. However, people at the Max Planck Institute, Hamburg, are working on it and developing algorithms for retrieving spectral data. So we hope to have SAR observations of the wave spectrum for model development eventually.

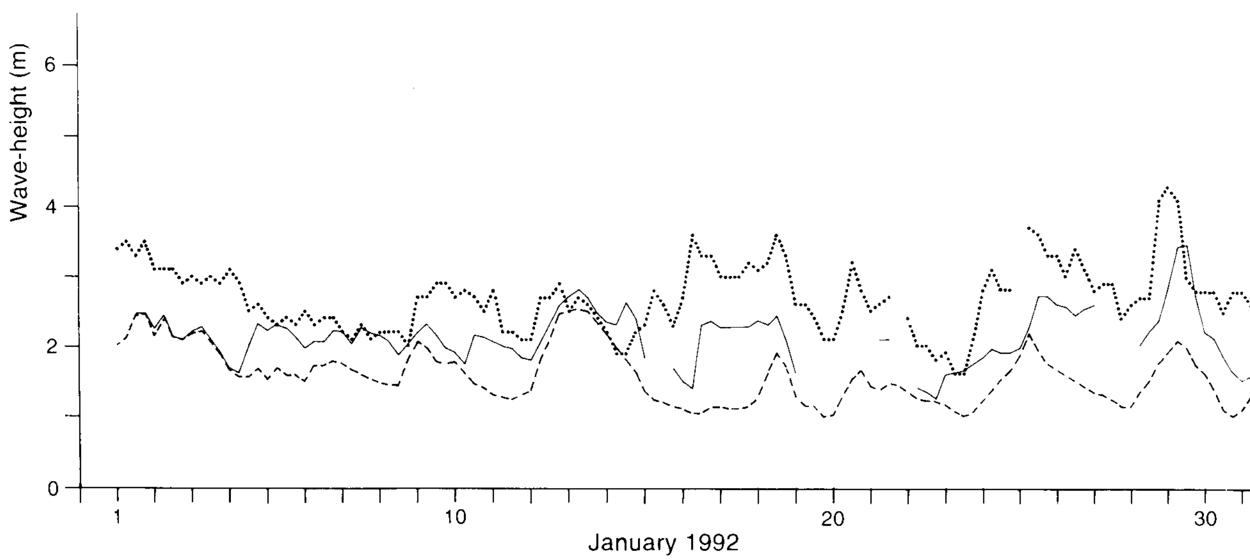

Figure 8. Time-series of wave heights near Hawaii; dotted line is observed, dashed line the operational forecast from the model then in use, the continuous line is the model run with assimilated data.

6. Wave–atmosphere coupling

I will now move on to some early looks at coupling the wave model to the atmosphere model. It is important to get boundary conditions correct in the atmosphere model, the correct surface stress and the correct drag. This is done by means of parametrization; you have to get the drag coefficient (C_D) right or, equivalently, the roughness length. Traditionally this is done in our Unified Model at the moment by the Charnock parametrization, which defines a roughness length depending on wind speed. Effectively the drag depends on wind speed only (remember the C_D is given by surface stress divided by the square of the 10-metre wind speed). There are various parametrizations from data sets of observations, usually in the form of a linear increase with wind speed. Now observations of C_D over the sea show that it can be greater than the mean value for the wind speed, if the wind has recently increased or changed direction. If the wind speeds have fallen then it is found that the C_D could be less than the mean value for the wind speed. Measurements over shallow water found the C_D was larger than expected, and measurements of growing waves under a sea breeze showed that the C_D actually decreases as the waves grow and then we reach a steady state. So there is clear evidence that the C_D depends on wave heights. The explanation is that in shallow water waves are steeper and present a rougher surface to the atmosphere. Now there are in fact very few observations of C_D over the sea for waves greater than 8 m or indeed wind speeds greater than 50 kn (for obvious reasons).

We can look at two particular expressions, one due to Large and Pond, familiar to climate modellers, and a more recent one by Blake incorporating wave height and wind speed (Fig. 9). Although it is still early days yet, I will show you some idea of the dependence on wave height, and how to calculate those two expressions for a particular wind speed and for growing waves from rest. Obviously the C_D depends upon wind speed, we can see there is more drag for small waves, and as the waves grow, the C_D decreases. You can see the Large and Pond data set has a fair mix of young growing waves and the mature waves, lying almost in the middle of the range of C_D given by Blake's expression. Now a look at how these things vary over the globe. The expression of Large and Pond, calculated on a particular day, shows a typical spatial variation of drag coefficient dependent on wind speed only. Comparing this with Blake's expression, the wave height dependence has reduced the C_D in areas of strongest wind. I might add that there are any number of different values quoted for the constant, so the reason I looked at the Large and Pond figures was because the measurements were over the open oceans, so it seems to make sense to use that.

7. The future

Now the longer term plan is, of course, to couple the wave model and the atmosphere model to get the stress right, probably by running the wave model and using the surface stress from the atmosphere model; we would then calculate the C_D or roughness length, including the wave information, and feed that back to the atmosphere model. However, within the Unified Model system that is not yet possible. There is quite a bit of effort needed with the internal diagnostics and the way information is passed between the models before we can do that. We cannot yet do the full coupling where the atmosphere gets the benefit of the wave information, but we can do the one-way coupling where the output from the wave model can be fed back to recalculate the surface stress that the atmosphere model is giving.

Work is also in hand with coupling waves to the Proudman Oceanographic Laboratory's tidal surge model. The point here is the coupling will include the wave–current interaction, you will have the varying

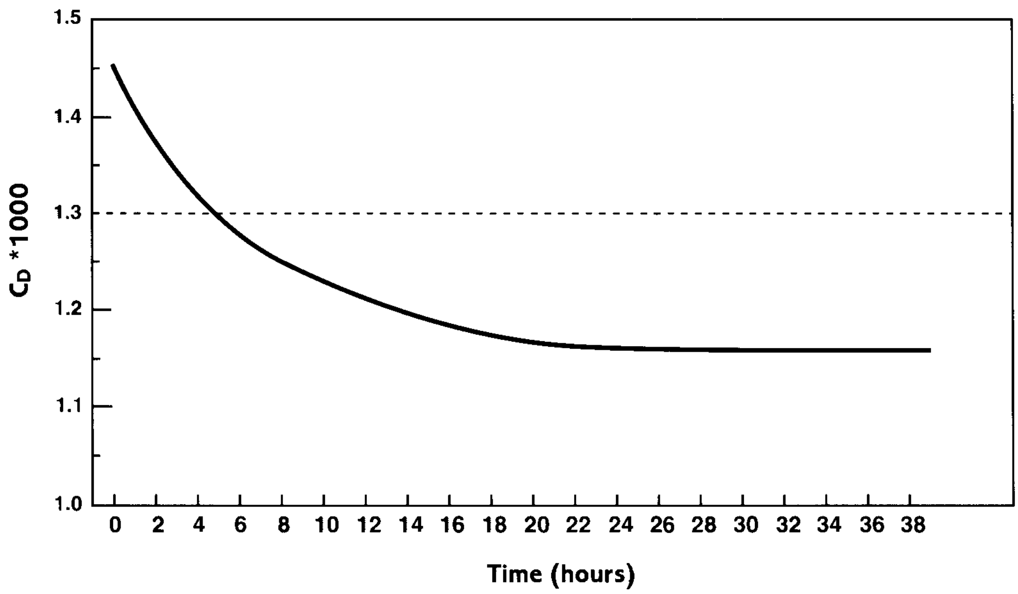

Figure 9. Two formulations of C_D for a wind speed of 15 m s^{-1}.

depth as well (at the moment the shallow water model does not use tidal variations of depth), so we could use those effects also to give a more realistic wave forecast.

We are looking at global shallow water (less than 200 m in this context), particularly at the request of Commercial Services Division because they want to open offshore markets in the South China Sea; and there is also the North Sea. The Global Model resolution may just be adequate to benefit from the inclusion of shallow water terms or maybe we will go ahead and develop a regional model. Then there is swell dissipation, nobody actually knows how much swell should be dissipated after it leaves the generation area and travels across the oceans; we certainly think we probably have too much dissipation of swell in the model. Finally we will look at possibility of assimilating altimeter data into the operational model. (Note: this assimilation became operational in June 1993.)

Editorial

Dear Reader,

This issue was prepared late in July 1994! That will explain why the magazine appeared to come to a premature end. I can only apologise for the long gap, caused by work on the Meteorological Office Annual Report and because much Editorial input was required for the two main articles. The paper on *Modelling Ocean Waves* had to be converted from a tape of a profusely illustrated talk, to something shorter while retaining the easy grammar that flows from the use of the first person. The paper on the *Corsican squall* had to be translated from the French into easy English; it was easy to understand when reading through quickly, but it was much more difficult to actually write down.

I ought to write a few words about recent Meteorological Office publications.

*The *Forecasters' Reference Book* sold so well when it was published in 1993 that stocks were rapidly exhausted. A further 1000 copies have been printed and are again available at £15 each (including handling).

The *Meteorological Office Annual Report 1993/94* is now available in three parts.

(i) **The Review* is a full colour popular account of developments in the period April 1993 to March 1994, and is available by post for £1 (to cover handling and postage); free on personal application.

(ii) *The Annual Report and Accounts* (ISBN 0 10 248394 9) is a legal requirement, is legal and financial, and probably not interesting to the majority of you. It costs £7.35 from HMSO.

(iii) **The Scientific and Technical Review* is in full colour for the first time this year and gives an interesting and, I hope, readable account of our research work. Copies are sent free to collaborators outside the Meteorological Office and to other Meteorological Services. However, if you do not fall into these categories, you may buy a copy for £5 (including handling) while stocks last.

The third edition of the *Handbook of Aviation Meteorology* (ISBN 0 11 400365 3) was published early this summer and is available from HMSO via good bookshops for about £30. It weighs 1.1 kg so postal charges may be important. It is so up-to-date that the Annex includes code changes introduced this year. It is essential reading for all aviators and so comprehensive, lacking in mathematics and well written by a team of experts, that I would strongly recommend it to all keen meteorologists who can afford it.

* To buy these send a sterling cheque made out to 'Public sub-account HMG 4712' to Publications, room 707a, Meteorological Office, London Road, Bracknell, Berks, RG12 2SZ.

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Wave cloud

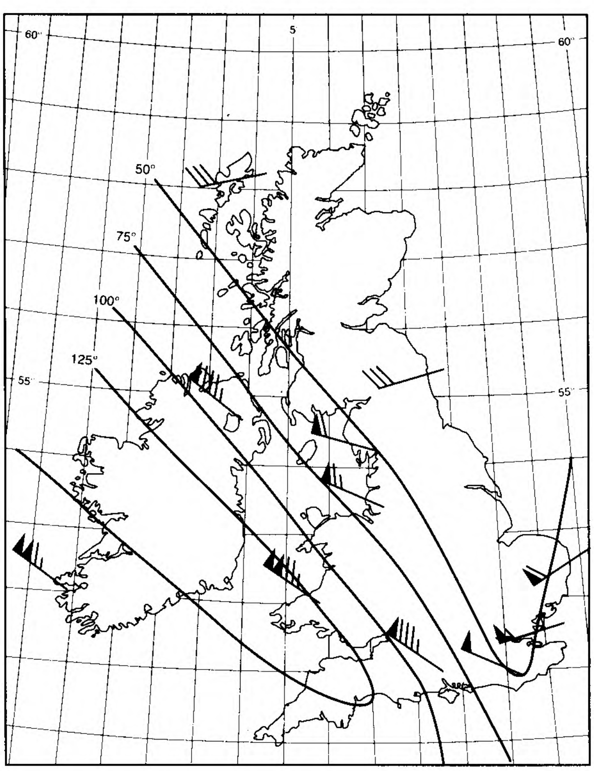
Figure 1 shows a fine set of Kelvin–Helmholtz billows taken by Mr. G.W. Oswin in Farnham, Surrey, England late in the afternoon of 7 December 1993. A powerful jet stream was approaching from the west and the core must have been close by at this time. The editorial staff saw the display from Bracknell but had no camera handy, and the official photographer was out on a job. It was with great joy that we learned that Mr. Oswin had taken the picture and sent it to the Enquiries Officer asking about the cloud formation.

As can be seen from Fig. 2(a), the horizontal shear ahead of the core was strong at around 45 kn per 60 nautical miles.

The hodograph of winds at Aberporth (A on Fig. 2(a)) is given as Fig. 2(b). The vertical shear between 500 and 400 hPa is 48 kn which in a standard atmosphere is about 10 kn per 1000 ft. The rules set down in the *Forecasters' Reference Book* suggest severe clear air turbulence should be forecast on both counts.

Figure 1. Kelvin–Helmholtz waves photographed about sunset on 7 December 1993 from Farnham, Surrey by G.W. Oswin.

(a)



(b)

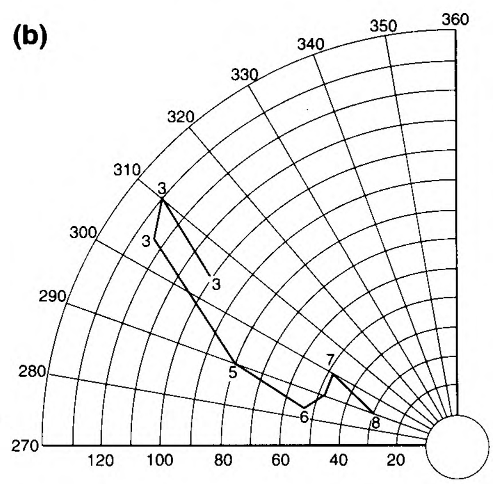


Figure 2. (a) Chart of 400 hPa winds over the British Isles at 1200 UTC on 7 December 1993. Isotachs are drawn at intervals of 25 kn. (b) Hodogram of winds reported by Aberporth at 1200 UTC on 7 December 1993. Small numbers refer to the pressure at each point in hundreds of hectopascals, speeds are in knots and angles in degrees true.

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Orographic cirrus generated by Iceland and the Faeroe Islands — 4–6 May 1993

T.D. Hewson
Joint Centre for Mesoscale Meteorology, Reading

Summary

Fig. 1 provides two clear examples of orographically generated cirrus cloud, north-east of the Faeroes in 1(a) and north-east of Iceland in 1(b). Animated hourly images show the south-western edges of these cloud masses to be almost stationary, whilst filaments within the cirrus stream away to the north and north-east, wavering occasionally to the left or right. The appearance resembles that of a flame, or a flag being blown by the wind.

Insets in Fig. 1 show UK Met. Office limited area model (LAM) data for times close to those of the respective images. The south-westerly upper flow is broadly consistent with the location and behaviour of the cirrus.

It should be appreciated at the outset that most (if not all) theories and numerical simulations relating to orographic cirrus assume orographic barriers of infinite length. This brief study will relate cirrus features to individual peaks, and consider the effect of such peaks on downstream flow; in this respect the work is new. For this reason the results in sections 2, 3 and 5, which draw upon past work, must necessarily be treated with some caution.

1. Introduction

The cirrus to the lee of the Faeroes first appeared at 2030 UTC on 4 May 1993, and ceased developing around 1030 UTC on the 5th. Separate filaments of cirrus are labelled A, A′ and B on Fig. 1(a). Filaments A and B can be identified through most of the sequence. However A′ is transient; it originated some hours before in the position occupied at 0230 UTC by A, and then drifted eastwards, slowly decaying. The persistence of A and B suggests they can be related to topographical features of the Faeroes. The distance between the points of origin of A and B is very similar to that between the cluster of high peaks at the northern end of the Faeroes and the isolated 610 m peak at the southern end (Fig. 2), implying that the northern peaks probably gave rise to A and the southern 610 m peak to B.

The impression given by Fig. 1(a) that A and B diverge from their points of origin is slightly misleading. Images for other times shows their orientations to be similar.

Cirrus generation over Iceland began near the eastern edge of the island around 1030 UTC on the 5th and continued until 0630 UTC on the 6th. Filaments C, D and E were generally less persistent than those generated by the Faeroes — probably because of the complexities of Iceland's topography. Of the three D was the most persistent and C the least. Allowing for the fact that in Fig. 1 high cloud near Iceland appears about 40 km north-north-west of its true position*, it seems probable that the high-level glaciated region centred on 64.6° N, 17.2° W (Fig. 2) triggered D, and that the 2119 m peak triggered E.

*In overlaying a coastline on a geostationary satellite image it is generally assumed that cloud tops seen by the satellite lie directly above land features which would have been seen by the satellite had the cloud not been present. This procedure always positions cloud tops further away from the sub-satellite point than they actually are. Errors are usually small, but increase with both cloud height and distance from the sub-satellite point. At 0° W, 65° N, for example, cloud tops at a height of 10 km would appear about 34 km (or 0.3° latitude) north of their true position. Such errors are present in Fig. 1.

2. Waves at cirrus level

Orographic cirrus develops in the ascending branches of steady-state upper-tropospheric waves. These waves radiate well to the left and right of the region immediately downwind of the orography responsible for their generation. This explains (i) why on Fig. 1(a) the orientation of filaments need not be quite the same as the direction of the upper tropospheric wind (or 300 hPa height contours), and (ii) why on Fig. 1(b) the sharp cloud edge between 9° W and 14° W, and 65° N and 66° N (which was a semi-permanent feature) can also be attributed to Iceland's topography (see also Fig. 3).

Because vertically propagating orographic waves must tilt upstream with height (Durran 1986) waves in the upper troposphere typically begin some distance upwind of the triggering orography. Directly above this orography it is common for the air to be descending. This counter-intuitive result is supported by Fig. 1(b) — the dark band running from about 65.5° N, 18° W to 65° N, 15° W is due to cloud evaporation in a descending branch (referred to as a 'Foehn gap' in Reid (1975)).

A rough estimate of the upper tropospheric wavelength can be made on the basis of Fig. 1(b). Assuming that the coldest cloud in the cirrus filaments (at 65.9° N, 13.5° W) lies in a wave crest and that the warmest cloud just upstream (at 64.9° N, 15.2° W) lies in a wave trough gives a wavelength of about 260 km. This is not unreasonable given that wavelengths of vertically propagating waves should be much greater than the 4 to 40 km typical of trapped lee waves (which are responsible for the multiple cloud bands often seen in the middle and lower troposphere).

(a)

(b)

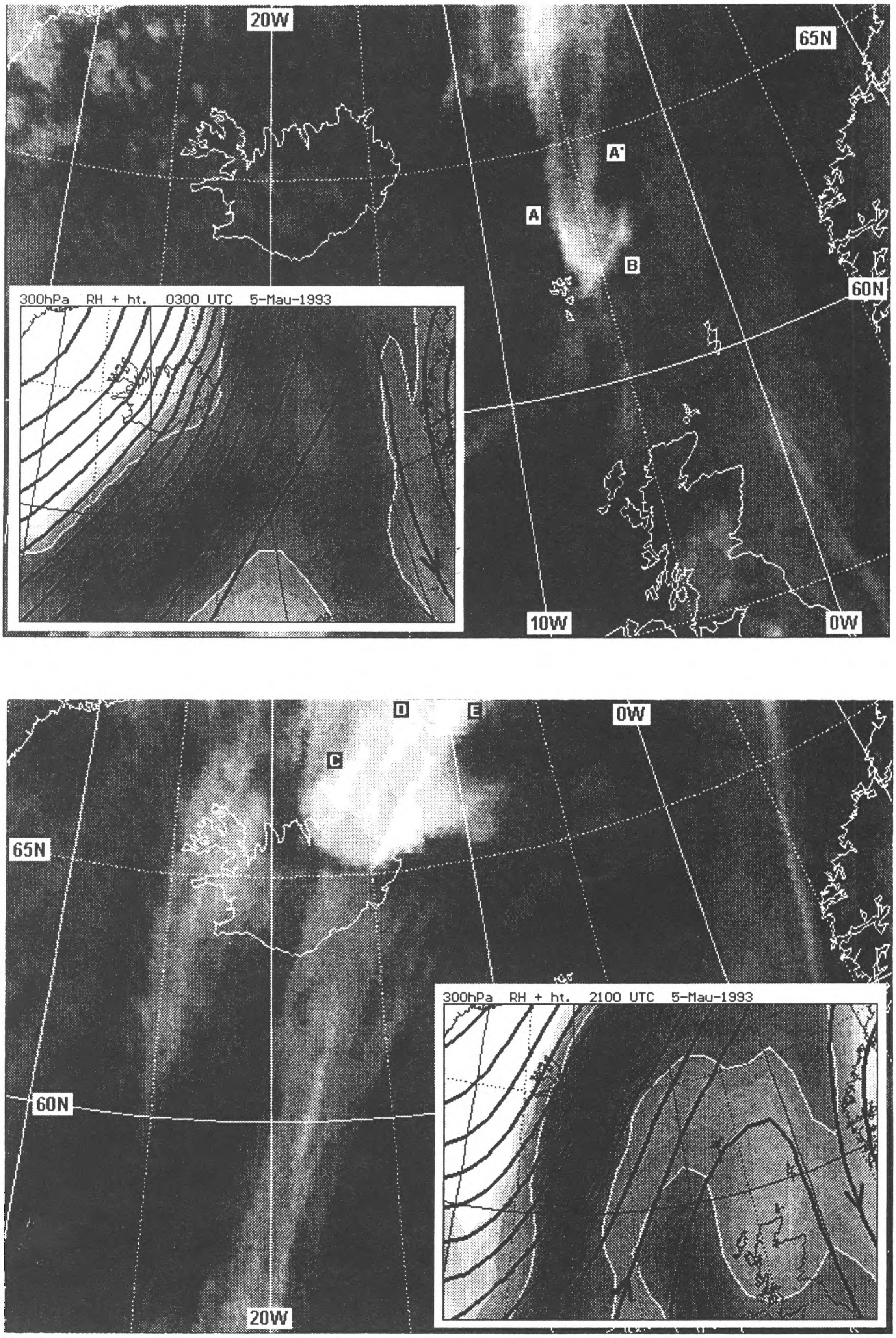

Figure 1. Meteosat infrared images for (a) 0230 UTC, and (b) 2230 UTC on 5 May 1993. Filaments of orographic cirrus are labelled A, A′, B, C, D and E. Insets show 3-hour forecast fields from the LAM for the 300 hPa level at 0300 UTC (a) and 2100 UTC (b) on 5 May 1993. Black contours are of geopotential height at 6 dam intervals. Shading indicates relative humidity with respect to liquid water. Darker shades indicate higher humidity, whilst white contours represent 60%. At temperatures of −50 °C at 300 hPa a 60% relative humidity with respect to water equates to about 100% relative humidity with respect to ice.

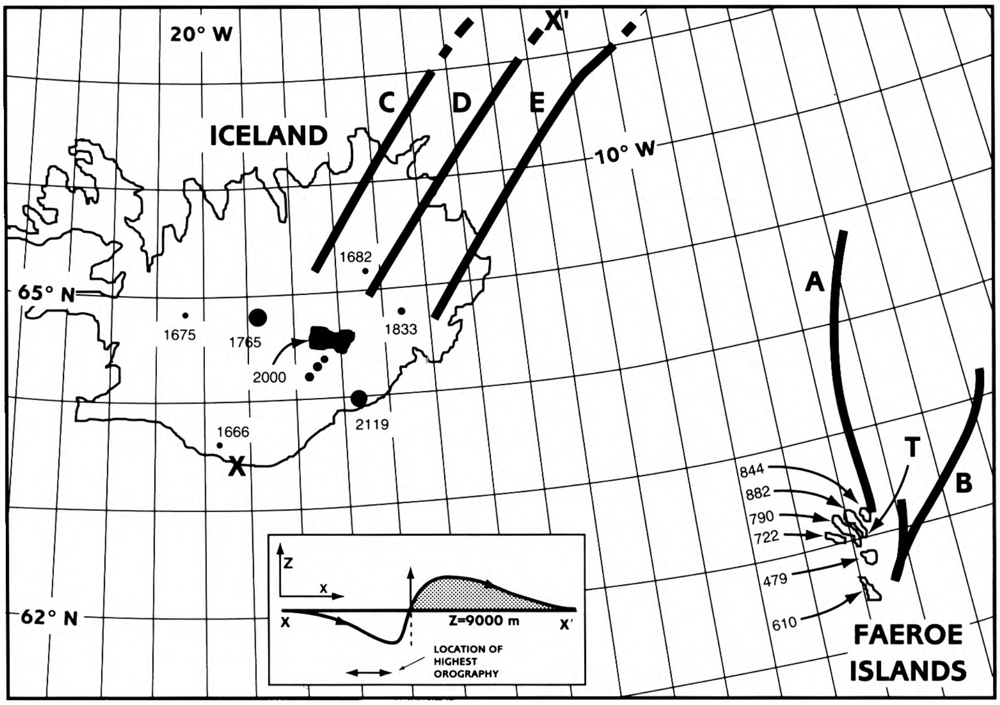

Figure 2. Topographical features of Iceland and the Faeroe islands. The major peaks in Iceland, and the high points on each of the six main Faeroe islands are labelled (heights in metres). Land/ice above 1600 m is blacked out. T marks the location of Thorshavn. Lines A, B, C, D and E represent the axes of the filaments marked on Fig. 1, having been corrected for the error noted in the footnote on page XX. The inset is a schematic representation, in a vertical plane, of a streamline through a steady-state upper-tropospheric wave (which gave rise to filament D on Fig. 1(b)). End points XX' are marked on the main figure. Shading indicates the approximate location of the orographic cirrus. The small vertical arrow and dotted line are equivalent to those shown on Fig. 4.

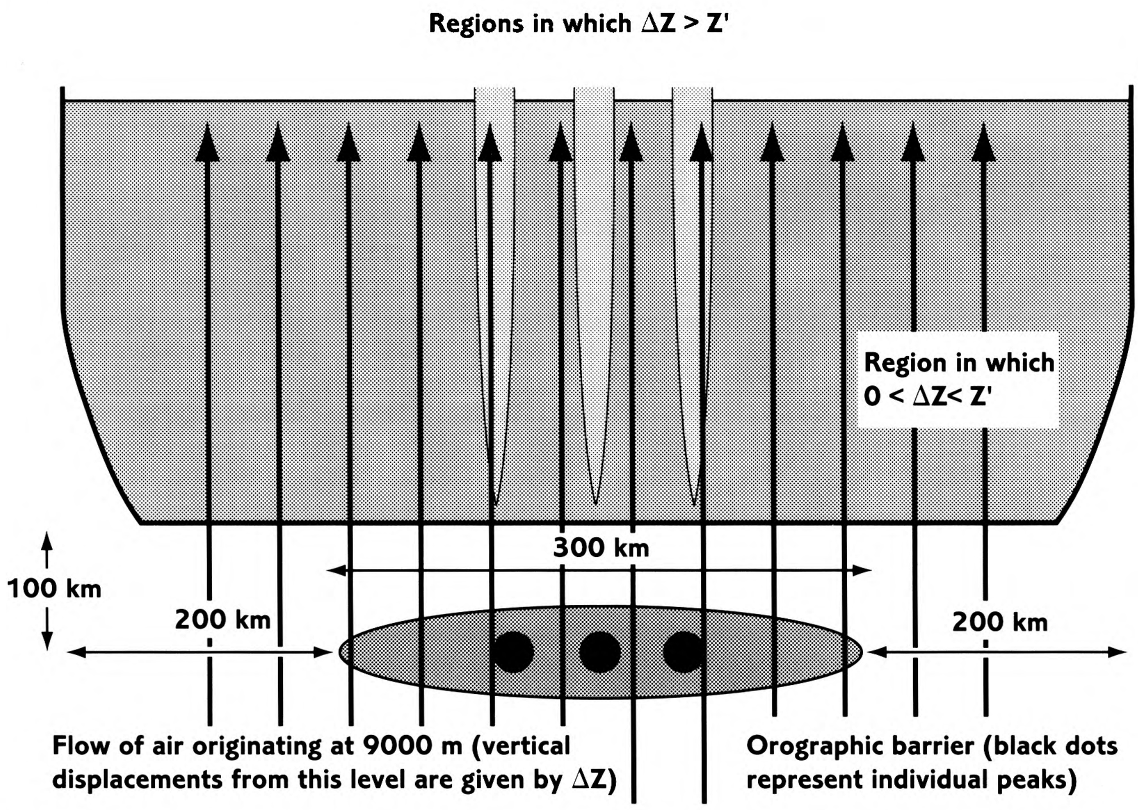

Figure 3. Schematic plan illustrating the regions (shaded grey and light grey) in which upper-tropospheric air can undergo positive vertical displacements as a result of flow across a finite orographic barrier (shaded dark grey). The diagram is based on observations in this case-study, and not on a numerical simulation of the problem. Approximate distances have been included. These are based on images of the orographic cirrus near Iceland.

In general there is only one wave trough and one wave crest. Downstream of the wave crest air descends relatively slowly, back to the level of zero displacement (see inset on Fig. 2). For this reason the cirrus' ice particles do not evaporate readily in the downstream direction.

3. Vertical motion at cirrus level

Cloud-top temperatures for the orographic cirrus were analysed using a sequence of hourly Meteosat infrared images. The minima attained in the lee of the Faeroes were −52 °C (in filament A) and −50 °C (in B). Downwind of Iceland the minimum (amongst C, D and E) was −57 °C. Comparison with the Thorshavn sounding for 0000 UTC on the 5th in Fig. 4 (assuming this is representative) suggests the coldest tops were just above the 300 hPa level, at heights of about 9900 m (A), 9600 m (B) and 10 600 m (C, D, E). These heights can be

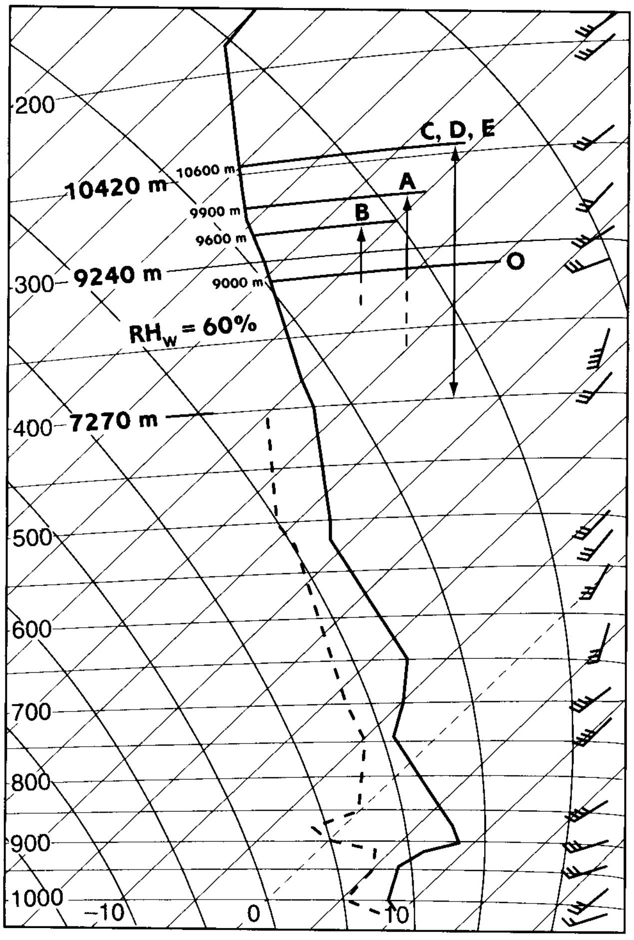

Figure 4. Tephigram for Thorshavn (see Fig. 2) for 0000 UTC on 5 May 1993. Winds are plotted conventionally, such that one full barb equals 10 knots. The geopotential heights of the 200, 250, 300 and 400 hPa levels are included. Heights shown for other levels have been interpolated from these values. Arrows give the maximum vertical displacements estimated to have occurred during the 4th, 5th and 6th in the ascending branches of the orographic waves which produced the cirrus filaments labelled in Fig. 1 (see text). The level of zero displacement is marked O. Dotted lines represent ascent between wave trough and level O (compare with inset in Fig. 2). A cross indicates the dew-point on the sounding (at level O) which would equate to a relative humidity with respect to water of 60%.

compared with those of the orographic features thought to be responsible for their generation, i.e. 900 m (A), 600 m (B) and 2100 m (C, D, E). The spread in the two data sets is similar, i.e. 1000 m (for the heights if the coldest tops) compared to 1500 m (for the heights of the orographic features). In addition the height differences between (A) and (B) are the same (300 m) in both. If it can be assumed that the orographically induced waves have the same level of zero displacement, and that there exists a relationship of the form

$$(\text{Maximum wave amplitude}) = k*(\text{Orographic height})$$

(where k is peculiar to the atmospheric structure characteristic of this case study) then the similarities noted in the previous two sentences imply k is equal to or slightly less than 1. In other words the maximum amplitudes of the upper tropospheric waves which gave rise to the cirrus were probably similar to or a little less than the height of the orography below (enabling arrows and the level of zero displacement to be plotted on Fig. 4). Earlier observational work suggests such amplitudes are certainly plausible; in investigating cirrus generated by flow over hills in southern Britain, Ludlam (1952) concluded that hills 1000 ft high could cause vertical displacements of over 2000 ft at cirrus levels.

4. Thermodynamic aspects

Cirrus production requires ice supersaturation, i.e. a relative humidity with respect to ice (*RHi*) in excess of 100%. In the case of orographic cirrus this can be produced by forcing air with a RHi of about 100% to rise (and hence cool) within the ascending branch of the orographically induced waves. On the Thorshavn sounding the 300 hPa temperature is −47 °C; at such temperatures a relative humidity with respect to water (*RHw*) of about 60% will ensure saturation with respect to ice. The insets in Fig. 1 indicate 300 hPa *RHw* in both regions of orographic cirrus to be in excess of 60%. Indeed throughout 5th May orographic cirrus was generated exclusively where *RHw* was greater than 60% (LAM data). The time at which the drier air shown near 56° N, 15° W on Fig. 1(a) was advected across the Faeroes coincided exactly with the time at which orographic cirrus ceased to be generated there. Not only do these observations lend some support to the LAM's upper-tropospheric humidity analysis, they also suggest that LAM *RHw* fields could help in predicting orographic cirrus.

5. Vertical propagation of orographic waves

The generation of cirrus by flow over orography requires not only high humidity in the upper troposphere but also conditions which are conducive to the vertical propagation of orographically induced waves. In a two-dimensional mathematical representation these 'conditions' can be defined by four parameters; the width of the orographic feature d, the wind speed U, a stability parameter N (the Brunt–Väisälä frequency), and the vertical derivative of the wind shear (see Durran (1986)). If the latter term is neglected (note that wind shears are small on Fig. 4) then vertical propagation will occur provided

$$3U/N<d \qquad \text{(SI units)*}. \qquad (1)$$

Substituting a typical value of $N=0.015\ s^{-1}$ gives

$$U<10d \qquad \text{(with } d \text{ in kilometres and } U \text{ in knots).}$$

So the propensity to generate orographic cirrus increases with increasing width of the orographic barrier. Narrower barriers generally require lower wind speeds. For $d \sim 7$ km (the approximate width of the southernmost Faeroe island in Fig. 2) U needs to be less than about 70 knots. Winds on the Thorshavn sounding are about 30 knots, so equation (1) appears to be satisfied.

Equation (1) also indicates that in general upward wave propagation is less likely if there is low stability ($N \rightarrow 0$); such as would be found in polar air masses over oceans, or during high insolation over land (see Ludlam (1952)). Conversely the marked inversion at 900 hPa on Fig. 4 (caused partly by prolonged advection across colder waters of air of tropical origin) would increase the chances of small orographic features, such as the Faeroes, being able to trigger orographic cirrus.

The magnitude of vertical displacements in the upper troposphere (and hence the propensity to produce orographic cirrus) depends partly on the amount of wave energy transported from below. This energy is larger if the wind speed at the level of the orography is larger. Thus the strong low-level winds over the Faeroes must also have aided cirrus production (given that they appeared not to have exceeded the upper limit imposed by equation (1)).

* To generate orographic waves Durran assumes a bell-shaped hill whose height h is defined by $h(x)=h_0 d^2/(d^2+x^2)$; where h_0 is the height of the hilltop, and d the horizontal distance from that hilltop to a point on the hillside where $h=0.5h_0$. In writing equation (1) it has been assumed that the 'width' of such a hill is approximately $3d$.

6. Implications for forecasting

The moist upper-tropospheric conditions required to produce orographic cirrus are frequently found in the vicinity of frontal zones, where jet-stream cirrus and cirrus generated by large-scale ascent are also common. For this reason the identification of orographic cirrus is usually more difficult than in the clear-cut example in Fig. 1. Nevertheless the benefits of positive identification are potentially quite high. Consider, for example, a case where high-level frontal cloud is cooling downwind of a range of hills. Realising that this is unlikely to be related to precipitation intensification would clearly be beneficial.

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World weather news — July 1993

This is a monthly round-up of some of the more outstanding weather events the month, three preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

South America

I know July is Winter down here, but it came as a surprise to learn that the Argentinian station at Maquinchao had a minimum of −23 °C on the 5th and Esquel a minimum of −13 °C. The Chilean capital Santiago nearly had a new record on the 12th when the temperature fell to −4.3 °C. Another cold day was the 25th when the Argentinian coastal town of Mar del Plata awoke to a temperature of −5.9 °C which was only 0.2 °C from the record for July.

North and Central America

On the 6th the west coast of Mexico battened down the hatches as hurricane *Calvin* approached from the Pacific heading towards Acapulco with winds of 85 kn and gusts near 105 kn. Much of the country was already suffering heavy rain from a tropical depression. By the 8th there were states of emergency in a broad band from Yucatan to Jalisco and more than 30 had died as a result of the incessant rain. Onshore winds did a lot of damage as well while the storm moved slowly north-west up the coast. One of the major causes for concern was a grounded chemical tanker with 4000 tons of sulphuric acid aboard: after the storm had passed the ship was reported to be empty and news of the environmental consequences was awaited. A weakening *Calvin* then gave southern Baja California a taste of gales and heavy rain before dissipating over the ocean.

The major story has been the phenomenal rains over the Mid-Western states of the USA. which lead to catastrophic flooding over wide area astride the rivers Mississippi and Missouri. Nearly every day there were reports of record water levels and heavy rains (several centimetres). As with temperature references like 'twenty below', it is often difficult to tell what the datum is for quoted water levels. As the waters rose to cover locks the main channel became unusable for navigation and the massive barge trains stopped moving. Diverting the freight to the railways involved long diversions as many sections of track were under water and bridges in a dangerous state. On the 1st Lubbock, Texas, got its entire average July rain fall of 55 mm in one go: Bismarck, North Dakota, had 69 mm on the 2nd which was almost a record for July. Further north, Regina, Saskatchewan (Canada) had 91 mm between the 3rd and 5th (130% of the month's average). There was a further outbreak of heavy thunderstorms in the American Mid-West on the 7th which is said to have killed 15 and added to waterlogging problems (116 mm at Columbia, Missouri and baseball-size hail in Kansas with squalls over 50 kn.). The Mississippi finally burst its banks as it has threatened to do for some weeks; at St Louis its width was 7 miles. On the 9th parts of Iowa and Illinois had a further 70 mm (near record daily falls) and just after a flood crest had passed through Rock Island another 80 mm of rain fell overnight. On the 11th the levees around Des Moines were overtopped and the city's water processing works went under 3 m of water; Wichita's thunderstorm produced a gust of 88 kn and Princeton, Missouri collected 137 mm. By the 15th, with the Mississippi flowing at seven times the normal rate, sandbag-reinforced levees were giving way, spreading the floods, though reducing the level elsewhere. However, more rain was falling and the National Weather Service expected no major change for the next thirty days. The 16th saw the breaking of a levee which closed the last remaining highway bridge along a 200 mile section of river. Further thunderstorms added more water on the 18th, caused some more levees to fail and left 250 miles of the Mississippi without a usable bridge between Burlington, Iowa and Alton, Illinois. Upstream of St Louis there was a 300-mile uncrossable stretch until a bridge was reopened on the 19th. By the 20th the problems had spread further west as heavy rain overfilled dams and the Kansas River flooded.

A plateau seems to have been reached in flood levels by the 22nd but there were still some violent thunderstorms about with the threat of more widespread ones to come. The storms duly arrived over the weekend and the forecast date of the flood peak was put back until 3 August. Hamburg, Iowa, had more than 250 mm in the five days 21th–26th. Flood crests passing down the Missouri and Kansas were not in phase when they reached Kansas City on the 27th alleviating the threat of catastrophe. At the end of the month the city of St Louis was waiting behind its flood wall for the predicted 49 ft flood crest on August 2nd: the wall top is at 52 ft. By the end of the month estimates put the cost at 41 lives, $12bn and 16 000 square miles flooded.

Almost lost in the news of the floods came mention of a heatwave in the eastern states which had caused the deaths of 47. Temperatures over 30 °C in eastern Canada on the 10th were eclipsed on the 11th by an all-time high of 41 °C in New Jersey; more surprising was another new absolute record of 34 °C at Umiat, Alaska on the 15th. Towards the end of the month the northern states of Ohio and Pennsylvania were struck by storm of hail and wind, nearing 90 kn, that did nearly $45m of damage.

Australasia

This information is based on that kindly given by the Australian Bureau of Meteorology.

The 7th was a notably wet and windy day in South Australia and Victoria. Parts of south-west Victoria had storm force easterlies which closed the port of Portland for the day and mean speeds of 40–45 kn were quite common: the wind did more than A$1m damage around Adelaide. The heavy rain, around 60 mm over a large area, broke century-old records for daily rainfall: one of the biggest changes was at Murray Bridge in South Australia where the 107-year record changes from 23 to 37 mm. In the monthly total stakes there were many contenders for the prize, but at Temora the 113-year data set had 1891 as the wettest July with 130.2 mm; the record there is now 158 mm. In the prelude to this storm the wet 6th was especially cold at Broken Hill, New South Wales (NSW), where the maximum of 6 °C was the lowest for any month since at least 1948. In contrast much of NSW and Queensland had their warmest July on record; the mean minimum was a record high in many places and the mean maximum was also a record high in some.

The month ended with wild weather at two extremes; around Perth on the 29th many coastal sites recorded gusts of over 50 kn accompanied by thunderstorms: the next day damaging northerly winds struck Melbourne with 61 kn reached in gusts at the Dunns Hill AWS.

Asia

Heavy rain that started at the end of June over Zhejiang Province of eastern China continued into July leading to the deaths of six people by the 5th. Next day Hunan Province (central China) reported that their death toll had reached 33; further north there were fears that the Yellow River might burst its banks. In contrast Sichuan and west Hunan were suffering severe drought. The 13th brought news that the death toll from flooding in southern China was rapidly rising towards 100 after several days of heavy rain, especially in the province of Jianxi where, despite the efforts of a million workers, the town of Wuzhou was buried under the deepest floods in its history. Korea could hardly expect to escape the fate of south China, and accordingly 'a wet front' dumped lots of rain over the south starting on the 11th; Seoul had over 170 mm, but Chonju, 125 miles further south had 250 mm. Six died and more rain was forecast. The north Chinese province of Shanxi took its turn to be flooded mid-month when seven were said to have been killed by the heavy rains. Train services were suspended (almost literally) on the 20th between Lanzhou and Urumqi in the extreme north-west of China after heavy rain caused flooding and washed away ten long sections of track; about 18 000 were caught on trapped trains. The last three or four days of the month brought further devastating rainstorms to Hunan and Sichuan Provinces — one report wrote of 530 mm in 21 hours near Emei City; not surprisingly there were floods and landslides which killed at least nearly 200 stranded thousands and washed away a freight train.

Tropical storm *Lewis*, born in the Philippines earlier in the month, affected Vietnam on the 12th then Laos and Thailand leaving a trail of flooding in his wake, but the death toll seems to have been small. Extraordinary rainfall of 315 mm in 15 hours at the southern end of the Japanese island of Kyushu caused havoc with at least seven killed by landslides, some of which were lahars from the volcano Mt. Ontake. In the last few days of the month heavy rain over Japan lead to flooding and landslides that killed seven people. According to a spokesman for the Japan Meteorological Agency, Kagoshima in the south of Kyushu had ten times the rainfall in St. Louis (USA) during this month.

On the 26th an Asiana Airlines Boeing 737 crashed in foul weather near Mokpo in the south-west of Korea on a flight from Seoul. Apparently it made some failed approaches before crashing into a hill 50 km away in driving rain: 42 of the 106 aboard a reported to have survived. Heavy rain in the Philippines caused some flooding in Manila on the 29th. The three-day downpour triggered lahars down Mount Pinatubo which in turn caused some secondary explosions.

Indian subcontinent

As I expect all our readers know, the dominating story this month was again one of severe flooding around the rivers draining the Himalaya where the monsoon rains continue to be frequent and heavy. On the 1st there were reports of 18 deaths around Darjeeling as a result of huge landslides. In the extreme north-east 14 were reported killed by a landslide on the 5th. On the 8th a landslide swept away two villages in Nepal killing at least 28; the same day 40 were feared to have died in Himachal Pradesh as a result of flash flooding. On the 10th scores were killed in Assam, Gujurat, Punjab and Uttar Pradesh and also in Kashmir. The 11th was no better and some were said to have been killed when the roofs of the houses collapsed under the downpour. On the 13th flood peaks had generally passed but forecasts of more rain soon gave no room for cheer. On the 16th fresh floods in the Punjab claimed 34 lives and 50 villages. On the 18th the Indus town of Sukkur reported heavy rain with 'storm force winds'; floodwater was knee-deep and further rain was expected. The 20th brought further reports of flooding; this time in Assam and West Bengal, the latter's excuse was that 790 mm of rain had fallen in the last 24 hours! Next day the focus was further north as it became clear that Kathmandu, and many other towns, were cut off from the rest of Nepal. In Bangladesh lightning was claiming dozens of lives about this time. In the Punjab 314 mm is said to have fallen in 24 hours to the 22nd and the whole of north-east India was cut off from the rest of the country. There were floods as far away as Rajastan, which is normally pretty dry. The port of Chittagong became unusable from the 23rd to the 25th as the floodwaters in the Karnaphuli river were augmented by a massive discharge from the Kaptai hydroelectric dam to prevent it becoming flooded as the water rose to 20 ft above normal. On the 25th the river Sutlej broke its banks in the Punjab adding to the disaster that had already befallen the area. It was about this time that the threat of a cholera epidemic became apparent. Almost half of Bangladesh was under water then but the worst seemed to be over by the end of the month for the whole region. However, heavy rain continued in the west, triggering more flash floods in Maharashtra State. In states south of the flood zones the reverse has occurred and many mid-eastern states suffered drought and crops suffered. By the end of the month the Indian death toll was about 1100, Nepal 3000 Bangladesh 400, total 4500 with more than six million displaced and short of food and safe water.

On a lighter note, the test match between Sri Lanka and India at Kandy (cricket of course) was abandoned with only 50 minutes play possible out of the five days to the 22nd — apparently this equals the record for the shortest test ever.

Africa (except the north coast)

The following notes are kindly supplied but the South African Weather Bureau.

Over most of South Africa it was the eighth consecutive month with below average rainfall, but it was very wet around the Cape. Here the period 6th to 14th saw a series of cold fronts bringing prolonged rain leading to the worst flooding for several years: 460 mm fell in five days near Goudini so that by the second week both the Berg and Breede rivers were in flood with the highest levels in 50 years. Problems were compounded on the 9th by storms over the Peninsula which blocked drains with hail: Nowlands collected 169 mm of rain that day which was so stormy that Cape Town harbour had to be closed. Another big hailstorm moved north across Durban on the evening of the 29th causing considerable damage and disruption. Although the highest temperature reported was 33.3 °C at Skukza on the 10th, the season was confirmed by a night minimum of −9.0 °C on the 30th at Buffelsfontein and snowfall on the Southern Cape mountains until the 19th.

Europe, North Africa and Arabia

On the 6th Meteosat images showed a large Cb approaching Bordeaux and our ATD lightning detectors showed it to be electrically very active. Its passage eastwards across France left a trail of devastation. Two were drowned and 60 had to be rescued from rivers transformed into torrents; hailstones the size of tennis balls fell on an open-air concert at Vienne injuring a dozen (one had a fractured skull). The same report wrote that much of Beaujolais wine crop was damaged.

After the rains earlier this year swarms of locusts are reported to have crossed the Red Sea into Yemen causing the customary devastation to crops in their path.

Throughout the month rain fell heavily over the Ukraine leading to severe flooding in the north and to at least six deaths. By the end of the month conditions were beyond local control and foreign help was being sought. Neighbouring Belarus (Belorussia) also suffered badly, with flooding being especially severe in the south with 2 million tonnes of grain and half the potato crop under threat. Flood damage was put at $35m.

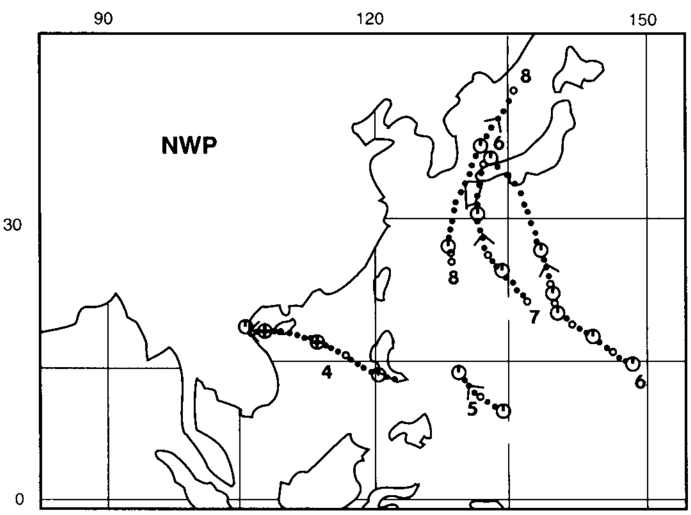
July tropical storms

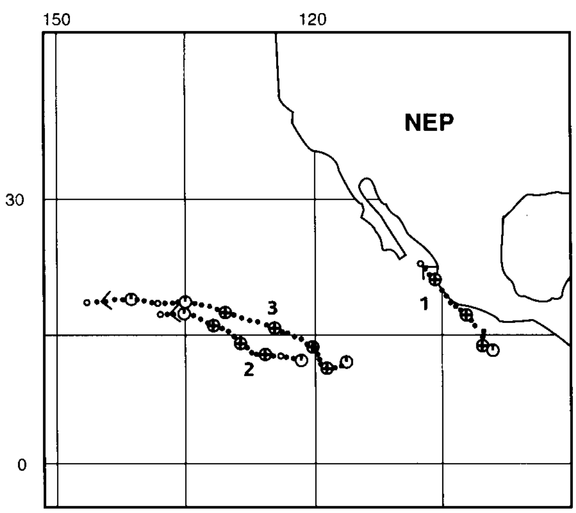
This is a list of tropical storms, cyclones, typhoons and hurricanes active during May 1993. The date are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during this month. The maps show 0000 UTC positions: for these I must thank Julian Heming and Susan Coulter of the Data Monitoring group of the Central Forecasting Office.

No	Name	Basin	Start	End	Max. (kn)
1	Calvin	NEP	4 Jul	8 Jul	90
2	Dora	NEP	14 Jul	21 Jul	110
3	Eugene	NEP	16 Jul	25 Jul	110
4	Lewis	NWP	7 Jul	12 Jul	85
5	Marian	NWP	13 Jul	17 Jul	45
7	Ofelia	NWP	25 Jul	28 Jul	45
8	Percy	NWP	27 Jul	30 Jul	75

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific: I — Indian Ocean; WI — west Indian Ocean; AUS — Australasia.

Cyclone Konita followed a hook-shaped course to SW, S and finally NNE. Adele did a lot of damage on the Trobriand Islands off New Guinea.





The publication of the *Meteorological Magazine* will cease with the issue for December 1993.

The December 1993 issue of the *Meteorological Magazine* will be a bumper one of about 40 pages celebrating the Magazine's contribution to the development and dissemination of meteorological knowledge. It will contain a selection of highlights from 1866 up to around 1986.

The first edition of the *Meteorological Magazine* was published in 1920 by HMSO. It took over from *Symons's Meteorological Magazine* which started in 1866. This decision therefore brings to an end a continuous publishing record of 129 years (except for the duration of World War 11). It is understood that legal obligations accepted when *Symons's Meteorological Magazine* was adopted are fulfilled by the continuing production of the *Monthly Weather Report* and *Rainfall 19XX* and our internal journal mentioned below.

As one of the leading European establishments for research into meteorology, our publications should be subject to external peer review: this is already the case for much Meteorological Office work. The publication of a new international and European quarterly journal by the Royal Meteorological Society (called *Meteorological Applications*) provides a suitable vehicle for most kinds of articles that have appeared in *Meteorological Magazine*, namely on research, practice, measurements, reviews articles, applications of meteorology, book reviews, etc. Enquiries should be addressed directly to the Royal Meteorological Society.

The United Kingdom Meteorological Office (UKMO) Annual Scientific and Technical Review 1993/94

This Review describes the major developments in science and technology within the UKMO over the year April 1993 to March 1994 and is produced as part of the Meteorological Office Annual Report and became available in July 1994. If you wish to be put on the mailing list for future years please write to:

The News Desk, Publications (room 707a), Meteorological Office, London Road, Bracknell, Berks RG12 2SZ.

If you want a copy of this year's Technical Review, please see the Editorial on page 247.

Informal communications

The UKMO has instituted an in-house periodical for informal and rapid dissemination of the latest relevant science and technology news to its staff and outside collaborators. Most contributions come from UKMO staff, but offers of material from outside will be welcome — though there is no guarantee of publication.

Back numbers

Limited stocks of back numbers from 1970 to date are available from:
Vic Silk, The Library, Meteorological Office, London Road, Bracknell, BERKS, RG12 2SZ; telephone 01344 854074. Copies cost £1.50 each (inclusive). Please send sterling cheques made out to 'Public sub-account HMG 4712'; leave the amount blank but cross them and endorse with the maximum so that the transaction can be made even if some of the requested issues sell out. Please send an addressed label with the order. Remaining stocks will be disposed of in March 1995.

Full-size reprints of Vols 1–75 (1866–1940) are available from Johnson Reprint Co. Ltd., 24–28 Oval Road London NW1 7DX.

Complete volumes of *Meteorological Magazine* commencing with volume 54 are available on microfilm from University Microfilms International, 18 Bedford Row, London WC1R 4EJ. Information on microfiche issues is available from Kraus Microfiche, Rte 100, Milwood, NY 10546, USA.

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Evaluation of a local climatological model — test carried out in the county of Halland, Sweden

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Summary

The present paper deals with an evaluation of the Local Climatological Model (LCM) developed at the Department of Physical Geography, University of Gothenburg. The control measurements included in the report are mainly focused upon three different parts in the LCM: (i) variation in road surface temperature under both clear day conditions, and synoptic conditions characterized by cloudy, windy, (ii) control functions in the LCM and (iii) test regarding the possibility of predicting temperature development along stretches of road.

1. Introduction

The local climatological model (LCM) which has been developed at the Department of Physical Geography, University of Gothenburg, is used for calculation of air and road surface temperatures. This paper is a part of a series of reports dealing with modelling of local climate and the extrapolation of temperatures from measuring stations to be valid for larger areas. Previous publications consist of, for example, Bogren (1991), Bogren and Gustavsson (1991a, b), Gustavsson and Bogren (1991a, b), Gustavsson (1990a, b).

The idea behind a road surveillance system is that stations measuring temperatures, humidity and wind should be located in such areas that an early warning of road icing can be achieved. This requires that the stations have various types of locations as different weather situations result in a different temperature patterns.

The background idea behind the LCM is that information about temperature variations along a stretch of road in a given area could lead to a more efficient surveillance of the winter roads. If the decision about salting action is based upon more diversified information, compared to that received only from the locations of the field stations, the right decision is made more easily. The road attendant can, for instance, decide whether an action needs to be taken or not, and give priority to certain stretches as well.

If a LCM is to be used to give additional information, it is of the greatest importance that the data presented are correct and relevant. Because of this, control measurements were carried out in an area where the model has been adapted. The study presented in this paper was carried out in the county of Halland, in the south-western part of Sweden, and it is focused upon control measurements along specific stretches of road as well as validation of the formulae used in the LCM. This is the second report dealing with this subject. The first (Bogren and Gustavsson 1991b) was mainly concerned with temperature distribution during clear nights and the variation caused by the local topography.Some preliminary studies were also carried out in order to verify the temperature pattern under other types of weather conditions.

The importance of topography on the variation of air and road surface temperatures has also been studied by, for example, Tabony (1985) and McLean and Wood (1992). The effect of different weather conditions on the temperature pattern has been discussed by Thornes (1989).

Prediction of road surface conditions is made by use of numerical road ice prediction models, e.g. Rayer (1987), Thornes and Shao (1991). The results of such models are used to give information about the forthcoming temperature development at a specific site.

The control measurements presented in this report were conducted by the use of instruments attached to specially designed cars and from analyses of recordings from stations in the Road Weather Information System (RWIS). The study is mainly focused upon the following parts:

(i) the temperature pattern during clear days, and the difference in road surface temperature (RST) due to the varying intensity of solar radiation;
(ii) road surface temperature variations during cloudy, windy conditions and especially the control functions in the LCM related to this specific part;
(iii) the development of temperature patterns during nights with falling temperatures, both regarding the cooling rate for different areas and also the division of the road into smaller segments and;
(iv) the variation of temperature patterns during periods with a change in temperature.

2. Principles behind the local climatological model

To be able to calculate the temperature pattern along roads using the LCM, several factors need to be considered. For an adaptation of the LCM to a specific area the following data is used.

Thermal mapping: Basic background information is received from thermal mapping of the road net in the county in question under different weather conditions. The results from thermal mapping give valuable information about magnitude and frequency of RST variations along the road caused by different topographical features.

Topographical maps/field studies: From topographical maps and field measurements, information about topography and geographical aspects is considered together with the temperature information from the thermal mapping.

RWIS: Information from the RWIS field stations gives the possibility of considering historical recordings to confirm the temperature variations determined from the thermal mapping.

The integration of these factors results in a classification and separation of different segments along the stretches of road. The most important topographical segments are: valleys, screened areas, variations in altitude and bridges. Proximity to water and regional climate are also taken into account when a certain area is considered. These fundamental topoclimatological parameters, which must be known in order to calculate temperature variations along a stretch of road, have been described in previous papers (Bogren and Gustavsson 1986; Bogren *et al.* 1992; Gustavsson *et al.* 1987; Bogren 1990; Gustavsson 1990).

When the basic background information is adopted into the model it is possible to start the calculation and extrapolation of the temperature pattern. This process can be divided into three parts. Firstly, the variables measured at the RWIS are collected and stored for 6 hours so that trends can be calculated. Secondly, the algorithm in the model compares air and road surface temperatures for determining the 'type' of temperature variations currently existing in the area in question. The temperature situations included are day/clear, night/clear, cloudy/windy and regional pattern. Thirdly, the model uses empirical formulae to calculate which temperature values should be valid for the segments along the road.

The county of Halland, in which the model has been implemented, was divided into three parts, North, Middle and South. The areas overlap each other to give efficient coverage. Each part has its own reference stations to fulfil the required demands about small topographical influence and a high degree of exposure.

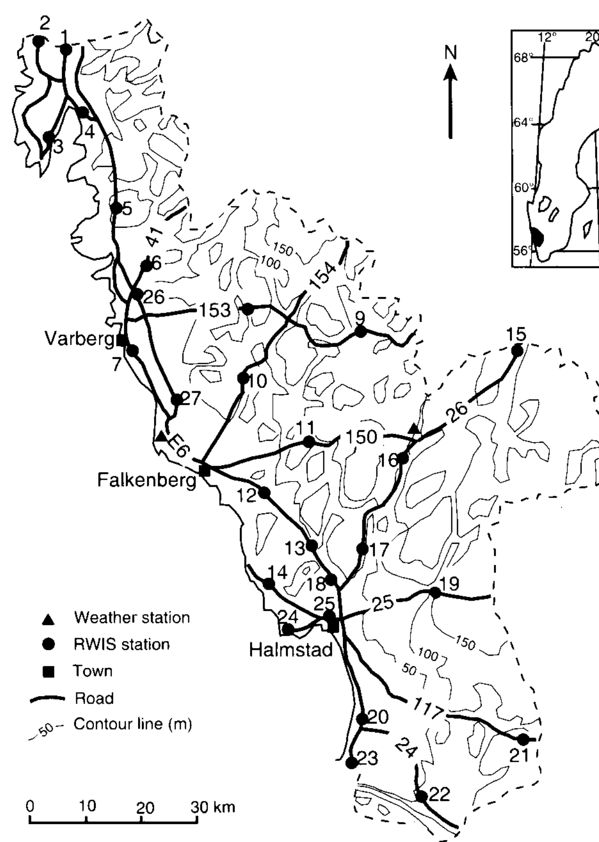

Figure 1. Map of the study area; the county of Halland.

3. Study area

The county of Halland is situated in the south-western part of Sweden between latitudes 56° and 58° N. In this area, 27 RWIS stations are used for the surveillance of winter road conditions. The stations are located along the main roads in the county as shown in Fig. 1. Halland is characterized by a varying topography. In the western part, the coastal zone is flat, mainly arable land. To the east, the open country is succeeded by a hilly, forested landscape. The climate in south-western Sweden is to a high degree determined by the west wind regime. This means that, especially during the winter period, the frequency of low pressure passages is very high. The regional climate is to a large extent influenced by the nearness of the sea. Another significant factor is the change in altitude which occurs approximately 10 to 15 km from the coast. The difference in height between the coastal zone and inland is more than 200 m in some parts.

The coastal zone is often affected by strong winds; further inland, the increasing relief reduces their strength. The precipitation pattern is characterized by a successive increase towards the eastern parts where the elevation increases. Another phenomenon which is important during ice-free winters is that the warm sea can generate a tongue of relatively warm air which reaches inland.

4. Test of the models

4.1 Day/Clear

The effect of screening as a factor causing large road surface temperature variations is connected to clear day conditions. The largest influence of screening, which can affect the risk of slipperiness, occurs during late autumn and early spring. Depending on such factors as orientation, extension and composition of the object causing a shadow pattern in combination with the position of the sun, the magnitude of the temperature differences between sun-exposed and shaded areas varies. Empirical studies using the abundant information supplied by the RWIS and thermal mapping show that it is possible to calculate the screening effect by knowing the orientation of the object and the solar elevation.

The variation in temperature difference between screened and sun-exposed sites, and how the temperature varies according to the time of year is clearly seen when comparing the magnitude of the difference between sun exposed and screened areas at different times of the year. The detail of the two thermal mapping on 5 February and 30 March, respectively, in Fig. 3 illustrates this effect.

This indicates that the greater the amount of incoming solar radiation, the greater the potential for a pronounced screening effect. Assuming this regularity between solar elevation and temperature deficit at screened locations, it is possible to use the solar elevation as a predictor of the road surface temperature difference between sun exposed and screened areas.

The maximum road surface temperature difference between screened and sun-exposed stretches can be predicted according to the solar elevation. The relation between solar elevation and RST_{diff} is expressed by the equation,

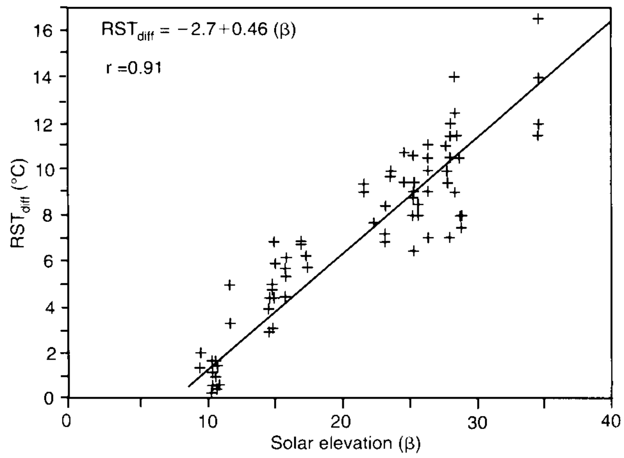

Figure 2. Maximum road surface temperature difference between sun exposed and screened areas as a function of solar elevation.

$$RST_{diff} = -2.7 + 0.46(\beta) \qquad (1)$$

where β is the solar elevation in degrees

Using the relation expressed by equation (1) it is seen that during December/January when the midday sun is lowest at approximately 10° above the horizon, the temperature difference is very small, just 2 °C. At the end of March, when β is 35°, the difference increases to more than 13 °C, Fig. 2. These calculated temperature differences are in good agreement with those shown by Fig. 3.

In the model, the variation in the solar elevation throughout the season is calculated. The progress of the increasing solar elevation at noon changes according to a non-linear relation throughout the year. The change of the daily variation in solar elevation is given by

$$\sin\beta = \sin\phi \sin\delta + \cos\phi \cos\delta \cos h \qquad (2)$$

where ϕ is the latitude of the site, δ is the solar declination and h is the hour angle.

The declination (δ) as a function of the day of the year (N) is given by

$$\delta = -23.4\cos(360(N+10)/365). \qquad (3)$$

The maximum solar elevation at noon is calculated using $\beta = (90° - \phi) + \delta$.

For practical use, when adopting the local climatological model, it is necessary to distinguish six different types of screening situations to observe this effect along a road: S0 — sun exposed, S1 — screened during the morning hours, S2 — screened at noon, S3 — screened in the afternoon, S4–S1 and S2 in combination, S5–S2 and S3 in combination, S6–S1 and S3 in combination.

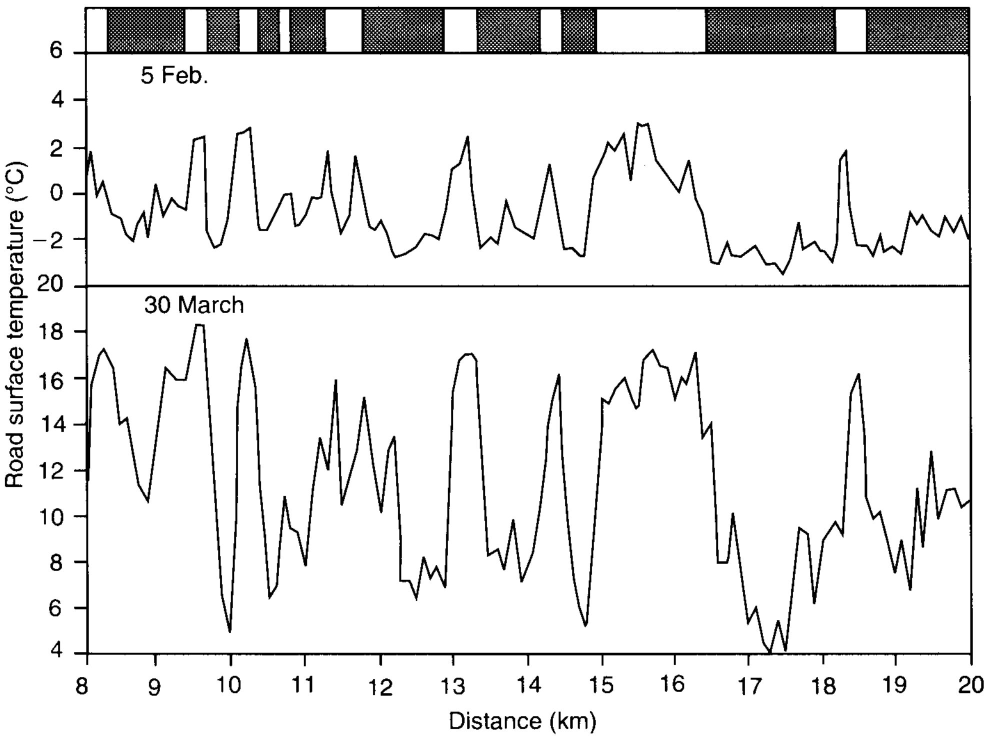

Figure 3. Detail of thermal mapping along road No. 25, from 5 February and 30 March, 1992. The screened areas are marked on the top of the figure.

Large areas of Halland are affected by screening. However, most of the screening effect is caused by dense coniferous forest and, in some cases, the screening effect is strengthened by local topography. Screening by road rock cuts occurs in only a few places.

A good example of how the RST can vary along a road as a result of alternating screened and sun-exposed areas is given by the detail from thermal mapping in Fig. 3. The two sections are from thermal mapping carried out just after noon along road No. 25 east of Halmstad on 5 February and 30 March, respectively.

Three main features regarding the effect of screening on the RST are obvious. Firstly, that the drop in temperature associated to the screened section occurs very distinctly within a short distance and, secondly, the shadow pattern is kept throughout the season. Thirdly, the difference between sun exposed and screened areas grows according to the established relation with the increasing solar elevation.

If clear/day conditions should be valid, the recorded RST_{diff} between reference stations and screened stations must fulfil the requirements which are stipulated by the algorithm in the LCM. The limits for the formulae, which determine whether there is a screening effect or not, are adjusted according to the time of the year and time of the day to allow for variations in solar elevation.

4.1.1 Control measurements

The test of the day/clear temperature pattern was performed for the roads in Halland. Regarding the screening effect, the results from road Nos. 150, 26 and 25 are presented in Tables I, II and III. The roads were thermally mapped during three different periods, 5 February, 4 March and 30 March 1992. The control measurements were carried out during the forenoon and at noon. The results from these measurements (meas) are compared to the calculated values (calc). The weather conditions in these situations are characterized by clear sky and moderate winds.

The result from the day/clear situations shows that the segmentation matches well with the temperature pattern which is generated by the alternation between screened and sun exposed. Comparing the calculated RST_{calc} and the measured RST_{meas} it is seen that the differences vary depending on the time of day and the time of year when the control measurements are performed.

The best correlation between calculated and measured is found close to noon. This can be explained by the orientation of the roads which favours distinct shadow patterns during the midday hours. There is also a tendency towards an increased error when the solar elevation is very high late in the season. During this period the slope of the sun-exposed road has a great influence on the insolation which makes the RST of the sun-exposed parts vary. When the sun-exposed areas (S0) get temperatures in the range well above +10 °C the accuracy of the calculated temperature is somewhat worse. It should be pointed out that the accuracy of the temperature calculation of the S0 segments is of no importance when the model is in use for winter road surveillance. However, when testing the day/clear temperature pattern, it is found that the difference between calculated and measured values is generally less than 1.0 °C throughout the season. An important result is

Table I. Comparison between measured and calculated road surface temperatures along road No. 150 for clear day conditions.

Segment No.	Distance (km)	Type	5 Feb. Calc	5 Feb. Meas	5 Feb. Diff	4 March Calc	4 March Meas	4 March Diff	30 March Calc	30 March Meas	30 March Diff
1	00–12	S0	3.3	3.0	0.3	12.5	12.0	0.5	17.3	17.5	0.2
2	12–15	S1	−1.9	−2.2	0.3	12.5	13.0	0.5	17.3	17.0	0.3
3	15–18	S2	−1.9	−3.0	1.1	6.6	4.0	2.6	4.0	6.0	2.0
4	18–19	S3	3.3	3.0	0.3	4.0	4.0	0.0	4.0	6.0	2.0
5	19–36	S1	−1.9	−3.0	1.1	12.5	12.0	0.5	17.3	17.0	0.3

Table II. Comparison between measured and calculated road surface temperatures along road No. 26 for clear day conditions.

Segment No.	Distance (km)	Type	5 Feb. Calc	5 Feb. Meas	5 Feb. Diff	4 March Calc	4 March Meas	4 March Diff	30 March Calc	30 March Meas	30 March Diff
1	00–05	S0	1.8	1.0	0.8	12.6	12.0	0.6	7.5	10.0	2.5
2	05–10	S6	−2.4	−1.5	0.9	6.8	4.0	2.8	−0.1	2.0	2.1
3	10–12	S0	1.8	1.0	0.8	12.6	12.0	0.6	7.5	10.0	2.5
4	12–13	S6	−2.4	−1.5	0.9	12.6	12.5	0.1	−0.1	2.0	2.1
5	13–16	S0	1.8	1.0	0.8	12.6	13.0	0.4	7.5	10.0	2.5
6	16–25	S1	−2.4	−2.8	0.4	12.6	12.0	0.6	0.1	2.0	1.9
7	25-29	S0	1.8	1.0	0.8	12.6	13.0	0.4	7.5	10.0	2.5
8	29–39	S4	−2.4	−2.5	0.1	6.6	4.0	2.8	0.1	2.0	1.9

Table III. As Tables I and II but for road No. 25.

Segment No.	Distance (km)	Type	5 Feb. Calc	5 Feb. Meas	5 Feb. Diff	4 March Calc	4 March Meas	4 March Diff	30 March Calc	30 March Meas	30 March Diff
1	00–10	S0	3.5	4.0	0.5	14.5	13.0	1.5	16.8	18.0	1.2
2	10–11	S2	−1.7	−2.0	0.3	8.2	7.0	1.2	3.4	4.5	1.1
3	11–12	S0	3.5	4.0	0.5	14.5	13.0	1.5	16.8	18.0	1.2
4	12–15	S1	3.5	4.0	0.5	14.5	13.0	1.5	16.8	18.0	1.2
5	15–16	S0	3.5	4.0	0.5	14.5	13.5	1.0	16.8	17.5	0.7
6	16–17	S1	3.5	4.0	0.5	14.5	13.0	1.5	16.8	17.0	0.2
7	17-19	S5	−1.7	−2.0	0.3	8.2	7.0	1.2	3.4	4.0	0.6
8	19–27	S0	3.5	4.0	0.5	14.5	13.5	1.0	16.8	18.0	1.2

that calculations of the RST at the screened segments (S1-S6) give good agreement with the measured values.

4.2 Cloudy/windy

Depending on the temperature change with height, the atmosphere can be classified as unstable, neutral or stable. If the atmosphere is neutral the temperature lapse rate is equal to 1 °C/100 m; in an unstable atmosphere the temperature change with height is larger and the opposite is the case for a stable atmosphere. Factors with an influence on the vertical temperature gradient are the wind and the amount of cloud.

A relationship between the meteorological conditions and the type of stability was presented by Pasquill (1961) (Table IV). This type of relationship is widely used in connection with calculations of concentrations of air pollution. However, this knowledge can also be used in the LCM as a base for decisions concerning the type of temperature formulae that should be used.

Under daytime conditions, insolation is a most important parameter. Several studies have demonstrated a close relationship between type of clouds and rate of insolation, e.g. Nielsen *et al.* (1981). However, the road surface temperature is affected in a somewhat different way compared with the air temperature. Studies by

Table IV. Meteorological conditions defining stability types according to Pasquill (1961).

Surface wind ($m\ s^{-1}$)	Daytime insolation: Strong	Daytime insolation: Moderate	Daytime insolation: Slight	Night-time: Thin overcast or >4/8 low cloud	Night-time: Cloud <3/8
<2	A	A–B	B	E	F
2–3	A–B	B	C	E	F
3–4	B	B–C	C	D	E
4–6	C	C–D	D	D	D
6	C	D	D	D	D

A = Extremely unstable; B = Moderately unstable; C = Slightly unstable; D = Neutral; E = Slightly stable; F = Moderately stable.

Bogren (1991) and Gustavsson and Bogren (1991) have shown that large variations in RST can exist despite the fact that the difference in air temperature is very small. The result is that the model uses the formulae for clear day conditions for all wind speed classes listed in Table IV. The variation owing to decreased insolation/increased amount of clouds is dealt with from comparison of the temperature differences between reference locations, i.e. in sun-exposed areas, and screened locations.

Under night-time conditions, a clearer distinction exists between the different types of formulae to be used in the model. If the cloudiness is less than 3 oktas and the wind speed is below 5 m s^{-1} the model uses the algorithm for clear night-time conditions. This part of the model further includes a division made owing to the prevailing wind speed during the latest 3 hours, determined from RWIS stations with wind-speed sensors.

The regional pattern is used in the LCM if the criteria for temperature decrease with height is not fully achieved or if the temperature pattern is too complex to be classified as belonging to any of the other types. In the case of regional pattern, the local RWIS station is used as a base for the extrapolation of the temperatures to be valid for parts of road.

The conclusion that can be drawn from Table IV is, however, that the formulae used for neutral and unstable conditions are several. Especially with a relatively high wind speed and reduced insolation during the day, or reduced cooling during the night, the criteria for the conditions related to 'variation in altitude' are normally fulfilled. Another important matter is that cloudy, windy weather situations are very frequent in southern Sweden which makes this part of the model a most important subject to study in more details.

The temperature lapse rate can be determined from temperature measurements on towers, masts, etc. However, RWIS stations sited on different altitudes can also be used to determine the lapse rate. Several stations must be included in the calculation and it is also important that the formula is limited to a relatively small area as local variations in the weather can have a large effect on the temperature.

In the model, the correlation coefficient is used as a control for the calculations. The correlation between temperature and variation in altitude must be high for the model to calculate the temperature for stretches of roads according to this division. Furthermore, a division is made according to the calculated lapse rate, i.e. the lapse rate must be greater than a fixed value if the model should use this part.

As previously mentioned, the amount of cloud and the prevailing wind speed are most important factors determining the temperature lapse rate. The following example shows the development from a scattered temperature pattern (regional pattern in the LCM) to a fully mixed atmosphere — neutral and later unstable air stratification. The stations in the northern part are used to illustrate the development, as well as the temperature pattern revealed by the recorded road surface temperature at the RWIS stations. In total, 8 stations were used for the calculation of the temperature lapse rate and the correlation coefficient for the time period 0200 to 1600 hours, Figs 4 and 5. The wind speed recorded for the same time period at station 7 is shown in Fig. 6.

The meteorological conditions during this episode (1 to 2 December 1990) were characterized by a change in the weather. During the evening of 1 December, the sky was clear and a light wind was blowing, i.e. large temperature contrasts developed owing to the local

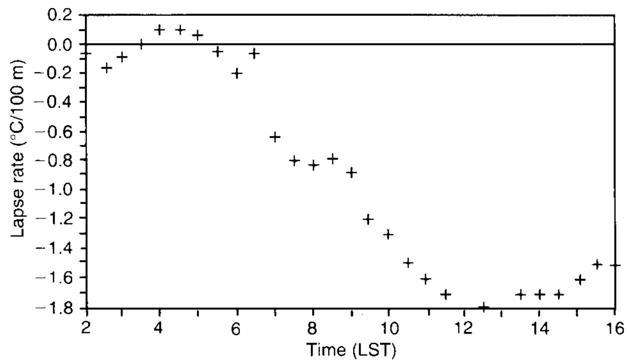

Figure 4. Plot of calculated temperature lapse rate for the northern stations in Halland, 2 December 1990.

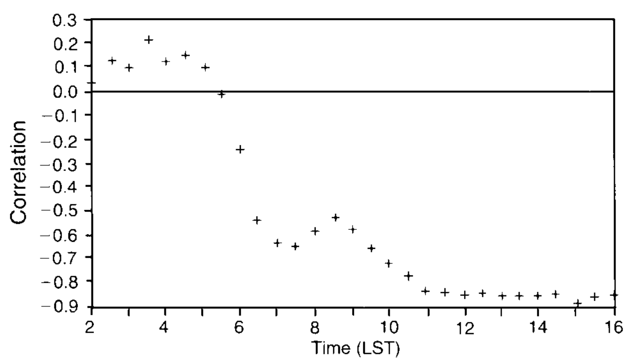

Figure 5. The correlation between height and road surface temperature for 2 December 1990.

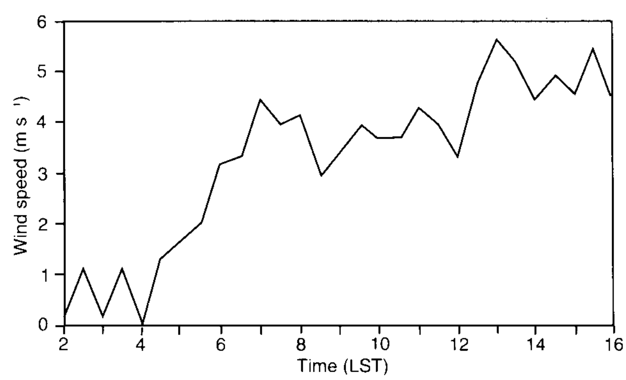

Figure 6. Wind speed recorded at station 7 for 2 December, 1990.

climatological environment and other factors near the different station sites. A front reached the western part of Sweden early the following morning. The wind speed increased from 1–2 m s^{-1} to 4–6 m s^{-1} and the amount of cloud changed from no cloud to overcast conditions. The calculated temperature lapse rate shows that, during the first hours of the weather change, the temperature variations are not related to the variation in altitude. This is further confirmed by the correlation coefficient between height and RST. During periods with low correlation and a complex temperature distribution, the model uses the regional pattern for calculation of the variation along stretches of road. As the correlation increases and the lapse rate indicates a temperature decrease with height, the model chooses the part of the LCM dealing with variation in altitude. From comparison of the data presented in Figs 4, 5 and 6 it is obvious that a close relation exists between the factors. A relatively high wind speed leads to a mixed atmosphere, and as the lapse rate increases the correlation increases as well.

4.2.1 Control measurements

Several temperature measurements have been carried out under cloudy, windy conditions, and the roads from the coastline towards the county border in the east were specially chosen for study; they were chosen because a rather large change in altitude occurs here.

A height profile for road No. 25 is shown in Fig. 7 together with a recording of the RST during 26 February 1992 at 1900 h (Fig. 8). The measurement started outside of Halmstad, at 20 m above sea level and ended at the county border at a height of approximately 150 m AMSL. A distinct change in altitude occurs at 16 to 18 km from the starting point.

The difference in road surface temperature is equal to 1 °C, a drop from 3.8 to 2.8 °C. However, the drop in RST is not only controlled by the regional variations in altitude, other small variations have an effect on the temperature distribution.

In general, there is a good agreement between height and surface temperature. Additional factors which influence the surface temperature is the relative openness around the road, i.e. the occurrence of trees and woods. Another important factor is the history of the surface temperature. The measurement shown in Fig. 8 was conducted a few hours after a change in cloud amount, and the effect from the weather type preceding the measuring trip also has some influence on the temperature pattern. A calculation of the temperature lapse rate from the RWIS stations in the actual area shows a good agreement with the pattern depicted in Fig. 8. The temperature difference between station 14, sited close to the coastline, and station 19, located close to the county border in the eastern part of the study area, amounts to 0.9 °C. This temperature difference was kept during the night owing to the stable weather situation. From analyses of temperature recordings from the RWIS station in the middle part of the county it is also clearly seen that a change in weather occurred during the day as

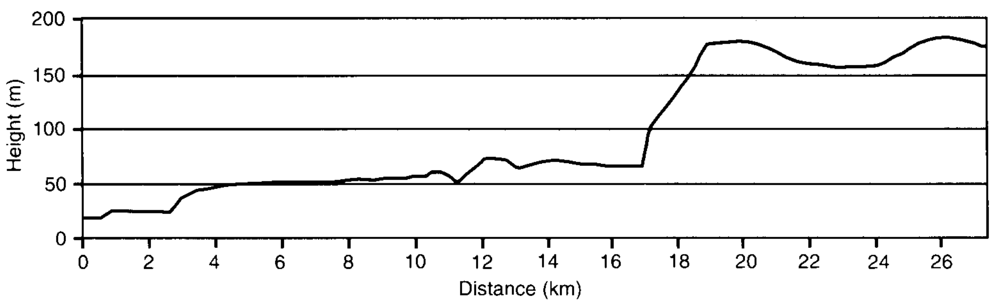

Figure 7. Height profile road for No.25.

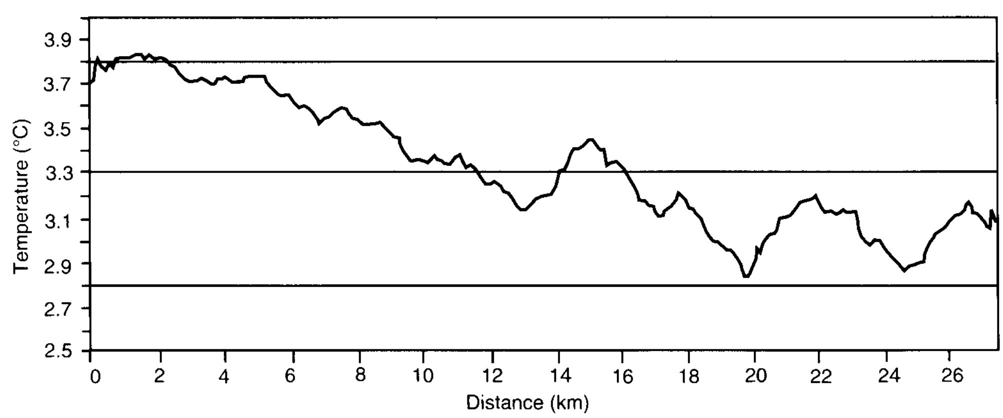

Figure 8. Surface temperature of road No. 25 recorded on the 26 February 1992 at 19:00h.

previously discussed for the measurement along road No. 25.

4.3 Temperature development

Repeated temperature measurements were carried out along the same routes during periods with falling temperature. These measurements have been analysed in order to determine the cooling rate of both the air and the road surface. Temperature recordings from RWIS stations show that the temperature development for the air as well as for the surface differ during the cooling period. The cooling rate (Cr) can be defined as

$$Cr = dT\, dt^{-1} \quad (4)$$

were dT is the change in air or RST over the time period considered (dt).

It is obvious from analyses of recordings from different RWIS stations that the cooling rate is influenced to a large extent by the local climatological factors such as topography, sky-view factor, degree of wind shelter, etc. A study of factors influencing the cooling rate for both the air and surface is presented in Gustavsson (1993). It was shown that, for example, the sky-view factor had a great influence on the development of the surface temperature during clear nights but the effect on the air temperature was very small.

The air temperature pattern along road No. 153 in the northern part of Halland is shown in Fig. 9. The two curves represent measurements carried out at 2100 h (the upper curve) and at 0600 h the following morning. The patterns of the two measurements are very similar and it is clear that the local degree of wind shelter and the local topography had a pronounced effect on the air temperature.

The segments for road No. 153 are also included in Fig. 9 for clear night-time conditions. The resemblance between the temperature pattern and the different segments is most evident. The lowest air temperatures were to be found in the small valleys that the road crosses and in open wind-sheltered locations in the forested eastern part of the road.

The difference in air temperature between the two measuring trips shows that the cooling rate differs between the segments along the discussed road (Fig. 10). In the figure, the zero values indicate that no change in temperature takes place during the 9 hours which have passed since the first recording was carried out. Negative values show that the area has been relatively colder.

A very important conclusion that can be drawn from the data presented in Figs 9 and 10 is that the relation between the segments developed during the first measuring trip is kept throughout the night. Another important conclusion is that the relative position, the borderlines between the segments, does not change during the cooling period. These two facts are essential to the basis of the model as they show that no alternation of the segments should be made in relation to the length of the cooling period and that the formula linked to each segment could be kept during the night. However, it is important that it is possible to change the relative difference between the segments, i.e. the formulae should not include static correction terms; instead a dynamic correction is required.

The recordings of the RST are shown in Fig. 11 for the same occasion as in Fig. 9. Measurements of the RST with the use of infrared equipment are very sensitive to small variations in the emissivity as well as other factors affecting the surface but not the real temperature. In order to exclude RST values which do not represent the true temperatures, the average temperature values have been used in the analyses. Running means of 10 values were used in the calculation and these are the data presented in Fig. 11.

The temperature distribution along road No. 153 is very similar for both measuring trips. The resemblance between the pattern in Figs 9 and 11 (air and RST) is also clearly seen, i.e. there is a close correlation between segments with a low air and road surface temperature.

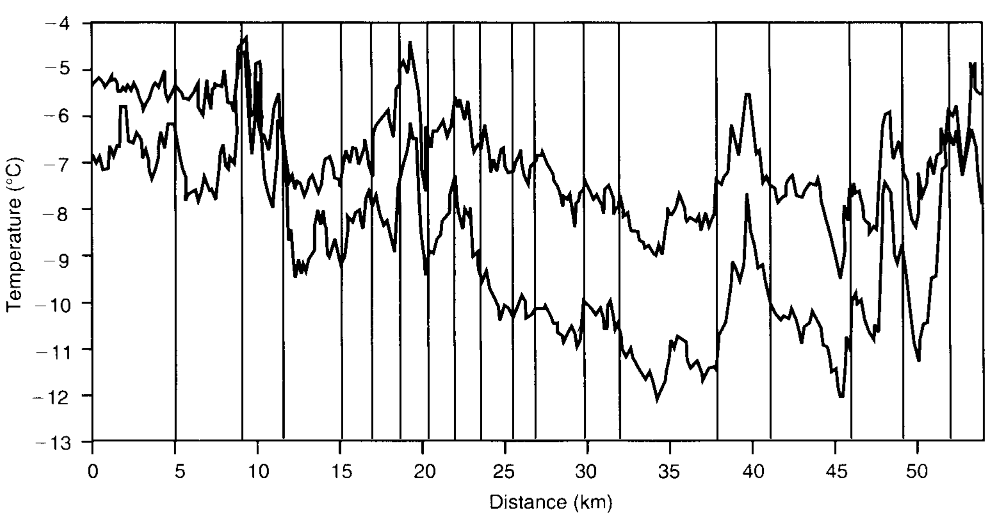

Figure 9. Air temperature pattern along road No.153 at 2100 h and at 0600 h. The vertical lines mark the different segments along the road.

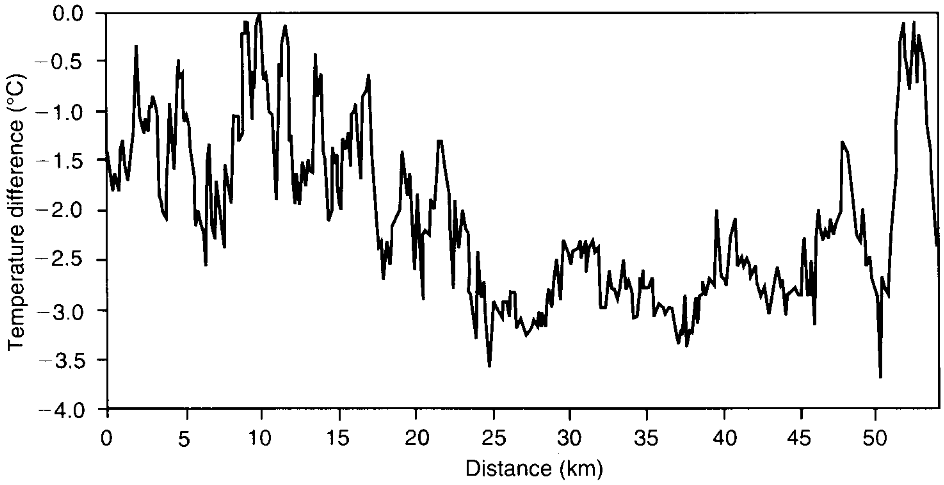

Figure 10. Difference in cooling rate between segments along road No. 153. The zero value indicate that no change in temperature takes place.

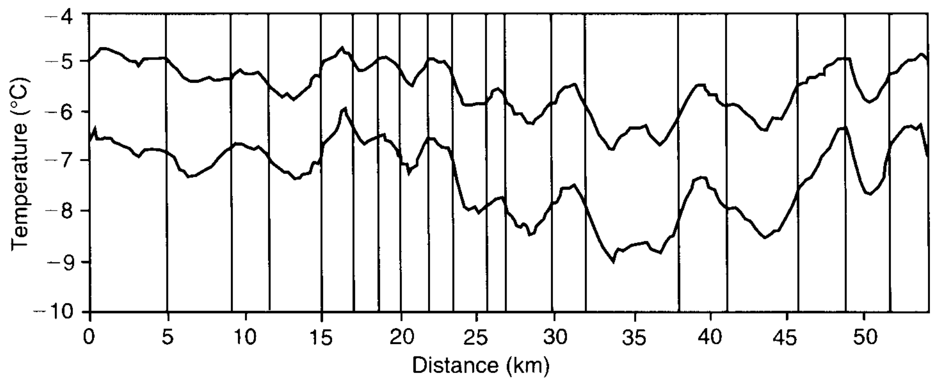

Figure 11. Recording of road surface temperature along road No.153, see also Fig. 10.

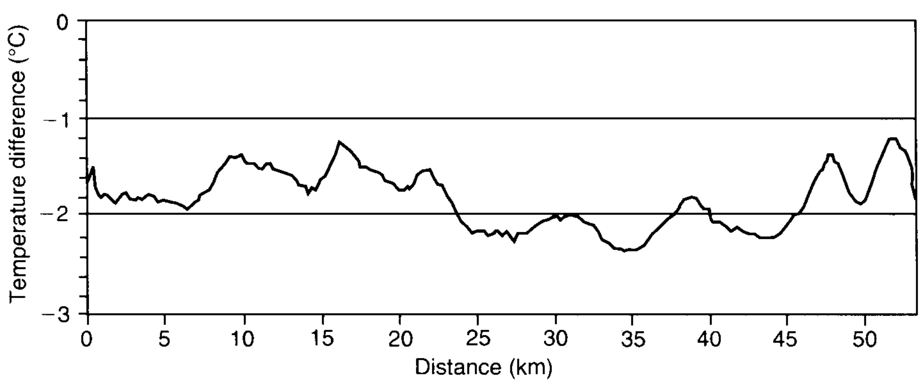

Figure 12. Difference in road surface temperature between measurements at 2100 h and 0600 h respectively.

As for the air temperature, the difference in RST was calculated between the two measuring trips, Fig. 12. It is clearly seen that the cooling rate differs between the segments which is in good agreement with the result shown for the air temperature. The mean values for each segment were used to calculate the change in temperature from 2100 h to 0600 h as well as the resulting cooling rate for each area, Table V.

The cooling rate varies from 0.15 to 0.28 °C h^{-1}. The largest cooling rate is associated with the area which has the lowest temperature during both measurements. This indicates that the contrast in surface temperature becomes larger with a longer cooling period. The areas with the smallest *Cr* value are small hills and areas with trees close to the road side. These two factors both lead to a reduced cooling. On hills, the accumulation of cold

Table V. Calculated cooling rate for the measurements along road No. 15 and the relative difference in temperature between the segments.

Segment	Temp. (°C)	Diff.* (°C)	Temp. (°C)	Diff.* (°C)	Cooling rate (°C h^{-1})
1	−4.9	0.1	−6.7	0.5	0.2
2	−5.4	0.6	−7.3	1.1	0.2
3	−5.3	0.5	−6.7	0.5	0.15
4	−5.6	0.5	−6.7	0.5	0.19
5	−4.8	0.0	−6.2	0.0	0.2
6	−5.2	0.4	−6.6	0.4	0.15
7	−4.9	0.1	−6.4	0.2	0.17
8	−5.4	0.6	−7.2	1.0	0.2
9	−5.0	0.2	−6.6	0.4	0.18
10	−5.8	1.0	−8.0	1.8	0.24
11	−5.5	0.7	−7.8	1.6	0.25
12	−6.2	1.4	−8.4	2.2	0.24
13	−5.5	0.7	−7.5	1.3	0.22
14	−6.4	1.6	−8.9	2.7	0.28
15	−5.5	0.7	−7.5	1.3	0.22
16	−6.3	1.5	−8.5	2.3	0.24
17	−5.2	0.4	−6.5	0.3	0.14
18	−5.8	1.0	−7.5	1.3	0.19
19	−5.2	0.4	−6.5	0.3	0.14

*Diff = Difference in RST versus segment No.5

air is prevented and trees close to the road side obstruct cooling by radiation.

The relative temperature differences along the road are also included in Table V. This difference was determined in relation to the warmest segment, No. 5, on both occasions. During the first trip, the maximum difference amounted to 1.6 °C but the average value is less than one degree. The relative difference in RST increased during the second trip compared with the recording carried out during the evening. The maximum difference was 2.7 °C and several segments were more than 1 °C colder.

The knowledge obtained from this analysis is essential making a temperature prognosis with the use of the LCM. However, the integration of an external prognosis, and the corrections that must be made in the model, are subjects which need to be studied further before such a function could be included in the Local Climatological Model.

5. Discussion

Tests of the local climatological model which were performed in Halland show that by use of such a model it is possible to increase the information available from the RWIS. The local climatological model gives the advantage of temperature information for entire stretches of road based on the measurements at the RWIS stations together with the different topographical segments along the roads.

When implementing the model into a new area, it is necessary to have access to high-quality thermal mapping in order to segment the road. Thermal mapping must also be available for all the different weather conditions which are included in the model. Results from thermal mapping also serve as a complement to the historical RWIS data when the different formulae are determined for the different segments and limits for the varying weather conditions are established.

The results of the different tests reported in this study show that calculated temperatures along the stretches of road are in good agreement with control measurements. The evaluation shows that the design of the criteria which are used at present are well suited to separate the thermal pattern at the main weather categories which are used today. In the discussion of how well the measured values fit the calculated values it is important to include the question of the spatial resolution demanded.

The formulae which are used for the calculation of the temperature pattern allows a higher resolution on the temperature calculation than is needed. For practical purposes one must limit the length of the different segments on the different occasions to not less than 500 m. A higher resolution is not applicable when a dense network is surveyed. This means that the average conditions within the segment must be established.

However, it is necessary to develop the functions to take all possible temperature patterns into account. A possible way of developing the control criteria would be to include a comparison with historical temperature distributions, i.e. a comparison with statistically verified temperature patterns is made in the LCM before the data is extrapolated to be valid for stretches of road.

Further work with the model will include an addition of a road surface temperature prognosis to the present model. To make a prognosis have good validity, it is important to include some sort of external forecast giving information of, for example, cloudiness. It is especially important to study further the variation in such factors as cooling rate to be able to determine the difference in temperature development for the segments along roads which must be used in connection with the temperature forecast which is given for the specific RWIS station.

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Low-level wind shear at cold fronts

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1. Introduction

This study was made to investigate not only the values of vertical wind shears commonly encountered near to, and ahead of cold fronts, but also their time history and persistence.

A brief survey was also undertaken of some of the extreme values of shear that occur together with their frequency and persistence.

To this end, wherever possible, active cold fronts were considered. Fourteen cases were examined, namely those of 15/3/88, 22/3/89, 10/2/90, 13/3/90, 5/6/90, 21/2/91, 26/2/91, 6/4/91, 26/6/91, 11/7/91, 3/10/91, 19/12/91, 9/5/92 and 16/11/92. Three of these cases (21/1/91, 26/2/91 and 6/4/91) were found to have split-front characteristics.

2. Method

Raw wind data comprising azimuth, elevation and slant range from radiosonde and radar wind soundings are received by Cossor radar and processed to give spot winds; in the case of the Mk. III radiosonde system (1988 to 1990) these were received every 7 seconds and with the Mk. IV system (after 1990) they were received every 2 seconds.

Spot wind values at 150-metre intervals are measured at Larkhill on a routine basis and these were used to calculate the wind shears. To increase the accuracy, a smaller height interval was tried but found to be unsatisfactory as it introduced abnormally high shear values. Crossley (1962) has in fact quoted a source (unpublished) which substantiates such values, the argument being that the smaller the height interval taken the greater is the trend for the vertical shear to increase excessively to unrealistic values, due to its increased dependency on the local eddy structure.

In order to calculate the times of occurrence of shears above the surface relative to the cold front it was necessary to construct a vertical profile of the front on to a graph having height as the vertical axis and time as the horizontal axis. This was done by plotting a hodograph of the first sounding done in the air mass immediately behind the cold front, in order to establish the height of the frontal surface at this time.

Shears were measured in kn/1000 ft from 1000 to 5000 ft AGL, at 500 ft (150 m) intervals, taking both speed and direction into account. Data below 1000 ft AGL were not used since these values often had to be estimated due to the time taken to lock-on to a radar target. It should also be noted that the vertical shears measured are apparent rather than true values, being the difference between two radar-sensed winds averaged over a layer.

Owing to the limited period each day over which flights were done for operational requirements, it was found that there was a time window of about ten hours (from T−7 to T+3, where T is time of passage of surface cold front) outside of which wind shear data was unobtainable or unreliable.

3. Results

3.1 Mean value

Shears for the fourteen cases were meaned and varied from around 3 kn/1000 ft at distances greater than

200 miles from the front and at levels above 2500 ft, to 10 kn/1000 ft near the bottom of the boundary layer. This latter value was taken as a suitable lower limit for the study which follows.

The mean shears are calculated using the highest value found (when this exceeds 10 kn/1000 ft at a specific height). In Table I, column three (No. of cases) refers to the sample size (maximum 14 occasions) used to calculate mean shears.

3.2 Low-level jet

Fig.1 shows mean start and finishing times of shears ≥10 kn/1000 ft, for the fourteen cold front cases and plotted at eight spot heights between 1000 and 5000 ft. Pecked lines are isopleths of shears ≥20 kn/1000 ft, i.e. the zone where and when extreme values occur. This higher limit is discussed in section 3.5.

A vital factor in the development of low-level jets is the existence of a tongue of warmer and moister air just ahead of the cold front due to the increased gradient often found within about 60 miles of many cold fronts. One of the effects of this warm, moist tongue is to create a reversal of horizontal temperature gradient fairly close to the cold front (i.e. temperature rising somewhat as the cold front approaches), extending up to around 6000 ft AGL. This has the effect of causing the geostrophic wind to decrease with height, reaching a minimum at or close to the 10 000 ft level near the top of the thermally driven convective layer. A jet maximum is thus created lower down (Browning and Pardoe 1973).

3.3 Persistence

A similar pattern to the time-history figure is evident when a study of the shear persistence scatter diagram (Fig. 2) is made. It is interesting to note the high incidence of short-lived shears near to and just above the low-level jet core; these shears are probably associated with the maximum jet-core speed.

3.4 Distribution

The relationship between height interval and shear values was discussed briefly in section 2. It was thought pertinent to include some examples of this from the investigation. Two cases were examined and the results are tabulated in Table II. In addition, the relationship between height interval and shear persistence was investigated and, as can been seen below, this gave the reverse effect to shear size, though this only became apparent with the smallest height intervals.

3.5 The frequency and persistence of extreme vertical wind shears with values ≥20 kn/1000 ft

Fourteen cases were examined out to an average distance of 300 miles from the cold fronts. In five cases no extreme values were reached in the layer 1000 to 5000 ft AGL. In the remaining nine cases there was a

Table I. Statistics on magnitude of shears >10 kn/1000 ft

Height	Mean shear	No. of cases	Max. shear
5250	14.0	4	18.0
4750	12.8	8	19.5
4250	11.4	12	15.0
3750	12.6	11	16.0
3250	15.4	10	22.0
2750	14.7	10	20.0
2250	15.0	11	20.0
1750	15.4	13	21.0
1250	16.7	12	28.0

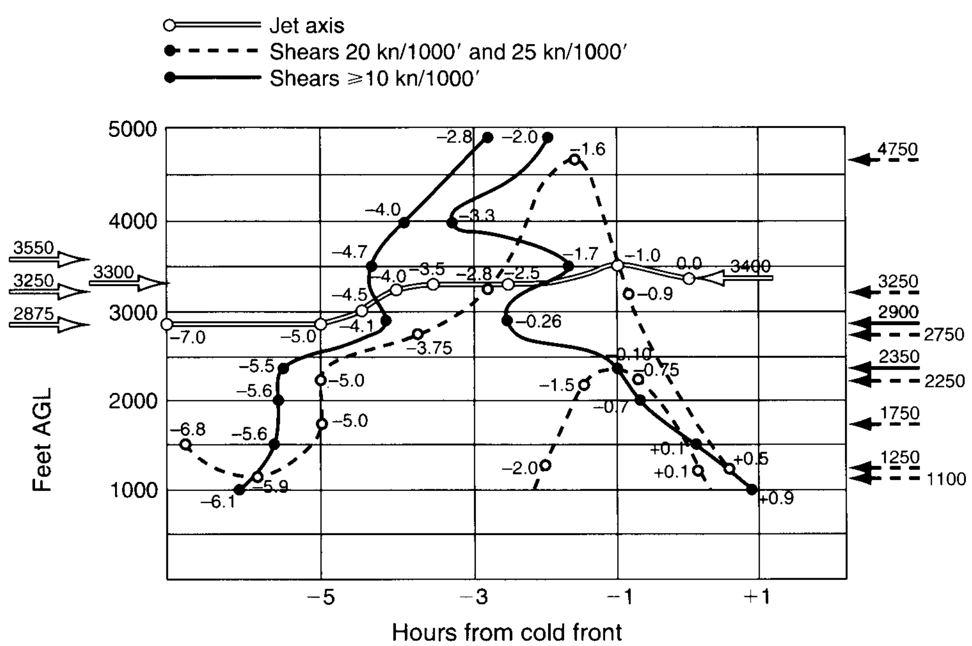

Figure 1. The time-history of shears ≥10 kn/1000 ft prior to the passage of ana-cold fronts.

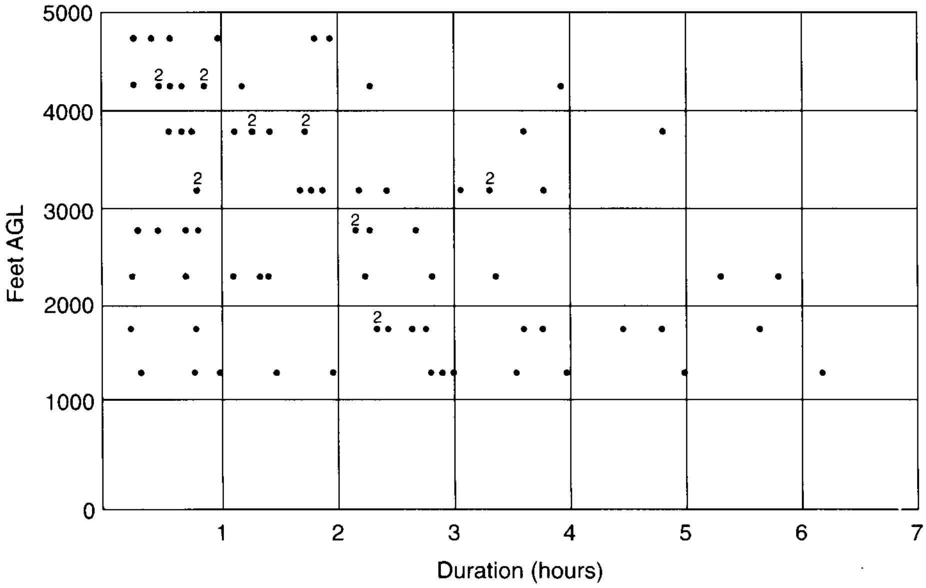

Figure 2. Persistence of shears at different heights.

Table II. Two examples of shear size and persistence (all times UTC)

Shear size in kn/1000 ft on 15 March 1988

Height\Time interval (ft)	0700	0900	1100	1300
1000	3	4.5	7	10
500	5	6	10	12
100	20	16.5	16.5	33

Shear persistence in kn/1000 ft on 15 March 1988

Height\Period interval (ft)	07–09	09–11	11–13	Mean (07–13)
1000	1.5	2.5	3	2.3
500	1	4	2	2.3
100	3.5	0	16.5	6.7

Shear size in kn/1000 ft on 15 March 1988

Height\Time interval (ft)	0700	0900	1100	1300
1000	10	4.5	9.5	5.5
500	11	5	12	14
100	16.5	11	23.5	20.5

Shear persistence in kn/1000 ft on 15 March 1988

Height\Period interval (ft)	07–09	09–11	11–13	Mean (07–13)
1000	5.5	5	4	4.8
500	6	7	2	5
100	5.5	12.5	3	7

remarkably even distribution both temporally and spatially of extreme values.

It was found that those furthest from the cold front had durations varying from 15 to 45 minutes, while those nearer the frontal boundary were a little more persistent lasting from 45 to 90 minutes.

As might be expected from their high values, the frequency of extreme shears was low, in the layer 1000 to 2000 ft where the highest values were most common, extreme shears accounted for only 3.6% of total occasions.

4. Anomalous case history

In the thirteen of the cold front cases considered, the presence of the low-level jet was apparent in varying strengths close to or slightly above the 3000 ft level.

There was, however, one occasion (21 February 1991) when this pre-frontal jet was absent. An examination of the wind profile ahead of the front on this occasion showed only very weak warm advection at all levels to 5000 ft, suggesting an absence of the characteristic tongue of warm air. In view of the drier and somewhat cooler track than usual of the low-level flow (southerly rather than west or south-westerly as in other cases), this conclusion seems reasonable. Also, this particular front was identified as having split front characteristics with much drier air probable above about 6000 ft ahead of it, little significant precipitation falling through the lower layers just ahead of the front, and therefore less moisture available to help jet development.

5. Conclusions

1. Shears below 5000 ft occurred in two main bands: (a) within the boundary layer (below 2000 ft AGL) where values up to 28 kn/1000 ft were recorded (15 March 1988) and (b) close to the low-level jet in the region of 3000 to 4000 ft AGL. Core wind speed maxima in this jet varied quite widely, a peak value of 70 kn was recorded some 30 miles ahead of the front on 15 March 1988.
2. In the zone 4000 to 5000 ft which lies above and beyond the effects of the low-level jet, shears were fewest and most short-lived.

3. The most persistent shear was found in the lowest layers where such shears also occurred most frequently. A secondary frequency peak was evident between 3000 and 4500 ft AGL though here it was generally much shorter at under 2 hours duration.

4. Extreme values of vertical wind shear showed little correlation in time or space with their position relative to the cold fronts, but those lying within 2 hours of the front tended to be a little more persistent than those more distant.

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A severe hailstorm in northern Greece

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Summary

On 15 June 1988, an unusually severe hail storm occurred over northern Greece. This storm produced hail in excess of 5 cm in diameter, and caused considerable damage to the Halkidiki region of Greece and the See of the Greek Orthodox Church on Mt. Athos. Surface observations and radar data archived by the Greek National Hail Suppression Project show that the storm was strongly tied to terrain influences.

1. Introduction

The Summer of 1988, here defined as the period between 15 April through 30 September, was particularly active over Greece. Hailstorms occurred more frequently, and hail was larger than experienced by the Greek National Hail Suppression Project during previous years (Rudolph *et al.*1989).

The purpose of this paper is to give a brief study of the activity on 15 June 1988 which produced, what is for Greece, exceptionally large hail. The changes which occurred in the synoptic environment over the preceding days are examined in as much detail as possible and the storm is followed across northern Greece through observations and radar data archived as the storm crossed the region.

There are three areas, referred to as Areas 1, 2, and 3, over which hail suppression operations are carried out over northern and central Greece. Areas 1 and 2, the two northern areas shown in Fig. 1, are supported by operations out of Thessaloniki International Airport. Operations for Area 3 are run from the facilities of the Greek Air Force Base at Larisa. The storm complex examined here tracked south-eastwards between Areas 1 and 2.

2. Synoptic-scale conditions

There were two particularly active periods during the 1988 season. The first occurred from 16–29 May and the second between 10 and 29 June. Here we examine the period 10–16 June with particular emphasis on 15 June 1988.

The synoptic-scale maps of the *European Meteorological Bulletin* indicate that no frontal systems affected

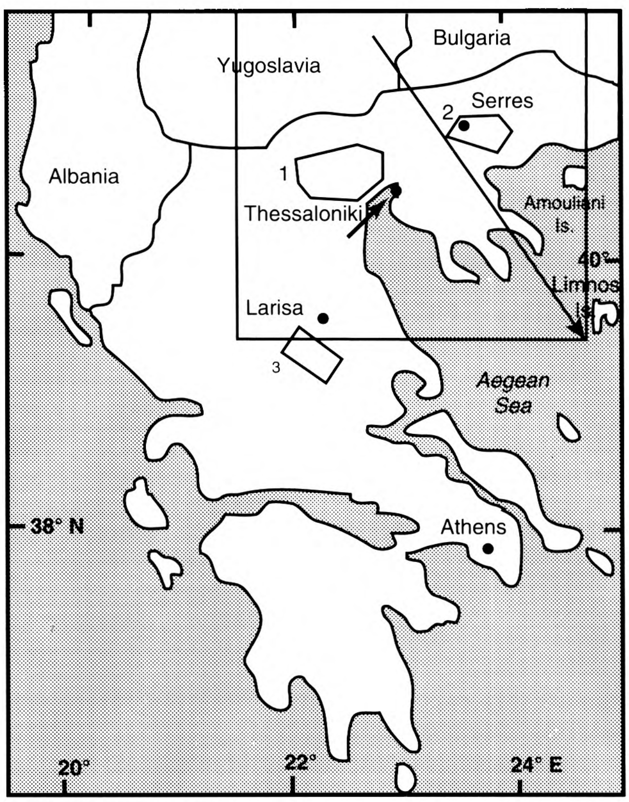

Figure 1. Hail suppression project areas in Greece. The storm track is indicated by an arrow between the project areas.

northern Greece during the period. The surface pressure field was relatively flat with a weak high pressure centre located over the Tyrrhenian Sea (the area between Corsica, Sardinia, Sicily, and Italy). The Cyprus low pressure centre, which forms during the Summer off the south-west coast of Turkey, was just beginning to form.

The mid-troposphere flow, as characterized by the 500 hPa chart, was weak and generally westerly with a broad band of low heights extending from off the west coast of Spain east-north-eastwards to the western part of former Soviet Union. By 0000 UTC on 13 June a jet streak associated with the subtropical jet (STJ) had begun to cross the Mediterranean Sea from Gibraltar to Rome. This jet streak was strengthening in response to ridging over north central Africa. By 0000 UTC on 14 June it extended far enough eastward that north-eastern Greece was located under confluent north-westerly flow. A jet streak in the polar jet stream (PJ) was dropping southwards across central Europe, from Denmark to Austria, and the merger of these two features over the Balkan Peninsula set the stage for strong convection over the region.

At 0000 UTC on the 10th, the STJ was located between the Madeira Islands and Gibraltar. On 11 June it extended from the Canary Islands to south-eastern Spain and by the 13th had advanced to central Italy. By 14 June a well defined STJ existed from the Canaries to central Italy and then south-eastwards across the Balkan and Asia Minor peninsulas. This orientation placed northern Greece under strong north-westerly flow, and as the PJ streak approached from central Europe and crossed the region on 15 June, Greece was placed under the left rear (entrance) region of the reinforced upper-level jet streak in a zone of upper-level confluence. Given subsequent events, it is safe to assume that this region was conducive to upper-level frontogenesis as is usually the case in such a situation (Holton (1979) p. 239). By 0000 UTC on the 16th, the STJ extended in a well defined band across the Mediterranean. After the 16th, it had drifted far enough south of the project areas that a short-lived lull in convective activity occurred over the next three days as the upper-level flow over Greece took on a more zonal nature. The advance of the jet streaks can be easily followed at the upper (300 hPa) levels as well (Fig. 2.)

During the same period, the 850 and 700 hPa charts show the development of ridging in both the height and thermal fields over the Mediterranean. They show that the ridge amplified and drifted eastward from an initial position west of Italy on the 10th to having its axis running along the west coast of the Balkan Peninsula by the 15th (Fig. 3). As the STJ pushed southward on the 16th, the low-level ridge retreated to the west of Italy

At the surface, on the synoptic scale, a weak high pressure system (1015 hPa) dominated the region over the entire period. This system was centred near Italy with

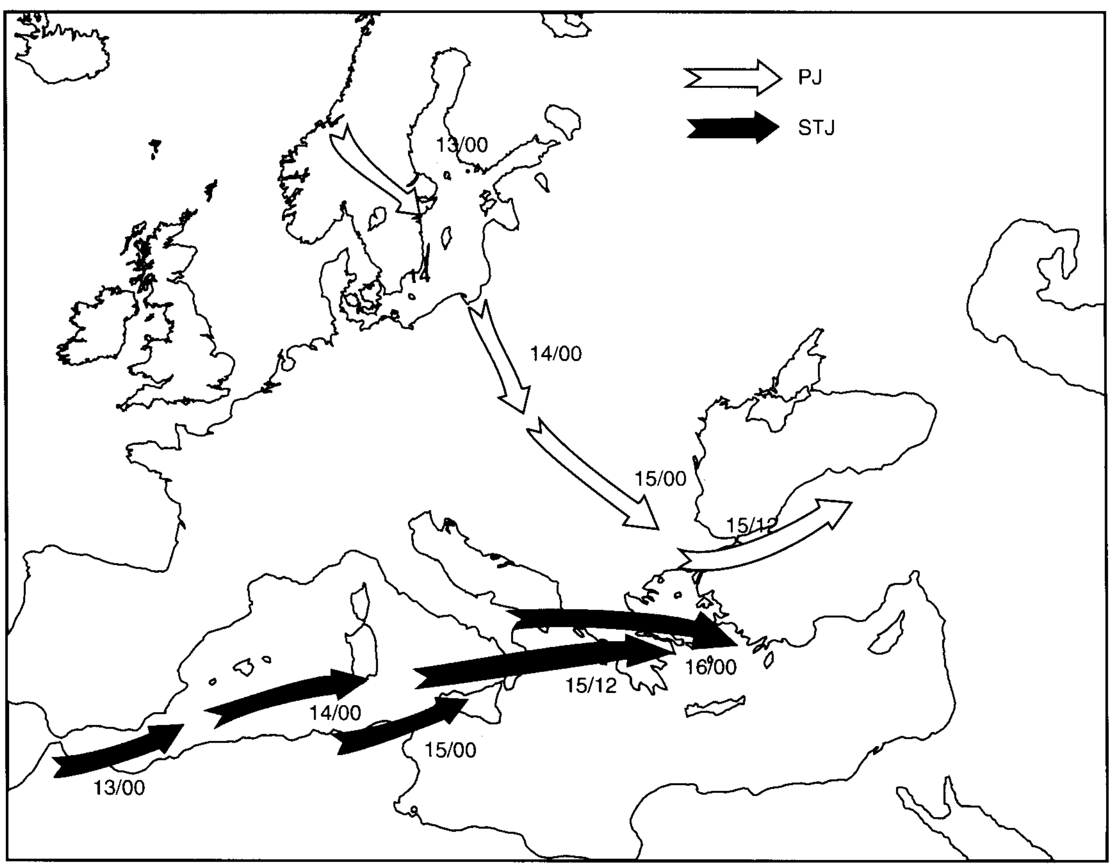

Figure 2. The evolution of the jet streaks between 13 and 16 June 0000 UTC from 300 hPa maximum wind analysis. STJ and PJ indicate the subtropical and polar jets. The numbers related to the arrows are date/time.

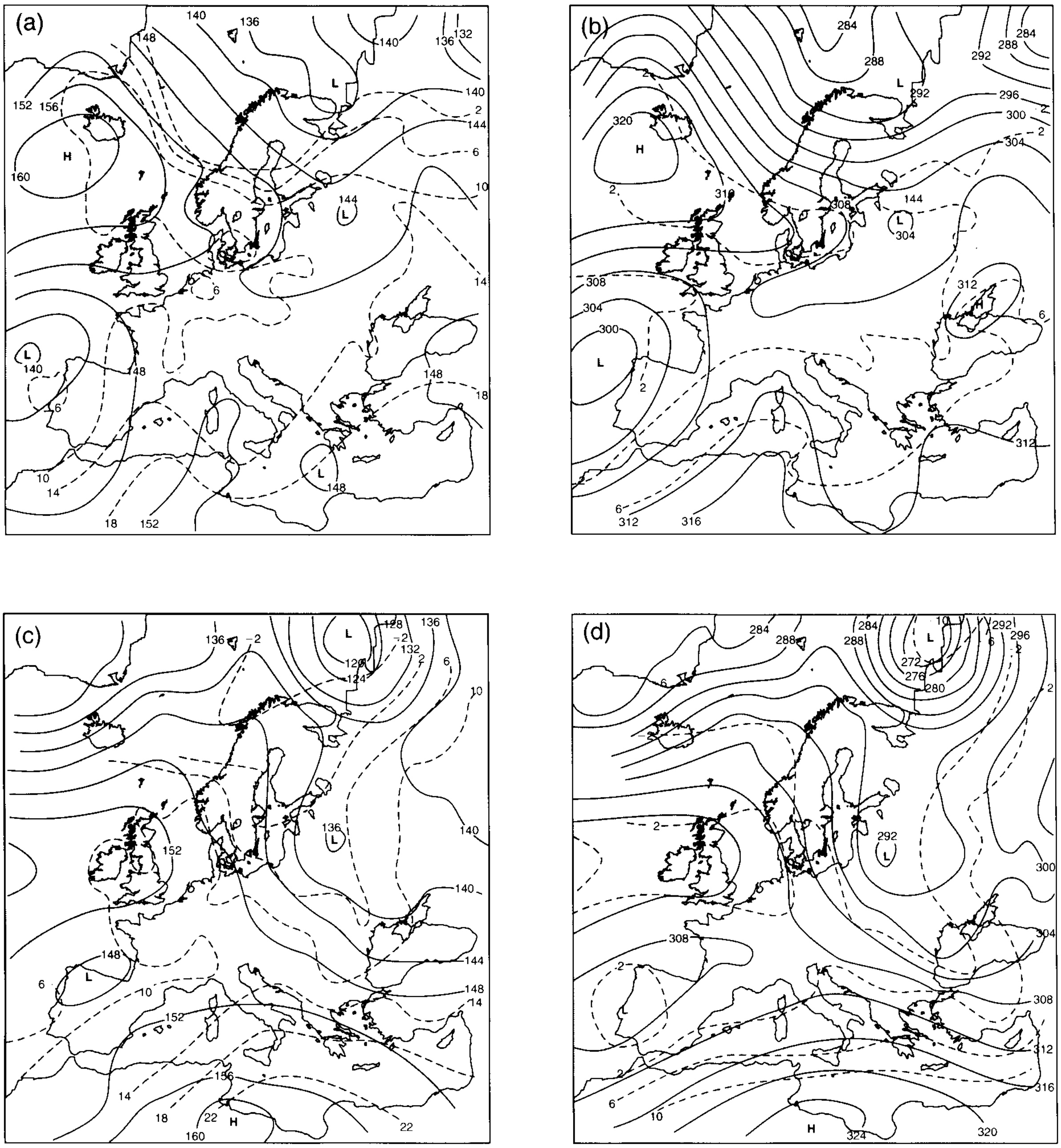

Figure 3. Synoptic analyses adapted from *Meteorological Bulletin* at 0000 UTC, (a) 10 June at 850 hPa, (b) 10 June at 700 hPa, (c) 15 June at 850 hPa, and (d) 15 June at 700 hPa.

the highest pressures usually between the Tyrrhenian Sea and the Gulf of Sidra. As mentioned, the maps of the *European Meteorological Bulletin* show no significant frontal activity over the Mediterranean during the period. This picture changes, however, as one focuses on the sub-synoptic scale.

3. Sub-synoptic-scale analysis

3.1 Surface analysis

At 0000 UTC on the 13th a detailed (2 hPa interval) analysis of the surface chart (not shown) revealed the development of an inverted trough over the Adriatic Sea. This trough was probably a hydrostatic response to the advance of the 850 and 700 hPa thermal ridges mentioned earlier. By 0000 UTC on the 14th, in response to the surface pressure falls, the advance of the low- and mid-level thermal ridges, and the development of confluent, frontogenetic flow aloft, a boundary was beginning to form along a line between Rome and Athens. Closed low-pressure centres were found near both of these locations.

At 0000 UTC on the 15th (Fig. 4) this distinctly warm-frontal boundary was found along the east coast of the Adriatic. The low near Athens had weakened and drifted northward to near Larisa. At the same time, a second region of frontogenesis had developed north and west of the Black Sea as a weak polar front advanced south-eastward ahead of the polar jet streak (Fig. 5).

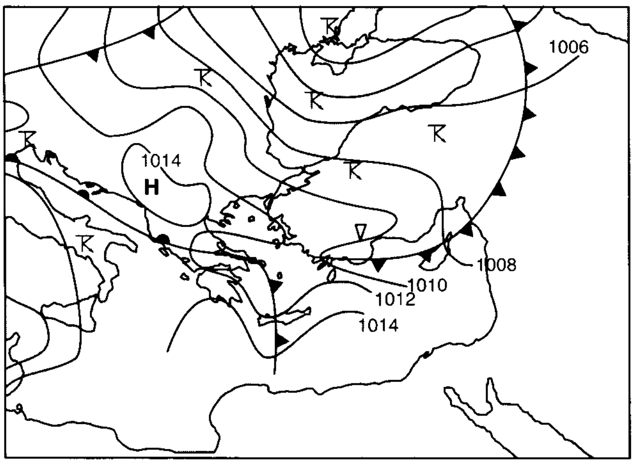

Figure 4. Subjective 2 hPa surface analysis at 0000 UTC on 15 June.

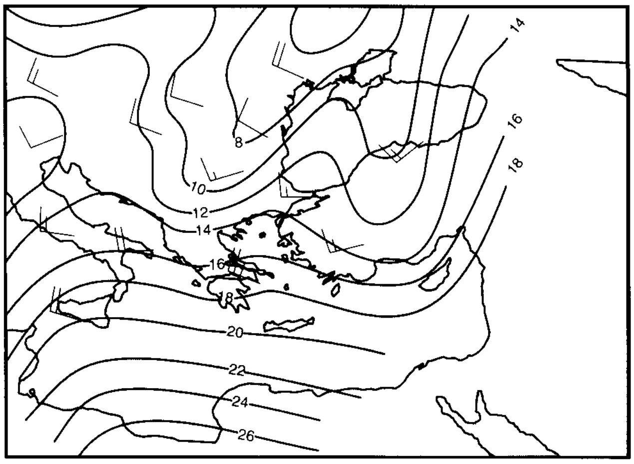

Figure 5. Subjective 2-degree 850 hPa analysis of thermal field at 0000 UTC on 15 June.

The evolution in space and time of the two systems can be better followed in a series of 1 hPa surface analyses every three hours (Fig. 6). The analyses showed a number of sub-synoptic features (squall lines and bubble highs) which affected the northern Balkans. The stationary front over western Greece at 1200 and 1500 UTC retreated as the cold front advanced from the north. By 1800 UTC the two fronts had merged over Greece and the low over Larisa had drifted southwards to be over the Aegean Sea.

Between 0900 and 1200 UTC the pressure at Thessaloniki dropped 2.1 hPa as the cold front approached from the north. Both pressure traces for Thessaloniki and Serres indicate the front passed near 1500 UTC (Fig. 7).

3.2 Thermodynamic aspects

The 0600 UTC Thessaloniki sounding indicated instability with a subsidence inversion at 550 hPa and a weak frontal inversion at 850 hPa. Strong winds were observed aloft. With the advance of the short wave from north-west, the temperatures dropped in the layer between 550 and 300 hPa. An increase in temperature due to differential advection was observed in the layer between 850 and 700 hPa and the levels below 850 hPa were approximately dry adiabatic. The effect of these temperature changes in the 1200 UTC sounding, in combination with an increase in moisture below 700 hPa, enhanced the pre-existing instability (Fig. 8). A slight backing of the winds between 700 hPa (300/41) and 600 hPa (290/52) was enough to cool the layer at an intense rate of 0.7 °C h^{-1}, smoothing the inversion observed in the 1200 UTC sounding. After approximately five hours a 3.5 °C drop in the mean layer temperature was confirmed by the patrolling aircraft (Fig. 8). The high levels of instability and wind shear were strong indications of severe weather.

3.3 Radar history and storm-related events

At 0300 UTC on 15 June 1989, stratiform clouds were widespread over northern Greece. Radar indicated the tops of these clouds to be generally 2 km or less. By 1000 UTC convection had begun to be detected over Bulgaria with reflectivities reaching 40 dbz and tops extending to near 8 km. At 1430 UTC cells were detected over Yugoslavia at a range of 110 km from Thessaloniki. These cells were moving very rapidly toward the south-east, reflecting the strong north-west flow over the region associated with the PJ. Speeds reached 30 kn as the storms moved south-eastwards. While predominant cell motion followed the 700 hPa wind direction, the storm motion deviated 20° to the right of the mean tropospheric wind. At the same time reflectivities between 35 and 40 dbz were measured at altitudes between 4 and 4.5 km and tops reached 9 km. Convection then began to develop rapidly and by 1512 UTC a cluster of cells extended from Lake Doirani to Lake Kerkini (Fig. 9). Two 48 dbz reflectivity maxima were present by this time and tops had climbed to 10 km. Two villages between these lakes reported hail damage to crops the next day.

As these cells moved between Project Areas 1 and 2, they continued to intensify. Fig. 13 is a photograph taken from Thessaloniki International Airport showing the appearance of the storm at 1647 UTC. Fig. 10 gives some indication of the appearance of the storms on radar at this time. The storm in Fig. 13 is seen as the 60 dbz maximum in the south-eastern quadrant of Fig. 10. The same figure shows a second cluster of cells located north-north-west through north of the radar site. This activity moved along nearly the same track as the first cells. The weak returns south-west to north-west and south-east of the radar are ground clutter, the 38 dbz core in the south-west quadrant is Mt. Olympus. Fig. 9 is a time-position plot of the activity as it crossed north-eastern Greece.

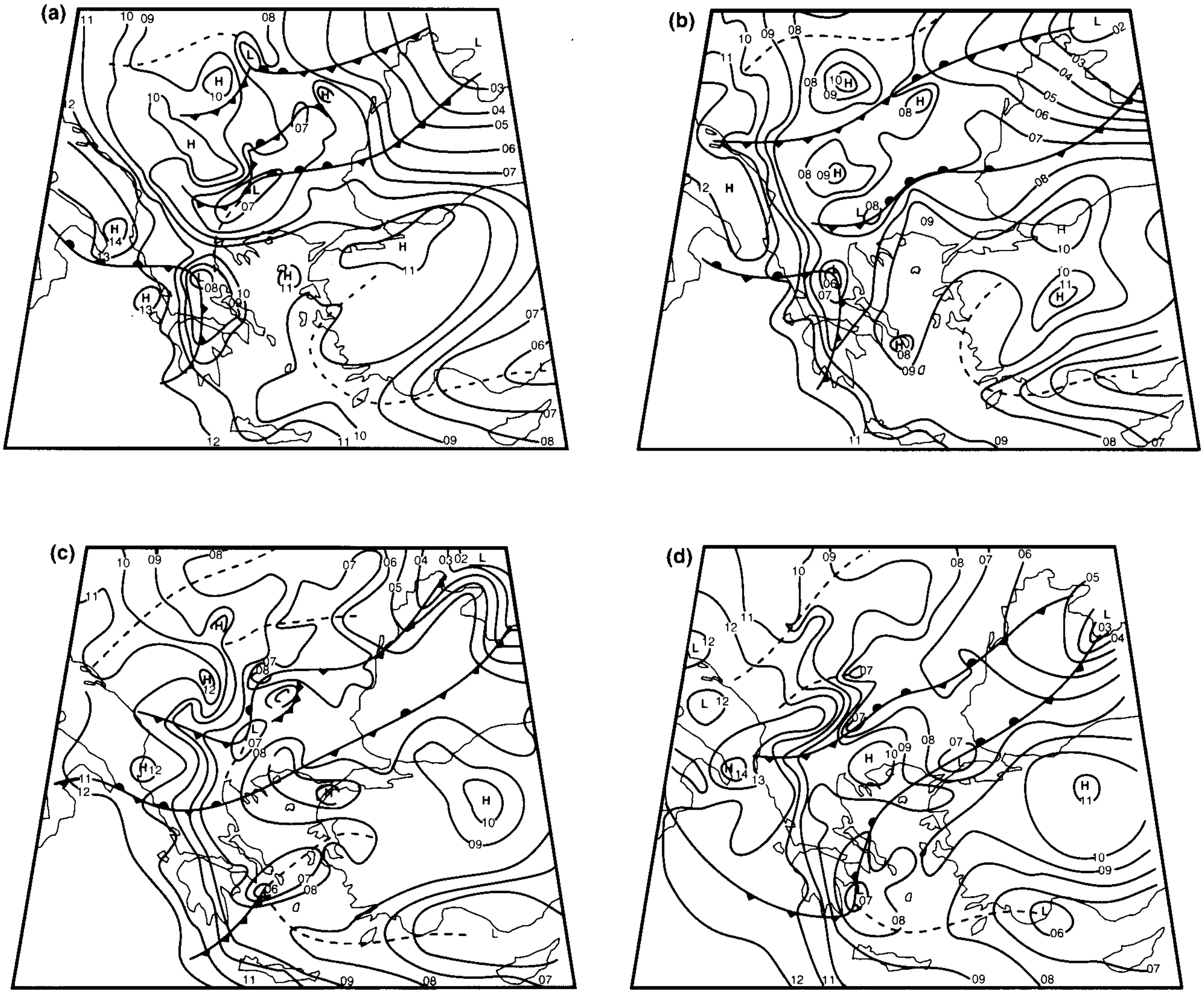

Figure 6. Subjective 1 hPa surface analyses for (a) 1200, (b) 1500, (c) 1800, and (d) 2100 UTC on 15 June. Dashed lines represent pressure troughs.

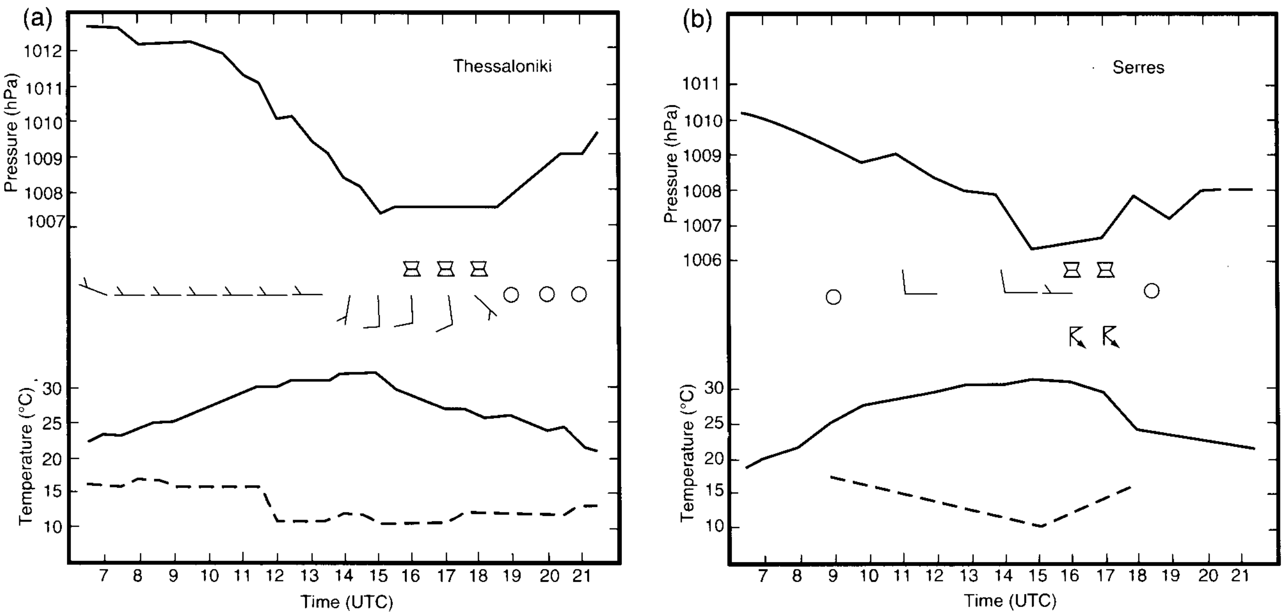

Figure 7. Time section based on surface observation of pressure, temperature, dew-point, wind, and weather for (a) Thessaloniki and (b) Serres stations.

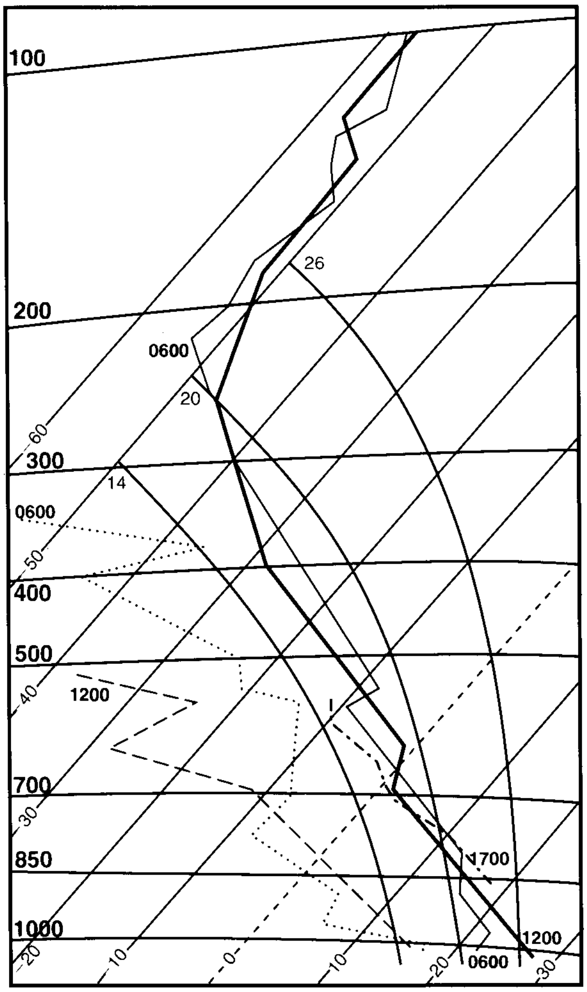

Figure 8. Thessaloniki soundings on 15 June for 0600 and 1200 UTC and the aircraft temperature measurements at 1700 UTC (dashed–dot line). The dotted and the dashed lines are dew-point traces at 0600 and 1200 UTC, respectively.

Close study of the archived data shows that the cells generally intensified when in the immediate vicinity of mountains, especially if they tracked along a south-facing slope. Further, the cells weakened noticeably when they passed over the Gulf of Ierissos. While this is only one case documented and examined in this detail, it is strong support for coupling convective activity and topography over the region.

The surface divergence field shown in Fig. 12 for 1500 UTC reflects some of these terrain influences. The two convergence maxima (negative centres), related to the approach of the cold front (Fig. 6(b)), are separated by a divergence area over the Gulf of Thessaloniki. This is to be expected and is due to the sea breeze effect, which is strongest by this time. A diffluent zone is usually developed as the breeze winds blow approximately normal to the coast. The extension of the convergence maximum, east of Thessaloniki over Halkidiki peninsula, can be attributed in a similar way to the sea breeze effect. At 1800 UTC the weak divergence centre over the same region is probably related to the low-level storm outflow. This is one reason for the more westerly path of the second storm. Another reason for the difference in paths may be that west-facing mountain slopes at that time were a more favourable place for storm formation.

After crossing the Gulf of Ierissos, the cells reintensified with the largest hail of the day being reported from Amouliani Island at approximately 1800 UTC (Fig. 14). Fig. 11 is a radar image of the storm at the time maximum hailstones was reported. Echo appearance is similar to that called 'fingers' and is considered to be reflections from the hail shafts (Grebe (1982) p. 55). The reflectivity core continued to move south-eastward along the Mt. Athos peninsula where considerable damage occurred. By 1900 UTC, the cells were 120 km south-east of Thessaloniki, approaching Limnos Island, which reported a thunderstorm with winds gusting to 40 kn at 2000 UTC with 32 mm of rain between 1925 and 2010 UTC.

A total of 22 villages along the 150 km path of the storm reported hail damage. On Amouliani Island alone, over 500 houses and 200 cars were badly damaged by hailstones in excess of 5 cm in diameter. While such levels of damage are not unknown in Greece, the size of the hail and the extent of the damage produced by the storm were exceptional by local standards.

4. Conclusion

A number of synoptic and local factors were responsible for the severity and extent of hail which occurred on the evening of 15 June 1988. The meteorological features can be summarized as follows:

(a) The convergence of subtropical and polar jet streaks over the Balkans established the conditions favourable for the enhancement of convection.

(b) The peak of activity which occurred at 1800 UTC was related to the strong cold advection in the mid-levels which continuously acted as a destabilization mechanism for more than five hours. The trigger was provided by the advance of the cold front.

(c) The storm of 15 June 1988 was a multi-cellular storm with right deviation of the storm motion vector relative to the mean tropospheric wind.

(d) Radar PPIs recorded during the hail fall support the relationship between 'fingers' and ground observation of hail.

(e) Specific characteristics of storm evolution can be explained by topographic influences on storm propagation and intensity. The storm complex slowed when it reached the coast, especially the diffluent zone produced by the sea breeze around a bay. The activity peaks over the south-facing mountain slopes can also be attributed to the warmer air over the inclined ground.

(f) A surface analysis at 2 hPa and an analysis of the 850 hPa thermal field at 2 °C resolution is necessary to reveal significant features of the summer weather on a continental scale. A surface analysis at 1 hPa is necessary to relate mesoscale and radar features.

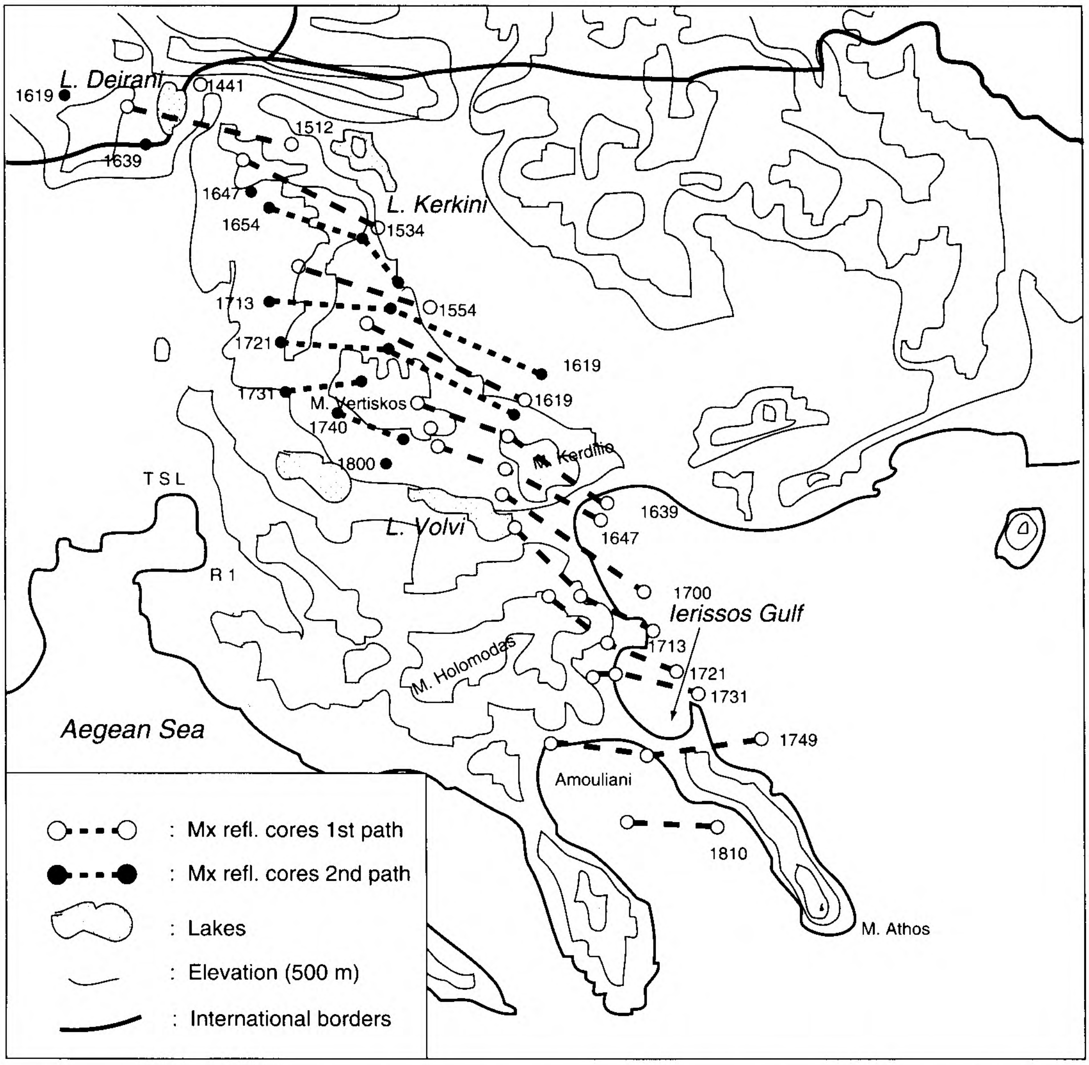

Figure 9. Time-position plot of the maximum reflectivity cores for the two storm complexes. The cores are connected with dashed lines for the first path and dotted lines for the second.

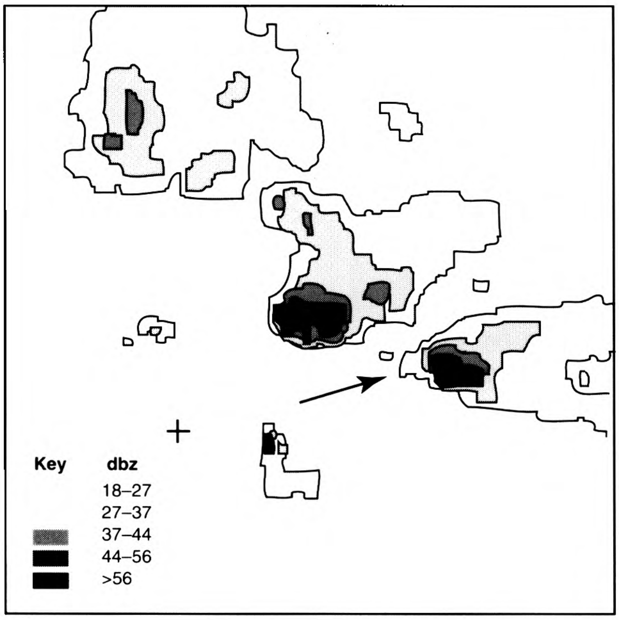

Figure 10. Radar image at 1647 UTC showing the two storm complexes. Arrow indicates storm in Fig. 10.

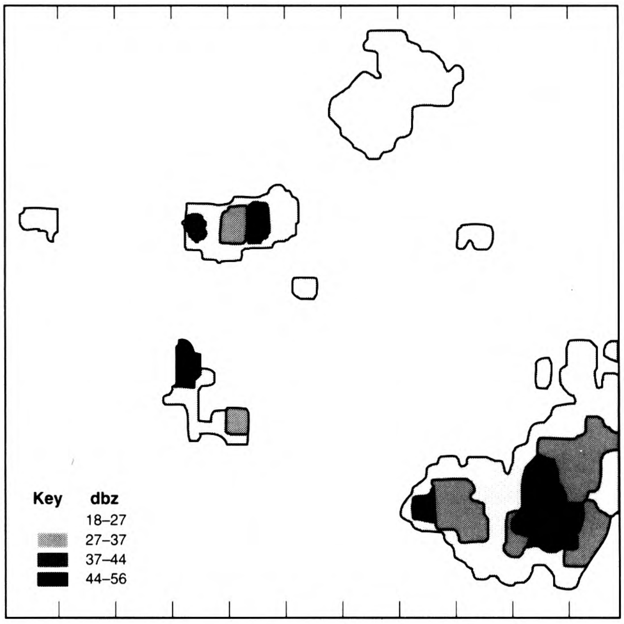

Figure 11. Radar image at 1758 UTC showing the appearance of the echo at the time of maximum recorded hail fall.

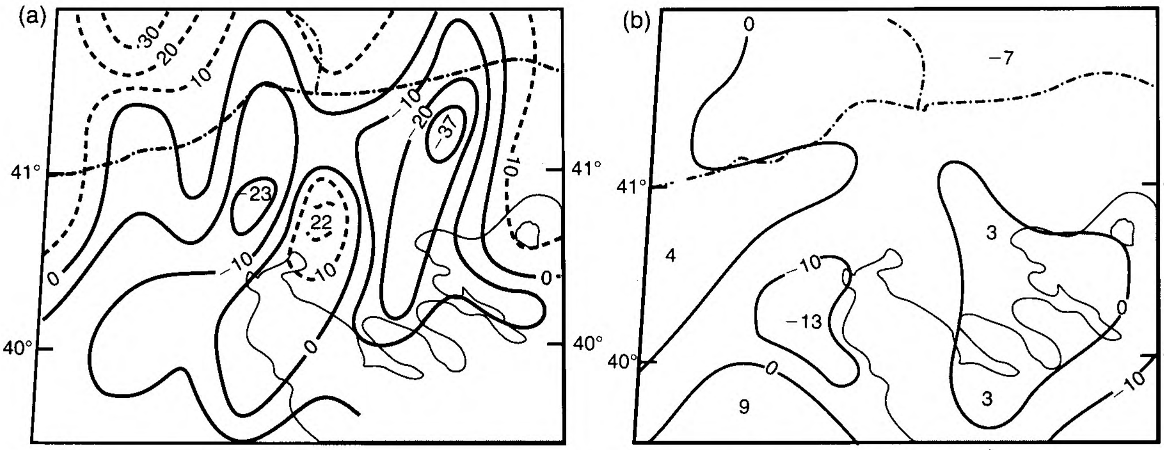

Figure 12. Surface divergence fields calculated from surface wind data at (a) 1500 and (b) 1800 UTC ($s^{-1}\ 10^{-5}$).

Figure 13. Photograph taken from Thessaloniki at 1645 UTC showing the first storm complex.

Figure 14. Photograph (taken on the morning of 16 June) of a refrigerated hailstone.

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Polar lows over the North Atlantic

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A prolonged cold air outbreak over the North Atlantic on 6–11 January 1991 provided examples of many different types of polar lows. The different structures and locations within the air mass of these systems reflect the different physical processes that are believed to be responsible for their genesis and intensification. At least three distinct types of polar low (labelled A, B, and C) are visible on the single infrared image in Fig. 1. Fig. 2 shows 900 hPa absolute vorticity (colour) and wet-bulb potential temperature (contours) taken from an operational analysis of the UK Met. Office fine-mesh model, at a time three hours before the satellite image.

System A is a comma-shaped cloud pattern, whose formation was initiated by a large amplitude, upper-level short wave. The life cycle of such systems is similar to that of many large-scale baroclinic cyclones, despite the weakness of the low-level thermal gradients in the cold air mass. The small amplitude of the 900 hPa perturbation associated with this system is apparent in Fig. 2, especially when contrasted with the frontal cyclone (labelled AA), located just to the east. Release of latent heat can substitute for low-level thermal advection, producing a development that closely resembles the usual baroclinic pattern (Craig and Cho 1992). The two vortices labelled B in Fig. 1 formed along a shallow shear zone, or 'arctic front'. This is visible as a region of high vorticity and warm θ_w in Fig. 2, which indicate the presence of high moist potential vorticity. Such strips are barotropically unstable and can rapidly roll up into a train of small cyclones (Joly and Thorp 1990).

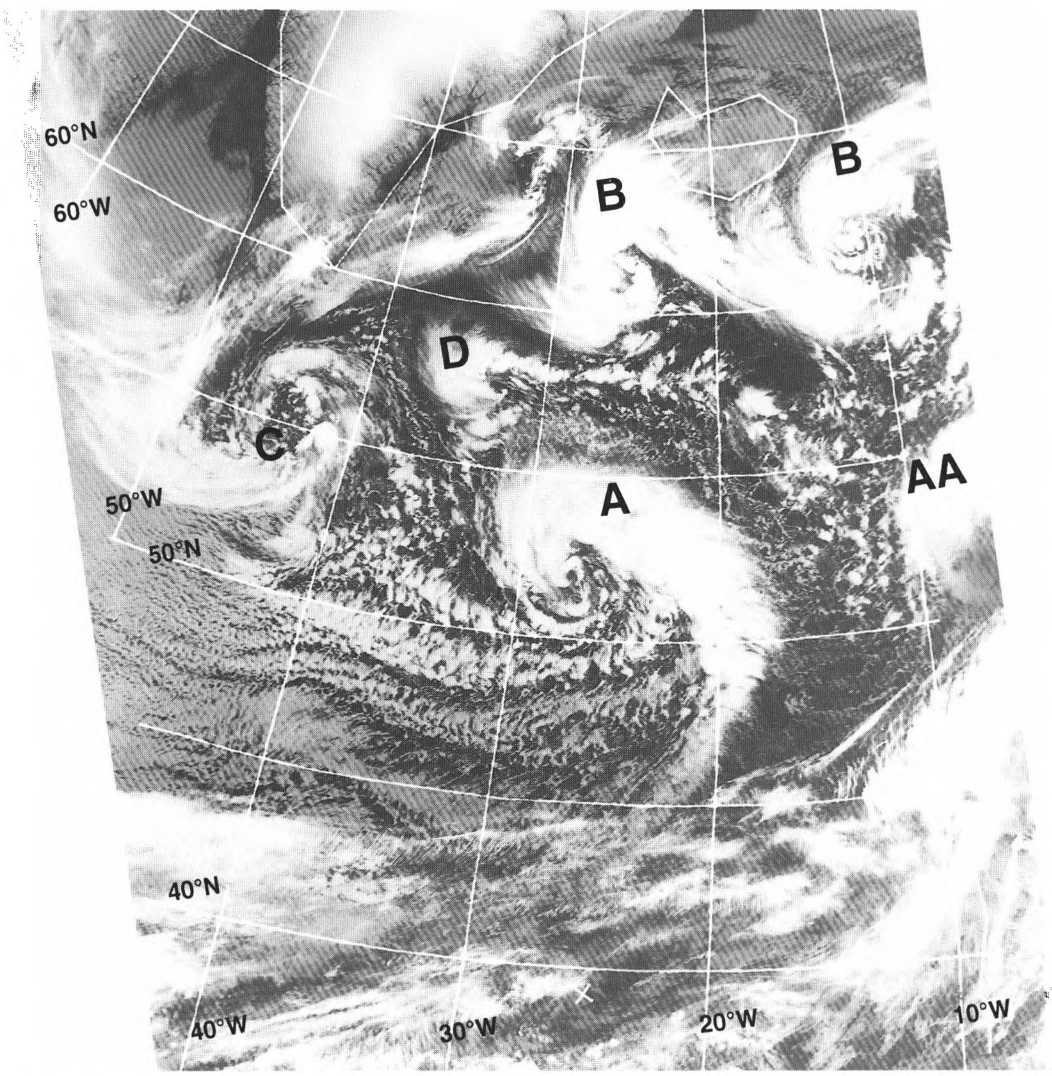

Figure 1. NOAA 11 infrared satellite image for 1526 UTC on 8 January 1991. Letters identify cloud systems referred to in the text.

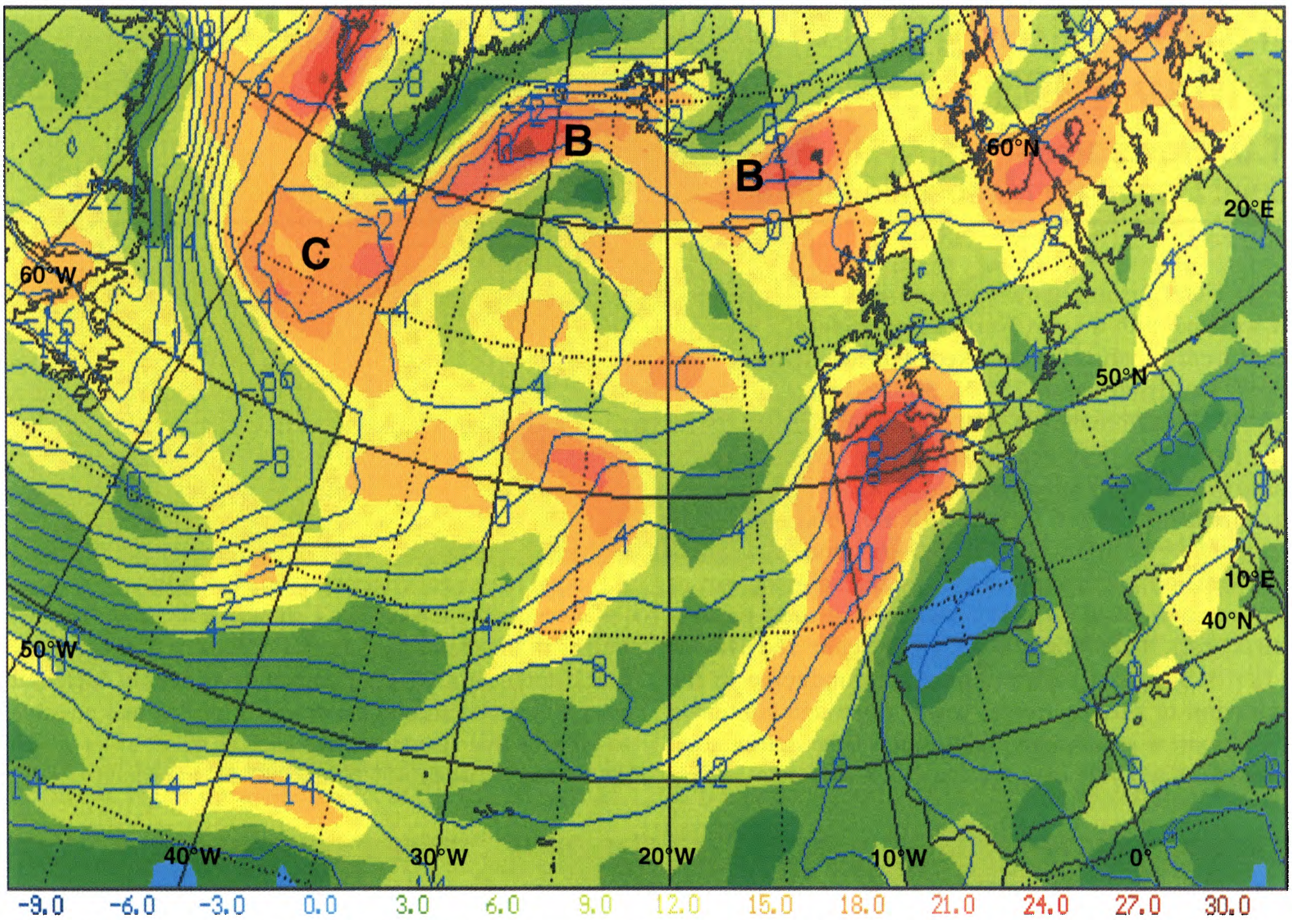

Figure 2. Absolute vorticity and wet-bulb potential temperature θ_w, at 900 hPa for 1200 UTC 8 January 1991. Absolute vorticity is shown by colour shading, with the scale at the bottom of the figure; for example, yellow shading indicates vorticity in the range $12–15 \times 10^{-5}$ s^{-1}. Contours show θ_w (interval 2 K).

The genesis of vortex C appears to be intimately associated with orographic effects. Two patches of high vorticity formed to the east and west of Greenland, then merged at the tip and were shed off into the Atlantic. The two maxima are still visible at the time of Fig. 2. For a period of about twelve hours, the vorticity decayed as the vortex moved southwards, but then reintensified, apparently due to enhanced convection as the system passed over warmer water. The vortex persisted as it moved south and then eastwards, arriving three days later over the United Kingdom. The structure at this later time was discussed by Grant (1991). At no point in its development did the system appear to be associated with any upper-level forcing, and except at the genesis stage near Greenland there was no significant baroclinicity.

As discrepancies between the satellite image and vorticity analysis suggest, a major difficulty in studying and forecasting polar lows is the lack of high-resolution data. In the case of small vortices such as the one labelled D in Fig. 1, very little is known at all.

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World weather news — July 1993 — apology

A gremlin caused the deletion of tropical storm No. 6; please insert

6	Nathan	NWP	19 Jul	25 Jul	70.

Regrettably there is no room for World weather news in this or the December issue.

Infrared imagery showing upper-level waves — 3 May 1993

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Figs 1 and 2 show the circulation and frontal systems associated with a large North Atlantic depression. The cold front is particularly marked, extending over at least 3500 km, from about 25° N, 50° W to about 65° N, 25° W. Data from the UK Met. Office limited area model (LAM) in Fig. 2 indicates that at low levels along the length of this front there are both strong thermal gradients (changes in 900 hPa wet-bulb potential temperature of up to 18 °C in 500 km), and a 'classical' deformation pattern (as shown by the splaying out of isobars in the cold air, when looking in a south-easterly direction). Theoretical work (e.g. Schar and Davies (1990)) suggests such features are conducive to the initiation of surface frontal waves (although continued development requires the relaxation of the deformation pattern). The LAM data does in fact hint at two surface waves, near 48° N, 37° W and 61° N, 26° W. Whilst high-resolution models regularly generate frontal waves in circumstances such as this, the sparsity of surface observations over oceans often makes their existence difficult to verify. In such instances forecasters commonly use satellite imagery to aid the surface analysis. The imagery in Fig. 1 is broadly consistent with the position of the LAM waves, showing colder cloud-tops just south-west of Iceland, and a prominent bump in the cloud mass centred around 49° N, 40° W.

Closer inspection of Fig. 1 shows there are in fact two bulges in the cloud mass near 49° N, 40° W (marked by black dots). In a 21-hour animation of hourly Meteosat images (centred around the time of Fig. 1) it was possible to identify five discrete bulges such as these; all of which developed between 45° N and 50° N, translated rapidly

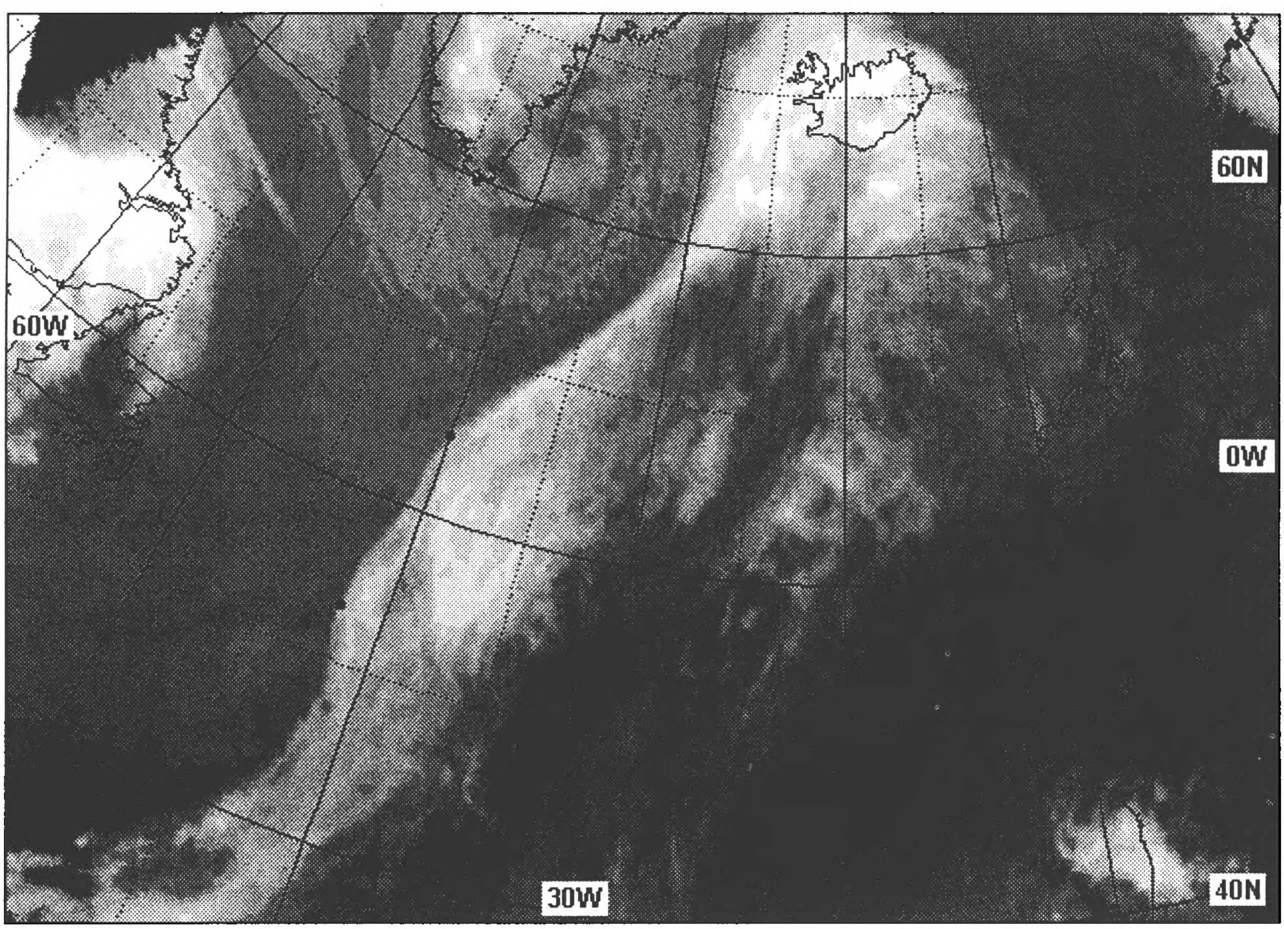

Figure 1. Meteosat infrared image for 2100 UTC on 3 May 1993. Black dots near 50° N, 40° W indicate the tips of two bulges in the cold front cloud band. These appear to be upper-level waves (see text).

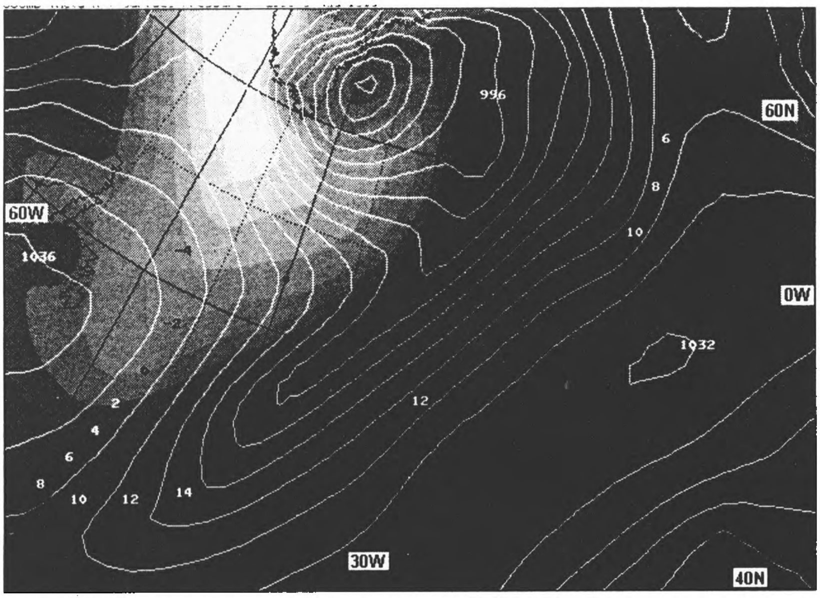

Figure 2. LAM data for 2100 UTC on 3 May 1993 (a 3-hour forecast based on the 1800 UTC analysis). Shading indicates wet-bulb potential temperature at 900 hPa. Each shade covers a 2° C range, using darker shades for higher values. White contours show surface pressure at intervals of 4 hPa. Black dots are as in Fig. 1.

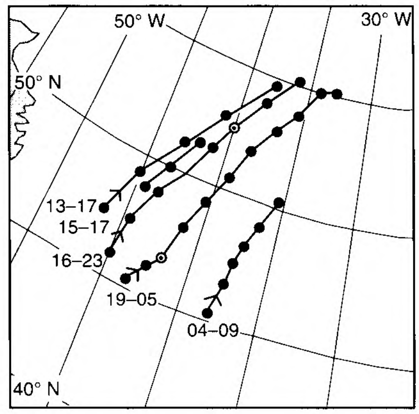

Figure 3. Tracks of upper-level waves between 1200 UTC on 3 May 1993 and 0900 UTC on the 4th. Dots show positions, at hourly intervals, of the tips of bulges in the cold front cloud band. These were tracked using animated Meteosat infrared imagery. Text indicates the time span (UTC) covered by each track. The two ringed dots are those depicted in Figs 1 and 2.

north-north-east, and then disappeared between 50° N and 55° N. Fig. 3 shows the tracks of the tips of each of these*.

In chapter 4 of Images in Weather Forecasting (Bader *et al* 1994) it is suggested that satellite image sequences can help in distinguishing between frontal waves extending throughout the troposphere and those confined to upper levels. Whilst convex bulges in the cloud mass of a frontal zone are characteristic of both, what differentiates an upper-level wave is that these bulges (i) move rapidly along the upper flow, and (ii) have a relatively short life-time

The tracks in Fig. 3 satisfy both these criteria. Mean tip speeds range from 60 to 120 knots, whilst life-times range from 2 to 10 hours. Additional LAM data for 2100 UTC (not shown) for the upper troposphere (at 300 and 500 hPa) indicates winds whose direction and speed are very similar to those of the tracks in Fig. 3. This too suggests the waves are upper-level waves.

*As no satellite data were available between 0900 and 1130 UTC on the 4th the progression after 0900 UTC of the fifth track is not known.

The surface wave at 48° N, 37° W hinted at in Fig. 2 was monitored using further LAM data, at 3-hour intervals for 0000 through to 1200 on the 4th. It appeared to move south-south-east, developing into a cut-off low around 42° N, 35° W. whilst the existence and history of this wave cannot be verified using surface observations, it is nevertheless clear that the motion portrayed within the model is very different to that of the cloud bulges shown in Fig. 3.

Thus whilst the image in Fig. 1 seemed to indicate the presence of surface frontal wave(s) in mid-Atlantic (around 49° N, 40° W), further investigation using animated hourly images has shown that this impression is probably incorrect. The cloud bulges are more likely to be symptomatic of only upper-level waves.

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CORRECTIONS

Page 281, Figure 2 see replacement below (original version too indistinct)

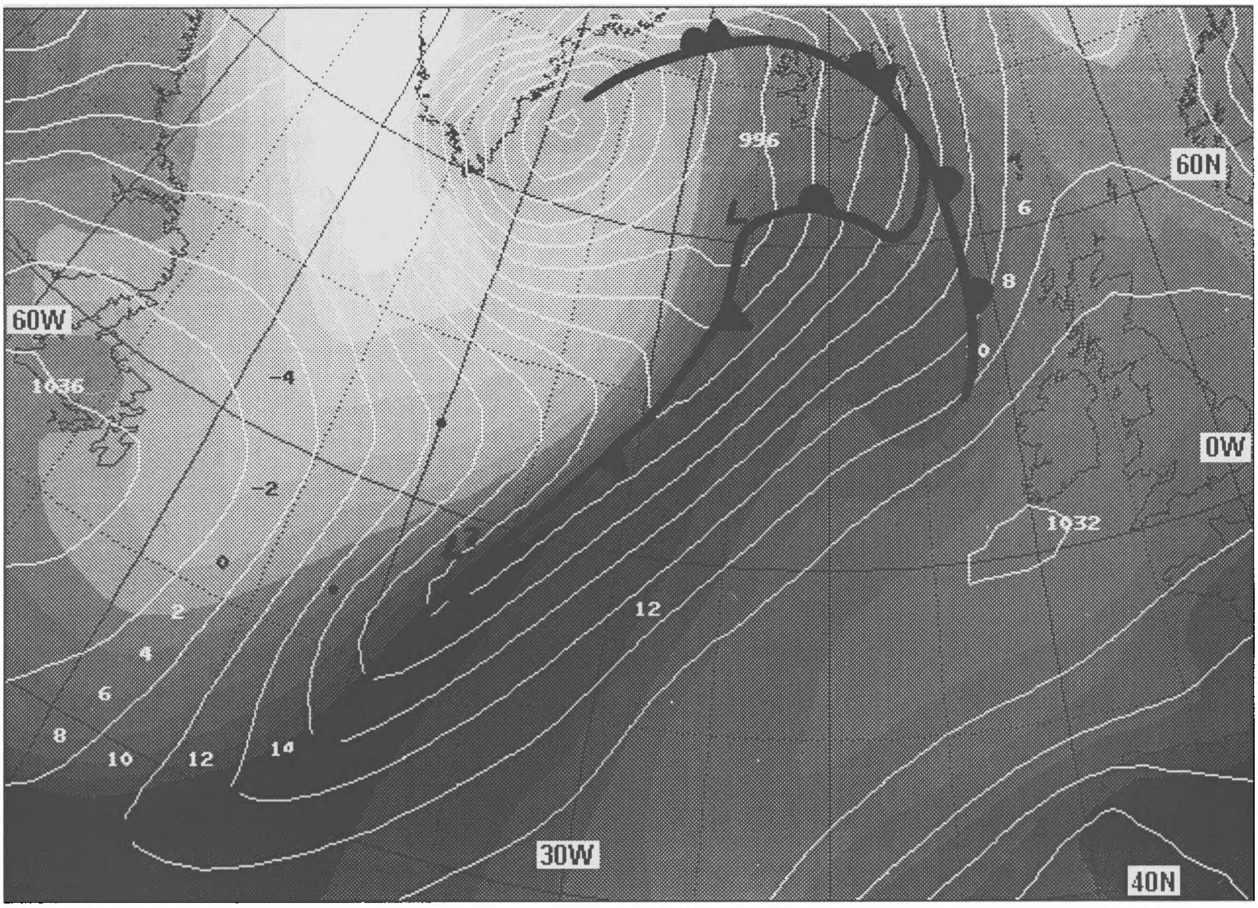

Figure 2.

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Use of Willmott's index of agreement to the validation of meteorological models

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Summary

An important aspect of the meteorological model development process is the evaluation of model performance. In this paper we made a discussion about the estimations provided by the Willmott's index of agreement d_2 as compared to those predicted by other more usual statistical indicators. The results we present were obtained during the validation of a simple empirical relationship between cloud shade (CS) and point cloudiness (PC). 1740 pairs of monthly average values (CS, PC) from 29 weather stations in Romania were used. Generally, the index of agreement was found out to be in good concordance with the other indicators. However, some non-concordances were observed when a finer analysis was considered.

1. Introduction

The evaluation of model performance is an important aspect of the model development process. For this reason, the evaluation of methods that may be used to determine and compare the accuracy of models is of primary concern. In the field of meteorology sound work on this subject was performed by Willmott and co-workers (Willmott 1981, 1982, 1984, Willmott *et al.* 1985) and by other authors (e.g. Fox (1981, 1984), Preisendorfer and Barnett 1983, Won 1984, Zwiers and Thiebaux 1987, Hanna 1989, Lorimer 1989, Ross and Fox 1991).

There is a general point about the use of verification that is important to recognise. Because there are different meteorological communities (e.g. modellers, forecasters, customers) interested in the results, there is a genuine need for different sorts of statistics to be used to present verification results. Of course, these different statistics represent different ways of packaging the same information from the variables involved in verification. However, each packaging now in use has some worthwhile advantage which persuaded a certain community of users to adopt it. As we know, the correlation- and skill-based indices are now in widespread use. In the latter, time difference or error measures were strongly recommended to be used during the valuation of models (Willmott 1985). Sometimes non-dimensional indices are required. In order to avoid some difficulties raised by the existing adimensionalization procedures, Willmott (1984) proposed two new non-dimensional statistical indicators, d_1 and d_2, named 'indices of agreement'.

In this paper we intend to make a brief comparison between the estimations provided by some usual difference measures, on one hand, and the index of greement d_2. The results we present here were obtained during the validation of an empirical relationship between cloud shade and point cloudiness.

2. Empirical relationship of cloud shade to point cloudiness

Many authors reported on the empirical relationship between cloud cover and bright sunshine (Reddy 1974, Rangarajan *et al.* 1984, Harrison and Coombes 1986). Their studies are of a special interest for the solar radiation computing methods developed on the basis of long-term averages of bright sunshine (e.g. the International Energy Agency (IEA 1984)) because sunshine records are not always kept at weather stations, but long-term records of observed total cloud cover are available for most observing stations of the world. Recently, we reported on the empirical relationships between cloud cover and bright sunshine for the Romania climate and latitudes (Badescu 1990). For a given period of time (say a month) we denoted by S and PC (point cloudiness) the ratio between the actual and the maximum possible number of hours of bright sunshine and the average total cloud amount (in tenths) observed by eye, respectively. The complement of S is often called cloud shade $CS=1-S$. The three simple relationships we previously analysed have the following forms:

$$CS=a_1+b_1PC \quad (1)$$

$$CS=a_2PC+b_2PC^2 \quad (2)$$

$$CS=a_3PC+b_3PC^2+C_3PC^3 \quad (3)$$

where a_i, b_i ($i=1, 2, 3$) are regression coefficients whose values were determined by a least squares fit of the Equations (1–3) to the observed values of cloud shade (CS_{obs}). Once a_i, b_i were obtained, the three equations were used to compute new values of cloud shade (CS_{comp}).

In this paper we refer exclusively to the simple relationship given by Equation (2). Note that this non-

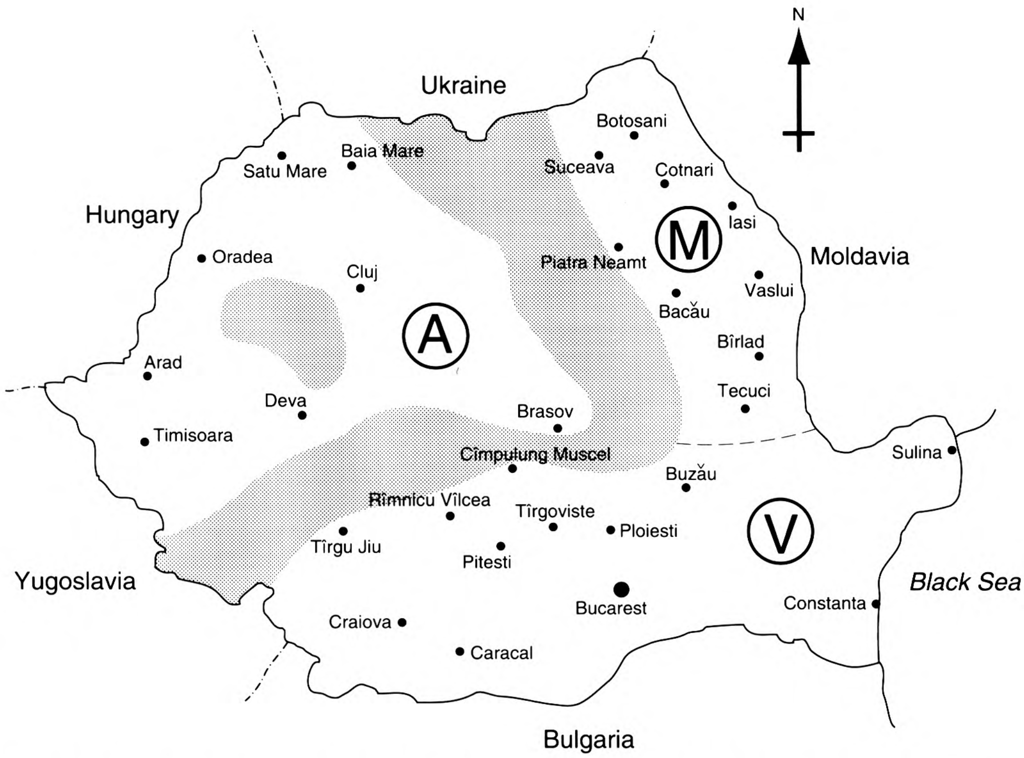

Figure 1. Locations of the 29 Romanian weather stations where the relationship of cloud shade to point cloudiness (Equation (2)) was verified. The dashed area shows the Carpathian Mountains. The three historical Romanian provinces are: A — Ardeal, M — Moldavia, V — Valahia.

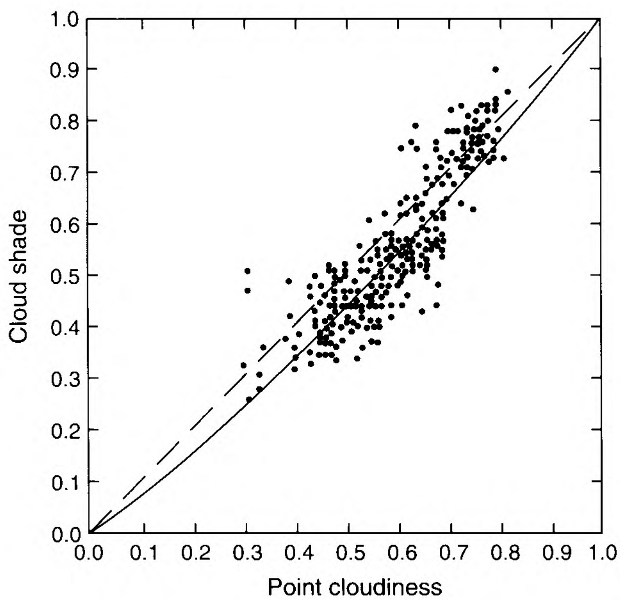

Figure 2. Cloud shade (*CS*) versus point cloudiness (*PC*) for 29 Romanian weather stations (5-year monthly average values).

linear formula was also preferred by Rangarajan *et al.* (1984) and Harrison and Coombes (1986).

3. Data basis and statistical indicators of accuracy

Meteorological data were collected from 29 Romanian weather stations selected to give a broad coverage of the country in both latitude and longitude (Fig. 1). In computations we used 1740 pairs of *PC*/*CS* monthly average values from a five-year interval. The 348 multi-year monthly average values are shown in Fig. 2. Note that some of these values are superposed.

First, the accuracy by which the Equation (2) evaluates the monthly average values of *CS* was verified by using three usual statistical indicators of accuracy, namely the mean bias error (*MBE*), the second centred moment of the error distribution (S_D) and the mean absolute error (*MAE*) given by:

$$MBE = (1/N) \sum_{i=1}^{N} (CS_{\text{comp.}\,i} - CS_{\text{obs.}\,i}) \tag{4}$$

$$S_D = (N-1)^{-1} \sum_{i=1}^{N} (CS_{\text{comp.}\,i} - CS_{\text{obs.}\,i} - MBE)^2 \tag{5}$$

$$MAE = (1/N) \sum_{i=1}^{N} | CS_{\text{comp.}\,i} - CS_{\text{obs.}\,i} | \tag{6}$$

where N is the number of monthly average values. Second, we computed the index of agreement d_2, defined by Willmott *et al.* (1985) as:

$$d_2 = 1 - \frac{\sum_{i=1}^{N} (CS_{comp,i} - CS_{obs,i})^2}{\sum_{i=1}^{N} (|CS_{comp,i} - m_{CS(obs)}| + |CS_{obs,i} - m_{CS(obs)}|)^2} \quad (7)$$

where $m_{CS(obs)}$ is the mean of the observed values of CS. The index of agreement varies between 0.0 and 1.0 where a value of 1.0 expresses perfect agreement between CS_{comp} and CS_{obs} and 0.0 describes complete disagreement.

4. Results and discussions

We applied Equation (2) to compute cloud shade by using only meteorological data from each of the three historical provinces of Romania. Table I shows the results. The empirical relationship we tested has close enough performance on the whole of Romania. This can be verified by means of any of the four indicators we used. Note that all three 'classical' indicators (MBE, S_D and MAE) agree with the fact that the simple relationship we tested has the worst performance in Valahia. However, the index of agreement d_2 does not recognize this fact.

Next, we tested the four statistical indicators to study the accuracy of the Equation (2) when applied in areas other than the one where the regression coefficients were determined. First, we analysed the accuracy of the regression formula that we determined by using the whole set of data, when applied in each of the 29 weather stations of Fig. 1 (case 1 in Table II). We compared with the accuracy of the formulae that we determined by using only data from the respective weather stations (case 2 in Table II). All the four indicators recognize the fact that, generally, the regression formulas obtained in case 2 are more accurate. However, some non-concordances were observed when we analysed a few particular situations.

Table I. The accuracy of the Equation (2) when applied in Valahia, Moldavia and Ardeal. $m_{CS(obs)}$ — the mean of the observed values of cloud shade. MBE — mean bias error, S_D — second centred moment of error distribution, MAE — mean absolute error, d_2 — Willmott's index of agreement (Equation (7)).

	Valahia	Moldavia	Ardeal
$m_{CS(obs)}$	0.5479	0.5812	0.5798
MBE	−0.001	−0.001	−0.001
S_D	0.0706	0.0691	0.0671
MAE	0.056	0.053	0.053
d_2	0.9510	0.9433	0.9515

Table II. The accuracy of Equation (2) when applied in different weather stations. Case 1 — regression coefficients determined by using the whole set of data. Case 2 — regression coefficients determined by using only data from the respective weather station. For MBE, S_D, MAE and d_2 see Table I.

	MBE		S_D		MAE		d_2	
Location	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Botosani	−0.018	−0.001	0.048	0.048	0.041	0.038	0.973	0.976
Suceava	0.019	−0.000	0.057	0.056	0.047	0.042	0.941	0.949
Cotnari	−0.036	−0.000	0.048	0.048	0.048	0.037	0.959	0.973
Iasi	0.038	−0.000	0.069	0.069	0.062	0.053	0.925	0.945
Bacau	−0.008	−0.000	0.043	0.043	0.033	0.032	0.975	0.976
Vaslui	−0.002	−0.001	0.057	0.056	0.043	0.042	0.967	0.970
Birlad	0.092	−0.001	0.081	0.073	0.099	0.068	0.855	0.940
Pt Neamt	0.017	−0.000	0.062	0.062	0.051	0.050	0.928	0.931
Tecuci	−0.037	−0.001	0.042	0.043	0.047	0.034	0.970	0.982
Tg Jiu	−0.042	−0.000	0.079	0.079	0.067	0.065	0.915	0.933
Craiova	0.013	−0.000	0.072	0.070	0.059	0.057	0.957	0.963
Caracal	−0.032	−0.000	0.063	0.062	0.059	0.050	0.955	0.968
Rm Vilcea	−0.021	−0.000	0.060	0.060	0.049	0.048	0.951	0.956
Pitesti	−0.016	−0.000	0.056	0.055	0.046	0.043	0.960	0.967
Tirgoviste	0.037	−0.000	0.071	0.070	0.068	0.056	0.908	0.933
Ploiesti	−0.003	−0.001	0.057	0.057	0.045	0.045	0.966	0.966
Cl Muscel	−0.034	−0.000	0.046	0.043	0.047	0.035	0.940	0.960
Bucarest	0.034	−0.000	0.081	0.079	0.072	0.065	0.930	0.947
Buzau	0.020	−0.001	0.062	0.062	0.053	0.050	0.956	0.961
Constanta	−0.007	−0.000	0.048	0.048	0.039	0.038	0.983	0.984
Sulina	−0.055	−0.003	0.070	0.070	0.072	0.071	0.056	0.963
Satu Mare	0.025	−0.001	0.065	0.064	0.055	0.051	0.947	0.957
Baia Mare	0.015	−0.000	0.065	0.065	0.055	0.052	0.951	0.957
Oradea	0.001	−0.001	0.081	0.071	0.066	0.066	0.930	0.929
Cluj	−0.021	−0.001	0.054	0.053	0.047	0.044	0.964	0.971
Arad	−0.017	−0.000	0.066	0.065	0.056	0.052	0.949	0.959
Timisoara	0.003	−0.001	0.066	0.065	0.053	0.052	0.957	0.959
Deva	0.000	−0.000	0.072	0.072	0.057	0.057	0.941	0.940
Brasov	0.008	−0.001	0.055	0.055	0.042	0.043	0.955	0.955

So, for both cases 1 and 2, the indicators *MBE*, S_D and *MAE* show the Equation (2) as having the best performance at Bacau. On the other hand, the index of agreement *d* estimated the best results at Constanta. The four indicators are in good concordance, showing Birlad as the weather station with the worst results when case 1 is considered. However, in case 2 the index of agreement changes its estimate, showing Piatra Neamt.

A last question that we studied regards the accuracy of Equation (2) when applied in other time-periods than the one when the regression coefficients were determined. First, the empirical relationship obtained by using the whole set of data was applied during six different years (Table III, case 1). The results were compared with those obtained with the regression formulae determined by using only data from the respective years (case 2 of Table III). As expected, the best results were obtained in the case 2. In both cases 1 and 2 the indicators *MBE*, S_D and *MAE* show Equation (2) to have the best and the worst performances in the years 1969 and 1968, respectively. Note that the index of agreement is always in good concordance with the other indicators. Second, we analysed the accuracy of the formula we obtained by using the complete set of data, when applied in all the year months (case 1 of Table IV). We compared with the accuracy of the formulas that we determined by using only data from the respective months (Table IV, case 2). Generally, the index of agreement is in good concordance with the other indicators showing the best results were obtained in case 2. However, note that d_2, S_D and *MAE* disagree concerning the months with the best and the worst results, respectively.

5. Conclusion

In this paper we compared the estimations provided by the index of agreement d_2 proposed by Willmott (1982, 1984) with those predicted by other more usual statistical indicators of accuracy. The results we presented were obtained during the validation of a simple formula (Equation (2)) relating cloud shade to point cloudiness. Generally, the index of agreement was found to be in good concordance with other indicators. However, when a finer analysis is considered, some non-concordances were observed. This is not really surprising but a confirmation of the usual perception that no better statistical indicator exists. Consequently, the index of agreement can be used during model validation, together with other statistical indicators.

Acknowledgments

The author thanks Dr C.J. Willmott for the useful information concerning model validation. and also thanks the referee for his valuable remarks and suggestions. Part of this work was performed at the

Table III. The accuracy of Equation (2), when applied indifferent years. Case 1 — regression coefficients determined by using the whole set of data. Case 2 — regression coefficients determined by using only data from the respective year. For *MBE*, S_D, *MAE* and d_2 see Table II.

	MBE		S_D		*MAE*		d_2	
Year	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
1967	−0.015	−0.000	0.063	0.063	0.051	0.050	0.952	0.954
1968	0.020	−0.000	0.075	0.073	0.060	0.056	0.945	0.955
1969	0.005	−0.001	0.060	0.060	0.047	0.046	0.973	0.974
1970	0.010	−0.001	0.071	0.070	0.056	0.055	0.947	0.949
1971	−0.006	−0.001	0.969	0.069	0.054	0.054	0.947	0.946
1972	−0.003	−0.000	0.072	0.072	0.058	0.058	0.910	0.911

Table IV. The accuracy of the Equation (2) when applied in different months. Case 1 — regression coefficients determined by using the whole set of data. Case 2 — regression coefficients determined by using only data from the respective month. For *MBE*, S_D, *MAE* and d_2 see Table I.

	MBE		S_D		*MAE*		d_2	
Month	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
January	−0.065	0.000	0.052	0.040	0.070	0.032	0.848	0.944
February	−0.019	−0.000	0.051	0.046	0.043	0.037	0.884	0.892
March	0.013	−0.001	0.053	0.048	0.042	0.037	0.930	0.933
April	0.050	0.000	0.058	0.049	0.059	0.038	0.825	0.886
May	0.061	0.000	0.057	0.050	0.067	0.038	0.732	0.822
June	0.049	−0.000	0.060	0.054	0.062	0.043	0.775	0.825
July	0.018	−0.001	0.058	0.048	0.046	0.036	0.871	0.880
August	0.026	−0.000	0.061	0.045	0.050	0.035	0.871	0.903
September	−0.001	−0.000	0.054	0.048	0.043	0.039	0.941	0.942
October	−0.041	−0.001	0.049	0.046	0.053	0.036	0.913	0.945
November	−0.034	−0.000	0.046	0.048	0.049	0.036	0.927	0.948
December	−0.067	−0.000	0.053	0.054	0.071	0.043	0.836	0.939

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Forecasting thunderstorms using thermodynamic indices

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and
M. El-Menshawy
Meteorological Authority, Cairo, Egypt

Summary

A number of verifications were carried out to investigate the performance of thermodynamic indices as thunderstorm predictors. With two added conditions, the probability of predicting thunderstorms using the K index could reach 85%. The vertical profile of static energy or equivalent potential temperature was found to be very useful in the forecast procedure.

1. Introduction

Thunderstorms are mesoscale phenomena whose formation are influenced by meteorological conditions such as humidity and instability; and the interaction between synoptic and mesoscale effects makes the forecasting problem more difficult. Over Egypt, thunderstorms are most frequent during most of the so-called 'cold season' which extends from late Autumn to late Spring. However, climatological analysis of thunderstorm frequency shows that the majority occur at Mersa Matruh and Cairo during November. Early studies of thundery activity over Egypt concluded that thunderstorms occur when the Sudan monsoon low extends to the north. The warm, humid south-east current from the Red sea then interacts with cold air in the rear of low pressure at the eastern part of Mediterranean. This type of thunderstorm occurs only in spring and Autumn and is more frequent at Cairo; the winter-type thunderstorms occur when depressions travelling along the Mediterranean stay near Cyprus for few days and are more common at Mersa Matruh. The use of thermodynamic indices has been used for a long time to predict these occurrences. But these indices tend to be a local property, and the phenomenon is also a local one. In this paper some indices will be used to predict thunderstorms and the evaluation will also be included. Mersa Matruh (62306) and Cairo (62366) were chosen because they are radiosonde stations, and in this paper 'thunderstorm' means thunder was heard at the station; it may not have rained.

2. Thunderstorms and static stability

Normally a thunderstorm occurs when, in a conditionally unstable atmosphere, a trigger forces boundary layer air up to the level of free convection. Therefore the use of a measure for stability will certainly be helpful in this matter. Baily (1955) introduced the K index as

$$K = T_{850} - T_{500} + T_{d850} - (T - T_d)_{700} \qquad (1)$$

and cases of $K \geqslant 20$ should describe favourable conditions. Two years (1981-1983) of twice-daily observations were used (for Cairo and Mersa Matruh). The computations indicated that K is not a sufficient condition. Two more indices were examined;

$$TT = (T_{850} - T_{500}) + (T_{d850} - T_{d500}) \qquad (2)$$

$$AA = (T_{850} - T_{500}) - (S_8 + S_7 + S_6 + S_5) \qquad (3)$$

where S_i indicates dew-point depression at level i. Equations (2) and (3) were found to give unsatisfactory results, and so we will concentrate on the use of the K index. Recently Andersson *et al.* (1989) used the same index as predictor of summer-time thunderstorms. Our analysis justifies the use of the same pattern. In some cases K was much greater than 20 but there were no storms.

Two additional conditions were found to represent the occurrences.

(a) $(T - T_d)_{700} \leq 5$ °C, and

(b) $T_{500} \leq -15$ °C.

In Table I final scores of successful and unsuccessful forecasts are presented. One condition simply means that $K \geqslant 20$, three conditions means (a) and (b) in addition. Combining the three conditions simply means that $(T + T_d)_{850} > 0$. This will easily identify conditions suitable for thunderstorms. The K index was found to be enough to express the category of the thunder

K value	≥20≤25	>25≤30	35
Category	isolated	Widespread	Intensive.

Table I. Final score of successful and unsuccessful forecasts.

Station	No. of cases	1 condition yes	1 condition no	3 conditions yes	3 conditions no
Mersa Matruh	38	30	8	33	5
Cairo	14	8	6	12	2

Table II. Skill prediction for both stations where P_d is the probability of detection, P_f is the probability of false alarms and P_s is the probability threat score.

Station Criteria	Cairo one	Cairo three	M. Matruh one	M. Matruh three
P_d	57	86	79	96
P_f	43	18	22	2
P_s	40	70	68	71

Some statistics of success for forecasts at the two stations are shown in Table II. For perfect forecast $P_d = P_s = 100$ and $P_f = 0$ (see Andersson *et al.* (1980)). As was mentioned earlier, the K index with two more criteria gives a reasonable estimate for thunder occurrences, but this estimate is not very helpful in so far as it may be able only to predict thunder at a point. We used system of linear equations to predict parameters of the K index for at least 12 hours in advance and therefore thunder activity. T_{850}, T_{700} and T_{500} were predicted using equations of the form

$$T_{hhh} = a + b.T_{1000} + c.T_{850} + d.T_{700} + e.T_{500} + f.T_{300}$$

and T_{d850} and T_{d700} from

$$T_{dhhh} = a + b.T_{d1000} + c.T_{d850} + d.T_{d700} + e.T_{700} + f.T_{850}.$$

Inspection of days of thunder occurrences proved that some changes were reported at the 700 hPa level, a similar conclusion reached by Pickup (1982) at 500 hPa. This led us to examine the vertical profile of equivalent potential temperature (θ_e) and static energy (E_s), which were calculated by the formulae

$$\theta_e = \theta \exp [(3.376/T_L - 0.00254) \times (1 + 0.81 \times 10^{-3}.r)]$$

where θ is potential temperature, r is the mixing ratio, and T_L is the absolute temperature at lifting condensation level (Bolton 1980) and

$$E_s = T(k) + 9.8 \times 10^{-3}.z(m) + 2.5r \text{ (g kg}^{-1}).$$

The vertical profile of θ_e was calculated and it was noticed that on days of thunder activity its value was smaller at 700 hPa, than in other cases (Fig. 1). It was noticed that a minimum of equivalent temperature <285 at 700 hPa will definitely be associated with thunderstorms. This simply shows the combined effect of

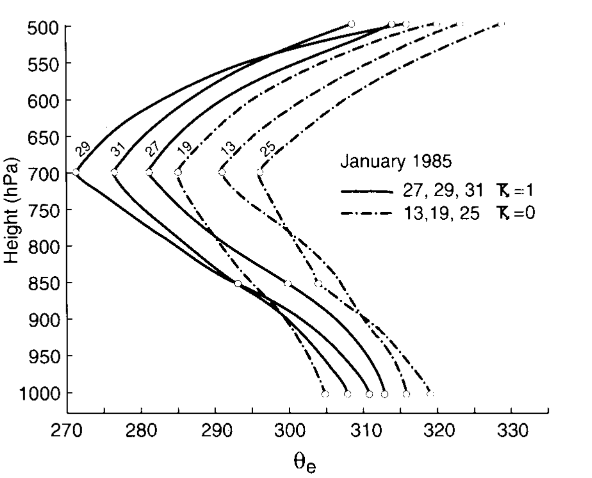

Figure 1. Some cases of stability and instability for equivalent potential temperatures.

temperature and moisture, such potential instability may be released by ascent associated with synoptic-scale motion. Turbulent diffusion of heat and moisture in the vertical act to reduce potential instability, since the net result of the vertical mixing processes is to reduce the vertical gradient of θ_e. The same result has been described other ways in terms of static energy. The solid curve in Fig. 2 show the atmosphere in normal conditions and it need an extra energy of ΔE_s to be added on all levels while the minimum static energy still remains at 700 hPa. This index (E_s) was found also to be very successful in describing storm conditions. On the other hand if looking to the boundary force it should also be very valuable in describing storm conditions. This was used by Stone (1984) and Andersson *et al.* (1989) as

$$E=R_d \int_{P_1}^{P_2} (T_p-T_e)\, d \ln p$$

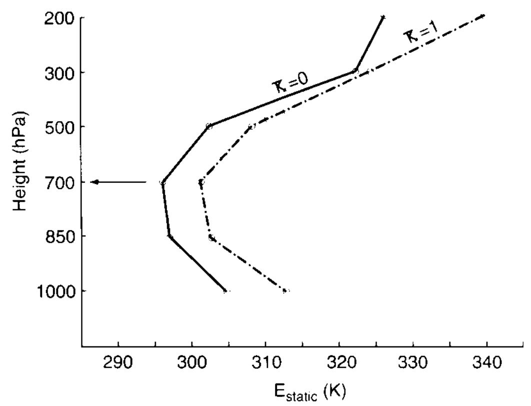

Figure 2. Vertical profile of static energy for two cases with and without thunderstorms.

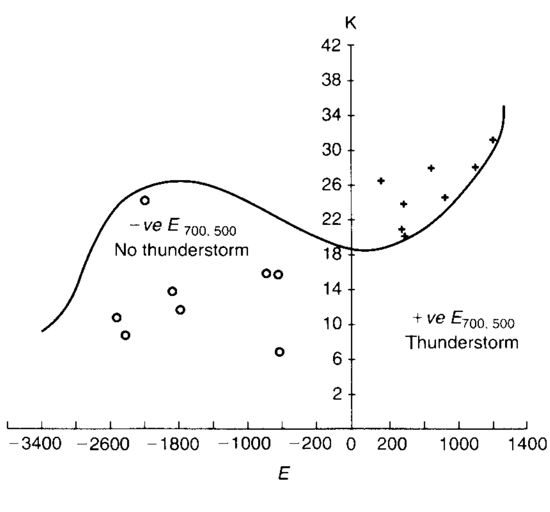

Figure 3. Relationship between E and K index for Cairo.

where P_d is the gas constant for dry air and P_1 and P_2 were taken as 700, 400 hPa respectively and T_p, T_e refer to the parcel and environment temperatures. There are three different cases which can encountered in the atmosphere, the case when $T_p > T_e$ and therefore E is positive, this makes it possible for vertical motion to develop in the atmosphere usually leading to the formation of convective clouds. In the second where $T_p < T_e$, the energy of instability is negative and upward motion is impossible. Finally, in the case where $T_p > T_e$ at some sub layer and $T_p < T_e$ on another, the overall energy is the algebraic sum of the layers, but usually the cases are too weak to produce thunder. In Fig. 3, a sketch of E and K is given and cases of occurrence are defined, cases were unpicked by K index as in Table 1, but reported using the (E–K) combination. A final form using the 4 indices are given in Table III, where skill may reach 90%.

Table III. Combination of different indices using predicted parameters

Station		Index K	K, θ_e	θ_e, E_s	k, e, E
M. Matruh	P_d	88	91	90	92
	P_f	15	12	11	10
	P_s	71	70	73	73
Cairo	P_d	66	68	72	88
	P_f	32	27	25	21
	P_s	54	61	65	69

3. Conclusion

The main conclusions resulting from this study are as follows (1) The use of the standard K index with two more criteria was found to be a very good indication of thundery activity with skill around 85%. (2) The vertical profile of equivalent potential temperature confirms that a minimum of 285 K or less at 700 hPa is definitely associated with successful prediction if combined with K index. (3) Forecasts of temperature and dew-point temperature will provide a minimum of 12-hour forecast of the phenomenon. (4) Measures of static energy and stability energy may be switched into the forecast procedure, this skill achieved here with a probability of false alarm of about 10%.

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The publication of the *Meteorological Magazine* will cease with the issue for December 1993.

The December 1993 issue of the *Meteorological Magazine* will be a bumper one of about 40 pages celebrating the Magazine's contribution to the development and dissemination of meteorological knowledge. It will contain a selection of highlights from 1866 up to around 1986.

The first edition of the *Meteorological Magazine* was published in 1920 by HMSO. It took over from *Symons's Meteorological Magazine* which started in 1866. This decision therefore brings to an end a continuous publishing record of 129 years (except for the duration of World War II). It is understood that legal obligations accepted when *Symons's Meteorological Magazine* was adopted are fulfilled by the continuing production of the *Monthly Weather Report* and *Rainfall 19XX.*

As one of the leading European establishments for research into meteorology, our publications should be subject to external peer review: this is already the case for much Meteorological Office work. The publication of a new international and European quarterly journal by the Royal Meteorological Society (called *Meteorological Applications*) provides a suitable vehicle for most kinds of articles that have appeared in *Meteorological Magazine*, namely on research, practice, measurements, review articles, applications of meteorology, book reviews, etc. Enquiries should be addressed directly to the Royal Meteorological Society. Non-members should write to:

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The United Kingdom Meteorological Office (UKMO) Annual Scientific and Technical Review 1993/94

This Review describes the major developments in science and technology within the UKMO over the year April 1993 to March 1993 and is produced as part of the Meteorological Office Annual Report and became available in July 1994. If you wish to by put on the mailing list for future years please write to:

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Complete volumes of *Meteorological Magazine* commencing with volume 54 are available on microfilm from University Microfilms International, 18 Bedford Row, London WC1R 4EJ. Information on microfiche issues is available from Kraus Microfiche, Rte 100, Milwood, NY 10546, USA.

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Some highlights from early editions

Full contents on back cover

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The
Meteorological Magazine

December 1993
Vol. 122 No. 1457

The last editorial

One of the joys of editing *The Meteorological Magazine* has been that it has no tradition of printing Editorials. These slots are a trap for the unwary and provide a superb location for putting one's foot in one's mouth in public, making prophecies that fail spectacularly, and generally making a fool of oneself. Myself, I have from time to time taken the opportunity to add italicized comment, as with our very last item in this issue.

A quick check recently suggested that as many as one third of our articles have been from outside the UK in recent years. This issue contained none until a letter to Hong Kong brought forth the kind of reply (on the back pages) of which editors dream. There is one other foreign item that might escape your attention; this is on the back outside cover. My friends in Météo-France printed what amounts to an obituary in *La Météorologie* for which I thank them publicly here. We had intended to collaborate with Deutsche Wetterdienst to ensure that interesting articles appeared in three of the main European languages for the benefit of readers who would otherwise have had to make their own translations. I can only hope that the infant *Meteorological Applications* takes up the idea.

A final editorial must also pay thanks to three teams of unsung heroes, well known to authors but perhaps not to readers. The sub-editors go through the final text and catch all the howlers that the editor and author have missed. They also remove the blemishes that would cumulatively irritate the reader and give the magazine a second-rate appearance. The second team is our Graphics Studio who have seen to it that the quality of illustrations and diagrams have been to the highest standards and rarely bettered by contemporary journals. Last, but by no means least is Her/His Majesty's Stationery Office who have organized the publication of the Magazine since taking over from Edward Stanford in 1920; we are grateful to them for granting us 40 pages for this issue *at no extra cost to the subscriber.*

I should like to remind readers that many of the the techniques that are described in the *Forecasters' reference book* appeared first as papers in this magazine. Almost all these papers would require at least four or fives pages here, plus diagrams and, often mathematics; to have selected just one would have been invidious and take up the space of two or three shorter items, so all have been omitted.

Since 1864 many fascinating, enlightening and instructive papers have appeared in our pages. What follows are just a few highlights, in chronological order; I regret the omission of those for which there is no room despite the extra pages. My choice of topics is, I hope catholic, but it is biased towards brevity and accessibility and away from complicated typesetting and figures. A few special pages are facsimiles of the originals, most have been reset. No changes have been made to punctuation or usage of English; nevertheless the Victorians seem to have had a penchant for very small type which may have led to a few trivial errors during enlargement and conversion to the typeface you see here.

Finally, a warning. If you would like to read some of the old back numbers please allow plenty of time. They are a trap for the unwary, full of fascinating insights and the intended ten-minute browse will miraculously take half a day!

Farewell,

R.M. Blackall

SYMONS'S RAINFALL CIRCULAR.

JANUARY, 1864.

	STATIONS. [The Roman numerals denote the division of the Annual Tables to which each station belongs.]	Height of Gauge. Above Ground.	Height of Gauge. Above Sea Level.	Depth of Rain. Total in the Month.	Depth of Rain. Greatest Fall in 24 hours. Depth.	Depth of Rain. Greatest Fall in 24 hours. Date.	Days on which Rain, Snow, or Hail was measured.
		ft. in.	feet.	inches.	inches.		
ENGLAND AND WALES.	I. Camden Town, London	0 4	100	1·07	·32	20	9
	II. Linton Park, Staplehurst	0 6	200 ?	·77	·14	24	15
	II. Selborne, Hants	4 0	500 ?	1·97	·39	19	15
	III. Banbury	7 0	345	·94	·30	24	17
	III. Wisbech	0 6	10	·73	·32	18	12
	IV. Culford, Bury St. Edmunds	1 2	...	·83	·32	17	6
	V. Calne, Wiltshire	0 11	321	1·66	·27	1	18
	V. Goodamoor, near Plymouth	0 2	580	4·24	1·10	19	16
	V. Taunton, Somerset	1 6	38	1·65	·64	1	15
	VI. Orleton, Worcester	0 9	200	1·31	·22	23	16
	VII. Wigston, Leicester	0 6	220	·88	·22	23	12
	VII. West Retford	0 6	50	·87	·21	18	13
	VII. Derby	5 0	180	1·08	·20	17	15
	VIII. Manchester	3 0	106	1·72	·55	20	13
	IX. York	0 6	50	·82	·30	21	13
	IX. Arncliffe, Yorks	3 0	750	4·18	·85	19	13
	X. North Shields	1 0	124	1·00	·48	20	14
	X. Seathwaite, Cumberland	1 0	422	13·23	2·34	22	13
	XI. Haverfordwest	2 0	60	5·12	1·44	15	15
	XI. Cefnfaes, Rhayader	2 0	880	2·70	...	...	16
SCOTLAND.	XII. Dumfries	0 5	70	2·80	·50	12	16
	XIV. Auchendrane House, Ayr	2 3	94	2·40	·57	22	15
	XV. Oban, Argyll	0 4	10	5·80	·85	12	16
	XVI. Nookton, Leven, Fife	0 6	80	1·86	·67	15	15
	XVI. Deanston, Perth	0 0	60	4·45	1·25	31	11
	XVII. Aberdeen	0 7	55	1·44	·32	23	19
	XVIII. Culloden, Inverness	3 0	104	·45	...	...	7
	XVIII. Portree, Isle of Skye	0 4	60	11·38	1·66	26	22
	XIX. Scourie, Sutherland	0 3	26	2·80	...	...	10
	XIX. Sandwick, Orkney	2 0	78	1·37	·42	27	15
IRELAND.	XX. Cork	5 0	50	4·07	1·55	31	14
	XX. Waterford	4 0	60	3·75	1·00	11	18
	XX. Killaloe, Clare	0 5	123	2·95	·52	9	18
	XXI. Portarlington	9 0	236	3·97	·73	1	26
	XXI. Monkstown, Dublin	0 6	90	3·21	1·23	1	16
	XXII. Galway	6 0	25	4·62	·62	23	22
	XXII. Bunninadden, Sligo	1 3	...	3·04	·39	17	18
	XXIII. Owendoon, Bawnboy	...	...	2·63	·41	23	19
	XXIII. Waringstown, Down	0 4	191	1·65	·33	12	12
	XXIII. Leckpatrick, Strabane	0 5	260	2·21	·36	10	17

REMARKS.

ENGLAND AND WALES.

Camden Town.—Sharp frost until 10th. Min. 15°·1 (on grass 8°·8) on 6th.

Linton Park.—Sharp frost, and very dry the first 10 days, afterwards mild. No snow.

Selborne.—Min. temperature 9°·5 on 7th. Pale aurora on 9th, 23rd, and 27th.

Banbury.—Lowest temperature 10°. Much fog.

Wisbech.—For 23 days the barometer was above 30 inches. Min. 15°·1; (on grass 11°·8) on 6th. Slight snow on 3rd.

Culford.—Very slight snow on 2nd. Min. temp. 9° on 6th.

Calne.—Snow on 3rd. Snowdrops in bloom on 8th; crocuses on 15th. Dense fog from 13th to 16th, and again on 18th. A fine month.

Goodamoor.—Sharp frost from 3rd to 9th; on morning of 5th the min. temp. was 10°, and on the grass 8°.

Taunton.—Cold set in on 3rd, and on the 4th, 5th, and 6th the temp. fell to 13°.

Orleton.—Severe frost till 10th; rivers all frozen. Min. 10°, and on grass 6°·8, on 7th. Dense fog from 12th to 19th. On 22nd and 23rd violent winds in the morning.

Wigston.—Rainfall below the average, and much fog. Severely cold weather from 5th to 8th.

West Retford.—Min. 10° on 7th; frost on 22 nights.

Derby.—Rainfall 1·20 in. below the rainfall of 14 years.

Manchester.—January has been remarkable for the cold week ending Jan. 9th—the mean temp. of which was 12°·2 below mean of 15 years; but the ground has never once been covered with snow. Rainfall 0·75 in. below average of 70 years.

Arncliffe.—Min. 16°. No snow.

North Shields.—Fog prevalent from 5th to 20th; snow on 6 days; lunar halos on 19th & 21st.

Seathwaite.—No rain till 11th; 1·53 on 12th; 1·28 on 23rd; 1·73 on 27th; 1·03 on 28th; and 1·59 on 31st.

Haverfordwest.—Intensely cold during first 8 days. Min. 10° on night of 5th. Slight snow on 1st. Last three weeks stormy, with heavy floods.

Cefnfaes.—Min. 14° on 7th.

SCOTLAND.

Dumfries.—Frosty until 11th; min. 17° on 6th; snow on 21st and 23rd, but a mild month on the whole.

Auchendrane.—Rainfall 2·30 in. below the average of 8 years. Hard frost the first 11 days, but the rest of the month mild and stormy.

Oban.—First 10 days fine and frosty; min. 14° on 6th; remainder of month mild and wet.

Nookton.—A fine January; very cold, with severe frost (min. 11° on 8th) from 2nd to 9th; no snow or hail except on 31st.

Deanston.—Min. 12° on 6th; no snow on the low grounds, except a slight shower on 31st.

Aberdeen.—Barometer very high at commencement of month; min. temp. 22°·8 on 8th.

Culloden.—Fair until 21st, with sharp frost the first 10 days; min. 22°·2 on 6th.

Portree.—No rain the first nine days; upwards of an inch on 21st, 29th, and 30th. Thunderstorm on 19th. Lunar halos on 19th and 21st.

Scourie.—Clear and frosty until 9th. Hail on 31st.

Sandwick.—The driest January during the whole period of observation (23 years), the average being 4·17 in. Aurora on six nights; large halo on 3rd. January has been as pleasant a month as December was the reverse.

IRELAND.

Killaloe.—Some fine bright days, but on the whole a dark, damp, cheerless month.

Monkstown.—Severe frost from 5th to 8th; min. temp. 20°·5 on 7th. Lunar halo on 19th. Latter part of month mild and stormy.

Waringstown.—A remarkably fine month, and mild, except during the first week, when the temperature fell to 17°.

Leckpatrick.—No rain till 9th. Min. 24° (on grass 19°) on 6th. Southerly winds throughout the month.

NOTE.—Frost very general during the first ten days—most severe in the midland and eastern counties of England. Rainfall not much exceeding half the average.

G. J. SYMONS.

Camden Road Villas, February, 1864.

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INTRODUCTORY.

I BELIEVE that it is a rule *not* to judge of a serial by its first number, and I hope that the rule will be adhered to in the present instance, since future numbers will, at any rate, receive more time and attention than the present one, which having to appear simultaneously with *British Rainfall*, 1865, has had to be cared for in scraps of time snatched from its more bulky *confrère*. But let not this semi-apology be construed as a promise of future brilliancy, on the contrary, I would now, as ever, rather promise nothing, and let all I do sink or swim by its own merits; still it may be well to state that I *hope* to give in future numbers, Tables of Foreign and Colonial Rainfall, Notes on Thunderstorms in England during 1856-7 and 8, also on those in 1864 (these are somewhat voluminous, and contain not only curious results as to colour, &c., of lightning, but also as to its mechanical effects); Notices of Meteorological Books, new and old; and, above all, the latest rainfall intelligence, both as to its fall, its measurement, its publications, and its instruments. Lastly, I need hardly say, that its future depends very much on its readers; if they will send me prompt and full information of any unusual occurrence in their neighbourhood, and if they will (if they think it good) recommend it to their friends, the two essentials of high quality and a paying circulation may be obtained; and so I may be able to enlarge it, though my maxim always is, say everything in as few words as possible.

G. J. SYMONS.

136, Camden Road, N.W., Feb. 7th, 1866.

ON THE STORAGE OF WATER FOR COUNTRY VILLAGES.

THE severity of the drought during the last two or three summers has helped to force public attention to a point not generally appreciated at its full import. I refer to the influence of drainage operations on the supply of water available for man and beast in the summer months and periods of drought. It is very desirable the

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August 1866

A NEW ENEMY TO RAIN GAUGES.

MY DEAR SIR,—I have just encountered a new enemy to rain gauges, which had I not discovered it in time, or had I not kept several gauges of different sizes, heights, &c., might have caused me considerable annoyance. On looking into the receiver of my Apps' gauge (5 in.), I detected a small leaf, and, supposing it to have been blown in by the wind, proceeded to remove it, when I saw several more equally small, and some fragments. On carefully examining these leaves and fragments, I discovered that the pipe of the receiver of the gauge was completely filled up with nine nests of one of the genus Megachile, or leaf-cutter bee. I had great difficulty in removing them, so beautifully were they fitted and soldered as it were to the tube. To prevent the recurrence of this, I have fastened a little cap over the aperture of the pipe, leaving just sufficient space to allow the rain to trickle through freely, but small enough to exclude a similar invader on any future occasion. Thinking you might like to notice this in the next number of your *Meteorological Magazine*, I send you this account. Yours always, very truly,

Strathfield Turgiss Rectory, July 20th. C. H. GRIFFITH.

THE TRUE HISTORY OF A THUNDERBOLT.

ON July 2nd one of the London daily papers startled some of its readers by inserting a letter on the thunderstorm of June 30th, in which the writer said, "At six o'clock it broke out again with increased violence, the rain descending in torrents, and at a few minutes past seven a thunderbolt fell in the gutter opposite my house (in Westbourne Park, Notting Hill,) and was smashed to pieces, one of which I have at the hour at which I write. Numbers of persons are still searching for the fragments."

Feeling certain that there was a weak point somewhere, inasmuch as "thunderbolts" have no existence, we called on the writer of the letter and other residents, found the story amply confirmed, received several pieces of the "thunderbolt" (by the bye, some were sold at 10/- and 15/- each), and eventually ascertained that one of the pupils of an analytical chemist had availed himself of his tutor's absence to fill a capsule with materials calculated to burn vigorously, and explode in heavy rain, and, during the height of the storm, had thrown the burning mass into the gutter, so making an artificial thunderbolt. It is no wonder that the neighbours were taken in by a trick so well-arranged.

September 1866

THE METEOROLOGICAL DEPARTMENT OF THE BOARD OF TRADE

THE appointment of chief of the above office could scarcely be a sinecure in a country like this, where ceaseless alternations require attention, and where so many fancy they possess the key of nature's secrets, and can tell whence the wind cometh and whither it goeth. Admiral FitzRoy, however, took such unusual steps to bring his work before the public that it is no wonder that during the ten years in which he presided over the Department constant criticism was his lot; and that with his total lack of management, all his energy, experience, self-devotion, and zeal, were inadequate to cope with the pressure of work necessarily incidental to the position he held. However, the good old Admiral is gone, and we can only repeat the sentiment of one of the leading journals "He is gone to his rest, and many a storm-sheltered mariner will look to the signal drum, and grieve with a manly sorrow for the loss of Robert FitzRoy."

Shortly after his death, a letter was addressed by the Board of Trade to the President of the Royal Society asking the advice of the Royal Society — (1) As to the extent to which the Department had fulfilled the objects for which it was organized; (2) As to the reliability of forecasts and storm signals; (3) As to the future conduct of the Department. About a month afterwards (June 15th, 1865), General Sabine, on behalf of the Royal Society, replied — that they considered the evidence submitted to them justified their recommending that the forecasting should remain in the hands of Mr. Babington, by whom it had been virtually carried on for some months past; that the meteorological observations made at sea by the captains of the royal and merchant navies be transferred to the custody of the Hydrographer, with a view to the introduction of the results into the Admiralty Charts; and lastly, that an entirely new system be organized for observing the "Land Meteorology of the British Islands," the stations being not less than six* in number, and provided with self-recording apparatus, the records from which should be sent weekly or otherwise to Kew Observatory, which is hereby proposed as the centre of

*Falmouth, Kew, Stonyhurst, Armagh, Glasgow, and Aberdeen, are proposed.

this system. The Board of Trade subsequently expressed a desire for more thorough consideration of the progress made in marine meteorology, suggested the appointment of a small committee of investigation, and intimated that they saw some difficulty in the proposed maintenance of two establishments, one at Whitehall and one at Kew. Eventually, the following three gentlemen were appointed (in November, 1865) a committee of investigation:–

Royal Society — Francis GALTON, Esq., F.R.S., General Secretary of the British Association.

Admiralty — STAFF-COMMANDER EVANS, R.N., F.R.S., Chief Naval Assistant to the Hydrographer.

Board of Trade — T.H. FARRER, Esq., one of the Secretaries to the Board of Trade.

Their report was presented to Parliament last session, and proves three points at once — first, the desirability of such a thorough investigation, the efficacy of the committee proposed by the Board of Trade, and the ability (if that wanted proving) of the persons nominated. It is rather voluminous (81 pages folio), and so replete with facts and details of importance as to render it extremely difficult to present an abridgment doing it full justice. After giving a clear and succinct account of the origin and original functions of the Department, it notices the steps taken to obtain meteorological observations at sea, and their results; also the method adopted by the Department in extracting observations, which comes in for detailed criticism of an exhaustive character, and a plan for future use is suggested of considerable value, and which we will therefore examine rather fully. Of course the essential difference between the meteorological register of a ship, and an observatory, is that the place of observation is movable in one case and fixed in the other. This difficulty is obviated by portioning out the ocean into squares embracing 10° of latitude and 10° of longitude — of course, therefore, of variable real area, but still readily recognized divisions. The old plan was to have "Data Books" for each subject, paged to correspond with the squares just referred to; then if the Department were working up any subject, the ships' registers were searched for that one detail only, and the rest was left uncopied; thus at least eight or ten separate searches were made, involving quite fourfold the trouble of the plan now proposed, which is, that each register should be copied out at once on to a set of printed cards, which could then be searched, sub-divided to any extent, and available in any way. We have seldom seen a more sensible or useful suggestion. The Committee proceed to enumerate and comment on the publications of the Department, which as a rule are condemned for their want of method. Among their suggestions for future practice is that of a form (Appendix p. xviii.) in which certain observations might be tabulated for publication, which is either an absurdly complicated misprint, or it requires explanation. The year is divided into four quarters, as follows: — December, January, February; (2) March, April, June; (3) July, August, September; (4) August, November, December. May and October are therefore omitted, and August and December mentioned twice. We cannot comprehend this at all.

We have already remarked that the Board of Trade suggested a possible difficulty by the maintenance of a duplicate establishment at Kew; a paragraph, however, on p.17 of the report under notice shows a third branch of the Meteorological Department: — "The Admiralty Hydrographic Department are now devoting considerable pains to the preparation of physical charts — such as Ice, General Ocean Currents, and Wind Charts. In these it is proposed to embody the results collected by the Meteorological Department in a form available to seamen."

The second part of the report is occupied by an account of the origin, and a rigorous examination of the Forecasts and Storm Warnings issued by the Department; it is far too voluminous for extract, but the following are the conclusions arrived at by the Committee:–

"(1) That the maxims on which the Department act in foretelling weather have not been reduced into any clear or systematic form, and are not shown to have been established by sufficient induction from observed fact.

"(2) That as matter of fact the Daily Forecasts are not shown to be correct, and that they are not in our opinion useful.

"(3) That the Storm Warnings, so far as they indicate the force of coming gales, have been sufficiently correct to be of some use, and that their utility is widely admitted. Also, that they have improved, and that they are probably capable of still greater improvement.

"(4) That the Storm Warnings, so far as they indicate the direction as well as force of coming gales, are not shown to have been so far precise or correct as to be of use."

After mentioning the benefit conferred by the erection by the Department of 95 good barometers at some of the poorest of the fishing villages, the report notices and approves the suggestion of the Royal Society as to the establishment of the six stations with self-recording, instruments already referred to, proposes that they be supplemented by about sixty secondary stations, lighthouses, &c., and that the returns thus obtained should be laid down on maps similar to those of M. Le Verrier, and published at a low price. They insist on the officer issuing a storm signal "noting down at the time, and reducing into exact shape afterwards, the maxims or principles which have guided him in making the Signal of Force, or Prediction of Direction; the facts to which those maxims are applied; the mode in which he has applied or combined them, the value he has attached to each of them, and the value of the probability he has thus obtained, and which is indicated by the signal or prediction"; they also propose that a rigorous check on the signals be kept by collating all available records with the predictions.

They further propose that the collection of ocean statistics should continue much as it was originally arranged by Admiral FitzRoy, but that the discussion of the results should be on the improved plan already explained; that additional buildings be erected at Kew, and the branch department there should be under the control of a scientific body receiving a grant of about £7000 per annum from Government, and out of it defraying all expenses incidental to the thorough and systematic collection of weather statistics of the British Isles, and the maintenance of the system of storm warnings. As far as we can see, the estimated expense of the Kew and Board of Trade Meteorological Departments would be about £15,000 per annum, to which must be added the expenses incurred at the Hydrographic Department in getting out and publishing charts. The report goes on to express the hope that at no distant day one international centre may be established, and thus all divided and therefore duplicate labour be avoided; and concludes with the following paragraph:–

"We feel, moreover, that we should be doing great injustice to ourselves if we were to allow it to be supposed that we undervalue either what the late Admiral FitzRoy attempted or what he effected. To his zeal and perseverance is due the credit of establishing a system of Storm Warnings, which is already highly prized by the seafaring class. And if a more scientific method should hereafter succeed in placing the practice of foretelling weather on a clear and certain basis, it will not be forgotten that it was Admiral FitzRoy who gave the first impulse to this branch of inquiry, who induced men of science and the public to take interest in it, and who sacrificed his life to the cause."

June 1867

SEVERE HAILSTORM IN INDIA

"A CORRESPONDENT of the *Madras Athenaeum* at Goommanur,* near Bellary, informs us that very bad weather was recently experienced there. On March 28th a terrific hailstorm swept over the place. All the trees in the neighbourhood were stripped of their foliage, heavy branches were torn down, and many trees torn up by the roots. People's clothes were removed from their backs, and a tent was shivered to rags. The hailstones were as large as cocoa nuts and good-sized mangoes. Some four hundred sheep and twenty head of cattle were killed, as were also several human beings, a large number of whom were severely hurt. Thirty hours after the storm, hailstones were picked up in some of the railway cuttings the size of fowls' eggs" — *Homeward Mail, May 22nd,* 1867. — * Spelt Goomanoor in this article and Goommanur in the second one; the latter is believed to be correct.

"In the early part of April the collector of the Kistna district reported to Government that on the evening of March 27, there occurred a storm of wind, accompanied by rain and hail at the village of Goveravaram, in the Nandigama talook in this district. The hailstones were as big as limes. They continued to fall for about quarter of an hour, and lay on the ground to the depth of span. Men and cattle were reported to have been severely bruised by the hailstones, which remained in heaps unmelted till nine o'clock a.m. the next day. The collector of Bellary also reports that on the afternoon and night of March 28 and 29, a very severe hailstorm passed over this district.

'In Adoni to the north of the talook, at Nukkulmittah and other villages, the hail is described as being of the size from cocoa nuts to woodapples, and lying to one foot in depth; in some places destroying the wet and dry crops. In Gooty, at eight p.m. on the 28th, the hail was described as ranging from the size of bullets to limes; some sheep were killed and crops destroyed. The villages indicated are Hunchinbal, Karakamookkala, and Koncondla. In Anantapur talook the size of the hailstones is apparently incredible. I give, however, the local report that in a field of the village of Bondalavada some of the stones were two-thirds of a cubic yard in size. In the village of Chadula a cubic span, and in other villages of six seers, or three pounds weight; this last was verified by the Tahsildar. Two men, 2,470 sheep, and eight cattle were killed, and some thatched houses were destroyed. In Alur, on March 28 and 29, to south of the talook, at Goormmanur and other ten or twelve villages the hail was described as ranging from the size of cocoa nuts to mangoes, and lying half a yard in depth in some villages, destroying the dry crops, two men were killed, and one carried away by the flood in a nullah close to Goommanur. Looking from the talook of Hospett on that evening, a vast pile of electric clouds was seen towards the east, similar to those which collect on the western coast before the commencement of the monsoon. I have had no intelligence of hailstorms in the western talooks, or from those furthest south, so that as far as I am at present informed, the storm must have extended over the north, centre, and south-east of the district.When further details are received regrading the loss of crops a report will be made, if any, and what consideration should be shown to the sufferers.' Tho collector of Cuddapah reports that a severe storm, accompanied by hailstones of extraordinary size, was experienced in different villages of the three talooks, Pulivendala, Royachoty, and Kadiri. In the Pulivendala talook seven individuals received serious wounds and lost their lives. The storm in the other villages swept away the standing crops and stacks, and also killed some sheep." — *Homeward Mail, June 4th, 1867.*

January 1868

CYCLONE IN BENGAL

ALTHOUGH there is certainly no present proof of community of origin, it is at least a singular coincidence, that almost at the very same moment that Tortola was being laid low by a cyclone unequalled in destructive power for thirty years, "Calcutta was astonished at a return of wet weather," followed in a few days by a violent Cyclone.

The disasters in Bengal were far heavier than in the West Indies but as only three years have elapsed since the former district suffered from one of the most destructive storms on record, the present catastrophe has been deemed less important than it otherwise would have been. The cyclone of October 5th, 1864, swept over Calcutta in the day-time, yet 50,000 lives were lost, and property worth upwards of two millions was destroyed. In 1867 the lives lost are computed at 3000.

The following extracts from the Calcutta *Englishman* give a vivid description of what is often deficient — namely, the premonitions of the storm.

"For weeks past the weather has been a foremost topic of conversation. The rains had apparently ceased, when Calcutta was astonished, on 26th October at a return of wet weather. During all last week rain seemed threatening, and on Thursday the threat began to be fulfilled. The sky on Friday was overcast and lowering, the pall of cloud was unusually low, and masses of scud were whirled swiftly away to leeward all day long. The gloom of the day was added to by frequent rain-squalls; the day, in fact, was just one of those for which November in England has acquired so unpleasant a reputation. As the day wore on the signs of bad weather increased. About three o'clock the barometer began to show signs of falling, and the wind came down in fiercer gusts. Matters remained in this state till dusk, when it was evident to the most careless that Calcutta was about to be visited by a storm, which would rival the now famous Cyclone of 5th October, 1864. Men went home from office to hurry through dinner and prepare for the struggle, and although some daring spirits went to the Opera, they were the exception. At ten o'clock, the fastenings of doors and windows began to be severely tasked, and the storm rushed over the city with a heavy murmurous roar, like a fierce surf beating on a shingle beach. This roar never lulled until daylight, but every few minutes it swelled up into a thunder of wind and rain, marking the approach of heavier squalls. Up to half-past one the storm was content with rattling doors and windows furiously, but now it forced its way into the well-guarded dwellings of the European portion of the city, and tore off here a sash, here a venetian, here a door. The houses shook under the force of the blows dealt them, and often and anxiously were the time-pieces consulted to see how the night wore away. Soon after two, however, there was a sensible abatement of the storm, the gusts were as fierce as ever, but the intervals between them were longer. By half-past three the strength of the gale had greatly abated, and by four the hurricane had become a strong westerly gale, and people began to count up the damage they had sustained, and to hope for daylight, to enable them to ascertain the losses of their neighbours. Few slept last night, and there are few who could wish to pass such another night, or to battle again with a gale which has wrought the city, as much, if not more, injury than even the great cyclone."

"The following is the official report from Mr. Blandford, the Meteorological Reporter, on the storm of Friday night:– On the night of 1st and 2nd November, Calcutta was visited by a severe cyclone, the centre of which passed to the east of Saugor Point and Calcutta, in a northerly direction. Threatening indications were noticed in the telegrams, received on the morning of the 1st, from Saugor Point and Cuttack, and the probability of an approaching storm was strengthened by a report sent from the former place at 12 h. 30 m. These, with the subsequent reports from Saugor Point at 16 h., 17 h. 30 m., and 19 h. were communicated at once to the Master Attendant of the Port, but up to 19 h., the wind at Saugor Point shewed no sign of veering, and it was uncertain whether the cyclone had actually formed. At 20 h. no distinct telegraphic report could be received from Saugor, and the 19 h. telegram is the latest information received thence up to present date. At Calcutta the wind was from N.E., and shortly after dusk became fitful and threatening, the gusts gaining gradually in strength until they reached their maximum between 2 and 3 a.m. of 2nd (?). The wind was at first from the N.E. veering gradually to N. and to N.W., which was its average direction when most severe. The lowest barometric reading at the Surveyor General's office was taken at 3 a.m., viz., 28.6 inches.

"The maximum force could not be recorded, owing to the destruction of the anemometer at 2 a.m. The storm abated, and the barometer rose rapidly after 3 am."

"A native correspondent at Jessore, writing on the 3rd November, sends us the following:-

" 'Jessore has been swept by the terrible cyclone, unprecedented in the history of this little station. From the evening of the 29th October to 11 p.m. of 1st November, it rained heavily. At half-past eleven, a burning brilliant cloud was first observed in the north-east corner of the station. All thought at first that it was a fire, but it was not so; for the storm soon began, and changed its direction as the sky-flame changed its position, i.e., from north to east, to south, to west — to north-west, whence in the morning it disappeared. It was not a cloud, for clouds were distinctly seen running fast below it. When it was in the north-east several houses at Jhoonjhoonpoor (a small village north-east of the station) were burnt; when it was in the north-west fire set into some of the houses at Poorono Kuslea (a village north-west of this station); similarly to some houses in another village in the east. I have yet received no news from south and west. The fires may have been accidental, but the brilliant flame, which guided the course and direction of the great cyclone, deserves enquiry. The spiritualists here attribute it to supernatural agency, but let the materialists, or the so-called scientific world explain the phenomenon! It was not a delusion, for it as observed by the majority of the residents. I write you to know this, for you have many literary and scientific readers, who, I hope, will kindly come forward and explain to us (ignorant men) the mystery of this mysterious flame! ! !

" 'Except a few *pucca* houses, all gone down! Rice crop at once ruined, prospect of winter crop very gloomy, and the people know not what to do.They attribute all these to the sins of their rulers. I am glad, however, to inform you that our magistrates are doing all that humanity could wish, or energy act.'

"This letter mentions a phenomenon preceding the storm which we do not remember to have heard of before, in connection with cyclones. Several correspondents have, however, spoken of a peculiar luminous appearance in the atmosphere at the height of the storm. The subject is one well worthy of investigation."

February 1881

EDITORIAL AND EXPLANATORY

DURING the past fifteen years it has several times been our duty and our pleasure, by special enlargements, to present our readers with complete accounts of remarkable phenomena. But on no occasion has there been such a strain put upon us, as has resulted from the mass of details furnished respecting the frost and the snow of the past month, which have come in along with sadly too numerous enquiries, "How to measure the snow" from observers who had neglected to read rule XV., which we reprint, in the hope that, with the recent snow-storm in their memory, all our correspondents will read it.

XV. — SNOW — In snow three methods may be adopted — it is well to try then all. (1) Melt what is caught in the funnel by adding to the snow a previously ascertained quantity of warm water, and then deducting this quantity from the total measurement, enter the residue as rain. (2) Select a place where the snow has not drifted, invert the funnel, and turning it round, lift and melt what is inclosed. (3) Measure with a rule the average depth of snow, and take one-twelfth as the equivalent of water. This being a very rough method, is not to be adopted if it can be avoided. Some observers use in snowy weather a cylinder of the same diameter a the rain gauge, and of considerable depth. If the wind is at all rough, all the snow is blown out of a flat- funnelled rain gauge. Snowdon pattern gauges are much the best.

Very fortunately the Council Meeting of the Meteorological Society was held on the night after the snow, and it was then resolved that all the data respecting the frost which could be collected should be forwarded to the Assistant Secretary, Mr. Marriott, who should discuss them and report the results to the meeting of the Society on February 16th. An abstract of this report will be found on page 25, and of course the report in *extenso* will appear in the Society's *Quarterly Journal*. Hence it is that none of the many letters which we have received upon the subject will found in our pages.

We undertook the investigation of the limits of the snow-storm; we applied specially to 150 of our observers and also to the managers or principal officers of the following railway companies, nearly all of whom have taken much trouble in the matter, and rendered most valuable aid, as is sufficiently evident from the letters and tables printed at the end of Mr. Wallis's report.

Although it has been a matter of considerable difficulty to get all this mass of material discussed in time for the regular-date of publication we are satisfied that accuracy has not been sacrificed to speed, and that such subsequent material as may arrive will in no way invalidate the conclusions arrived at in the following article.

Owing to the very exceptional character of the snow-storm many of the monthly returns on pages 30 and 32 are obviously incorrect. All the figures to which the is attached are not necessarily wrong; but the observers are requested to report what they believe to have been the average depth of the snow in their neighbourhood, and the nearest possible approach to the truth will be obtained before the publication of the annual totals. Few rain-gauges will hold 5 inches of snow, many will not hold 3 inches — where, therefore, the fall has exceeded those amounts it is evidently fallacious to report merely what was "found in the gauge." Rule XV., Sections (2) and (3), should have been generally followed, but even then some difficulty existed. It is neither easy nor pleasant to obtain accurate measurements of such a storm; we rejoice to notice the care which many of our observers paid to the matter; that which they have done will not merely render their own records perfect, but will help to check those of their neighbours, and in spite of all difficulties and a terrible addition to our ordinary work, we have no doubt that eventually few records will prove entirely spoilt. — G.J.S.

February 1881

ON THE SNOW STORM OFJANUARY, 1881

BY H. SOWERBY WALLIS, F. M. S.

AFTER the 9th of January snow fell daily on some portion of the British Isles, and on the 12th and 13th rather heavily over the greater part of them, so that by the 17th (on which day practically none fell), there was a considerable depth on the ground over the whole of the United Kingdom, the weather having been so cold that scarcely any had melted. This depth averaged three to four inches over the greater part of England, and rather more in Wales, the N. of England, and in Scotland. During the early morning of the 18th the wind, which was easterly, rapidly increased in force, and blew a strong easterly gale nearly all day, the wind falling again in the south at night, but in other parts of the country it lasted till about mid-day on the 19th. The gale was particularly severe on the east coast, but the number of wrecks and casualties all round our shores was very great; reports from many seaports stating that it was the most severe gale that had been experienced for more than 30 years. Much damage was done to roofs, &c., and a very large number of trees were blown down in the eastern counties — e.g., Lord Rendlesham reports over 1,500, most of them large ones, blown down on his estate, and there were many isolated cases of structural damage in other parts of the country. In London an extremely high tide, increased by the gale, overflowed the low-lying districts on the south of the Thames, causing great distress, augmented by the extreme severity of the weather, among the poorer classes.

The gale was accompanied by a heavy and steady fall of snow over all but the north of England, which lasted through the 18th and continued, though rather lighter, till about noon on the 19th. The amount of snow deposited over the whole of the southern portion of the country was very great, and was so drifted by the fierce wind, that communication both by rail and road was entirely disorganised, and it was more than a week before the railway and postal arrangements throughout the country recovered their usual regularity and punctuality; the interruption to business was further increased by the large number of telegraph wires which were broken by the gale or by contraction caused by the extreme cold.

Snow fell again on the 20th in the S; and S.W., very heavily in the Isle of Wight and neighbouring districts, blocking up many lines of railway that had with great difficulty been cleared from the fall of the 18th.

Among careful observers in all parts of the country where the snow fell with its full intensity, it appears to be the general opinion that to find anything like a parallel case we must go back to 1836 or to 1814; and it would appear that in most parts of the country the depth in those years was greater, but that the drifts were not so great. As regards the fall in the Isle of Wight and South Hampshire, it is believed to be altogether unprecedented in recent times.

One feature of the snow which appears to have been noticed nearly all over the country, was its extreme fineness and dryness, and the remarkable manner in which it penetrated in large quantities through roofs, the cracks of doors and windows, and even the most minute and almost imperceptible crevices.

The loss of life in England and Wales, entirely due to the snow, was very great, and probably an estimate of 100 persons would be very near the truth, and the amount of distress occasioned simply by the stoppage of the supplies of food and fuel to country districts from towns is almost incalculable.

Small birds died of starvation in vast numbers, their food being covered by the snow. At Littlehampton, in one shrubbery, more than 100 dead blackbirds and thrushes were found, and the following curious incident is reported in an Isle of Wight newspaper:– "A friend of ours looking from his window (in Shanklin) on Monday, saw some larks hopping about on his lawn. Presently some rooks swooped down upon the birds, tore several to pieces, and ate them."

It is very difficult to realise the magnitude of the snowstorm and of the drifts; perhaps some of the men employed in clearing the railways had the best opportunity of doing so. Locomotive engines and trains, in spite of their size and power, were snowed up by the dozen; not merely stopped, but buried for days together, and in some cases so completely as to be quite hidden. From the Tring cutting on the L. & N.W. railway, 1,700 truck loads of snow were taken. A railway truck is about 15 ft. long, therefore 1,700 trucks would form a train nearly five miles long. A train five miles long to empty one cutting on one railway, what length of train would it require to remove the snow from all the cuttings on all the railways in England?

The loss to the country was enormous; over more than half England business was practically stopped for one day at least, and the cost of clearing not only the railways but almost all the roads in the country, is incalculable, not to mention the more or less serious suffering and discomfort. Plymouth was deprived of water for nearly a week. Public and private meetings of all kinds had to be postponed; in short, that intercourse between man and man, on which the whole business and pleasure of life depend, was interrupted.

The accompanying map and following summaries for the different counties are founded on special returns from about 200 regular meteorological observers, and on the reports furnished by nearly all the great railway companies, which are especially valuable, as they are

DISTRIBUTION OF SNOW

January 17th to 21st, 1881

For explanation see page 300.

based on statistics furnished by the engineers and traffic superintendents of the various lines, who not only had special opportunities of ascertaining the various depths, but who are in the habit of dealing with accurate measurements, and are, therefore, less likely to be led into unconscious exaggeration than amateurs of all classes.

The depths of snow in the various cases must be understood to represent the greatest depth to which the ground was covered at my time between the 17th and 21st of January, as it was impossible to deal with it in any other way; but except in the extreme S. and S.W., by far the greater portion of it fell during the one continuous storm of the 18th–19th.

The map shows at a glance where the greatest amount fell. Over the white portion the depth exceeded 12 inches, and the part left black is where no appreciable amount fell on the 18th and 19th; the shaded portions represent respectively where the depth was less than 6 inches, and where it was between 6 and 12 inches.

There was also snow on the ground over almost the whole of Scotland and Ireland, which drifted considerably, and in some cases caused delay to traffic; but it has no interest in connection with the abnormally heavy fall of the 18th and 19th over the southern portion of England, and therefore needs no further notice. The special feature being that the heaviest falls occurred in those parts of the United Kingdom where ordinarily such falls are most rare.

List of Railways supplying data

Great Eastern
Great Northern
Great Western
London and North Western
London and South Western
London Brighton and S. Coast
London Chatham and Dover
Manchester, Sheffield and Lincolnshire
Metropolitan
Midland. *Reply too late for this month*
Somerset and Dorset
South Eastern. *Report not yet received.*

April 1885

FLOATING MID-ATLANTIC METEOROLOGICAL OBSERVATORY

INASMUCH as most of the changes in British weather are due to the passage of cyclonic systems which are traversing this quadrant of the globe from some Westerly towards some Easterly point, it is obvious, and generally recognized, that it is more difficult to forecast the weather which will occur on the West coast of Ireland than in any part of Europe.

It has never seemed to us a very wise arrangement that this forecasting should be done in the extreme East of the British Isles, in London, instead of at a Western centre such as Galway; but that is not the point now before us.

The great difficulty in forecasting British weather is the lack of information from the Westward. Excepting the Azores (and they are so far South as to be of little use), there is nothing but ocean West of Ireland until we reach Newfoundland.

Let us not, however, be misunderstood and said to be adverse to the establishment of regular communication with the Azores. By itself we believe that a daily telegram from the Azores would be, as we have said, "of little use" in forecasting British weather; but we think that it would be quite otherwise as regards the more Southern countries of Europe, and if obtained primarily for their benefit, should certainly be reported to our own office.

From the vast stretch of ocean between Ireland and Newfoundland there has hitherto been only one way of obtaining information, viz., that for which the credit will ever remain due to Mr. Gordon Bennett, of the *New York Herald*, and his clever meteorological assistant, Mr. Collins (who perished in the ill-fated Jeanette expedition). His plan was to combine the information of cyclonic movements on the American Continent as obtained from the Signal Office, with the meteorological data for the ocean as stated in the log books of Transatlantic steamers arriving at ports on the Eastern coast of America; he was thus able to track the cyclones after they left the American coast, and hence infer the trajectory which they would probably follow, and their velocity in it.

Collins, as we have said, perished in the Arctic regions. Had he still been alive, we should certainly have heard some comments from him upon the fact that while Mr. Bennett was at his own cost sending the telegrams to this country, they were stated to be useless and yet, eight years after they were commenced (the first *New York Herald* warning was sent February 14th, 1877*), we find the English Meteorological office arranging with the American Signal Office for the transmission of telegrams (at whose cost we do not know) with precisely the object for which Mr. Bennett sent them.

*Comptes rendu Congrès Internationale de Météorologie.–Paris, 1879, p.110

All this, however, is introductory to, and justificatory of, what we are going to plead for — viz., a floating Meteorological observatory in about Latitude 50° N. and Longitude 20° W. Of course, the first remark that will be made upon the proposal is that it is an impossibility, and the second that the idea is a very old one.

We are aware that the depth of the ocean at the above spot is about 2,000 fathoms, about 2¼ miles, and that a mooring chain of that length would be a novelty — but the days when novelties are regarded as impossibilities have surely passed. Is no encouragement to be derived from the fact that broken telegraph cables have been picked up at even greater depths, and raised to the surface. The precise locality is not, however, to be decided wholly on Meteorological considerations, Meteorologists have little chance of raising necessary funds, and the Observatory must be also a call station for passing vessels and for those in distress, and these conditions may require a different locality.

We start afresh with some more scraps of history. The first must be very incomplete, since we cannot lay hands on any printed account. About twenty years ago an attempt was made to establish a "call station" for merchantmen entering the Channel, by placing a vessel somewhere South of the Lizard, which vessel had telegraphic connection with the main land. We believe that the vessel was not constructed specially for the work, and the connection was so often broken, that eventually the scheme was abandoned.

The idea of establishing electro-telegraphic communication with ships in shallow water is by no means given up. In the Fisheries Exhibition of 1882 there was at least one full size specimen of a connection adapted for a light-ship, and some such connection has actually been fitted to, and is working from the "Sunk" light-ship nine miles distant, to the coast at Walton-on-the-Naze.

At the Fourth Annual Exhibition of Instruments, held by the Royal Meteorological Society, March 21st, 1883, there was an exhibit thus described in the catalogue:-

"78.— Cartoon of a Vessel designed for automatically compressing and storing air by means of the waves of the sea, and for the generation of electricity by means of this compressed air. The inventor considers that the vessel can be used as a telegraph ship, and is capable of being moored in 1000 fathoms of water, and connected with the shore at any distance with an electric cable.

"*Exhibited by* C.W. Harding, Assoc. M.I.C.E."

We believe that we are correct in supplementing this by the statement that Mr. Harding had a small vessel built for experimental trial, and that it was moored off the Norfolk coast.

Lastly, but by no means least, we reprint from our excellent contemporary, the *American Meteorological Journal* for March, the article which has led us to draw special attention to the subject — one which, for the reasons stated at the beginning of our paper, is of infinitely more practical importance to us than to our American friends; for such a station would rarely be able to warn them, and on the contrary would almost always be able to help us:-

METEOROLOGICAL STATIONS IN THE ATLANTIC

The widespread and increasing interest taken the information furnished by the U.S. Signal Service, as shown by requests to establish signal stations throughout the country, should met by establishing meteorological stations in the Atlantic over or near the commercial cable lines, when they would be in communication with both sides of the Atlantic.

The practicability of such stations has been demonstrated by the cable-laying steamship *Faraday* while laying the cable between France and the United States, and, holding on to the cable, found herself in the course of a cyclone which passed directly over the vessel without causing her to lose her hold of the cable, and which was at once reported to the European continent, the report giving wind changes and velocity with barometric changes. It is also demonstrated by the light-ship off Frying Pan Shoals, N C., which is anchored about twenty miles from shore, where it is exposed to the severe storms that occur off the Carolina coast. The value and importance of such stations is apparent; continuous observations could be had, not otherwise accessible; storms could be traced throughout their entire course, and the observations in connection with those of the signal stations on the Atlantic coast would decrease the danger arising from sudden storms.

The steamships of the great ocean lines and others could be warned by signal of storms raging across their path; communication by means of signals could be held with vessels, and vessels reported to owners; proximity of icebergs and wrecks reported, and it might be the means of saving many lives. If but one life were saved, it would compensate for the expense of establishing and maintaining stations. The stations, under control of chief signal officers of the army, and manned by observers of the Signal Service, would add valuable data to the science of meteorology.

F.S. COBURN
New River Inlet, N.C., January 25.

To this it may be added that the recording instruments recently brought out by Messrs. Richard Frères will all work on board ship, and thus we could have a floating observatory with continuously recording instruments, a gain of considerable importance.

How many years will the weather forecasters of Europe have to rely upon conjecture, owing to the non-establishment of such an observatory as above suggested?

March 1900

GEORGE JAMES SYMONS. F.R.S.

London, 6th August, 1838 — 10th March, 1900

THE Founder of the British Rainfall Organization and of this Magazine has passed away after a life, long in good work, though short of the allotted threescore years and ten.

In 1857 he started an organization for observing and recording thunderstorms, and soon after began the great work of his life in connection with British Rainfall. The first published volume contained the records for the year 1860, while the fortieth will be issued within a few months of his death. With 1866 he commenced the publication of the *Meteorological Magazine*, and this is the first number which has contained no article written by him.

For forty-four years he was a Fellow of the Royal Meteorological Society, and for twenty-seven years was its Honorary Secretary, except during three years when he occupied the presidential chair, to which he had this year been again elected as being best fitted to support the Society in the celebration of its jubilee. For forty-two years he supplied monthly records of meteorological observations to the Registrar-General; for forty years he was a member of the General Committee of the British Association, and served on many Committees; and for nearly forty years he was a member of the Scottish Meteorological Society. For twenty-seven years he was a member of the Société Météorologique de France, and served three times on the Council.

There is no need here to enlarge upon his work, but in illustration of his widespread activity may be mentioned "Notes on the Solar Eclipse of July 18th, 1860," "Meteorological Statistics and Bibliography of the Colonial Empire," "Inquiry into the Temperature of the Thermal Springs of the Pyrenees," "The Floating Island in Derwentwater," "The Lightning Rod Conference," "The Eruption of Krakatoa," and "Cowe's and Merle's Meteorological Registers," besides his great contribution to the bibliography of meteorology.

The honours of work fell to his share more than those of mere compliment, and he was elected president of innumerable congresses and committees at home and abroad, and Juror at meteorological exhibitions both in England and on the Continent. He received a Telford premium of the Institution of Civil Engineers in 1876; in 1878 was elected a Fellow of the Royal Society, was created a Chevalier de la Légion d'Honneur in 1891, and was selected by the Prince of Wales to receive the Albert Medal of the Society of Arts for 1897.

His great kindness and genial personality were known almost the world over, and among his innumerable colleagues on the Councils of the Royal Society, the Royal Meteorological Society, the British Association, the Société Mét. de France, the Royal Botanic Society, the Sanitary Institute, and on numerous other bodies, he is not known to have made a single enemy. The great majority will sincerely mourn his loss as that of a true friend, and will be able in some measure to appreciate what it must be to the writer of this brief memoir who has worked with him daily and hourly for nearly thirty years, and who is proud to have been selected by him as his successor in the work.

H. SOWERBY WALLIS.

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Air Ministry :: Meteorological Office

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Introductory Note.

WITH the first issue of *The Meteorological Magazine* as the official organ of the Meteorological Office, a few words of introduction may be desirable. Since 1916 the Office has issued each month a Circular, which has been found of value for the publication of official information and for the exchange of opinions on current meteorological topics. On the absorption of the British Rainfall Organization, the Office became respoisible for the continuance of *Symons's Meteorological Magazine*, which had been closely associated with that Organization throughout its long history. The continued existence of two separate publications was obviously undesirable, and the *Meteorological Magazine* is to be issued instead. For convenience in reference the serial numbers of *Symons's Meteorological Magazine* are being carried on.

With regard to the *Meteorological Office Circular* it may be noted that a classified index has been prepared. Typed copies of convenient size for binding will be supplied on application to the Office.

Contributions to the *Meteorological Magazine* from Observers and others who take an interest in the weather will be welcomed by the Editors, to whom they should be sent not later than the 5th of the month.

February 1920

Retirement of Sir Napier Shaw, Sc.D., LL.D., F.R.S.

THE retirement of Sir Napier Shaw from the Directorship of the Meteorological Office, on the completion of the third term of his appointment, will be received with regret by all who have been associated with meteorological work in this country and abroad. Sir Napier's connection with the Office has extended over 40 years, for it began in 1879, when, at the request of the Meteorological Council, he undertook an experimental comparison of the various methods of determining the hygrometric state of the air, the results of which were published in the Philosophical Transactions of the Royal Society in 1888. In 1897 he was appointed a member of the Meteorological Council to fill the vacancy caused by the death of Mr. E.J. Stone, F.R.S. In 1900 he succeeded the late Dr. R.H. Scott as Secretary to the Council. From that date the work of the office has been carried on under his immediate supervision, and the present eminence to which the Office has attained is due in no small measure to his personal initiative and "drive".

In 1905 the direction of the Office became vested in the Meteorological Committee appointed by the Treasury, with Sir Napier as Director and Chairman of Committee. Busy years followed. The planning of the new office building at South Kensington occupied much time and thought. It was to be no mere office, but a centre for meteorological and geophysical research, with ample library accommodation and a museum in which the results obtained might be adequately displayed. The building was completed in 1910 and the transfer from Victoria Street was accomplished in the summer and Autumn of that year. The educational side of the Office work benefited immediately and parties of students and teachers visiting the establishment to acquire at first-hand a knowledge of meteorological practice were frequently met with at the Office.

The transfer to the Meteorological Committee of responsibility for the work of the Observatories at Kew and Eskdalemuir in 1910 further widened the scope of office work and increased the duties and responsibilities of the Director. The Office ceased to be a purely meteorological institution and became the official centre for carrying out geophysical investigations, terrestrial magnetism, atmospheric electricity and seismology.

In the purely meteorological sphere, in addition to extending the work of the forecast service and of the stations and observatories directly under the jurisdiction of the Office, Sir Napier was ever anxious to bring the large number of voluntary observers into relation with the Office in order to render their work readily available for the public good. He devoted much time and thought to devising arrangements for supervising such voluntary work and directing it along useful lines. — The publication of summaries of approved observations in the *Monthly Weather Report* was the chief means adopted for attaining this end, and the Report came to be regarded as an index of the material available in the Office for "keeping the public memory of the weather."

The twenty years of Sir Napier's control of the Office have witnessed a rapid development of upper air research in this and other countries, and it became necessary to see that the Office took its proper share in this pioneer work. The spending of the available funds in a manner to secure the best results was no easy task. Sir Napier was fortunate in having the assistance of Mr. W.H. Dines, F.R.S., in this part of his work. He was singularly happy in devising arrangements under which Mr. Dines was enabled to carry on his individual work at Pyrton Hill, and subsequently at Benson, and bring it into close co-operation with the work of the Office. He was equally fortunate in securing co-operation between the Office and institutions like the upper air observatory of the University of Manchester or the private observatory of Capt. C.J.P. Cave, of Ditcham Park.

In international meteorological work Sir Napier was also called upon to play a large part. He became a member of the International Meteorological Committee soon after his appointment as Secretary to the Meteorological Council, and on the retirement of M. Mascart he was elected President of the Committee at the meeting held in Paris in 1907 From that time onwards he was constantly called upon to deal with questions of international co-operation between the meteorological services of different countries.

It had been Sir Napier's often expressed intention to resign from the Directorship in 1915 in order that he might have leisure to devote himself to furthering the academic side of meteorology, but the outbreak of war put all idea of resignation out of question, as it soon became clear that the national emergency would make great demands on the Office. Limitation of space makes it impossible to detail the steps which led to the formation of the separate meteorological services established by the Army, Navy and Air Force, but the Office organisation had to supply the essential information for all these, and to supply or undertake the training of a large part of the personnel required. The demands were not only for weather forecasts, but for help in the applications of meteorology to gunnery, aircraft construction and navigation, and numerous other subjects. The work of directing the Office operations became more than one man could accomplish, and arrangements were made, with the consent of the War Office, for Colonel H.G. Lyons to undertake the administration of the Office, leaving Sir Napier free to devote himself to the scientific problems which he was eminently fitted to solve. Among other things the need of an advanced text-book of meteorology for the training of expert personnel became acutely felt, and Sir Napier met that demand by compiling the *Manual of Meteorology*, of which Part IV., dealing with the relation of wind to the distribution of pressure, was issued early in 1919. The first three parts are still to come.

Some months after the signing of the armistice Colonel Lyons relinquished his temporary position as administrative head of the Office and the full responsibility once more evolved upon Sir Napier. During the months that have intervened the control of the Office has passed to the Air Ministry and Sir Napier has had to carry through the unification under a single control of the independent services established during the war. Another important step in the unification of meteorological work in this country also occurred at this time, namely, the transfer to the Office of responsibility for the work of the British Rainfall Organization, which took place during the summer of 1919.

We are glad to learn that Sir Napier's retirement from the Directorship does not involve his complete dissociation from active meteorological work at South Kensington. He has undertaken the duties of the Professorship of Meteorology at the Imperial College of Science and Technology in connection with the School of Aviation recently established there in association with the University of London, and as such will, with the courtesy of the Air Ministry, retain the use of a room in the building which he was instrumental in calling into being. The good wishes of all will go with Sir Napier in his new work.

September 1920

A Conference at Bergen

An extract from the Report by Sir NAPIER SHAW, Sc.D, LL.D., F.R.S.

ON the invitation of Professor V. Bjerknes, Director of Section B. of the Geophysical Institute, Bergen, a delegation of the Meteorological Office visited Bergen for the purpose of inspecting new methods of forecasting which have been developed by the meteorological staff of the Institute under the direction of Professor Bjerknes. The Geophysical Institute consists of two sections, viz., A., the Oceanographical Section, under Professor Helland-Hansen, who is also the Director-General of the Institute, and B., the Meteorological Section, under Professor Bjerknes.

The invitation had the practical support of the Bergen Steamship Company and the Bergen-America Line on account of the interest of these companies in the development of meteorological methods with a view to forecasting for North Sea steamers and ocean liners. The companies observe for the Institute at 8 h., 14 h. and 20 h. Norwegian time, and transmit their observations by wireless telegraphy for incorporation with other data on the regular maps.

The invitation was extended to four or more representatives of the Meteorological Office. The delegation consisted of Sir Napier Shaw, Director, Colonel L.F. Blandy, Controller of Communications, with Major A.H.R. Goldie, Mr. L.F. Richardson and Captain C.K.M. Douglas. The delegation left London on July 17th for Newcastle and landed at Bergen on the morning of July 19th. The members of the staff of the Bergen Institute who took part in the proceedings, besides Professors Bjerknes and Helland-Hansen, were Mr. J. Bjerknes, Mr. B. Björkdal and Mr. Rossby, who are in charge of forecasts, Mr. Fjeten, who is in charge of instruments. Professor Hesselberg, Director of the Norwegian Meteorological Service, came from Christiania, and Mr. Bergeron, a former assistant at Bergen and now in the Hydrographic-Meteorological Bureau of Stockholm, came with his colleague, Mr. Calwagen, from Stockholm. Dr. Jakobsen, a Danish oceanographer, was also present with Professor Helland-Hansen, and Mr. Jon Eyporsson, who is in training for the Meteorological Service of Iceland.

The ordinary daily programme of business was to meet in a lecture-room of the Bergen Museum in the morning (which lasts till 15 h.) for the discussion of scientific questions, and later in the afternoon to visit the Institute to inspect the working charts for the day and to consider as a committee the administrative aspects of the questions raised. This plan was followed on July 20th to 24th inclusive and July 27th to 30th. Proceedings commenced with a lecture followed by discussion, and the reading and discussion of supplementary papers.

The projects which the visit was designed to develop have arisen out of a discovery by the Bergen Institute, principally by Messrs. Solberg, J. Bjerknes and Bergeron, that the phenomena of the weather of the Northern Hemisphere are largely dependent upon the surface of junction of polar and equatorial air which can be detected at the earth's surface as a line of discontinuity in the conditions of pressure, temperature, wind-direction and force, humidity and visibility. The line of discontinuity passes through the centres of cyclones and connects the centre of one cyclone with those of the preceding and succeeding ones by a line which can be identified somewhere in the westerly current lying on the south side of the line of centres of cyclones. It may possibly be as far south as the margin of the permanent Atlantic anticyclone, and it may even be carried round with the north-east trade to the southern margin of the anticyclone. The polar air is identified at the surface as being cold, dry, very transparent, and often blowing from some easterly point, and the equatorial air as relatively warm, moist, with poor visibility, and always blowing from some westerly point.

The surface of demarcation between these two types of air is called the "polar front," which is divided into the "steering surface" or "anaphalanx" from the front margin of the cyclone to its centre, the intermediate section between the margin of successive cyclones, the "squall surface" or "kataphalanx" from the centre to the rear margin. Attempts to identify the line in which the polar front cuts the earth's surface on the detailed maps of Western Norway have apparently been generally successful, and it extension over Western Europe and ultimately round the earth is obviously a practical proposition. The complete front must be regarded as a surface of irregular shape extending from the line marked out at the earth's surface obliquely upward to a considerable, but at present unknown, height. The Bergen investigators set no limit below the stratosphere (say 33,000 feet). *A priori* we should regard it as belonging to the peculiar juxtaposition of relatively warm and cold air which is inevitable at the surface but not to be expected in the upper layers; observations in aeroplanes have, however, been adduced in support of the Bergen views. They associate most of the phenomena of cyclones with different parts of the polar front, and in particular on all their maps they set out definite rain areas in connection with the anaphalanx and the kataphalanx, the two parts of the front that meet in a cyclonic centre; and they use the two parts of the line in which the front cuts the surface (provisionally called the steering line and the squall line) as axes meeting in the cyclone-centre: to one or other of which they refer all the weather incidental to the passage of the cyclonic depression. The sector of the cyclone within the angle between the anaphalanx and kataphlanx they call the "warm" sector of equatorial air, and endow it with showery possibilities but not continuous rain.

Moreover, they find that the one part of the polar front the kataphalanx may encroach to such an extent on the warm sector as to reach the steering line or surface line of the anaphalanx and ultimately overlap it; thus it will cut off an isolated patch of the equatorial air, upon which the warm sector of the cyclone depends for its existence, and will bring about the "death" of the cyclone.

As to the nature and origin of cyclones, Professor Bjerknes, relying upon a proposition of Helmholtz that in consequence of the rotation of the earth the surface of separation at a discontinuity between polar air (or air moving eastward) would not be vertical, but would tend to become parallel to the earth's axis of rotation and therefore inclined to the vertical anywhere except at the pole, is developing a theory of the motion of air in a cyclonic depression as the result of wave motion, different in character on either side of the polar front and advancing in the inclined surface of separation which forms the front.

In consequence of these developments the Bergen meteorologists have come to consider that a new step in advance in practical meteorology is possible, and indeed almost certain, if attention is concentrated upon this new feature, viz., the polar front.

The more serious business of the meeting was interrupted for the 25th and 26th July for an excursion, on the invitation of Professor Helland-Hansen, to Väring Voss, at the head of the Hardanger Fjord, which was reached partly by rail, partly by motor over remarkable roads, and partly by the motor ship *Armauer-Hansen*, a craft belonging to the Oceanographical Section of the Geophysical Institute for the purpose of investigation of the fjords and the ocean. This afforded an opportunity of inspecting the methods of investigation of physical oceanography.

January 1940

A Pilot Balloon Returns to its Starting Point

At 17h. G.M.T on February 23rd, 1939, a 150-in. pilot balloon with an assumed rate of ascent at 700 feet per minute was released from one of H.M. ships lying in Palma Bay, Majorca.

Observations were abruptly curtailed by the balloon entering a layer of stratocumulus; but up to the moment of its loss to view, it had been carried to the north-eastward at a mean velocity of 45 knots.

Twenty-four hours later a balloon was observed, partly deflated, but with only a slight negative atmospheric buoyancy, resting lightly on the surface of the sea, and drifting past the ship in a westerly surface breeze. On recovery it was identified as that which had been released the previous evening. A pin-prick leak was the cause of descent.

Taking 7h. G.M.T. on February 24th as approximately the mean instant of the balloon's flight, the synoptic chart for this hour shows a depression (about 993 mbs.) centred 100 miles north-west of the ship.

There are two possible solutions to the cause for the balloon's return.

(1) It was carried anti-clockwise round the depression, getting extremely close to the centre whilst in the lower layers, and diverging again at higher altitudes, the reverse taking place on descent.

(2) It obtained its northerly and westerly travel from the cyclonic winds in the east and north sectors of the depression, and at a height of 15,000 feet or more entered the steady north-westerly stream which exists almost continually over the Mediterranean in the upper half of the troposphere. Single theodolite observations of ascents up to assumed heights of 20,000 to 25,000 feet on the previous few days during clearer weather had shown that the predominant wind was from 290°, at speeds varying with the time of day from 20 to 35 knots. Unfortunately no Spanish reports were available from which to enable the upper winds to be traced farther afield or possibly fix the position of a front.

In any case there seems little doubt that the balloon travelled at least 400 miles, and its return to the starting point was the result of an unusual and interesting combination of wind components.

P. G. SATOW.
H.M.S. "Vernon," Portsmouth. October 26th, 1939.

January 1947

FOREWORD

BY THE DIRECTOR OF THE METEOROLOGICAL OFFICE

(Sir Nelson Johnson K.C.B.)

The publication of the *Meteorological Magazine* ceased with the issue for June, 1940. The deciding factor was not so much the need for saving paper as the urgent necessity at that time of conserving manpower. The nation could not afford the time of the type-setters and other operatives involved in producing a journal of this kind.

It was not until publication had actually stopped that the value of the *Meteorological Magazine* was fully realised. We had not appreciated the important part it played as a means of keeping us informed of technical developments, as a link between Headquarters and outstations, and as a forum for the discussion of interesting technical points.

The zeal of the Editor, Dr. Brooks, did not allow the *Meteorological Magazine* to suffer complete eclipse, and a typescript edition, complete with diagrams and photographs, maintained a limited circulation. Some of the most interesting features which appeared in the "emergency" edition will be reproduced in the early numbers of this 1947 volume.

With the resumption of normal publication it is hoped not only to regain the original advantages which the magazine provided, but to make it of even greater value and interest than before the war. Articles will be included from time to time dealing with international meteorological matters, which will enable the meteorologist to appreciate how his own work fits into the general world pattern. There will be authoritative articles in simple non-technical language on the work of different sections of the Meteorological Office, and on interesting phenomena which occur from time to time. Regular accounts will also be given of the activities of the Meteorological Research Committee with an outline of the more important papers discussed at its meetings. It is further proposed to include a certain number of original papers on investigations carried out in the Meteorological Office, although the longer papers of this type will continue to be published as *Geophysical Memoirs* and *Professional Notes* as in the past. Articles will be given describing important developments, such as the recent decision to establish a network of weather reporting ships in the North Atlantic, and explaining the part which the Meteorological Office will play in the scheme.

Although the *Meteorological Magazine* has hitherto been intended primarily for the staff of the Meteorological Office and its collaborators, it is hoped that it will find many regular readers amongst those who worked with us for the first time during the war, and also amongst those members of the community at large who, while having no official connexion with the office are yet interested in the weather and the State weather service.

N.K. JOHNSON

February 1947

OCEAN WEATHER SHIPS

BY COMMANDER C. FRANKCOM, R.N.R.

History. — Prior to the year 1936, synoptic observations from the sea were provided almost entirely by voluntary observers in merchant ships, apart from those obtained from the relatively small number of naval vessels. These observations, although extremely valuable to the forecaster, were necessarily restricted in nature, and more or less haphazard as regards position.

As transoceanic aircraft became a possibility, it became obvious that more detailed information was necessary than could be obtained from voluntary observers in moving ships in order to provide meteorologists and aircraft with accurate information about weather conditions at sea, both on the surface and in the upper atmosphere.

In 1936–7, the British Meteorological Office placed a meteorologist aboard a cargo steamer on the North Atlantic trade route during several voyages and obtained a regular series of special synoptic observations as an experiment. Visual observations of cloud heights and of upper winds were obtained in this ship by the use of pilot balloons.

In 1938–9, the French Government fitted up the merchant vessel *Carimaré* as a stationary meteorological ship in the North Atlantic. Observations of conditions in the upper atmosphere by radio-sonde were successfully obtained in this ship as well as those of surface conditions, and results transmitted by radio. At about the same time, the Germans had two special vessels performing similar functions in connexion with their trans-oceanic airways — one operating in the North Atlantic and the other in South Atlantic. The British Meteorological Office was exploring the possibility of fitting up a vessel specially for this type of work in the summer of 1939.

The war of 1939–45 put an end to all the above activities, and in the early part of that war observations from the oceans were only obtainable from naval vessels and from aircraft. As the war progressed, both sides used various ingenious methods to obtain weather observations from the oceans for their own use. In the latter part of the war, owing to the large number of Allied aircraft regularly crossing the Atlantic, the United Kingdom and United States authorities employed a number of small naval vessels as stationary meteorological ships in that ocean.

When the war finished, the naval stationary vessels were gradually withdrawn, and observations were once more obtainable from merchant vessels. It was realised however, that such observations were not sufficient, and early in 1946 the Conference of Directors of the International Meteorological Organization at a meeting in London passed a resolution urging the establishment of stationary meteorological ships in certain ocean areas. Shortly afterwards, the Provisional International Civil Air Organization (PICAO) Passed a similar resolution in Dublin. In the summer of 1946, at a meeting of the member states of PICAO in London, it was agreed that a total of 13 stationary meteorological ships would be established in the North Atlantic by July, 1947.

The PICAO Agreement. — The United States, Canada, France, Holland Belgium, Norway, Sweden, Great Britain, Eire, Denmark, Iceland, Portugal and Spain were all signatories to the "Ocean Weather Ship" agreement. It was agreed that the allocation of stations would be as follows:—

United States	7
Canada and United States, jointly	1
France	1
United Kingdom	2
Norway, Sweden and U.K. jointly	1
Holland and Belgium, jointly	1

Eire agreed to provide an annual monetary contribution towards the scheme. It as decided that Portugal, Denmark and Iceland already contributed sufficiently to the safety

Met.O.1010

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The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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*December is a special edition to mark the cessation of the magazine and contains selected articles taken from past issues. These articles are not included in this index.

of transoceanic aircraft by the establishment of meteorological stations in the Azores, Greenland. and Iceland respectively.

It was decided that on an average it would need at least two ships to maintain one ocean weather station. The minimum size vessel which could satisfactorily perform the necessary duties was considered to be one of about 1,300 tons displacement, having a length of about 200 ft. and being of a suitable type for North Atlantic work.

The duties of the ship would include:

(a) *Meteorological observations.* — Surface observations every three hours. Special observations, when necessary, of meteorological phenomena and of important changes in the weather.

Upper air wind observations by radar methods not less than four times daily.

Upper air temperature, pressure and humidity by radio-sonde not less than twice daily.

All the above observations would be reported by radio at the appropriate international hours. In addition, observations from certain merchant ships and other ocean weather ships would be collected and re-transmitted by radio.

(b) *Search and Rescue Services* — for aircraft and shipping in distress, as necessary, for which the requisite equipment will be provided aboard the ships. This implies the provision of special boats and other life-saving equipment, radar and special radio equipment, including beacons on which aircraft can "home". The general scheme is that aircraft in distress can "home" on the ocean weather station and alight near enough for a rescue to be effected.

(c) *Navigational aids to aircraft in flight*, for which special radio beacons will be fitted aboard the ships.

(d) *Oeanographical and other scientific observations* as far as it is practicable.

The attached map (*not printed here*) shows the agreed distribution of the ocean weather stations, together with an approximation of the usual transatlantic steamer tracks. It should be emphasised that the establishment of these ocean weather stations will not in any way lessen the importance of observations from merchant ships. The network of observations from the oceans can never approach the density obtainable from stations ashore, but the closer the density the more able is the meteorologist to forecast coming weather changes. The ocean weather ships will merely approximate to islands from which regular observations, both on the surface and in the upper air, are obtainable - the immense gaps being filled in by observations from merchant vessels. It is hoped that the establishment of these stations will not only further the safety of transoceanic aircraft and shipping, but that they will also be the means of greatly improving the accuracy in forecasts for the benefit of the whole community.

The British plan for the operation of their two stations is to employ four ex-naval corvettes of the "Flower" class. These vessels are about 200 ft. in length, are built on whaler lines and have a loaded displacement of about 1,400 tons. They are oil-fired steam vessels, having reciprocating engines and a single screw, and a maximum speed of about 16 knots, economical speed 9 knots. They have established a reputation for being excellent sea boats, having been employed on convoy escort and other duties in the Atlantic, in all weathers, during the recent war.

The British ocean weather ships will carry civilian crews, and they will be administered by the Meteorological Office. Special accommodation will need to be fitted to house the crew of 12 officers, 20 petty officers and 22 ratings, to the modern standards laid down by the Ministry of Transport. A steel shelter will be erected on deck for the filling of radio-sonde balloons; special radio equipment, radar and motor lifeboats will need to be fitted. The work of conversion of these vessels will be carried out in Admiralty Dockyards. It is probable that the ships will be based in the River Clyde area.

The photograph facing p. 32 shows H.M. corvette *Snowflake*, one of the vessels which has been allocated to the Meteorological Office. It will be appreciated that with the removal of her guns and the structural alterations necessary to convert her to an ocean weather ship her appearance will be considerably altered.

In addition to a normal complement of Deck and Engine Room officers and ratings, stewards and cooks, the ships will carry meteorologists and radio technicians. It is anticipated that each vessel will spend about 27 days at sea. followed by a spell of 15 days in port — which latter period is necessary for leave to be given to the ships' companies and for necessary repairs, storage and refuelling to be carried out. It is anticipated that the accommodation and food aboard the ships will be good and that generous leave will be given to the ships' companies.

When on station, in the Atlantic, the ships will, as far as possible, remain "hove to", more or less head on to the wind and sea. Navigation will need to be accurate to ensure remaining in the vicinity of their station, as far possible, within reasonable limits in all weathers, but the ships will of course, make way through the water and vary their position from time to time. Life aboard these small ships at sea will be relatively exacting, at times monotonous, at times exciting — but for the man who likes ships and the sea an the study of the weather, it will, in general, always be interesting. The work will undoubtedly be unusual, and apart from its importance for scientific and practical meteorological purposes, its potential value for the safety of human life is without question. Those who go down to the sea in ships . . .

April 1947

THE CENTRAL FORECASTING OFFICE, DUNSTABLE

BY E.G. BILHAM, B.SC., D.I.C.

(The figures referred to in the text have been omitted, the first is well described, the second too complex to warrant the effort here, the photographs not good enough.)

On February 4, 1940, the Forecast Branch of the Meteorological Office took possession of its war-time headquarters on the outskirts of Dunstable. The decision, that in the event of war the communications centre for the forecasting service should be established in a provincial location, had been made nearly two years earlier. The principal requirement from the communications aspect was that the site should be conveniently placed in relation to the main Post Office land lines. This requirement, in conjunction with other desiderata such as reasonably easy access from London, proximity to a town to facilitate the housing of personnel, and good wireless reception conditions, led to the selection in 1938, of a site on high land (about 500 ft. above sea level) just outside Dunstable.

At a later stage it was decided that, as a war time provision, the main forecasting centre should be at the same place as the communications centre. Dunstable was therefore planned as a combined forecasting and communications headquarters of the meteorological service. Plans were prepared and were being considered when in the summer of 1939 the threat of war became so imminent that immediate action was necessary. New plans based on the use of standard hutting were quickly prepared and building was begun.

A modern forecasting centre such as Dunstable was planned to be involves, however, a great deal more than the mere provision of roofs and walls, and much still remained to be done when war was declared at the end of August 1939. As a temporary measure, pending the completion of Dunstable, the Forecast Division was evacuated to offices already prepared at Birmingham. This emergency centre was occupied at three day's notice, without disturbing the flow of current synoptic information outstations.

The move to Dunstable was made under appalling weather conditions and was a complicated operation. A 24-hour service had to be maintained without interruption, so it was necessary to move the staff by stages, the last contingent travelling by car over roads deep in thawing snow. The change over of teleprinter lines was made between 1500 and 1600 on February 4, 1940. The 1500 reports were dealt with at Birmingham and the 1600 reports were dealt with at Dunstable. It was an outstanding feat in the history of the Post Office Engineering Department and was accomplished without a hitch.

The location of the evacuation centre (at Birmingham) had been kept secret, and it was known by the code name of ETA (the Greek letter η). By the time Dunstable was ready for occupation, everyone had become used to speaking of the provincial headquarters of the Forecast Service as "ETA" and the name was retained for the new station.

To explain the role of ETA in the forecasting organization it is necessary to describe briefly the arrangements which are in operation for supplying the Royal Air Force with weather reports and forecasts. The general principle is that every important airfield has its own Meteorological Office, which is responsible for the meteorological services needed by aircraft using that airfield. This means that there are a very large number of separate forecasting offices in all parts of the country, in each of which charts are drawn and forecasts are prepared. In general, the forecasting offices also act as weather reporting stations. The normal procedure is to furnish a coded report every hour and to plot a chart every 3 hours, based on observations at the "synoptic hours" 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 G.M.T.

The first obvious necessity for such a service is that there must be a highly efficient network of communications to collect the hourly reports and redistribute them to the forecasting centres, so that all of them may be continuously supplied with up-to-date information for the whole area. The second necessity is a system of co-ordination to ensure that the views as to the main developments of weather expressed by the forecaster at one station will not differ materially from those expressed by the forecaster at another station close by.

Fig. 1 is an attempt to set out the organization diagramatically. At each operational Group Headquarters there is a Type I Meteorological office which exercises a sort of parental control over a number of subsidiary offices of lower categories. The fundamental analyses and forecasts are originated at the Central Forecasting Office (C.F.O.) which thus furnishes guidance to all the forecasting offices in the system. There are also Type I offices at Command Headquarters, and these are responsible for the general co-ordination of the meteorological services within the Command. Fig. 1 is of course purely diagrammatic and highly simplified. The number of local forecasting offices represented by the small circles actually amounts to some hundreds.

The requirement of a rapid and efficient network of communications is met by the meteorological teleprinter system. The general lay-out of this system is represented by the full lines in Fig. 1. Main lines radiate from C.F.O. to Group offices where they terminate on switchboards. The Group switchboards have connexions to all the stations controlled by the Group, which can thus be put into direct communication with C.F.O. whenever desired. In addition to the main lines to Groups and Commands, C.F.O. also has direct teleprinter lines to the British Air Forces Overseas Headquarters in Germany, the Headquarters of the American Forces in Europe, the Forecast Centres of the French, Belgian and Dutch Meteorological Services, Broadcasting House, the Central Telegraph Office, the Admiralty, etc. (see Fig. 2).

The system for collecting reports works in the following way. Each reporting station in a Group teleprints its coded message to the Group Headquarters where two teleprinters are available to receive them. The Group then compiles a collective message in standard form and teleprints it to C.F.O. At C.F.O. there is a separate teleprinter for each Group in the system, and there is, therefore, no delay in transmission. Connected to each of these teleprinters at C.F.O. there is a "reperforator" which produces a punched tape record of the message at the same time that it is received in typed form. By about 8 minutes past the hour practically all the hourly reports have been received in this way.

Punctually at 10 minutes past the hour the operator throws the switches on the main panel to the "send" position, and then passes the punched tapes through an automatic transmitter which broadcasts the messages at high speed to all stations. This main broadcast of British and near continental data is completed by the half hour. The remainder of the hour, until H 55 minutes, is occupied with broadcasts of foreign data upper air data, thunderstorm locations (SFERICS), ships' reports analyses and forecasts, and special reports of sudden changes. This main broadcast to all stations is supplemented by a second broadcast to Groups only.

The teleprinter room, though one of the most interesting features of C.F.O., represents only one side of the communications system. Parallel with the teleprinter room and almost equalling it size is the wireless reception room, manned by a civilian unit of the R.A.F. (No. 90 Group). Here are received practically all the meteorological transmissions of foreign data available for the northern hemisphere, as well as direct interceptions of reports from ships at sea and meteorological reconnaissance aircraft. Both rooms of course function continuously day and night. In the adjacent "auto room" transmissions are made continuously by radio channels to overseas and foreign services too distant to be connected to the teleprinter broadcast.

Mention must also be made of the AIRMET radio-telephony broadcasting system which is operated under the joint auspices of the Air Ministry and the Ministry of Civil Aviation. This service, which is the post-war successor to the "Borough Hill" broadcasts of pre-war days functions from 7 a.m. to 10 p.m. in summer, 6 p.m. in winter, and is intended primarily to serve the needs of flying clubs and private fliers using the smaller airfields. The hourly schedule includes navigational warnings, statements of the general weather situation and expected developments, reports of actual weather conditions from selected stations, and talks by the forecaster twice in every hour, in which the weather factors of importance for flying are dealt with in detail.

Dunstable also acts as the control station of the SFERIC service for the location of sources of atmospherics, within a range of 1,500 miles, using a radio direction-finding method. The results which are of great importance in relation to flying operations, and also as an aid to forecasting, are broadcast at frequent intervals on both the teleprinter and radio broadcasting systems.

In the forecast room surface charts covering most of Europe and the northern Atlantic are plotted every 3 hours and smaller scale charts are plotted every 6 hours (at main synoptic hours) for an area extending westward as far as the Pacific coast of North America, eastward to the Urals, northward to Spitzbergen and southward to north Africa. For the AIRMET service these are supplemented by large scale charts for the British Isles prepared hourly. Upper air contour charts are drawn every 6 hours for the 700, 500 and 300 mb. pressure levels. Full analyses for the main synoptic hours are made both for the surface and upper air distributions, and prognostic charts are prepared for periods of 24 hours ahead in the case of the surface charts, and 12 hours ahead in the case of the upper air charts. These analyses and prognoses together with detailed forecasts for aviation and technical appreciations of the situation are broadcast for the general guidance of outstations in preparing forecasts for local use.

The forecasts and warnings prepared at C.F.O. also include those broadcast by the B.B.C., forecasts for the Press, and a large number of special forecasts, warnings and notifications of specified conditions required by shipping, public services, industrial organizations, and members of the general public. The installations at C.F.O. include a printing plant operated by H.M. Stationery Office. Four large lithographic presses produce the Daily Weather Report which is now issued in three sections, the British Section (4 pages), the Upper Air Section (4 pages) and the International Section (2 pages of charts issued daily and 4 pages of data issued every four days). The lithographic transfers for these reports are prepared by draughtswomen in the forecast room. The C.F.O. printing plant also produces many of the blank plotting charts used in the synoptic service, instrumental charts and marine charts.

In this short account of C.F.O. it has not been possible to describe all its activities in full detail, but it is hoped to publish further articles in which special features such as the AIRMET broadcasting installation will be more adequately dealt with. The first of these, on SFERICS, follows immediately.

December 1947

FUNDAMENTAL PROBLEMS IN METEOROLOGY

Compiled by the Meteorological Research Committee

The Meteorological Research Committee has recently compiled a list of the problems which, in the view of members, are fundamental problems in the science of meteorology today. Some of these problems are suitable for attack by independent workers and steps have accordingly been taken to distribute the list to research workers in the Universities and University Colleges in this country. It is hoped that this action will stimulate interest in meteorological research.

The full list of problems is given below.

Dynamical or mathematical problems

1. Investigation of the formation, persistence and movement of anticyclones and wedges.

2. "Further outlooks" deduced from pressure distribution over northern hemisphere.

Mathematical examination is needed for these two problems in addition to the empirical study in the Meteorological Office.

3. Large scale air movements in the stratosphere and the extension of dynamical treatment to the stratosphere. The north or south movement of air in the stratosphere is of great scientific interest in meteorology.

4. Determination of the rate of travel of waves in the atmosphere.

5. Factors governing the travel of depressions.

6. Energy transformations in relation to the development of pressure systems.

7. Investigation of convergence and divergence and geostrophic departure of the wind.

8. Application of statistical methods to vector quantities.

9. Equations of motion. — (a) Solution of the equations allowing for the variation of the Coriolis force — extension of Grimes' solution[1]. See also classic paper by Guldberg and Möhn[2].

(b) Solution of equations for accelerated motion with constant uniform pressure field and its application to forecasting wind.

(c) Solution of equations for accelerated motion by expressing the pressure variation as exponential or circular functions (Fourier series) of the time.

(d) Investigation as to the reality of the oscillatory motion arising from geostrophic acceleration. See a paper by Hesselberg on atmospheric oscillations[3].

(e) The effect of friction; decay of atmospheric oscillations (see the paper by Hesselberg, in which it is assumed that the friction is proportional to the velocity); further investigation of the solution for unsteady motion and its extension to include initial departures from appropriate solution for steady state.

(f) Investigation of the effect of the movement of air across the isobars on the pressure distribution.

Physical problems

10. The distribution of temperature in the stratosphere.

11. Possible use of water-vapour content to identify air masses in the stratosphere.

12. Possible use of ozone content to identify air masses in the stratosphere.

13. Structure of fronts in the upper troposphere and stratosphere as indicated by temperature, humidity, ozone and winds.

14. Reliable climatological data for upper air from 0 to 24 Km. for each month and all possible parts of the world.

To include temperature, pressure (density), humidity, winds, height of tropopause and giving both average values and variations from day to day and year to year.

Much of this could be compiled now and is badly wanted. Data for less explored parts of the world and humidities of the upper air could be added as they become available. Some work is in hand in the Meteorological Office.

15. Radiation in the atmosphere. (As programme for Gassiot Committee)

(a) Measurement of absorption coefficient of atmospheric gases under atmospheric conditions.

(b) Theoretical discussion of absorption and radiation of heat by the atmosphere.

(c) Calculation of equilibrium temperature for an height, at any latitude and any season including diurnal variation of temperature.

(d) Rate at which air masses at different levels would acquire new temperature if transported to different latitudes.

(e) Measurement of water vapour at all heights, seasons and latitudes.

(f) Measurement of ozone at all heights, seasons and latitudes.

16. Physics of condensation and sublimation of water vapour in the atmosphere.

17. Formation of rain and snow from cloud.

18. Latent heat of vaporization of supercooled water.

Apparently no data available.

19. Factors affecting coalescence of water drops having diameters in the range 1 μ to 7 mm. Affects development of fog, cloud and rain.

20. Factors affecting the change of state from supercooled water in droplet form to ice. Affects development of clouds and ice accretion on aircraft.

21. Nature of sublimation nuclei.

22. Radiation from small particles floating in the atmosphere and the consequential effects of the temperature of the particles being different from that of the ambient atmosphere. Effects of radiation on the lapse rate and stability in a cloud layer.

23. The transfer of air downwards by the drag of a falling raindrop. The mixing resulting from this process may affect the structure and composition of the lower atmosphere.

24. The fundamental theory of turbulence and its relation to the distribution of eddy velocities in space and time.

The theory of atmospheric diffusion and turbulence has been largely built up on R_ξ the correlation of the eddy velocity of the same particle at various intervals of time ξ. This correlation is not directly observable, nor of itself important. In view of the conditions of continuity and conservation of momentum and vorticity, it seems probable that some relation must exist between R_ξ and the correlation of wind at one point at various intervals of time and at one instant at various points in space. Knowledge of such relations would enable studies in diffusion to be directly linked with wind observations and studies of "bumpiness". It would also lead to an understanding of the diffusion of water vapour by eddies too large to be observed except in wind variations.

25. The balance between radiation, diffusion and turbulence in the lowest layers of the atmosphere.

(a) With reference to fog and dew.

(b) With reference to air flow from water surface to land surface and vice verse. Kew already have in hand the simultaneous investigation of the diffusion of heat, water vapour and momentum and the flux of radiation. Similar work is also in hand at Rye and Cambridge.

26. Physics of thunderstorms.

Forecasting problems

27. Investigation of factors which govern the formation and dispersal of low stratus cloud.

28. Relation between horizontal temperature gradient and large-scale instability. Treatment of thunderstorm development to include horizontal temperature gradient as well as vertical temperature gradient.

Instrumental problems

29. Development of a method of measuring air temperatures on high-speed (jet) aircraft which will avoid the application of large airspeed corrections.

30. Design of a new method of humidity measurement in radio-sondes at all heights.

31. Design of a relatively cheap instrument to measure atmospheric ozone.

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October 1949

WEATHER FORECASTS BY TELEVISION

By E.G. Bilham, B.Sc., D.I.C.

On the evening of July 29 television viewers in Great Britain were able to see and hear a new feature in the programme broadcast from Alexandra Palace, namely a weather report and forecast illustrated by charts. This feature has since been included as the last item of the television programme each evening.

The weather report begins with a brief summary of the weather of the day, illustrated by a chart (see Fig. 1, p. 314) headed "Weather this evening" showing in a very generalised sort of way the weather over the British Isles at 5 p.m.. This is followed after a brief pause by a second chart (Fig. 2), headed "Weather expected to-morrow morning", with spoken text indicating the main features of next day's weather over the country as a whole. Next follows a more detailed forecast for London and south-east England covering the period 8 a.m. to midnight. The report concludes with a "Further Outlook" for London and south-east England. The actual text of the spoken script which accompanied the charts on July 29 (the Friday preceding August Bank Holiday) was as follows:

Television Forecast, Friday, July 29, 1949

Here is the Meteorological Office weather report and forecast. The first chart shows the general weather situation this evening.

A north-westerly air stream covers the British Isles. Weather is fine generally apart from scattered showers in Scotland and northern England. It has been fine all day in the south-eastern districts of England, where temperature has exceeded 70 degrees. In northern and western districts there have been bright intervals and scattered showers.

By tomorrow morning the weather chart is expected to look like this.

It will be fine over the whole country in the morning, and the fine weather will last all day in most districts. Rain moving east from the Atlantic will reach Ireland and west Scotland during the afternoon or evening.

Here is the forecast for London and south-east England for to-morrow, 8 a.m. to midnight:—

Fair and rather warm, with afternoon temperature 75 degrees or slightly higher.

Finally here is the outlook for London and south-east England for Sunday and Monday.

Occasional rain on Sunday but perhaps only in small amounts. Bright intervals on Monday with a cool breeze. A chance of a few showers in the afternoon and evening.

The planning of this television feature gave rise to a number of problems. The first trials showed that it was quite impossible to televise successfully anything resembling an ordinary synoptic chart with the usual plotting of wind, weather and temperature. It was essential that the viewer should be able to take in, without effort, what he saw on the screen, and he could not be expected to memorise symbols or to strain his eyes by trying to read small lettering or figures. After several trials it became manifest that the sort of chart required was one in which the main weather features over relatively large areas were indicated by boldly printed legends without attempting to indicate small local variations. In the charts as now televised the weather legends are half-inch block lettering. Wind directions are shown by very bold arrows, and the strength of the wind is roughly indicated by using a long arrow for winds of Beaufort force 6 or more and a shorter arrow for force 5 or less. Isobars are shown at intervals of 4 mb. and italic lettering is used to indicate centres of high and low pressure. Land areas are distinguished from sea areas by tinting the former in a carefully selected shade of light grey.

For technical reasons black lines on a white background do not televise satisfactorily, and paper is unsuitable because it tends to bend and cockle under the heat of the illuminating lamps. The charts used are therefore specially printed on light grey cardboard. As a further example of the technical complications it may be mentioned that this short item, lasting, only two or three minutes, necessitates the use of three television cameras, one for the announcer and one for each of the two charts.

As an introduction to the series Dr. J.M. Stagg gave a short talk, illustrated with charts in which he explained the main weather features associated with high and low pressure systems, and how forecasting depends primarily on estimating the movements and developments of these systems.

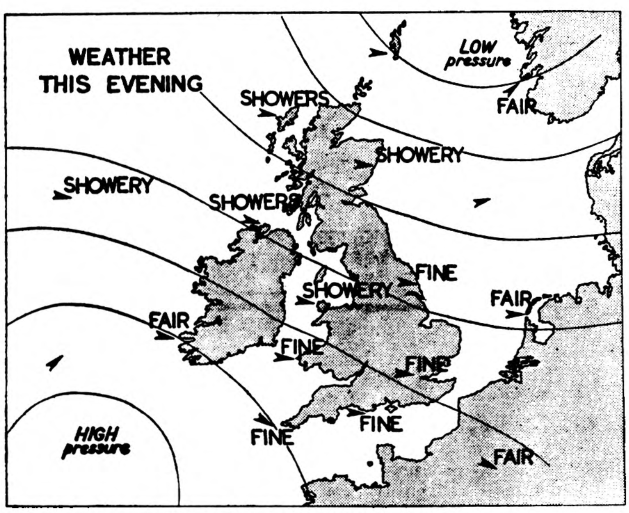

FIG. 1—FIRST CHART FRIDAY, JULY 29TH, 1949, 5 P.M.

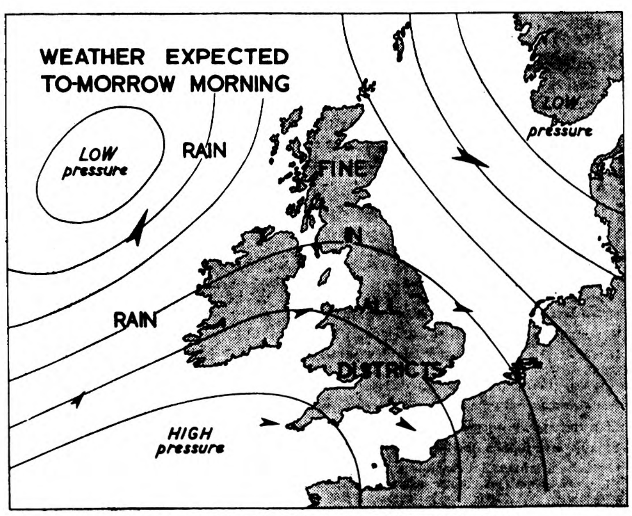

FIG. 2—SECOND CHART FRIDAY, JULY 29TH, 1949.

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March 1954

WEATHER FORECASTS ON TELEVISION

By The Director of the Meteorological Office
(Dr O.G. Sutton F.R.S.)

On January 11, the B.B.C. began the transmission of a new type of weather news item in the regular television programmes. Previously the forecasts had been read by an unseen announcer during the display of two "still" charts. As many readers of the Meteorological Magazine are aware, in the new programmes a member of the Office staff appears in the studio every night and spends five minutes discussing the weather situation, past, present and future, with the aid of simplified isobaric charts.

The new series has barely completed a month's run at the time of writing so that it is far too early to attempt any serious evaluation of the techniques adopted, but it is safe to say that, judged by the reaction of the press, the "live" presentation is generally looked upon as a big improvement on the old "static" programme. To a certain extent the present period is regarded by the Meteorological Office and the B.B.C. as experimental, and it was recognized that the forecasters chosen for this exacting work would need a little time to accustom themselves to their new duties. Actually, the three meteorologists who have initiated the new series — T.H. Clifton, G. Cowling, and P. McAllen — seem have struck the right note from the start.

There is, of course, nothing essentially new in this use of television, and the weather talk has been accepted as an essential ingredient of television programmes in the United States and in Canada for some time. However, the British system differs from those in vogue across the Atlantic in several ways. In at least one widely distributed American programme the forecaster speaks from his office to the announcer in the studio who draws a simplified map according to the forecaster's instructions. In other programmes the forecasts are given by one selected "weather man". I believe that the present policy of bringing the forecasters to the studio and of using a team, instead of an individual, is the right choice for this country. The method of presentation, namely the "serial story" which starts by a brief recital of the successes and mishaps of yesterday's forecasts followed by a quick run-over of present weather as a lead-in to the prebaratic chart and the area forecasts, is one which will have to be judged by results over a long period. Before the programmes were put on the air, the B.B.C. and the Meteorological Office co-operated in a long series of experiments with various types of presentation, including animation, but there is no finality in the choice of the present method and suggestions for improvements would be welcomed.

I believe that the introduction of this direct "forecaster to public" service is an event of considerable significance for the Meteorological Office. The communication of the conclusions of the meteorologist to the user is at least as important as the preparation of the forecast, and in this connexion it must be realized that the general public needs special attention. I believe it is generally recognized by the specialist users that a forecast is a statement of probabilities, a warning that the physical conditions obtaining in the atmosphere at a given time may lead to certain eventualities, and the prudent professional user makes his plans accordingly. Meteorologists should try to get the same view adopted by the general public to a greater extent than at present. In the present state of our knowledge of atmospheric processes it is often not possible to go beyond admitting a risk of certain unpleasant forms of weather, such as thunderstorms, in certain areas, but the forecast is not necessarily valueless if these possibilities do not materialize. The meteorologist, in fact, should regard himself as much an adviser as a prophet. The direct broadcast, especially on television, allows this approach to be made more easily and more convincingly than does the written bulletin, which tends to give the impression of hedging if it contains too many expressions of uncertainty. It remains to be seen if the new venture will achieve success in promoting a better understanding of the work of the forecaster; that it will engender a more lively interest in meteorology can hardly be in doubt.

For these reasons, if no other, the advent of the television weather programme is to be welcomed, and the Meteorological Office is grateful to the British Broadcasting Corporation for the advice and assistance which have been given so freely in the preparation and maintenance of the new programme.

July 1954

CONFERENCE ON HIGH-SPEED COMPUTING

By the Director of the Meteorological Office

The Director of the Meteorological Office, Dr. O.G. Sutton, accepted an invitation to take part in a conference on the application of high-speed computing to problems of meteorology and oceanography, sponsored jointly by the University of California in Los Angeles and the National Science Foundation of America, on May 13, 14 and 15. The conference brought together some of the leading workers in this subject, and was marked throughout by brisk discussions.

The conference opened with a short statement by Dr. Sutton on the historical background of the meteorological problem, in which he traced briefly the development of mathematical methods in weather forecasting from the early "mechanical models" of Rayleigh, Shaw, Exner and others, to the polar-front analysis of Bjerknes, the courageous but deeply significant attempt of Richardson in 1922 to apply the equations of hydrodynamics to the problem, up to the present stage. Dr. Sutton emphasized his view that the present attack, while not involving the extreme generality of Richardson's approach, was not restricted to any closely defined models of atmospheric systems and therefore appeared more promising, although it must be recognized that the mathematicians had deliberately omitted certain factors, not because they are small, but because they are too complicated to be included at present.

Major P.D. Thompson (United States Air Force Geophysics Research Directorate) followed with an interesting paper on the integration of the equations of hydrodynamics for large-scale non-geostrophic motions. Major Thompson pointed out the importance of Charney's discovery that it is possible to exclude certain classes of unwanted solutions (those corresponding to sound waves and gravity waves) by the judicious use of the hydrostatic equation and the geostrophic balance, without seriously endangering the solutions corresponding to the large-scale disturbances in which the forecaster is most interested. He concluded, however, that, for good predictions of weather, it is necessary to introduce some type of non-geostrophic motion, and he outlined a possible procedure for doing this.

Dr. Jules Charney (Institute for Advanced Study, Princeton), one of the best known workers in numerical forecasting, then gave a lengthy and deeply interesting account of the whole subject and of the progress made so far at the Institute for Advanced Study. As much of this account dealt in detail with the mathematical basis, it is not possible to give an adequate summary of Dr. Charney's lecture here. He pointed out the necessity for including more than two levels in the work and illustrated his theme by showing the calculated pressure field for the famous "Thanksgiving Day storm" of 1950. This occasion is one which is not likely to be forgotten quickly by American meteorologists because of a depression which formed near the northern coast of the Gulf of Mexico, moved up the east coast from Florida, and deepened rapidly as it approached the densely populated areas near New York, finally producing a heavy snowstorm which completely ruined the national holiday in that part of the country. The official forecasters did not foresee this development and public faith in meteorology received a rude shock. Calculations with relatively simple models fail to show any such pronounced cyclogenesis, but with the 3-level model a good approximation to reality was achieved. There seems little doubt that if such a result had been available to the routine forecasters at the time, they would have been forced to reconsider their forecast before publication.

Dr. Charney gave some interesting facts about the effort involved in producing a 3-level 24-hr. forecast for the United States. The solution of the equations necessitates about a million multiplications and divisions, ten million additions and subtractions and some thirty million mathematical "orders" to the machine. These can be done in 45 min. with an existing machine and there is good hope that this period can be reduced to about 15 min. A 5-level model would require not more than three hours to solve the equations for a 24-hr. forecast, and a 3-level 5-day forecast would be completed (as far as the pressure field is concerned) in perhaps 20 hr. of machine time, but of course, the value of such a forecast is problematical. Dr. Charney also discussed the difficult problem of handling the initial data objectively and outlined a possible method of bringing this within the scope of the machine.

Dr. Sutton explained what is being done in the United Kingdom and showed slides comparing the machine forecast with the prebaratics made by Dunstable for the same occasions. The tendency noticed in the Sawyer–Bushby scheme to exaggerate the deepening of depressions or the building-up of anticyclones is not as evident in the American results. On the other hand, there seems to be no case yet examined at the Central Forecasting Office, Dunstable, in which the machine scores a spectacular success over the human forecaster, as in the case of the Thanksgiving Day storm.

Dr. J. Namias (United States Weather Bureau) gave an account of his researches into long-range forecasting and provoked a lively discussion on this subject. Prof. H.A. Panofsky (Pennsylvania State College) gave an interesting talk on his investigations into the spectra of wind turbulence. Other speakers included Dr. H. Wexler (United States Weather Bureau), Prof. Syono (Japan), Dr. W.H. Munk (Scripps Institution of Oceanography) and Prof. J.J. Stoker (New York University). Between them they covered a wide field, ranging from tropical cyclones to tidal theory and river-flood prediction.

One of the high lights of the conference was a public lecture by Prof. J. von Neumann, who covered the whole field in his inimitable manner, quoting masses of figures and speaking without a pause for over an hour without (as far as the writer could see) a single note. Prof. von Neumann has a memory which rivals any electronic device yet devised.

The conference closed with a visit to the Scripps Institution of Oceanography at La Jolla, near the Mexican border, where the visitors experienced the far-famed Californian climate at its best.

The Director subsequently visited the astronomical observatory at Mount Wilson (including a discussion on turbulence in nebulae) and afterwards the United States Weather Bureau at Washington. Meteorologists will be interested to know that on July 1 it is proposed formally to institute in the United States a Joint Numerical Weather Prediction Unit, which will operate alongside WBAN (the joint aerological analysis unit). The staff, under the general direction of Dr. Wexler, will number about 32 in all, of whom at least half will be professional meteorologists, and the remainder mathematicians, programme experts, punch-card operators, etc. The machine, of advanced design, is expected to be delivered about October 1. Daily charts (and perhaps 2 per day) may be produced early in 1955 for comparison with actual charts, and it is hoped gradually to bring numerical forecasting into routine weather forecasting within the year.

This development will be watched with the greatest interest everywhere, and nowhere more than in the United Kingdom. If the scheme proves successful, 1955 may well mark one of the historic turning points of our science.

In conclusion, this was a highly interesting and successful conference, which brought many of the leading workers into contact with each other and succeeded in putting matters in proper perspective. For this one may thank the University of California in Los Angeles, and the National Science Foundation of America for their generous hospitality, and Dr. F. N. Frenkiel (Johns Hopkins University) in particular for his untiring and skilful administration of the conference.

June 1955 — Meteorological Office centenary issue

(This issue contained a wealth of interesting review articles, too long to reproduce here — especially as some of the source material has appeared on earlier pages. The following paper though is still topical! I have removed reference to the extensive bibliography quoted. Ed. (1994).

PRESENT POSITION OF THEORIES OF CLIMATIC CHANGE

By C.E.P. BROOKS, D.Sc.

In 1947 in an article in the *Meteorological Magazine* on the "Unsolved problem of climatic change" , five groups of theories were examined — variations of solar radiation, changes in the elements of the earth's orbit, movements of the continents, changes in the constitution of the atmosphere, and changes of configuration — but the conclusion was that all the theories so far advanced remained unproved. The seven years which have elapsed have, if anything, made confusion even greater. It may be of interest to take a brief glance at some of the recently published work and to assess the present position.

Variations of solar radiation, either alone or combined with some other cause are now first favourite. The theory which has been received with most interest is that of E.J. Öpik, first put forward in 1952 and completed in 1953, in which all changes of climate from major cycles of the order of 250 million years down to glacial and interglacial alternations are attributed solely to internal changes in the constitution of the sun. On the other hand, the theory of F. Hoyle and R.A. Lyttleton that variations of solar radiation are due to the passage of the sun through concentrations of inter-stellar matter, is still actively maintained by Hoyle and was supported by M. Krook in the volume on climatic change (reviewed in the *Meteorological Magazine* for November 1954) which also includes a discussion of Öpik's theory. Cycles of solar radiation with no ultimate cause assigned were also postulated by J. Wolbach in this volume. B.M. Rubashev combines cyclical variations of solar activity with variations in the speed of rotation of the earth. All these theories are at present almost entirely hypothetical, with little or no evidence to support them.

D.H. Menzel finds the cause of ice ages in clouds of ions reaching the earth from the sun and providing sublimation nuclei in the upper atmosphere, but he remarks that volcanic dust could adequately fulfil the same role.

Most writers adopt the view, which will certainly commend itself to meteorologists, that changes of solar radiation, especially in the ultra-violet, take effect through changes in the atmospheric circulation, but two opposing points of view still prevail. Thus H.C. Willett supports with modifications Sir George Simpson's view that glaciation could be attributed to increased solar radiation in selected wave-lengths acting through changes of circulation. His idea is that an increase of solar radiation would raise temperature in low latitudes more than in high latitudes, increasing the poleward transport of heat and water vapour and so causing more snow in the subarctic regions. In a later paper he summarizes a comprehensive review of the evidence as: quiet sun — interglacial; steady moderately disturbed sun (minor sun-spot maxima) — glacial; extreme solar disturbance (major sun-spot maxima) — chaotic climatic stress and deglaciation. On the other hand H. Flohn from a study of the circulation during the cold winters of 1939–42 attributes glaciation to a marked decrease of solar radiation, especially in the ultra-violet, resulting in a strengthened meridional circulation and weakened W. winds (low-index type).

Orogenesis and changes of land and sea distribution do not now appear to be accepted as the major cause of climatic changes, but several authors express the view that both solar and geographical changes are required for ice ages. R.F. Flint explains the glaciations of Alaska on these lines, with emphasis on the solar changes, while M. Schwarzbach places the emphasis rather on orogenesis, and B. Bell postulates high ground, a change of solar radiation and favourable topography, with possibly increased corpuscular radiation, to warm the polar stratosphere and so produce polar low-pressure areas.

Changes in the elements of the earth's orbit and the inclination of the axis are rather out of favour. They are still maintained by F.E. Zeuner and G. Bacsák, while D. Brouwer has produced a new solution, but they are rejected as insufficient by A.J.J. van Woerkom.

The third group, continental drift or pole shifts, also has a few adherents, among whom may be mentioned K.A. Pauly who adopts Sir Arthur Eddington's theory of a sliding of the earth's crust over the interior due to tidal friction, and J. Goguel who attributes displacements of the pole to winds, ocean currents and tides.

Changes in the constitution of the earth's atmosphere now reduce almost entirely to the effects of volcanic dust, H. Wexler having revived W.J. Humphreys's theory of the cooling effect of a volcanic-dust veil, while volcanic dust plays a subordinate role in several other theories. In a recent one by C.A. Zapffe volcanism in the Atlantic region plays a dual role, submarine eruptions causing a large supply of water vapour and aerial ones the necessary veil to lower temperatures generally, but Zapffe also brings in theosophy and destruction of Atlantis to buttress his case.

From this rapid survey it will be seen that the problem of climatic change is really little nearer to a solution than it was seven years ago. The theories current in 1947 are still being argued; even some old ones have been revived. Thus in 1950 E. le Danois brought back O. Pettersson's theory of climatic changes due to internal oceanic tides, and in 1952 H. Gerth revived C.E.P. Brooks's geographical theory of the Permo-Carboniferous glaciation. Perhaps the most hopeful sign is that in 1954 palaeoclimatologists are not quite so tied to single causes to the exclusion of all others as they seemed to be in 1947; it is becoming accepted that combinations of two or more causes are necessary to explain the facts. The most urgent need now is for some credible method direct or indirect, of reconstructing the variations of solar radiation during geological time; when that point has been cleared up the way may be open for the evaluation of other factors.

July 1955

Meteorological Office Staff Centenary Dinner

This was held on the evening of March 11 at the Holborn Restaurant and was attended by no less than 218 members, or former members, of the staff with their guests. Sir Graham Sutton acted as President and the company were graciously received by him and Lady Sutton.

After an excellent meal, reminiscent of pre-war standards, and the loyal toast to Her Majesty the Queen, Mr. H.L.B. Tarrant proposed the toast of the Meteorological Office, reminding his audience of the days when the staff numbered less than 40. In his reply, Sir Graham reminded his audience of some of the great names of the past and expressed his delight in seeing so many old members of the staff. He also paid tribute to the present staff for the way in which they carried on the great tradition of service, and said that he hoped in his term of office to see them brought closer together by the provision of a national weather building worthy of the name.

Before the toast of the Ladies, proposed in characteristic maritime vein by Cmdr Frankcom, each lady was presented with a thermos jug. In her reply, Lady Sutton looked forward to the day, already envisaged by Sir Graham, when, with the Headquarters establishments housed under one roof, social functions and activities of various kinds would be much easier to arrange and to attend; and wives would get to know each other better.

In proposing the toast of the officers and members of the Social and Sports Committee, Dr. Stagg outlined its history, and referred to the successes achieved on the football field and in the athletic arena, the winning of the Air Ministry Challenge Cup and the Bishop Shield for 7 and 6 years in succession respectively. Mr. N.H. Smith, Chairman, replied, paying a tribute to the organizing genius of Mr. Ben. G. Brame (Treasurer) and Miss Joan Wordsworth (Secretary) which had done so much to ensure the success of the dinner. He also reminded his hearers of the sources of committee funds, and that, but for support from those funds it would have been impossible to meet the expenses of those representative football and athletic teams which, under the enthusiastic guidance of Mr. H.A. Scotney, had proved so successful in departmental competitions. He also called attention to a Centenary Souvenir in the shape of an attractive perpetual calendar which was now available to purchasers on application to the Secretary.

Amongst former members of the staff present were Sir David Brunt, Sir George Simpson, Mr. E. Gold, Mr. R.G.K. Lempfert, Mr. R. Corless and Mr. W. Heinemann — a veteran of 90 years.

It was generally agreed that the occasion has proved a delightful and memorable one, although there was regret that time did not permit, as was intended, of the mingling together of old colleagues and friends in an after-dinner conversazione.

November 1955

Thunderstorm at Sharjah on November 14 1954

A storm with unusual intensity of rainfall and lightning occurred at Sharjah, on the Oman Peninsula in the Persian Gulf, on the evening of November 14, 1954

It had been noted that the ring of small isolated cumulonimbus clouds which had persisted most of the afternoon on the horizon were beginning to develop further. When dusk approached lightning became visible over the mountains to the east. As this increased in frequency and intensity it could be seen that considerable vertical development was taking place. This seems to have had a trigger effect on cloud to the west, south and north and by 2000 local zone time Sharjah was surrounded by towering cumulonimbus. Just before the storm broke at 2045, lightning was so frequent and intense as to appear one continuous vivid light, sufficient to read the small print of a newspaper in comfort. Rain, moderate at first, soon became violent turning to hail at 2100. The hailstones were up to 1 in. in diameter some of them of a flattened shape. precipitation turned to rain at 2115 and stopped abruptly at 2130. In a period of 45 min. 56.0 mm. (2.21 in.) of rain fell. The barograph trace showed a rise of about 7 mb. followed by a fall of about 5 mb. in this period.

There is unfortunately no record of the strength of the wind in the squall which accompanied the storm, but considerable damage was done to barousti* roofs. The whole area is sand with impervious consolidated coral beneath. The camp was quickly flooded and low-lying areas were under 30 in. of water. Some damage was done to a brick building by subsidence. The lightning was described by many observers as frightening but seems to have done no damage.

A.C. THOMAS

[The average annual rainfall at Sharjah (25° 20′N. 55° 24′E)† is 117 mm. (4.61 in.) and the average number of days in a year on which rain falls is 7; 108 mm. (4.29 in.) has been recorded in 24 hr. in November. Hail is very rare in the area. - Ed., M.M. 1955].

* Of woven cane.

† See London, Meteorological Office. Weather in the Indian Ocean. Vol. II, Part 3, The Persian Gulf and Gulf of Oman, 1941.

CHARLES ERNEST PELHAM BROOKS, I.S.O., D.Sc.

Dr. C.E.P. Brooks, an Editor of the *Meteorological Magazine* for some 22 years, died on December 14, 1957, at the age of 69, after being confined to his home at Ferring, Sussex, for a few months with heart trouble.

For 41 years Dr. Brooks worked full time in the Meteorological Office, retiring as Assistant Director in charge of the Climatological Division. Initially he was allocated to the Library, where his wide reading and remarkable memory made him of particular service to his colleagues and also enabled him to develop his main interest in World Climatology. Author of numerous papers he was awarded the Buchan Prize of the Royal Meteorological Society in 1931. His published books include: *The evolution of climate* (1925); *Climate through the ages* (1926, second edition 1948); *British floods and droughts* (1928) with Dr. J. Glasspoole; *Climate* (1929); *Climate in every-day life* (1950); *Handbook of statistical methods in meteorology* (1953) with Miss N. Carruthers; and *The English climate* (1954). He gained an international reputation, notably in the field of climatic change, and has left the results of his life work for the benefit of present and future generations.

Dr. Brooks put forward the theory that the dominant factors in producing climatic changes were geographical, including variations in the distribution of land and sea, systems of ocean currents, the vertical circulation of the sea, the elevation of the land and the amount of explosive volcanic activity. Along these lines he gave an explanation of the Permo-Carboniferous glaciation over low-lying areas in equatorial regions.

Dr. Brooks had the responsibility of moving the Library and the Climatological Records to Stonehouse, near Stroud, at the beginning of the war, and afterwards to Harrow. He had a reputation for swift action, but the sudden arrival of a large consignment of packing cases at the Office at South Kensington at the beginning of hostilities surprised even those familiar with his way of cutting through any red tape. He a did much to keep the staff happy, while in billets, and during the enforced long hours of work during the war. Then he had the responsibility of preparing climatological reports on various parts of the world, coping with many war-time climatological problems and also keeping together the corps of voluntary climatological and rainfall observers. Towards the end of the war he was directed to devote his full time to long-range forecasting, a problem in which he was especially interested. He did not spare himself, although this investigation did not produce the hoped-for results. Some indication of the scope of the work for which he was responsible is reflected by the various separate Branches which emerged under post-war conditions:— British Climatology, Rainfall of the British Isles and Hydrology, Agricultural Meteorology, Overseas Climatology, Upper Air Climatology, Library and Editing, and the Machine Pool using Hollerith cards for climatological data.

Dr. Brooks always had time to help and encourage his colleagues, and with his ready wit and understanding made even the most laborious extractions or computations of live interest to his staff. He set an example of energetic application to his work. He lived a full life, often claiming that he produced more useful work in his train journeys to and from Ferring than in the routine of Office administration. Following a short period of part-time employment at the Meteorological Office he found congenial work at home in abstracting meteorological literature for the American Meteorological Society, which later resulted in a visit to Washington.

Dr. Brooks' energies were not entirely confined to work. He started the Air Ministry Chess Club after the First World War and under his guidance the team moved steadily to the first division of the Civil Service Tournament. He was keen on swimming, lawn tennis, and on contract bridge.

Dr. Brooks was Secretary of the Royal Meteorological Society from 1928 to 1932 and later Vice-President. He served as the Meteorological Office representative of the International Meteorology Organization Commissions for Climatology, Hydrology, Agricultural Meteorology and Bibliography and Publications at Toronto in 1947.

Dr. Brooks married Miss Dora Buckeridge, whom he met at the Meteorological Office, and whose constant help he acknowledged in his books and papers. She survives him, as does also their son, and they have the sympathy of his wide circle of friends.

April 1960

HIGH ATMOSPHERE RESEARCH IN THE METEOROLOGICAL OFFICE

By the DIRECTOR-GENERAL *(Sir Graham Sutton C.B.E., F.R.S.)*

Meteorologists like to think that "the sky is the limit", but their upward ambitions, until recently, have been determined by the fact that balloons carrying instruments cannot ascend beyond about 50 kilometres. The position has changed in the last few years. The rate of development of the rocket as a geophysical tool has exceeded all expectations and artificial satellites are in orbit around the Earth. The old limits of accessibility no longer apply.

The Meteorological Office has kept well in the fore of high atmosphere research by means of the Meteorological Research Flight. This unique unit has added greatly to the stockpile of knowledge of the physical properties of the upper air and the structure of clouds. But aircraft capable of acting as flying laboratories are even more limited than balloons in the heights attained, and it has been evident for some time that meteorology must turn its attention to the rocket as a routine sounding device if the supply of data is to match the demands of the theoreticians.

It has therefore been decided to create within the Meteorological Office a new Assistant Directorate to deal with the problems of the high atmosphere. In meteorology the adjective "high" must be interpreted according to the facilities available at any given time. At the beginning of the century, when Teisserenc de Bort discovered the stratosphere, the "high atmosphere" extended only a few kilometres above the tropopause. Today, we may pause at about 100 kilometres, the level at which dissociation becomes significant and the stratosphere (if the name can still be used) merges into the ionosphere.

The decision to regard, for the time being, 100 kilometres as the "top" of the meteorologists' atmosphere does not, of course, imply that meteorology ceases at this level, but merely that this is a convenient height for the separation of techniques. In the mid-latitudes there is little change in mean temperature from the tropopause to about 20 kilometres, but above this height temperature increases to a maximum of about 20 °C at 50 kilometres, followed by a fall to a second minimum of about −80 °C at 80 kilometres, after which there is another rise. The lowest appreciable ionization in the atmosphere, the D-layer, lies between 70 and 90 kilometres, and the base of the all-important E-layer is between 100 and 120 kilometres. The E-region and above are regularly explored by radio waves, but the atmosphere between 30 and 100 kilometres is something of a no-man's-land, inaccessible to balloons except in its lowest 20 kilometres and too low for ionospheric techniques, except in its upper layers. This part of the atmosphere is of considerable interest to meteorologists if only for the reason that ozone reaches its maximum concentration between 20 and 40 kilometres. It is certain that regular measurements of wind, pressure, temperature, density and ozone concentration between 30 and 100 kilometres would be especially valuable in studies of the general circulation of the atmosphere.

In general terms the task of the new unit is to extend our knowledge of the movements, physical state and composition of the Earth's atmosphere up to about 100 kilometres. The measurements will be made by instruments carried by large balloons, rockets and, it is hoped, artificial satellites. The rocket work is planned on two main lines: (i) with "large" rockets, such as Skylark and, (ii) with specially designed "small" rockets capable of carrying an instrumented telemetering head to about 60 kilometres. In the field of satellite observations the Office has begun a design study for an experiment to determine the vertical distribution of atmospheric ozone by means of the solar spectrum in the ultraviolet and visible ozone bands at satellite sunrise and sunset. The same instruments will probably allow determination of the total ozone content over the sunlit Earth by examination of the albedo in the same absorption bands. It is planned to complete this instrument in time for its inclusion in the second United States–British "Scout" satellite.

The problems of instrumentation involved in this work are both difficult and fascinating, but observations are but means to an end. In the planning of the staff, provision has been made for theoretical studies of the data obtained both in this country and abroad, as they become available.

Although the creation of the new unit involves many novel concepts, in another sense it is simply a logical continuation of the exploration of the atmosphere which began with kites and the Dines balloon-meteorograph and received its greatest impetus to date with the development of the radiosonde and radar-wind equipment. To the vast majority of meteorologists, rockets and satellites are unknown tools, but their potentiality is evident. It is to be hoped that the coming generation of meteorologists will discover in their results as great an inspiration and as valuable an aid towards the understanding of the ways of the atmosphere as our generation found in the radio-sonde and radar-wind soundings.

December 1960

NOTES AND NEWS

Adoption of the Celsius scale of temperature within the Meteorological Office

It has been decided to adopt from 1 January 1961 the Celsius scale of temperature for all temperature measurements, including "surface" observations, made for internal use within the Meteorological Office and for international purposes. Most readers will know that the Celsius scale has been used in the Office since 1 January 1956 for upper air observations.

The decision to change to degrees Celsius follows from a Resolution of Third Congress (1959) of the World Meteorological Organization expressing, amongst other things, the hope that Members who do not use the Celsius scale would adopt it for use in coded messages before Fourth Congress meets in 1964. For the Office to have gone over to the Celsius scale only in international synoptic reports would have involved unacceptable extra work, loss of time and risk of error in recutting teleprinter tape at the Central Forecasting Office for the international transmissions.

Thus all synoptic reporting stations controlled by the Meteorological Office including the auxiliary reporting stations will transmit temperature observations in degrees Celsius from 1 January 1961. The voluntary climatological stations will continue to use the Fahrenheit scale. Temperatures will be published in the Celsius scale in both the *Daily* and *Monthly Weather Reports*. The *Daily Aerological Record* has, of course, used that scale since 1 January 1956.

There will be no change in the temperature scales used for forecasts and weather reports for the public which will continue to use the scale with which the recipient is most familiar. Thus the forecasts for the general public, broadcast by sound radio and television and published in the Press, will continue to state temperature in degrees Fahrenheit while those issued for aviation will naturally continue to use degrees Celsius.

Detailed instructions have of course been issued to all those whose work is affected by the change.

Definition of "ground frost"

Since 1906 "ground frost" has been recorded by meteorological observers when the thermometer on the grass has fallen to or below 30 °F (30.4 °F for thermometers read to tenths). The reason for the introduction of the practice in 1906 has not been found, despite extensive search. The first publication of a reason appeared in the second (1930) edition of the *Meteorological glossary* where it is stated that injury to the tissues of growing plants is not caused until the temperature has fallen appreciably below the freezing-point of water.

The introduction of the Celsius scale of temperature into Meteorological Office practice for all internal purposes has led to a reconsideration of the definition of "ground frost". It has been decided that the explanation given in the Meteorological glossary, supposing it is correct, does not justify the continued use of the definition because the occurrence of "ground frost" is of importance to a larger proportion of the community, for example, in connexion with motor transport, than it was over fifty years ago. Therefore it has been decided that the practice of attaching special significance to the attainment of a grass minimum temperature of 30 °F (or 30.4 °F) or below by terming these "ground frosts" should no longer be continued.

Hence, on and after 1 January 1961, grass minimum temperatures will continue to be collected as hitherto. However, in publications the term "ground frost" will no longer be used and present statistics such as "Number of days with ground frost" will be replaced by "Number of days with grass minimum temperature 0 °C or below". On the other hand, it will be convenient to retain the term "ground frost" for use in forecasts, and when so used it will imply a grass minimum temperature at or below 0 °C (or 32 °F).

December 1960

HEADQUARTERS RE-ORGANIZATION

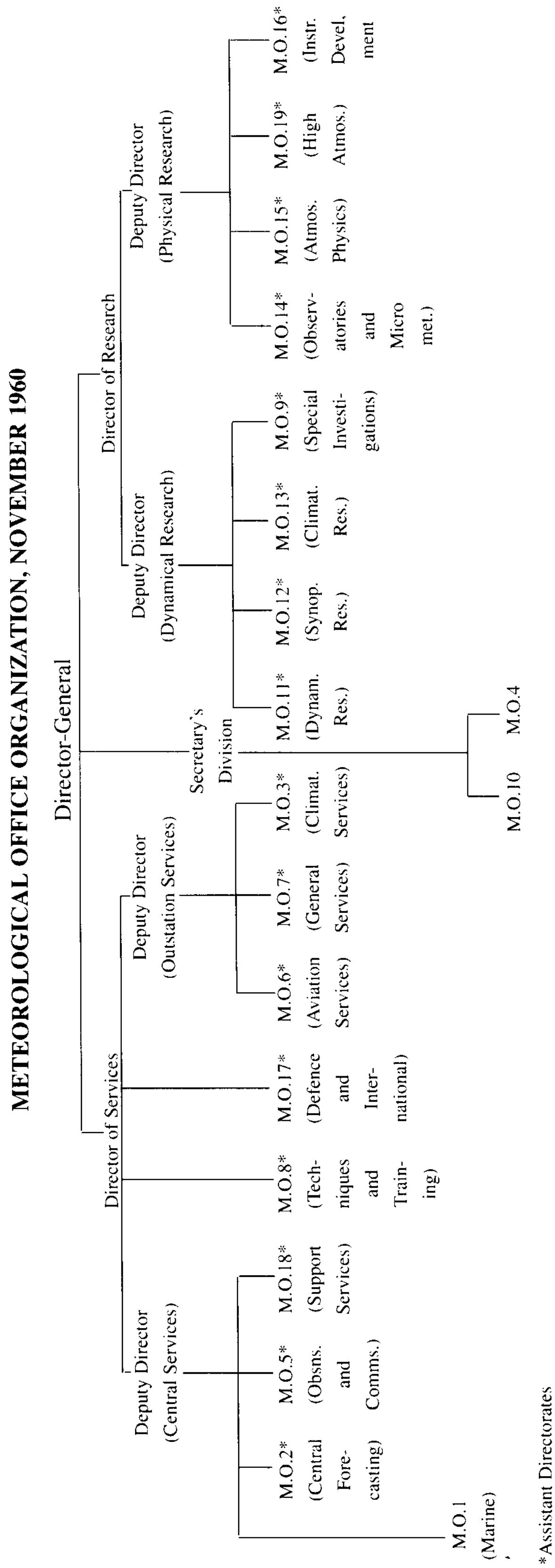
By The DIRECTOR-GENERAL *(Sir Graham Sutton C.B.E.,F.R.S)*

In 1957, as a result of the report of the Brabazon Committee, the structure of the directorate of the Meteorological Office was considerably changed. In 1961 the Headquarters sections of the Office, which for many years have been dispersed between London, Dunstable and Harrow, will come together at Bracknell. This has given an opportunity to reconsider the Headquarters organization in the light of experience gained in the last three years and the changes that are taking place in meteorology both as a science and a profession.

The outstanding feature of the Brabazon reorganization was the recognition of the dual role of the Office, namely, to provide meteorological services on a national scale and to act as the primary scientific institution of this country for the advancement of the science of the atmosphere, by the creation of two Directorates, of Services and Research, respectively. This fundamental division of responsibility has been maintained in the new structure. The Director of Research, Dr. R.C. Sutcliffe, F.R.S., has now become the senior Director and Dr. A.C. Best has succeeded Dr. Stagg as Director of Services.

This change necessarily means that the Director of Research, as deputy to the Director-General, has additional administrative and general policy responsibilities. A new deputy-director post has therefore been introduced into the research directorate. Mr. J.S. Sawyer has relinquished his personal post of Chief Forecasting Research Officer to become Deputy Director in charge of Dynamical Research. Other changes within the Research Directorate are that in future all public inquiries relating to areas outside the United Kingdom will be handled by Climatological Services (M.O.3), and the library and the editing sections will no longer be attached to Climatological Research (M.O.13), which, however, will absorb the long-range forecasting research unit from Synoptic Research (M.O.12). The last-named change reflects the view that long-range forecasting is more intimately related to the general circulation of the atmosphere than to ordinary synoptic meteorology.

The changes in the Directorate of Services reflect two features which have become prominent since the meetings of Lord Brabazon's Committee. In recent years there has been a continuing growth in demands for services not specifically related to aviation, and also something of a revolution in the handling and processing of the vast amount of information reaching the meteorological services. To meet the first situation, the administration of both civil and military meteorological services is now combined under one Assistant Director and, to reduce the load to manageable dimensions,



international work connected with civil aviation meteorology has been transferred to the Assistant Director in charge of Defence and International matters (M.O.17) who already handles relations with the World Meteorological Organization. In future this Assistant Director will report to the Director of Services, but he will continue to assist the Director-General when the latter acts as the United Kingdom Permanent Representative with the World Meteorological Organization or in his personal capacity as a member of the Executive Committee of the World Meteorological Organization.

A new post, that of Assistant Director (General Services) will cover all non-aviation matters outside climatology. The major interests of this assistant directorate will lie in the agricultural services and in the Weather Information Centres, of which three are now in existence, in London, Glasgow and Manchester. The Assistant Director (Climatological Services) takes over all climatological inquiries, including world climatology (as noted above) and marine climatology. The Marine Superintendent will concentrate upon the management of the Ocean Weather Fleet, the collection of data from ships, control of the Port Meteorological Officers, editing of the *Marine Observer* and the preparation of those of the publications of the Office that deal with the oceans. He and his Nautical Officer staff will act as advisers to the whole Office on problems calling for a seaman's professional knowledge of maritime matters.

The problems of data handling and processing have now grown so large and are so specialized that it has been thought advisable to create a new Assistant Directorate, called Support Services, to deal with these and other cognate matters, including the Library, Archives and all editorial and cartographical work for official publications. It is clear that in the near future the collection, analysis and storage of meteorological data must become part of an integrated system depending more than ever on machines. The problem of specifying such a system has been under intensive study in the Office for some time.

The new organization is shown in the diagram. The reunion of parts of the Office that have been separated geographically for so many years has made possible a closer integration and a more rational division of duties. It cannot be too strongly emphasized that the Meteorological Office is a single entity dedicated to the task of advancing the science of the atmosphere in both its pure and applied aspects. The new arrangement, it is hoped, will enable it to function efficiently and harmoniously in its new home.

January 1966

Press Conference

The Director-General held a Press Conference at Bracknell on 2 November, 1965 to mark the introduction of routine numerical forecasts in the Meteorological Office. The Conference was attended by a wide cross-section of the national and technical Press, the BBC, and a large corps of photographers.

An introductory talk by the Director-General was followed by 45 minutes of lively questioning. The Press were then invited to watch the production of the first routine chart on the line printer, each correspondent receiving a souvenir copy. There followed visits to the Central Forecasting Office and informal discussions with senior members of the staff.

The Conference was reported on radio and television, produced leading articles in *The Times* and the *Financial Times* and was extensively reported in the national and local Press. The substance of the Director-General's talk is given below:

Ladies and gentlemen, it gives me great pleasure to welcome such a large and distinguished gathering of the Press to the Meteorological Office. Today is a landmark in the history of forecasting in the Office — a history which goes back more than a century — because this afternoon you will see the production of our first routine numerical weather forecast by the computer. But first I should like to introduce some of my colleagues who are involved in this important project, and then take a few minutes to explain how the machine forecast is produced, its significance, its limitations, and something of our plans and hopes for the future.

As many of you will know, the traditional techniques of weather analysis and forecasting involve the preparation, at regular three- or six-hour intervals, of maps that give a two-dimensional representation of weather conditions at the earth's surface and at a number of levels in the upper air. Observations of pressure, temperature, humidity, wind and so on, made simultaneously at fixed hours at hundreds of stations all over the world are transmitted as quickly as possible to all countries on an internationally agreed basis. When these data are plotted on the maps the forecaster draws lines (for example isobars connecting places recording the same pressure and isotherms connecting places at the same temperature) which emerge as recognizable patterns that reveal the position, structure and evolution of weather systems. After careful study of these patterns in relation to similar charts for earlier times, the forecaster can extrapolate for some hours ahead the tracks of the main depressions and anticyclones and the movements of such features as troughs, ridges, fronts and rain areas. Here the forecaster relies upon a number of well-tested rules, his understanding of the physical processes, his experience of how similar situations have developed in the past, and his intuitive feeling for how the atmosphere works. This judicious combination of knowledge, experience, intuition, judgement and flair introduces a subjective element into the forecast. Nevertheless, even under the difficult conditions experienced in the British Isles, the main features of the daily forecast are correct on about 85 per cent of occasions; not unnaturally the public tends to remember only the mistakes which, by the way, are usually errors of timing.

But over the years it has become apparent that the traditional techniques have been pushed nearly as far as seems profitable; at any rate there is no real hope of further major improvements. The objective is, of course, more comprehensive, detailed and accurate forecasts that will remain reliable for longer periods ahead. Among other things, this will require many more observational data from larger regions of the atmosphere. Now clearly there is a limit to the quantity of data that a human forecaster can assemble, assimilate, analyse and interpret in the short time allowed by the fact that he has to keep well ahead of the actual weather. This is where the big computers come to the rescue. They are able to handle huge quantities of data and perform vast numbers of mathematical calculations at very high speed. For example, our KDF9 computer, named COMET, can make an addition or subtraction in one millionth of a second. We have, of course, to tell it exactly what to do and how to do it.

I shall now try to explain, in simple terms, the procedure for making a numerical forecast. We work with a large section of the atmosphere stretching from Hawaii to Malaya, from the North Pole to central Africa, and extending up to a height of about 40,000 feet, and we concentrate on developments at three levels — at the surface, at 20,000 and at 40,000 feet. We subdivide this huge region by a grid, similar to lines of latitude and longitude, that provides 1300 regularly-spaced grid points. Fed with weather observations made simultaneously from 1200 land stations, 300 ships, and 600 radiosounding balloons that transmit information on pressure, temperature, humidity and wind up to heights of 100,000 feet, the computer assigns a value for the pressure and temperature at each grid point at a convenient 'zero' hour. We also supply the computer with a very simplified mathematical description of the atmosphere — a set of differential equations to describe the gross behaviour of the air in our region and to allow the machine to compute how the pressure and temperature will change at each grid point during the next hour. (In practice it is more convenient to work in terms of two parameters called contour heights and thickness patterns, but these are closely related to pressure and temperature.) Using these new values the computer then carries the calculation forward in steps of one hour until, eventually, we have a forecast, for 12 or 24 hours ahead, of the distribution of pressure and temperature at the three levels. In addition, the machine calculates the large-scale vertical motions of the air which indicate regions of widespread cloud and rain and of dry settled weather. The whole operation takes less than one and a half hours.

Here I must emphasize that, because we are using only a very simplified model of the real atmosphere, the computer at present calculates only the gross features of the pressure and temperature field — the position and movement of the large weather systems such as the depressions and anticyclones. It does not attempt to deal with the detailed weather such as the occurrence of showers, thunderstorms and fog; these are added by conventional methods. Some progress along these lines is possible, at least in principle, but you will appreciate the magnitude of the problem when I tell you that one of our current research investigations on the development of a simple pair of fronts taxes the largest computer available in this country.

We show here a series of computed charts forecasting the conditions at midnight tonight; for comparison we also show the corresponding charts drawn by the human forecaster. I think that you will agree that, as far as the positions and magnitudes of the main pressure centres are concerned, the correspondence is very good. Such agreement is fairly typical in that, during the research trials, the computed forecasts of surface conditions were, on average, about as good as those produced by an experienced forecaster, while the computed upper air charts were consistently a little better. This degree of reliability in the numerical prognosis of the large-scale pressure field, essential to the production of a good weather forecast, is most encouraging. So, from today, the computed charts will serve as an additional aid to the forecaster. For a time he will continue to draw his conventional maps and use the machine forecast as a strong second opinion, but we hope and expect that, within a few months, he will acquire sufficient confidence in the computed charts to accept them unchanged. Since the machine actually prints the predicted values of pressure and temperature at each of the grid points on the chart, and will shortly be drawing the isopleths automatically, the forecaster may look forward to being relieved of much donkey work and to having more time for analysis and interpretation of his data and for presentation of his forecast to the customer.

Looking into the future, to more accurate forecasts for three, four or more days ahead, we shall need a number of things: a deeper understanding of how the atmosphere works on a global scale; a more sophisticated mathematical description of the atmosphere; many more observational data, particularly from the oceans and tropical regions and, perhaps, from the southern hemisphere; faster methods of communication to transmit these data; and bigger and faster computers. Given all of these and satellites too, we may look forward to gradual rather than dramatic improvements in the quality and range of the weather forecast. The atmosphere is an infinitely complex, subtle machine that will tax not only the largest computers, but more important, the best of our physicists and mathematicians for many years to come. Therein lies the challenge.

March 1977

THE METEOROLOGICAL MAGAZINE 1866–1977

The *Meteorological Magazine* has, in one form or another, been published for more than 111 years and we thought that our readers, particularly the new ones, would be interested in a brief history of how the Magazine came into being of its subsequent management and organization, including an account of the various editors. The Magazine, as the official journal of the Meteorological Office dates only from February 1920 and is really an amalgamation of *Symons's Meteorological Magazine* (published by the old voluntary British Rainfall Organization) and the official Meteorological Office Circular.

Symons's Meteorological Magazine

This magazine began its life in February 1866 as *Symons's Monthly Meteorological Magazine*, the monthly publication of the British Rainfall Organization, and hence owes its existence to that remarkable man George James Symons, F.R.S.. Mill (1938) has given a succinct account of Symons's life, of how he resigned in 1863 from the Meteorological Department of the Board of Trade (later to become the Meteorological Office) in exasperation at the attitude of official superiors, and of his immense achievement in creating the British Rainfall organization virtually single-handed. Although the Magazine was started primarily to inform and unify Symons's army of co-operating voluntary rainfall observers, and was an improvement on his 'Rainfall Circulars' of the previous few years, almost from the first it carried short articles and notes on a wide variety of climatological and meteorological phenomena very much as the monthly magazine *Weather* (published by the Royal Meteorological Society) does today.

For a number of years before the end of the century Symons was helped in the task of running the British Rainfall Organization — which included editing the annual British Rainfall as well as the monthly Magazine — by H. Sowerby Wallis. Symons died in 1900 and on 1 January 1901 Hugh Robert Mill, D.Sc., LL.D., was appointed joint-director of the Organization with Wallis. Mill edited the Magazine until his early retirement — due to ill-health — in 1919; his life and work are well described by Glasspoole (1950) and Carter (1951). Following Mill's appointment the word 'monthly' was dropped from the title of the Magazine.

Mill's eyesight had given him trouble since 1913, and an increasing share of responsibility for the Organization and its publications was taken by Martyn de Carle Sowerby Salter who became joint-director and joint-editor. Mill's retirement in 1919 coincided with the taking over of the British Rainfall Organization by the Meteorological Office, of which it became a Division with Carle Salter — as he was generally known — as its Superintendent. The last issue of *Symons's Meteorological Magazine* was for January 1920.

The Meteorological Office Circular

On 20 June 1916 the Meteorological Office began the publication of a leaflet called the 'Meteorological Office Circular' principally for distribution among observers. This provided a convenient means for the publication of Official notices, changes in observing staff, brief reviews of recent publications and other matters of general meteorological interest. The first four numbers were edited by R. Corless, and the remainder by F.J.W. Whipple. The last issue was dated 2 February 1920.

The Meteorological Magazine

The Meteorological Magazine was first published in February 1920, with a cover which in addition to line-portraits of FitzRoy, Symons, Sabine and Strachey bore the words: THE METEOROLOGICAL MAGAZINE, *Symons's Meteorological Magazine Incorporating the Meteorological Office Circular.* (This design of cover was used until January 1937, the last issue of Volume 72.)

The Magazine was edited jointly by Carle Salter and F.J.W. Whipple who was Superintendent of the Climatological Division. An editorial in the last issue of the old Symons's Magazine stated 'Whilst becoming, as a matter of course the organ of the combined meteorological services, the Magazine will, it is hoped, fully maintain its traditional character as a channel of communication between amateur meteorologists'; it is probably true to say that this hope was largely realized during the following twenty years.

In 1923 Carle Salter died at the tragically early age of 43 (see Mill (1923)), and Whipple was transferred to the British Rainfall Organization Division, becoming sole editor. In 1925 a reorganization of Meteorological Office structure took place, involving the setting up of Divisions of General Climatology and British Climatology with the British Rainfall Organization being attached to the latter. The Division of General Climatology was put under the charge of C.E.P. Brooks who was promoted to the grade of Superintendent; his job included supervision of the Meteorological Office Library, the study of world climatology and the Editorship of the *Meteorological Magazine*.

Brooks continued to edit the Magazine for 22 years including the period of second World War, although after June 1940 the need to conserve manpower led to the suspension of general publication in printed form and it was only a typescript edition — albeit with diagrams and photographs — that maintained a limited internal circulation. Proper publication was resumed with the issue for January 1947, the wartime break having given the editor an opportunity to begin his next volume with that month and not February, a mildly irritating practice that had continued ever since February 1866. In the late summer of 1947 Brooks was succeeded as Editor by G.A. Bull who was later to become Assistant Director (Support Services).

After the war, a change of policy in the editing became apparent. Before 1940, the Magazine contained short general articles on meteorology and climatology, with accounts of remarkable weather events, Meteorological Office news, accounts of personalities including retirements, obituaries, promotions and special appointments, and correspondence from members of the Office and amateurs; there was little or no mathematics and nothing that could really be described as a scientific paper suitable for a learned journal. After 1947 an increasing number of papers appeared describing the results of original investigations carried out in official time.

By the time that Bull was succeeded as Editor by R.F. Zobel in November 1960, the Magazine had largely assumed its present appearance and character, though minor changes of content and cover design still occurred from time to time. Zobel was replaced in April 1962 by A.H. Gordon who was in his turn succeeded in March 1963 by W.S. Garriock.

Garriock proved to be another long-standing editor who spent nine years maintaining the high standards of accuracy and sub-editing which had rightly become characteristic of a Magazine that acted as the official organ of an old-established Government scientific department; he retired in June 1972. Between June 1972 and September 1974 the post of editor was filled successively by F.E. Lumb, J.G. Cottis, and J.B. Andrews; the present editor is R.P.W. Lewis.

After the above was written, Lewis was in post until 1986; then in rapid succession came R.W. Riddaway, B.R. May, F.E. Underdown and myself, R.M. Blackall

REFERENCES omitted from the original printing, but added later:

CARTER, H.E.	1951	*Brit Rainf*, 1949, pp.1–2.
GLASSPOOLE, J.G.	1950	*Met Mag*, **79**, pp. 180–182.
MILL, H.R.	1923	*Met Mag*, **58**, pp. 97–99.
	1938	*Met Mag*, **73**, pp. 165–168.

August 1979

Brief historical note on the formulation of Buys Ballot's Law

The name of Buys Ballot is to be found in almost every textbook of meteorology and his law of the relation of wind direction and pressure distribution is taught in the many schools which nowadays include elementary meteorology in their curriculum. It may therefore be of some interest to trace briefly the formulation of this law. Professor Buys Ballot, Director of the Dutch Meteorological Institute and Professor of Physics at Utrecht was amongst the pioneers in the use of synoptic meteorology for the issue of forecasts and storm warnings. In dealing with observations of pressure and temperature he made use of deviations from average values and in a paper presented to the Paris Academy of Sciences in 1857* he discussed the results obtained from observations at three stations in Holland. After showing that strong winds are indicated by large differences between the deviations, he proceeded to explain that if pressure was higher at Den Helder than at Maastricht (that is to say, higher in the north than in the south) then the wind was from the east while if pressure was higher at Maastricht the wind was from west or north-west. In the *Jaarboek* of the Meteorological Institute of the Netherlands for the same year (published in 1858) p. 347, this conclusion is stated in more general terms. Translated into English it reads 'great barometric differences, within the limits of our country, are followed by stronger winds, and the wind is in general perpendicular, or nearly so, to the direction of the greatest barometric slope in such a way that a decrease of pressure from north to south is followed by an east wind, and a decrease from south to north by a west wind'. In 1860 he published a paper entitled 'Eenige regelen voor aanstaande weersveranderingen in Nederland' (Some rules for approaching changes in the weather in the Netherlands), in which the law appears in its well-known form (pp. 50ff). 'Thus the rule for wind direction is this: if one places oneself in the direction of the wind with one's back to the place from which it is coming, then one has the lowest place (i.e. pressure) on the left-hand just as in the case of hurricanes'. (These storms had long been known to have a whirling motion and the distinction between the anti-clockwise rotation in the northern hemisphere and the clockwise rotation in the southern hemisphere had been expounded by Dove in 1828.)

[The above text, authorship unknown, is to be found in a pamphlet held in the National Meteorological Library and dated 1930.]

*Note sur le rapport de l'intensité et de la direction du vent avec les écarts simultanés du baromètre. *CR Acad Sci, Paris*, **45**, 1857, 765–768.

A remarkable rainstorm in Hong Kong

It is with much pleasure that I am able to close this final issue with a report of a rainfall event which would have been missed if the issue had been on time! Readers will probably be aware that heavy rain is not unknown in south-east Asia; see the January 1993 issue of The Meteorological Magazine. *However, press reports of 1000 mm in less than two days seemed to be stretching credibility, so I wrote to Mr Lam asking for confirmation. This is the reply I got.*

Dear Mr. Blackall,

Mr. C.Y. Lam asked me to provide you with some rainfall data recorded at Tai Mo Shan area during the heavy rainfall on 22–24 July 1994.

Tai Mo Shan is the highest peak in Hong Kong with a height of 957 metres. The rainfall recorder is a 0.5 mm tipping-bucket type and data are telemetered to a central station in the Geotechnical Engineering Office of the Civil Engineering Department in the urban area through leased telephone line and modems. Tai Mo Shan is one of the 48 automatic rain-gauges in the network. The data are also relayed to the Royal Observatory. The rain-gauge at Tai Mo Shan was checked to be functioning properly a few days before the occurrence of this heavy rain.

I have copied on the attached sheet some daily, hourly and 5-minute rainfall data recorded at this station that you may find interesting. I also enclose a copy of our *Monthly Weather Summary* for July 1994, which has just been published, for your background information on this rainfall occasion.

The 30-year (1961–90) normal rainfall distribution in Hong Kong indicates the maximum area is at Tai Mo Shan with an annual amount of over 3200 mm against 2214 mm at the Royal Observatory.

I hope the above information is useful for your magazine. Please let me know if you need any further material.

Yours sincerely
K.P. Wong
for Director of the Royal Observatory

Selected 5-minute rainfall (mm) recorded at Tai Mo Shan on 22 July 1994

Hour minute	01	02	05	06	07	09	10
00–05	4.0	15.5	7.0	1.5	15.0	4.0	38.5
05–10	2.0	11.5	2.5	1.5	12.5	2.5	30.0
10–15	2.5	8.5	10.5	3.0	11.0	9.0	35.0
15–20	1.5	6.5	10.5	3.0	12.0	3.5	28.5
20–25	2.5	7.5	8.5	2.5	10.5	3.0	14.5
25–30	4.0	5.0	5.0	1.0	2.5	2.0	12.5
30–35	1.0	4.5	1.5	2.5	5.0	2.5	9.0
35–40	3.0	2.0	1.5	2.0	3.0	4.5	4.5
40–45	4.0	3.5	2.0	5.0	1.5	4.5	5.5
45–50	14.5	4.0	1.0	6.5	0.0	6.5	3.5
50–55	18.0	4.0	1.5	6.0	0.5	3.5	2.0
55–60	21.5	4.0	1.5	11.0	0.0	23.5	2.0
Hourly total	78.5	76.5	53.0	45.5	73.5	69.0	185.5

Hourly rainfall (mm) recorded at Tai Mo Shan

Hour	22 July	23 July
01	49.0	29.5
02	78.5	41.0
03	76.5	34.0
04	53.5	39.0
05	52.5	36.5
06	53.0	13.5
07	45.5	9.5
08	73.5	2.0
09	21.0	3.5
10	69.0	6.0
11	185.5	3.5
12	15.0	1.5
13	15.5	1.5
14	15.0	1.0
15	27.0	0.0
16	12.0	0.0
17	4.5	1.5
18	0.0	0.5
19	1.5	0.5
20	0.5	23.0
21	4.5	14.5
22	3.0	10.5
23	4.0	2.0
24	15.5	0.0
Daily total	875.5	274.5

Daily rainfall (mm) recorded at Tai Mo Shan

21 July	22 July	23 July	24 July
136.5	875.5	274.5	109.0

The publication of the *Meteorological Magazine* will cease with the issue for December 1993.

The December 1993 issue of the *Meteorological Magazine* will be a bumper one of about 40 pages celebrating the Magazine's contribution to the development and dissemination of meteorological knowledge. It will contain a selection of highlights from 1866 up to around 1986.

The first edition of the *Meteorological Magazine* was published in 1920 by HMSO. It took over from *Symons's Meteorological Magazine* which started in 1866. This decision therefore brings to an end a continuous publishing record of 129 years (except for the duration of World War II). It is understood that legal obligations accepted when *Symons's Meteorological Magazine* was adopted are fulfilled by the continuing production of the *Monthly Weather Report* and *Rainfall 19XX*.

As one of the leading European establishments for research into meteorology, our publications should be subject to external peer review: this is already the case for much Meteorological Office work. The publication of a new international and European quarterly journal by the Royal Meteorological Society (called *Meteorological Applications*) provides a suitable vehicle for most kinds of articles that have appeared in *Meteorological Magazine*, namely on research, practice, measurements, review articles, applications of meteorology, book reviews, etc. Enquiries should be addressed directly to the Royal Meteorological Society. Non-members should write to:

Journal Subscriptions,
Cambridge University Press,
Edinburgh Building, Shaftesbury Road,
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United Kingdom

Readers in the USA and Canada should write to:

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40, West 20th Street,
New York NY10011.
USA

The United Kingdom Meteorological Office (UKMO) Annual Scientific and Technical Review 1993/94

This Review describes the major developments in science and technology within the UKMO over the year April 1993 to March 1993 and is produced as part of the Meteorological Office Annual Report and became available in July 1994. If you wish to by put on the mailing list for future years please write to:

The News Desk, Publications (room 707a), Meteorological Office, London Road, Bracknell, Berks RG12 2SZ.

Back numbers

Limited stocks of back numbers from 1970 to date are available from:
Vic Silk, The Library, Meteorological Office, London Road, Bracknell, Berks RG12 2SZ; telephone 01344 854074. Copies cost £1.50 each (inclusive). Please send sterling cheques made out to 'Public sub-account HMG 4712'; leave the amount blank but cross them and endorse with the maximum so that the transaction can be made even if some of the requested issues sell out. Please send an addressed label with the order. Remaining stocks will be disposed of in March 1995.

Full-size reprints of Vols 1–75 (1866–1940) are available from Johnson Reprint Co. Ltd., 24–28 Oval Road, London NW1 7DX.

Complete volumes of *Meteorological Magazine* commencing with volume 54 are available on microfilm from University Microfilms International, 18 Bedford Row, London WC1R 4EJ. Information on microfiche issues is available from Kraus Microfiche, Rte 100, Milwood, NY 10546, USA.

LE MET MAG VA CESSER DE PARAITRE

C'est là une bien triste nouvelle: en 1994 *The Meteorological Magazine*, revue de vulgarisation et d'information générale du UK Met. Office, ne sera plus au rendez-vous chaque mois, pour des raisons apparemment 'politiques'. Il est probalble que la mission de vulgarisation et de service public que remplissait fort bien ce célèbre magazine a dû être estimée non 'rentable' (les guillemets pour signifier que ce vocable mériterait dans ce cas précis d'être explicité en termes d'intéret général, de connaissances pour le grand public, de culture et de civilisation dont l'apport ne peut être évidemment quantifié par les économists).

Qu'il nous soit permis ici de rendre hommage à *The Meteorological Magazine* et à tous ceux qui ont servi la météorologie grâce à ses colonnes depuis 1866, et en particulier à M. Rodney Blackall, son actuel rédacteur en chef.

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