THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

January 1986

Met.O.971 No. 1362 Vol. 115

Meteorological Magazine

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METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1362, January 1986, Vol. 115

551.556.4

The meteorological background to the fall of Saharan dust, November 1984

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Summary

This paper reviews the meteorological background to the Saharan dustfall of 9 November 1984 in Britain. A comparison with the published evidence for earlier falls shows this most recent event to have been unusual in its association with a quasi-stationary low pressure system. All earlier documented dustfalls have been a result of dust transportation within anticyclonic circulations.

1. Introduction

The fall of Saharan dust over eastern Britain on 9 and 10 November 1984 was one of the most notable of several such events during recent years. Since a fall in July 1968 others in Britain have been documented for 1977, 1979 (2), 1981 and 1983, but none appear to have compared with the dramatic events of February 1903 so well described by Mill and Lempfert (1904) from whose report it is clear that the opening years of the twentieth century were marked by frequent and spectacular dustfalls over wide areas of Europe north of the Alps from Britain eastwards to Austria. It is hard to believe that 65 years should separate two such clearly defined periods of activity with, as far as can be determined, no single intervening major occurrence. But if such a situation is indeed the case then some pertinent questions might be asked regarding the peculiar timing and circumstances of these groups of events.

2. Dustfalls and anticyclones

In all researched cases both mineralogical and meteorological evidence suggest a Saharan origin for the dust. In some instances possible sources have been identified far towards the south of the Sahara Desert. Tullett (1978), in describing the 1977 dustfall, persuasively argues for a source region south of the Ahaggar Mountains on a latitude of approximately 21° N. But even more northerly sources would still require journeys of several hundreds of kilometres in order to reach the latitude of northern Europe. And in this connection it should be noted that dustfalls are by no means restricted to the southern regions of Britain; they are common in Ireland (Tullett 1978, 1980, 1984; O'Connor 1980 and George 1981), not unknown in northern England (Pitty 1968; Pringle and Bain 1981) and observed even as far north as Skye (Bain and Tait 1977).

For such journeys to be completed without dispersal and total disruption of the dust cloud some form of persistent or slow-moving pressure system is required, yet with winds strong enough in the middle levels of the troposphere to carry the material great distances in atmospheric suspension. These conditions are most often encountered in the vicinity of anticyclones which, though mobile, tend to move more sluggishly when compared to the majority of their low-pressure counterparts. Conversely, the strong wind fields within depressions would tend to dissipate the dust through the atmosphere whilst the greater likelihood of rain would lead to washout of any material in suspension. Carlson and Prospero (1972) have already indicated the importance of anticyclonic conditions for the movement of dust westwards across the North Atlantic towards the Caribbean from African source regions. Indeed they found such activity to be concentrated into the summer and equinoctial seasons when the Azores anticyclone is at its most intense.

Further support for the anticyclonic hypothesis of dust transport is found in the accumulated evidence gathered this century in Britain. A summary of this information is given in Table I where, for documented dustfalls before 1984, the dependence on anticyclonic systems is complete. The centres of these extensive systems were all located over western Europe, especially France, and provided an arc of clockwise airflow from north Africa, across the eastern Atlantic, to approach the British Isles from the south-west. Some of the anticyclones listed in Table I were stationary during the transport of the dust; as, for example, in 1968 and 1977 with pressure centres over south-west and northern France respectively. Nevertheless, movement of the pressure systems may occur sometimes over great distances without apparently dispersing the dust clouds contained within their circulations. In November 1979 the anticyclone centre moved from northern France southwards to eastern Spain. More notable movements took place in 1981 and 1983 when the respective pressure centres both drifted from the region of southern England as far eastwards as Austria during the time of the dust cloud's movement from Africa to England. Bearing in mind the seasonality found in Carlson and Prospero's (1972) study the lack of seasonal preference in this admittedly small sample is noteworthy.

Table I. *Table of dates of dustfalls recorded in Britain. The central position of the controlling anticyclones are also given together with any change taking place during the movement of the dust within their circulations. The data are abstracted from contemporary maps and sources cited in the text.*

Date(s) of dustfall	Location of anticyclonic centre
21–22 February 1903	Northern France – eastern Spain
1 July 1968	South-west France
6 March 1977	Northern France
15 May 1979	Eastern France – Austria
28–29 November 1979	Eastern France – northern Spain
28–29 January 1981	English Channel – Austria
29 September 1983	Southern England – Austria

The influence of low-pressure systems appears to have been in every sense peripheral, their principal function being either to steepen pressure gradients around the anticyclones, thereby hastening the passage of the dust in the stronger winds, or to create conditions of rainfall in which the dust can be washed out of the atmosphere. However, the dust may not have an entirely passive role to play in these matters. Pitty (1968) has shown, and the present author more recently confirmed (Wheeler, in press), that while the median particle size of the dust is 9 μm the size of the majority of particles is less than 3 μm. No precise figures of atmospheric dust loadings are available for British falls, but it is clear from published sources that the total weights should be considered in terms of several millions of tonnes; Mill and Lempfert (1904) suggest 10 000 000 tonnes for the 1903 fall.

The presence of unusual concentrations of fine material in the atmosphere could have a profound effect on cloud formation and rainfall, particularly if the material were to behave as freezing and condension nuclei. Most dust material in this small size range consists of aluminosilicate (clay) particles of which the illite groups are common. The precise hygroscopic character of these minerals will determine their cloud- and rain-forming potential but, assuming them to have no disadvantage in that respect, the problem is not unlike that faced by cloud-seeders; a greater number of freeezing nuclei will enhance rainfall potential, but an over-abundance and the consequent competition for the finite volumes of water may not permit cloud droplet growth to a size sufficient for rainfall to occur. Only the dustfall of 1968 (Stevenson 1969) was accompanied by heavy rainfall. On the other hand, 'dry' dustfalls are not unknown, the best example being that of 1903 when huge volumes of dust fell with no simultaneous rainfall. In more northerly regions of Britain where rain was recorded there was, conversely, no dust. George (1981) has noted a more recent, though less intense, dry dustfall in January 1981. Light or moderate rainfalls are the most probable accompaniment, with the dust coming to earth within the raindrops either as nuclei or acquired by collision. But the possibility of dry dust descent coincident with the falling rain cannot be excluded although it might be difficult to detect.

3. The dustfall of 1984

A number of attempts, generally assuming isentropic motion, have been made to reconstruct the trajectories of dust clouds (Mill and Lempfert 1904; Stevenson 1969; Tullett 1978, 1980; Pringle and Bain 1981). Using these data Fig. 1 was prepared. The trend of the inferred movements reveals a

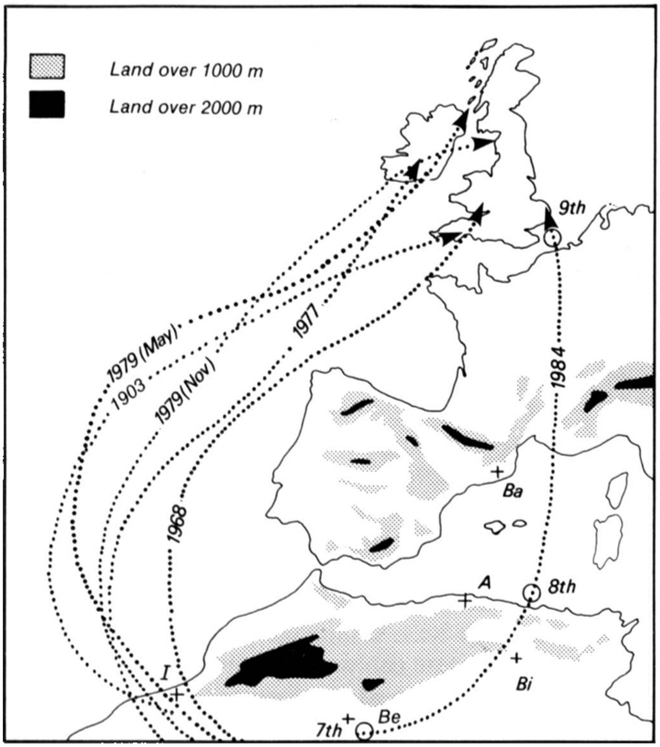


Figure 1. Summary map of Saharan dust cloud trajectories. The evidence of dustfalls before 1984 was obtained from items cited in the text. Place name key: Ba — Barcelona, Be — Béchar, Bi — Biskra, I — Ifni.

consistent pattern very much in accord with the airflows that might be interpreted from Table I. Such a concentration of pathways goes far to explain the relatively high incidence of dustfalls in Ireland and south and west England. But east coast falls are not unknown as Pitty's (1968) study shows. Nevertheless, the fact that the fall of November 1984 was so intense and localized to eastern districts suggested immediately that something unusual had taken place.

The reported intensities of the dustfalls showed south-east England to be most seriously affected with levels of activity decreasing northwards towards the Scottish border, although the author has received a report from as far north as Aberdeen (Dr D. C. Bain, Macaulay Institute, personal communication). An analysis of both the mineralogy and particle-size distribution of the material has shown it to be remarkably consistent with earlier falls and to support the theory of a Saharan, and certainly arid, source region (Wheeler, in press). The principal contrast is meteorological. Bearing in mind the established links between anticyclonic systems and British dustfalls this most recent event stands out by its association with a low-pressure system.

An almost stationary low lay over the Bay of Biscay as early as 5 November but extended both northwards and southwards on the 8th into a more complex and latitudinally elongated feature (Fig. 2). Along its eastern flanks a deep southerly airflow persisted until the system finally degenerated *in situ* on the 10th giving more than sufficient time for the dust to accomplish its long journey from north Africa to Britain.

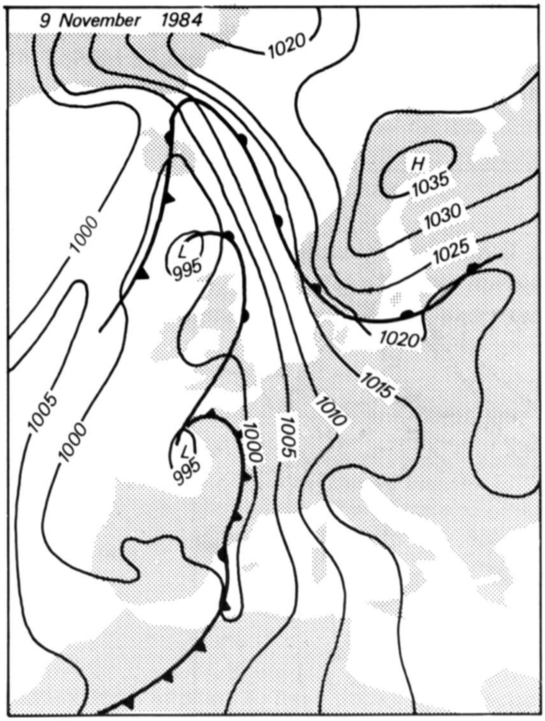


Figure 2. European synoptic chart for 1200 GMT on 9 November 1984.

The mechanism for introducing the dust into the atmosphere can only have been by dust storms through their associated turbulence. The information contained in the European Meteorological Bulletin was used to determine the possibility of any dust storms over north Africa in the days preceding

9 November. Meteorological stations are inevitably scarce in that inhospitable region but a general impression of conditions at the time can be reconstructed from the few data available.

The record for the Algerian station at Béchar (31° 37′N, 2° 14′W — see also Fig. 1) is most informative. Dust, in suspension but not raised by local winds, was reported at 1200 GMT on 6, 7 and 8 November. Meanwhile dust, this time due to local winds, was reported at 1200 on 5th and at 0000 on 7, 8 and 9 November. The last record was the final one during that spell of disturbed weather. Biskra (34° 48′N, 5° 44′E), some 600 km to the north-east but also south of the main Atlas mountain ranges, recorded locally-derived dust at 1200 GMT on the 9th. Perhaps most important, no other Saharan stations made any similar reports. Tamanrasset (22° 47′N, 5° 31′E) in the Ahaggar mountains, In Salah (27° 12′N, 2° 28′E) and Agadès (16° 58′N, 7° 59′E) all to the south of Béchar and more firmly within the Saharan domain remained seemingly unaffected. Other dust reports are far scattered. One was from the Niger valley east of Timbuktu where the river swings in its great penetrating curve into the southern Sahara. This appeared on the returns for 0000 GMT on 8 November and may have no strong connection with events on the opposite northern side of the Sahara. A further dust storm report was made from Ifni (on the Moroccan coast) at 1200 GMT on 8 November.

Two further reports, but of non-locally raised dust, are worth noting; they are for Algiers at 0000 GMT on 9 November and Barcelona at 1200 on the 8th. The latter is especially interesting and may represent a confirmed European sighting of the dust cloud on its northwards passage to Britain. If so, it remains the only such report until the eventual fall of the dust in northern Europe. The local winds at the time were east by south and could therefore have been drawing in air from a major dust concentration to the east.

On the basis of this evidence dust storms appear to have been localized within a possibly large area immediately to the south of the Atlas mountains which included within its limits the town of Béchar. From this source area the dust found its way towards Britain.

The surface isobars shown in Fig. 2 quickly convey the suggestion of a possible pathway for the dust cloud. But middle and upper troposphere winds provide a more reliable impression. Fig. 3 shows the 500 and 700 mb surfaces over the probably critical period between 7 and 9 November and both confirm the preliminary inference drawn from the surface charts, namely that the dust moved northwards along the low's eastern flanks. Starting from the north Saharan source region, the subsequent path involved negotiating the Atlas mountains, crossing the western Mediterranean, France and Belgium before reaching Britain. This trajectory is shown in Fig. 1 in which its distinctive character stands out clearly. The reconstruction is based on geostrophic wind patterns between 500 and 700 mb.

Both Stevenson (1969) and Tullett (1978) have presented good evidence for dust sources in the central Saharan regions in their respective studies of British dustfalls. In this case such southerly sources are improbable and a more northerly Saharan region is favoured. The geographical spread of the dust storms and the west to east geostrophic winds over the Sahara support this hypothesis even allowing for the incomplete nature of the evidence.

Isentropic analysis has not been attempted. Petterssen (1940) asserts that isentropic contours are often parallel to nearby fronts from which their orientations may be inferred. Given, therefore, the north to south alignment of the fronts within the low-pressure system no great differences between isobaric and isentropic trajectories were anticipated.

The dust storms were active over a period of several days between 5 and 9 November. The difficulty of not knowing the exact date on which the dust that reached Britain started on its journey can be tentatively resolved by examining wind speeds along the proposed trajectory. By working backwards from the known arrival time, which was early on the afternoon of 9 November in south-east England, some of the imprecision can be removed. Table II lists the average wind speeds at different levels over the period from 7 to 9 November. Although winds were increasing slowly throughout this time the

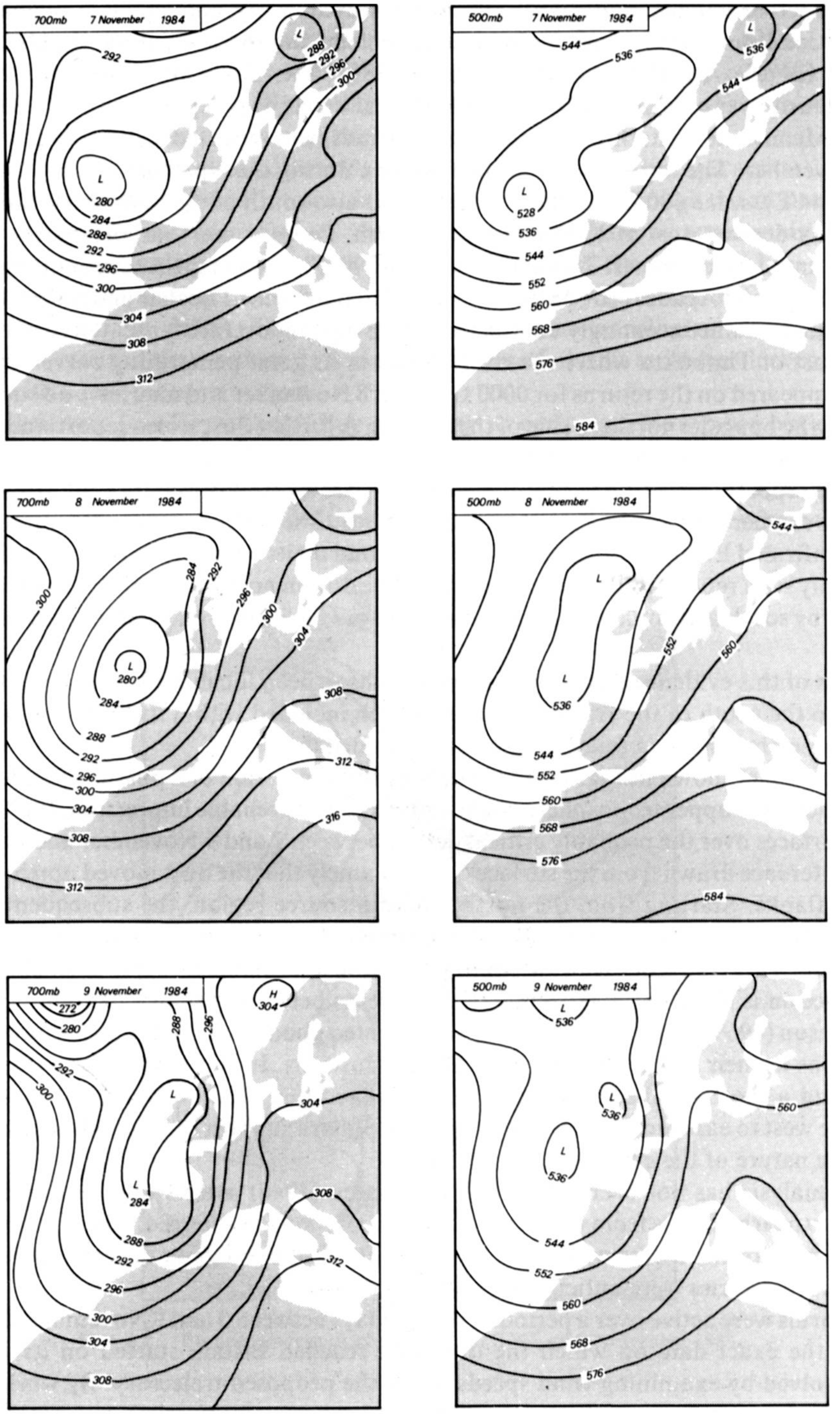


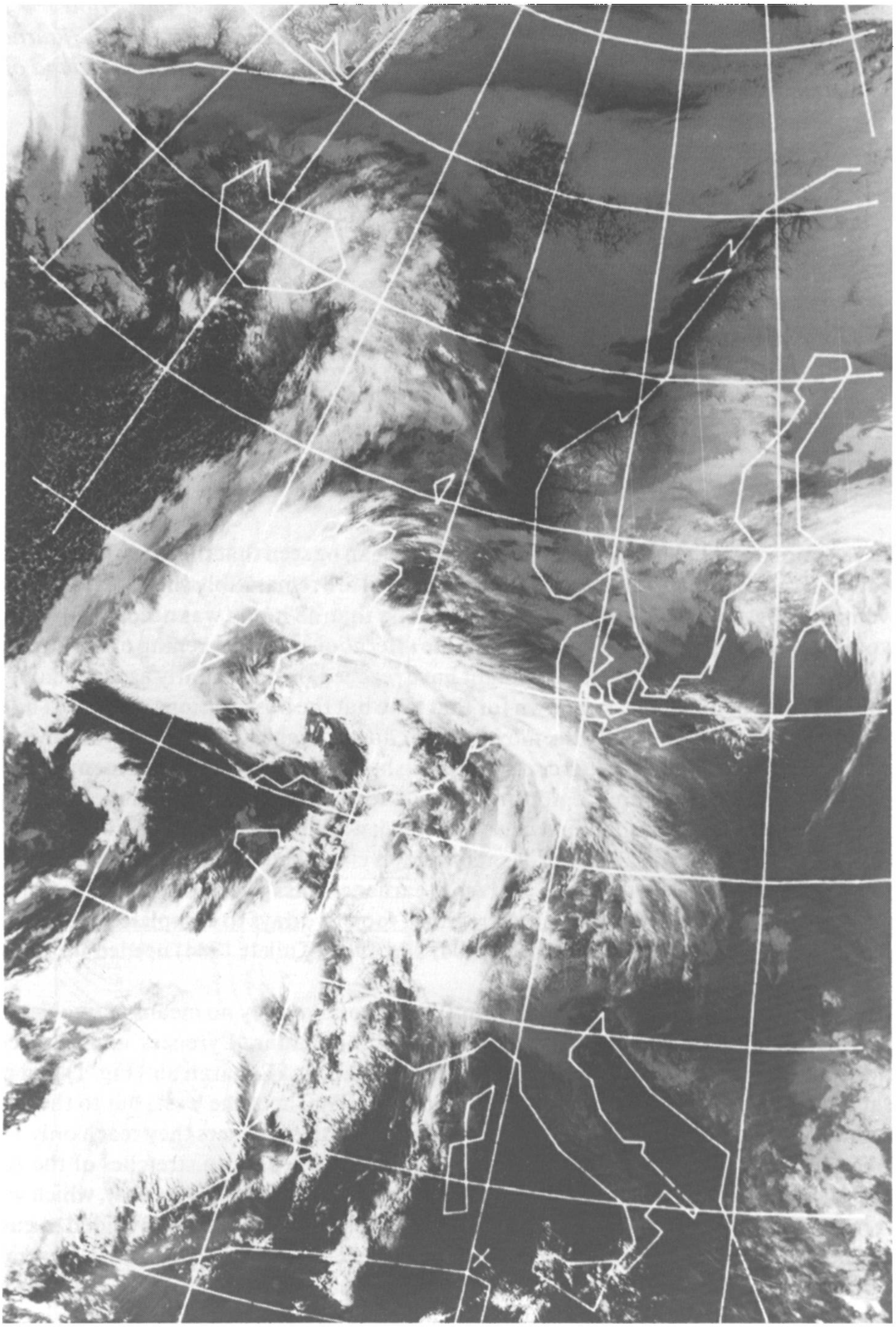
Figure 3. Compilation figure for the 500 mb and 700 mb surfaces at 0000 GMT on 7, 8 and 9 November 1984. The contours are marked in geopotential decametres.

Table II. *Average wind speeds (in knots) at different pressure levels over the period 7–9 November 1984 along the supposed trajectory of Saharan dust. The time taken to complete the journey is based on the average speed and a distance between the source region and south-east England of 2600 km. Data source: European Meteorological Bulletin.*

	Pressure altitude (mb)				
Date	1000	850	700	500	300
7 November	12	24	31	35	50
8 November	12	31	31	34	50
9 November	10	34	38	43	50
Mean	12	29	33	37	50
Time (hours)	116	46	43	36	27

day-to-day variation was slight. Using this information it can be seen that the times required to cover the 2600 km between the source region and south-east England are remarkably short. Assuming, initially at least, movement at between 500 and 700 mb a time of less than 48 hours was needed. On that reasoning the dust would have started its passage during the late afternoon or early evening of the 7th. If, however, some of the dust travelled at a higher level it might have reached Britain as early as the evening of the 8th. No confirmed reports of dustfalls are known for that time but the observations made by Thomas (1985) leave the possibility open. Conversely the movement of dust at high level would have allowed even later start times. In view of the developing configuration shown in Fig. 3 and the manner in which the apparent connection between source region and Britain becomes clearer towards the 9th this possibility should remain in contention. Dust, it should be remembered, was still crossing the Algiers area at 0000 GMT on the 9th. Whatever the precise timings of events were it is clear that the dust's movement was extremely rapid and in complete contrast with the record from earlier events. The dustfall of March 1977 (Tullett 1978), although originating in central Saharan regions, took five days to complete its marginally longer journey. The dust of 1903 (Mill and Lempfert 1904) and 1983 (Tullett 1984) needed four days to reach Britain.

Despite the speed with which the dust moved in 1984 its route was by no means as unobstructed as the oceanic pathway more commonly followed. The Atlas mountains, Pyrenees and Alps combine to present a formidable barrier to low-level northwards movement of Saharan air (Fig. 1) and could exert influence at higher levels. The Atlas mountains rise to over 3900 m in the west, but to the north-east of Bêchar they decline to a more modest 2100 m, while to the south of Algiers they reach only 1600 m. The winds implied in Fig. 3 provided a convenient passage over these eastern stretches of the Atlas range. Once into the Mediterranean basin the route is unimpeded as far as the French coast, which was possibly crossed over the area around the Rhone delta. Here the Alps and Pyrenees are avoided to east and west respectively as the winds draw the dust northwards over the Rhone valley. The Massif Central lies along this route but reaching only 2100 m is unlikely to have caused much disturbance. Thereafter northern France, Belgium and Holland offer no obstacles. The trajectory hypothesized in Fig. 1 is based on the pattern of geostrophic winds. However, it also has the distinct advantage of avoiding the high ground between Britain and Africa and therefore strengthens the arguments in its favour. Evidence of dustfalls on the 9th in Belgium also supports the detailed reconstruction.



Photograph by courtesy of University of Dundee

Figure 4. NOAA-7 infra-red image taken at 1453 GMT on 8 November 1984 showing what might be the Saharan dust cloud stretching northwards over the western Mediterranean from the Algerian coast towards southern France.

4. Conclusions

The evidence offered above provides a consistent impression of the circumstances surrounding the dustfall of November 1984. The detailed pattern of the hypothesized trajectory is not in perfect accord with the character of the upper winds but the agreement is close enough not to cast any serious doubt on the issue. Unfortunately the degree of cloud cover during the events makes visual identification and confirmation of the trajectory from satellite images impossible. Nevertheless, Fig. 4, taken on 8 November, reveals what could be the dust over an otherwise clear western central Mediterranean. If this interpretation is correct it gives further substance to the arguments put forward in this paper.

It would appear, finally, that anticyclonic systems, despite the weight of earlier evidence, do not enjoy a monopoly in transporting airborne material over great distances. Given the correct circumstances low-pressure systems appear to be equally capable of accomplishing this task.

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551.558.21:551.576.1(411.3/.5)

Unusual wave clouds over northern Scotland

By J. N. Ricketts

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Summary

On 19 February 1984, wave clouds were generated at a considerable height over the Grampian Highlands of Scotland, showing up clearly on infra-red satellite pictures. In this article, the appearance of the wave clouds and accompanying low-level rotor effects at a station in the lee of the mountains in described. The radiosonde ascent considered representative of the airmass producing the wave motion is examined and theoretical consideration is given to the likelihood that wave enhancement occurred as a result of interaction between the original wavelength generated and the separation between downstream ridges.

Introduction

Wave-type clouds occur relatively frequently over Scotland and are only mentioned in the remarks columns of observations books if they are spectacular or are in some way unusual. Sunday 19 February 1984 provided a display which fell into both categories. The clouds were evident long before daylight since they formed at high levels and could be clearly seen on the NOAA-7 infra-red satellite picture taken at 0345 GMT (Fig. 1(a)). The evolution of the cloud pattern could be followed throughout the day, until it became disorganized by the evening. Comparison of this picture with two taken at 1519 GMT (Figs 1(b), 1(c)) shows that the relative positions of the clouds changed little and none developed more than a few kilometres downwind of the coast of northern Scotland. The later pictures show 'ice-streamers' downwind of the wave clouds at higher levels. By contrast, wave development within the frontal cloud which crossed Northern Ireland and the Hebrides was more regular and extended for several hundred kilometres downstream of the point of origin.

Synoptic conditions, geography and their effects

The surface synoptic charts for 0000 and 1200 GMT on 19 February over the British Isles are shown in Fig. 2. A large anticyclone over western Russia dominated the situation and the progress of the cold front across the Western Isles became slower. Gradient winds across the Grampian Mountains were 50–55 kn during the morning and early afternoon.

The Grampian Mountains are set in a series of ridges which face a little east of south, all within a broad plateau which is higher than 200 m above sea level. In the south, the ground rises steeply above Strathearn and Strathmore while the descent northwards from the Cairngorm and Monadhliath Mountains is more gentle. The distance between adjacent ridges is generally around 35–40 km.

The radiosonde station at Shanwell is situated near the coast just south of Dundee and was upwind of the Grampians on this occasion, so ascents from there would have been representative of the airmass crossing the mountains. The 00 and 12 GMT ascents are shown in Fig. 3, and the profiles of wind components from 160° at 00, 06, 12 and 18 GMT in Fig. 4. Actual wind directions were close to 160° at all levels, but slowly backed throughout the day with a gradual decrease in speed in the afternoon. The midnight ascent shows two marked inversions, whereas the midday ascent is noticeably cooler and drier below 400 mb, the higher inversion having become an isothermal.

Observations from the Meteorological Office at RAF Kinloss indicate the effects of the synoptic conditions from a position to the lee of the mountains. The anemograph trace (Fig. 5) shows frequent large changes in wind speed, particularly in the afternoon, and occasional wild fluctuations in direction. These wind variations are associated with rotors reaching the surface. Another characteristic of rotors is

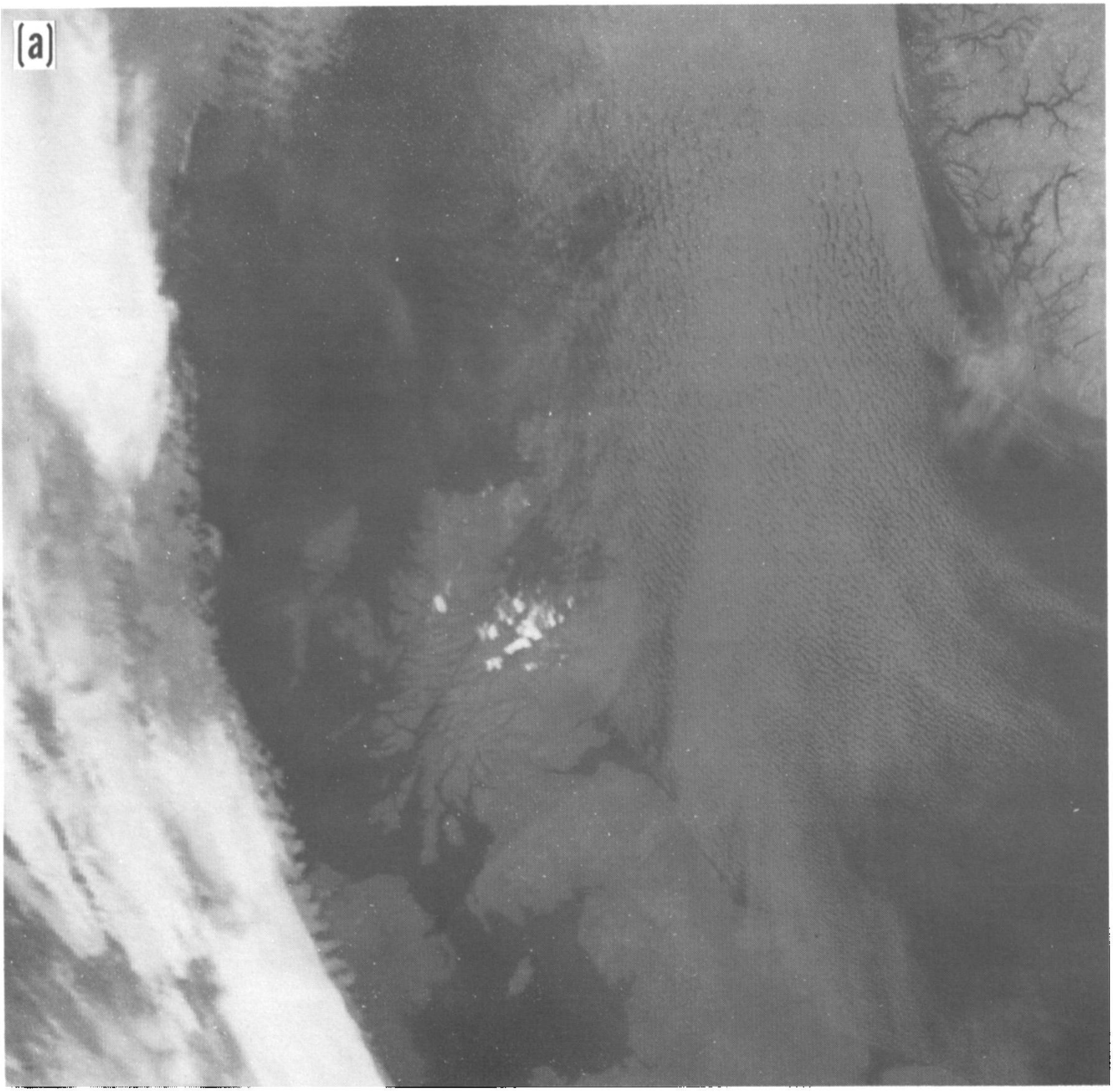

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Figure 1(a). NOAA-7 infra-red image, 0345 GMT 19 February 1984.

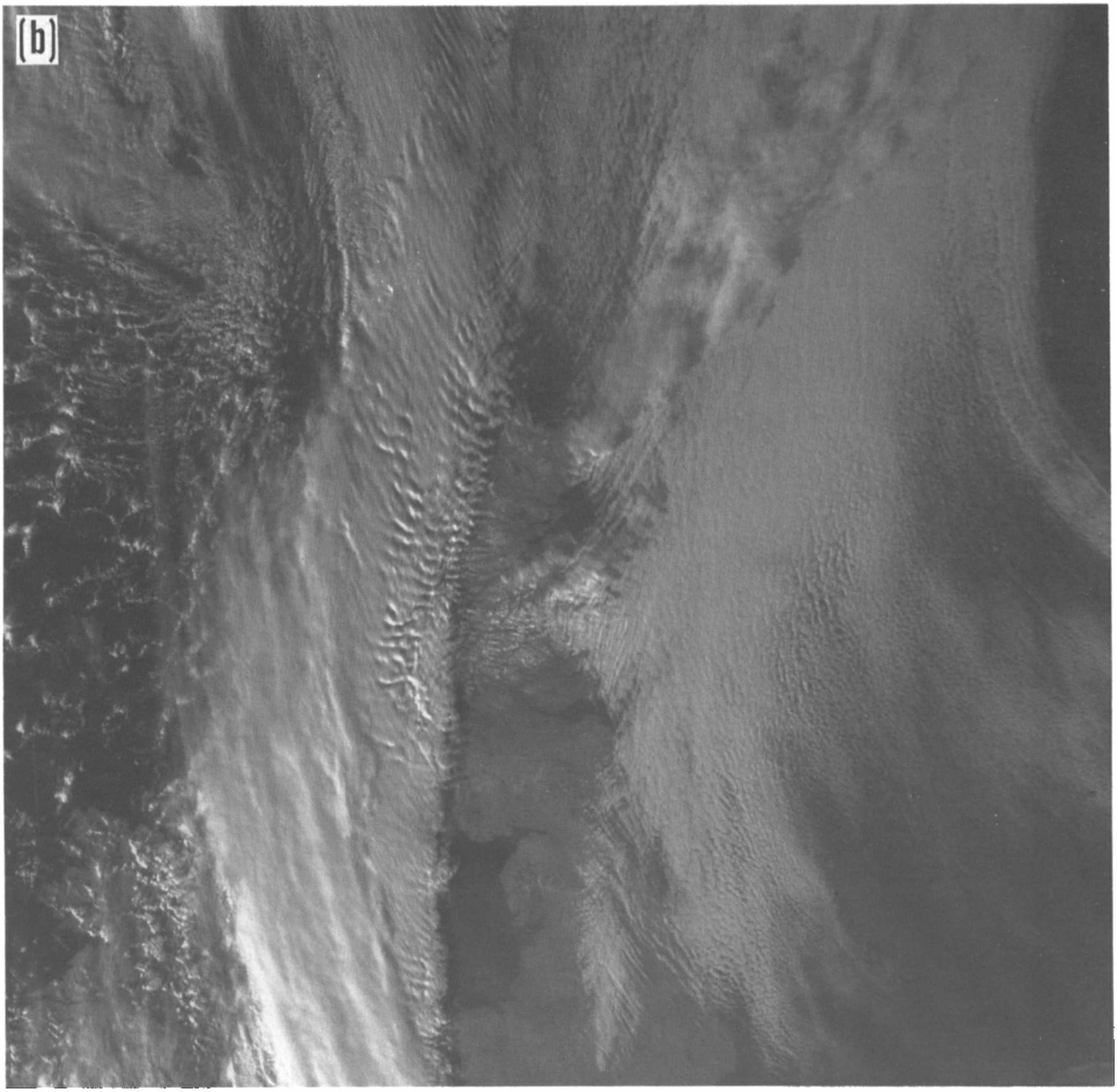

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Figure 1(b). NOAA-7 visible image, 1519 GMT 19 February 1984.

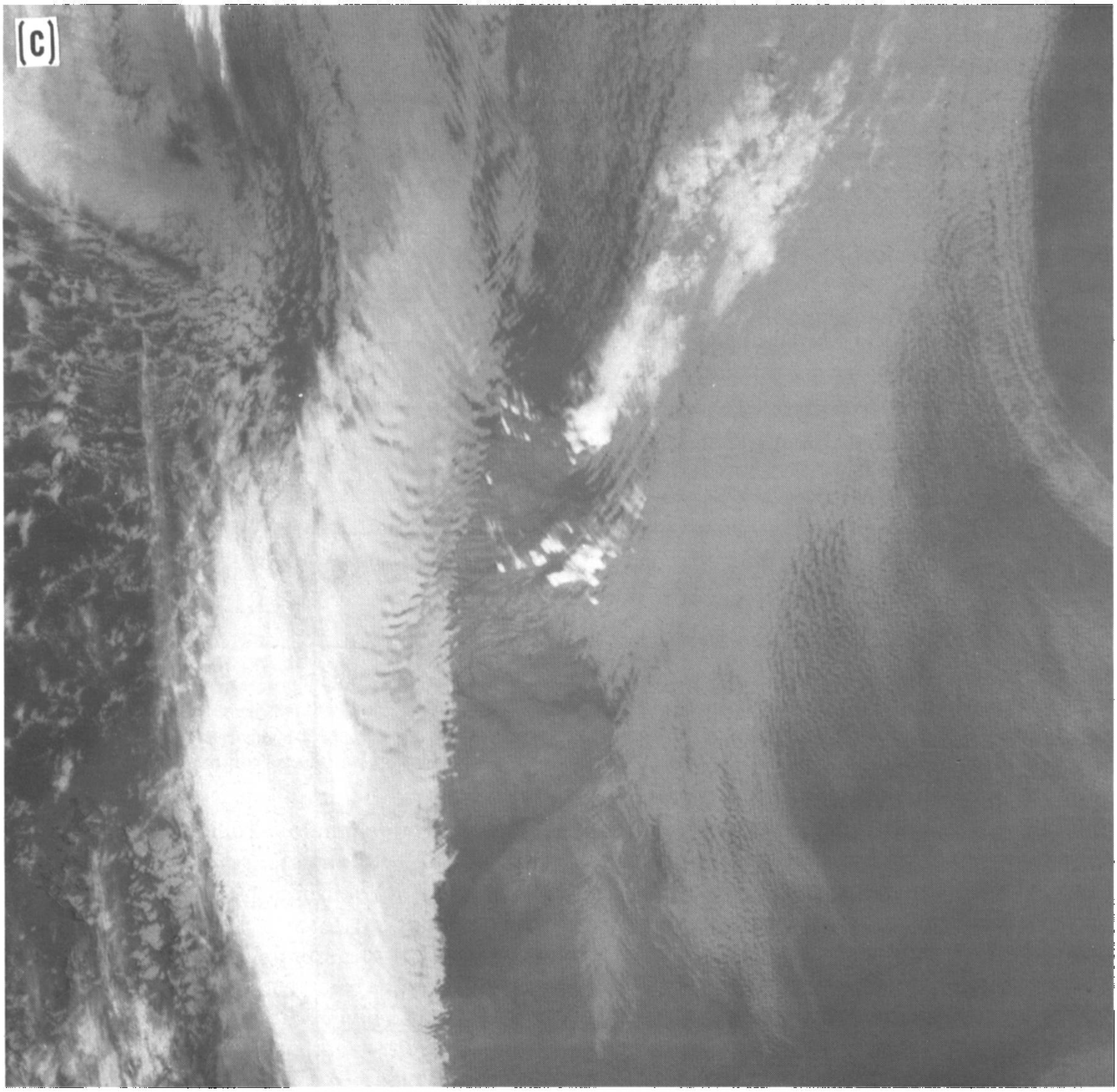

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Figure 1(c). NOAA-7 infra-red image corresponding to Fig. 1(b).

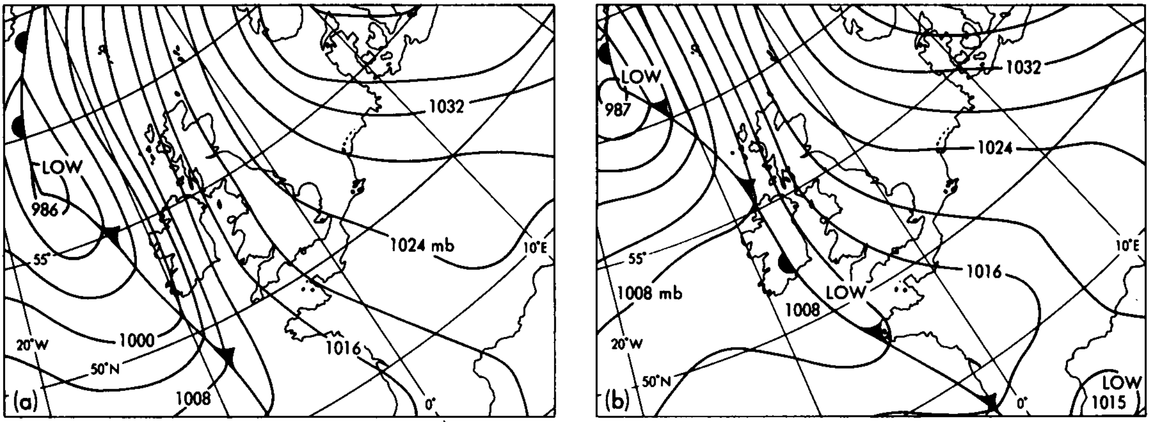

Figure 2. Surface synoptic situation on 19 February 1984 (a) at 00 GMT, (b) at 12 GMT.

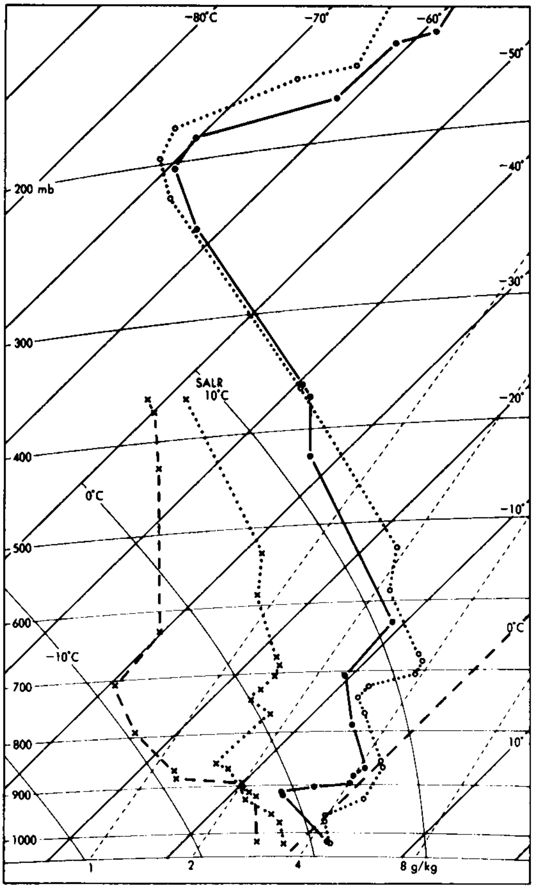

Figure 3. Radiosonde ascents made at Shanwell on 19 February 1984: the dotted lines show the 00 GMT ascent, and the solid and dashed lines the 12 GMT ascent.

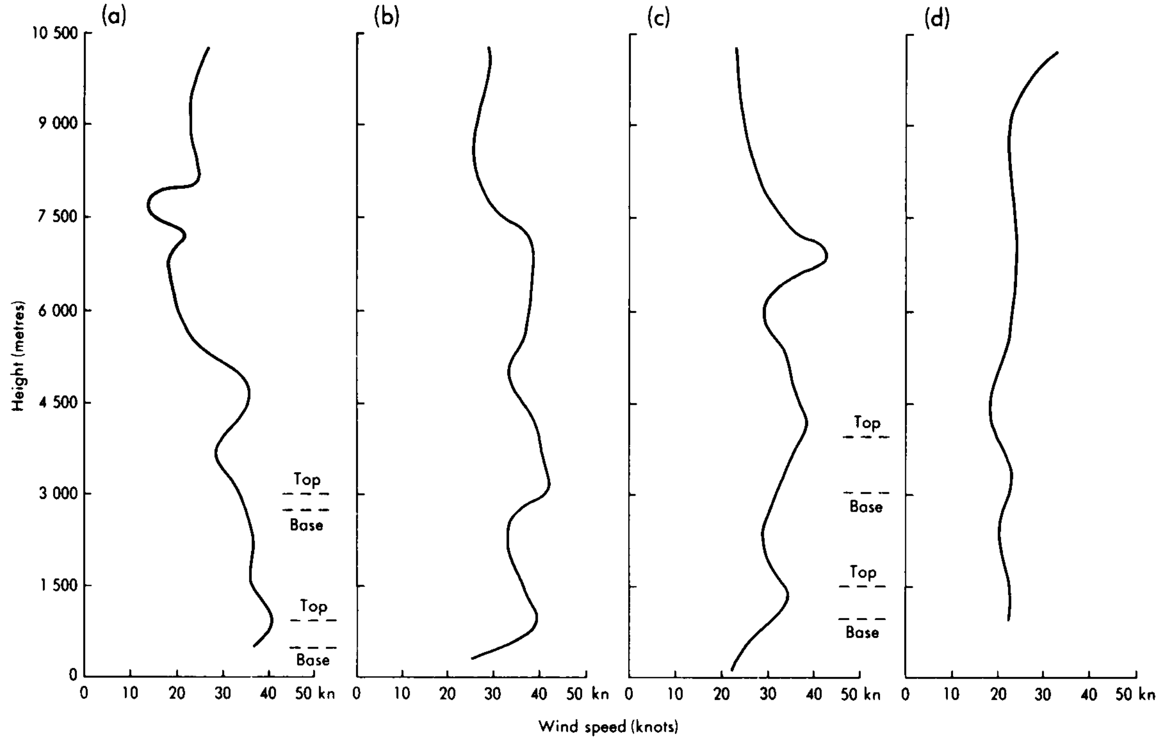

Figure 4. Wind profiles from 160° at Shanwell on 19 February 1984: (a) 00 GMT, (b) 06 GMT, (c) 12 GMT and (d) 18 GMT. The base and top of inversions are indicated on the midnight and midday ascents.

indicated in the remarks column opposite the 1100 GMT observation with the note 'wind on east side of airfield much stronger... (mean 20—25 kn?)'. The mean wind speed reported at the office was 14 kn. The conditions were also responsible for significant fluctuations in the barograph record.

Rotor clouds were evident for much of the day, appearing like cumulus which drifted slowly northwards before dissipating over the Moray Firth. Wave clouds were reported as altocumulus lenticularis with estimated base ranging from 3600 m (12 000 ft) to 4800 m (16 000 ft) and were described as 'well developed' at the 0900 and 1300 GMT observations. The 1400 GMT observation made mention of rotor cumulus, strong mock suns and 'lenticular cloud... at cirrus levels...'. Further remarks mentioned lenticular cloud to the south-west and the west, which is consistent with the satellite pictures. Also, a crew member from an aircraft which had landed at about 1330 GMT came in to the meteorological office to report that the cloud tops were 8400 m (28 000 ft) but wave motion was detectable in clear air up to 10 500 m (35 000 ft).

Theoretical discussion

Observational and theoretical studies have shown that when the air mass is stable a strong wind in a direction approximately normal to a long ridge is likely to produce wave motion over and to the lee of the ridge. Should there be further ridges beyond, the character of the wave motion will also be affected by them, depending on whether the atmospheric wavelength is in phase or out of phase with the separation between the ridges. Wave clouds may also be associated with conditionally unstable air overlying stable air of considerable depth (World Meteorological Organization 1960). This is broadly

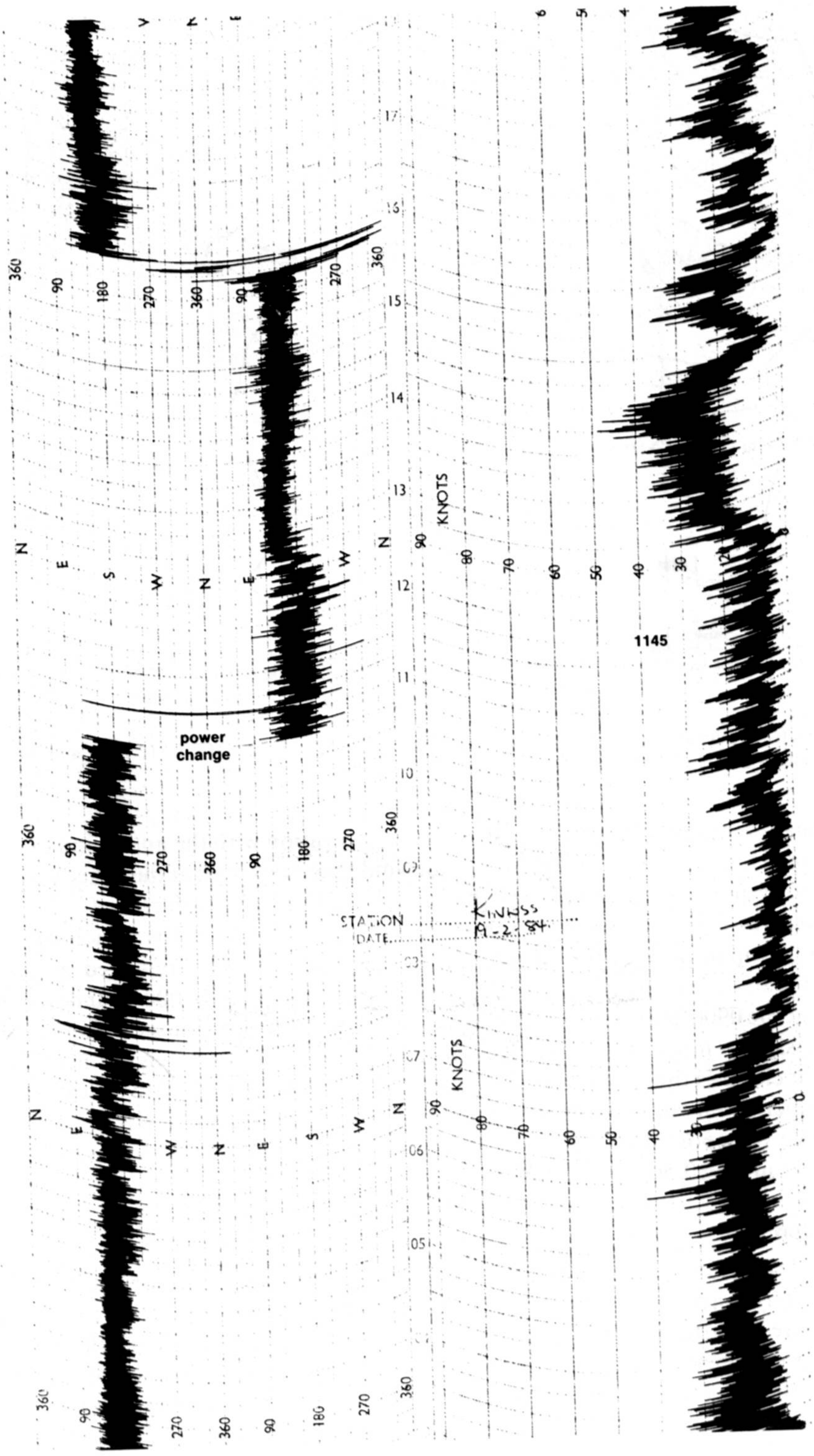

Figure 5. Anemograph trace from Kinloss, 03 to 18 GMT 19 February 1984, showing fluctuations in wind speed and direction associated with rotor effects.

shown by the midnight ascent at Shanwell. Lifting in the upper layers could lead to condensation at approximately 4200 m (14 000 ft), although above this level condensation is possible to a considerable height given sufficient vertical displacement. The midday ascent appears considerably less favourable for wave development.

A relatively simple if basic method of calculating the wavelength produced is given by Casswell (1966). Two sets of waves may sometimes be generated, depending on the depth of atmosphere that is favourable. Using the data from the Shanwell ascent for midnight on 19 February, the calculated wavelengths of the primary and secondary waves are given in Table I. Both values are approximate multiples of the distance between the ridges, and consequently wave enhancement might be expected. The wavelengths calculated from the midday Shanwell data are also given in Table I and in this case the secondary wavelength is out of phase with the ridge separation. This could explain why the higher level wave clouds tended to become more diffuse during the day. The vertical velocity values are appreciable if not extreme while the heights at which they occur are such that the maximum for the primary wave is within the higher inversion at midnight (although not at midday) and the maximum for the secondary wave is at the reported height of the cirrus clouds.

Table I. *Calculated wavelengths and vertical velocities in mountain waves — from Shanwell ascents on 19 February 1984*

	Primary waves			Secondary waves		
Ascent	Wavelength km	Maximum vertical velocity $m\ s^{-1}$	Height of maximum km	Wavelength km	Maximum vertical velocity $m\ s^{-1}$	Height of maximum km
00 GMT	9.3	5	2.8	12.5	3	7.5
12 GMT	9.2	6	2.4	15.5	7	7.5

Turbulent conditions and comparison with a similar synoptic event

Surprisingly, there were no reports of low-level turbulence from aircraft operating in the vicinity. By contrast, there were several reports the following day when conditions were not favourable for wave development and low-level winds were rather less strong.

It is interesting to compare this occasion with a similar synoptic situation on 21/22 January 1984. No wave clouds developed and examination of the Shanwell wind profiles from 1800 GMT on the 21st to 0600 GMT on the 22nd showed a marked wind veer above 3000 m (10 000 ft), which prevented wave development above that level.

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The Meteorological Office at Stonehouse 1939–45

By R.P.W. Lewis
(Meteorological Office, Bracknell)

Summary

An account is given of the move of the Climatological, Instrument, and Marine Divisions to the buildings of Wycliffe College at Stonehouse, Gloucestershire after the declaration of war in 1939. Reminiscences of official and leisure activities have been provided by several retired members of Meteorological Office staff who worked there between 1939 and 1945.

Introduction

Although certain aspects of the work of the Meteorological Office during the Second World War have been described in print, for example by Bilham (1947) and Scrase (1947), there exists no general account which gives due place to social upheavals and personal reminiscence. The official history (hereafter referred to as OH), issued as a classified document in 1954 by the Air Historical Branch of the Air Ministry and declassified only in 1975, although it contains much valuable information, is in many respects very dull to read. For example, the conventional anonymity of civil servants is rigidly preserved so that the only actual name to appear is that of Sir George Simpson who came back from retirement to look after the Observatories.

Various aspects of the move of the Climatological, Marine and Instruments Division of the Office to Stonehouse in November 1939, and the work that they did, are described in OH, but the accounts are scattered throughout the volume and no idea is given of the conditions of working of the staff and how they entertained themselves during the period of nearly six years that they were there; the present article is an attempt to fill this gap, at least partially. The author could not have written it had it not been for the readiness of many of the surviving wartime exiles to search their memories and put pen to paper. The chief regret is that all those who occupied senior positions at Stonehouse are no longer alive — Dr Goldie, Dr Scrase, Dr Glasspoole, Dr Brooks; they, no doubt, could have said much about their administrative worries and the fight to obtain adequate shares of scarce resources of manpower and equipment. For example, a file preserved in the Public Record Office demonstrates how Dr Scrase could not afford to divert staff to make the inventory checks demanded by the auditors because that would have meant failing to get the equipment to where it was urgently needed by Meteorological Office units in the battle zones.

Historical background

During the 1930s, the growing menace of the Fascist and Nazi dictatorships became more and more apparent and by 1936 a program of rearmament was embarked on by the United Kingdom Government, including of course an expansion of the Royal Air Force which would in its turn require increased meteorological support. The Meteorological Office began to grow and, for the first time, systematic training was given to new entrants. By 1938, thought was also being given to wartime dispersal of the Meteorological Office to a location or locations in the provinces, and initial planning was put in hand for a move of the Central Forecasting Office and telecommunications centre from Victory House, Kingsway to Dunstable, Bedfordshire, and of the rest of the HQ establishment from South Kensington to Southport. Early in 1939, the proposed site for South Kensington staff was changed to Tetbury, in Gloucestershire, but in the event the final choice fell on the buildings of Wycliffe College at Stonehouse, near Stroud (OH p. 31).

The move to Stonehouse

Wycliffe College is a Public School for boys founded in 1882 — though today some girls are taken as well — and the first intimation received by the Headmaster of the Government's decision to requisition his buildings in the event of war was contained in a letter from the Ministry of Works marked 'Very Secret' and delivered to him on Christmas morning, 1938 — probably the most unwelcome present he ever had. During the next few months he made arrangements for the accommodation of his school at St David's College, Lampeter, and on 7 September 1939, a few days after war had been declared, Air Ministry officials arrived at Stonehouse with a writ requisitioning all the school buildings save one or two occupied by the junior departments. The school was not to return until the war was over.

Meanwhile, Meteorological Office staff at South Kensington were told that they were going to be moved well away from London, but the exact destination was kept secret. During October and November, Commander Hennessey of the Marine Branch at Victory House visited the Stonehouse area with one or two colleagues to arrange emergency accommodation. Staff were told to have a bag packed ready for a move, and the books in the Library were all put into crates and boxes, the provision of which had been brilliantly organized by Dr Brooks (Glasspoole 1958). The move of the staff at South Kensington, and of the Marine Branch at Victory House, finally took place on 30 November, their destination being revealed only at the last minute.

Meteorological Office organization in wartime

Certain changes in the administrative structure of the Office were made following the declaration of war. On 1 September 1939, the Office was controlled by the Director (Mr N.K. Johnson, later Sir Nelson Johnson) and three Assistant Directors: ADMO I (R. Corless) in charge of M.O.1 (Marine), M.O.3 (Climatology), M.O.4 (Army and Instruments), M.O.10 (Personnel, General Services and Training School); ADMO II (E. Gold) in charge of M.O.2 (Forecasting and Civil Aviation), M.O.5 (Overseas) and M.O.6 (RAF); and ADMO III (A.H.R. Goldie) in charge of the Meteorological Office, Edinburgh and the Observatories. When war was declared, Sir George Simpson came back from retirement to take over the previous work of ADMO III, while ADMO III himself took charge of M.O.1, M.O.3 and M.O.4 (except as regards Army matters). On the move to Stonehouse, therefore, Dr Goldie was the senior officer on site, and remained so until the war was over. Subordinate to Dr Goldie were: as Marine Superintendent, Commander C.E.N. Franckom who went on active service in November 1940 being succeeded by his deputy, Commander J. Henessey; in charge of M.O.3, Dr C.E.P. Brooks; and in charge of M.O.4, Dr F.J. Scrase. In September 1939, the combined staff of M.O.1, M.O.3 and M.O.4 was a little over 100 and this increased to about 180 by 1945 (OH pp. 555–559).

Location of Branches at Stonehouse

The arrangement of the buildings of Wycliffe College, more or less as they were at the outbreak of war, is shown in Fig. 1. School House (Fig. 2) was occupied by M.O.3 (including the Library*), general administrative offices including receipt and despatch, and the kitchen and canteen. Dr Goldie was himself accommodated in School House, and occupied a room on the first floor. The Headmaster's room was for a time reserved for the Director in case he had to leave London, but was later used as an ordinary office.

Springfield (Fig. 3) was occupied by M.O.1 (including the Hollerith machines) and, at first, by M.O.4; later on, M.O.4 moved to Ryeford Hall (Fig. 4). When the new development section of M.O.4 was set up

* The Library in School House contained, it seems, only the most commonly used books and journals, the bulk of the reserve stock being located some 15 miles away in Cirencester. The room used was the 'Old Assembly Hall' which Wycliffe College themselves converted into a library in 1964.

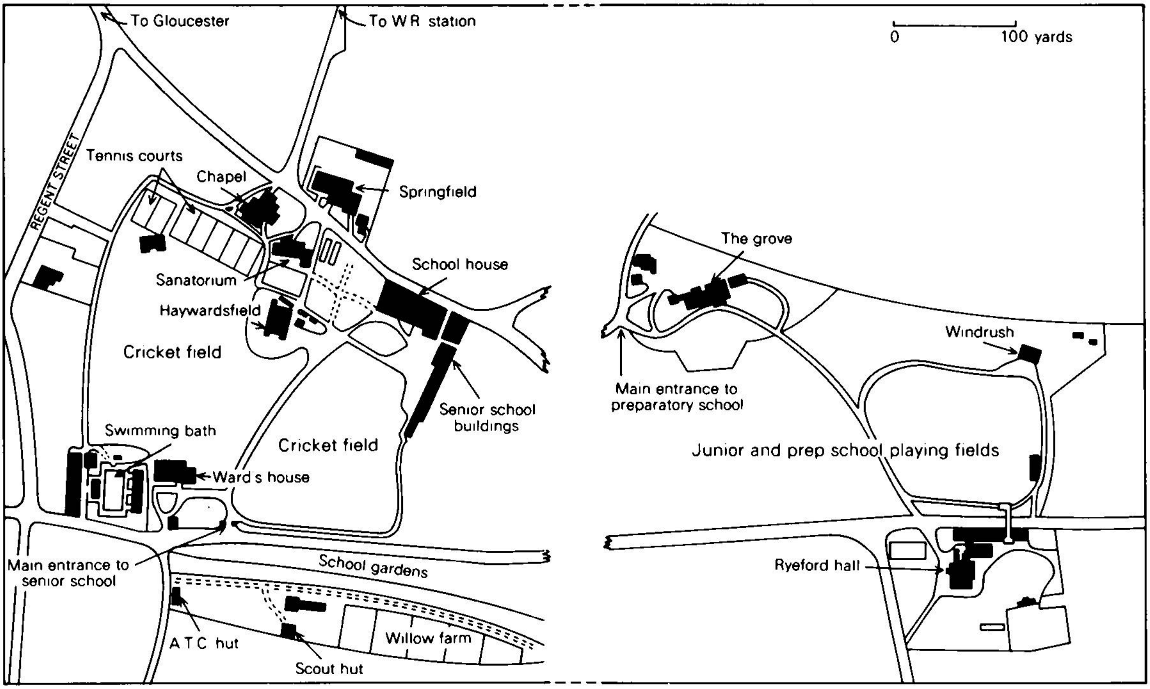
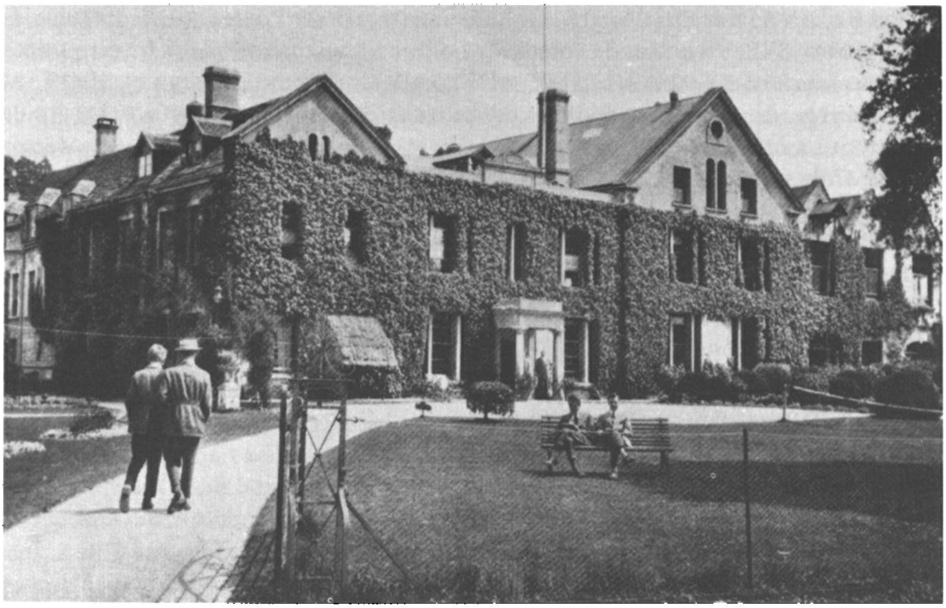
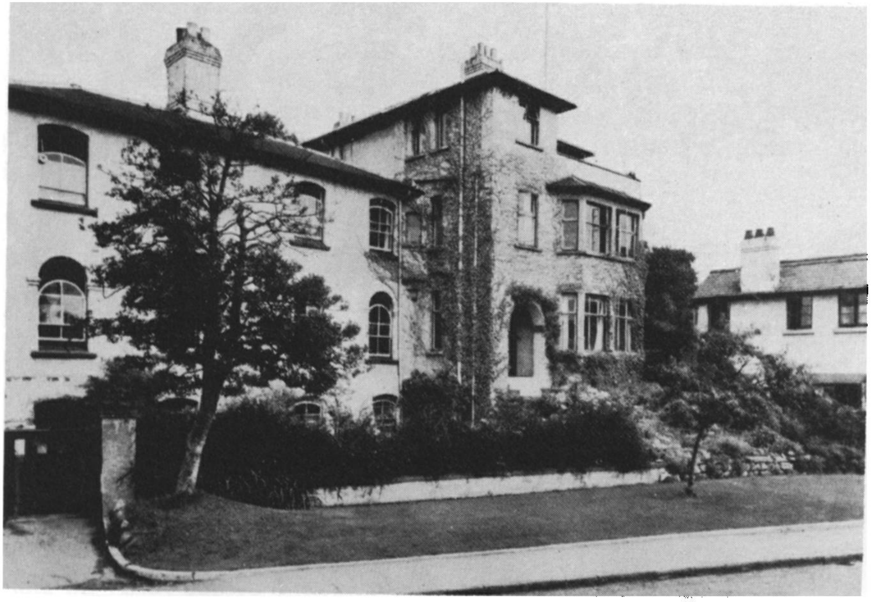


Figure 1. Location of the buildings of Wycliffe College, Stonehouse, late 1940s. (Copied by permission of the Headmaster and Governors from a plan in a school prospectus issued in 1950.)



Photograph by courtesy of the Headmaster and Governors of Wycliffe College.

Figure 2. School House, Wycliffe College.



Photograph by courtesy of the Headmaster and Governors of Wycliffe College.

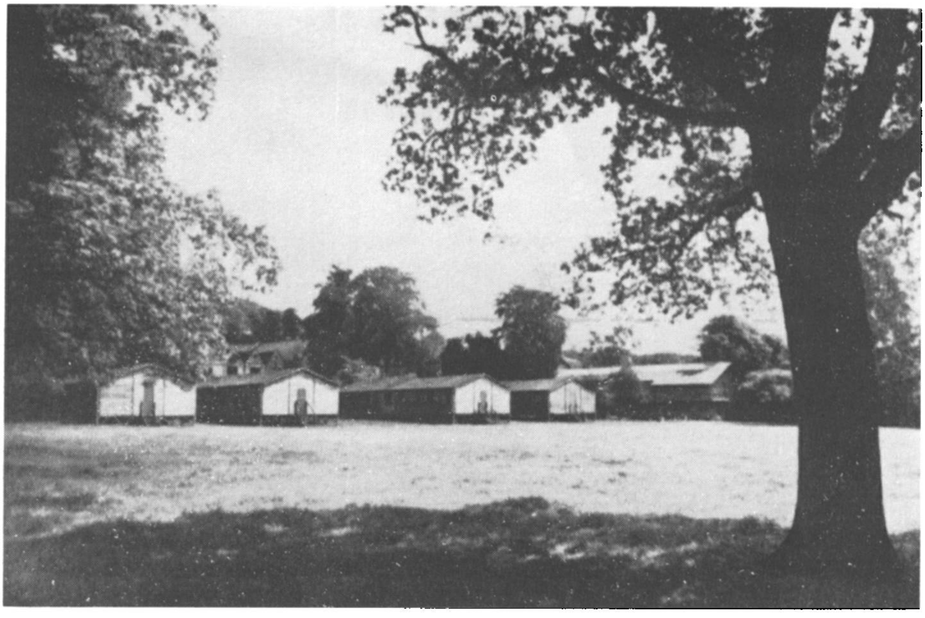
Figure 3. Springfield, Wycliffe College.

Photograph by courtesy of the Headmaster and Governors of Wycliffe College.

Figure 4. Ryeford Hall, Wycliffe College.

Photograph by courtesy of the Headmaster and Governors of Wycliffe College.

Figure 5. The Science Building, Wycliffe College.



Photograph by courtesy of the Headmaster and Governors of Wycliffe College.

Figure 6. Huts erected on Wycliffe College cricket field to provide extra offices for Air Ministry staff.

as a separate unit in 1942 (to become M.O.16 some years later at Harrow) it occupied the Science Building (Fig. 5).

As well as the Meteorological Office, some Air Ministry Finance Branches were accommodated at Wycliffe; initially they occupied Ryeford Hall, later taking over Haywardsfield and the Sanatorium and also erecting a group of wooden huts on the cricket field (Fig. 6); this last development understandably horrified the school on their return in 1945.

Work

The work carried out by the staff of the various Divisions stationed at Stonehouse was in part a continuation of their pre-war activities but also, and in much greater degree, a response to wartime demands. The Climatological Division continued to collect and tabulate British climatological data and to give advice to specialist customers such as water authorities, but publication of series such as *British Rainfall* and the *Monthly Weather Report* was postponed until the war was over. Publication of the *Meteorological Magazine* ceased after the fall of France. An important part of the Division's work was the writing of Naval Handbooks on Weather dealing with the main theatres of war. The greatly increased volume of enquiries concerned with strategical planning and tactical execution of operations by the RAF and the Army caused difficulties, exacerbated by the removal of the main Library to Stonehouse, and it was found necessary to set up a special section — the Investigations Branch — at London HQ which would liaise with the RAF and Army on the one hand, and with Stonehouse and Dunstable on the other. There were regular visits by appropriate people from Stonehouse to the Naval Meteorological Branch and the new Investigations Branch (OH pp. 518—520). The Library also helped to answer questions from, and supply data to, many other Government departments, and the annual total of loans increased tenfold (OH p. 531).

The Marine Branch lost their regular supply of data from British ships, except those of the Royal Navy, on the outbreak of war because of an embargo placed by the Admiralty on the recording of positions, but liaison was maintained with merchant ships so that full reporting could be resumed as soon as conditions allowed. The main wartime work of the Branch was the preparation of climatological, sea current and ice atlases which were urgently required for operational purposes (OH pp. 531—532).

The Instruments Branch (M.O.4) had the tasks of (a) supplying meteorological equipment to the Meteorological Office, the Naval Meteorological Service and (later) to the Dominion and Allied Services as necessary, and (b) developing new equipment and instruments. The task was immense, and total annual expenditure on meteorological equipment increased nearly thirty times compared with the 1929—1933 average. The factories of many of our suppliers suffered from bombing, and the fall of France temporarily cut off the supply of high-pressure hydrogen generators, stop-watches, and fusee chain (for aneroid barometers). Over 100 varieties of radio valves were required. Stores at Stonehouse were distributed over six different buildings, and temporary marquees were also needed; there was also an emergency reserve at Cheltenham. In 1941 it was found necessary to reorganize M.O.4 by creating three sections dealing with (a) all technical aspects (b) provision of equipment and (c) storage and issue, including accounting (OH pp. 565—570). Despite all difficulties, M.O.4 seems to have met the extremely heavy demands placed upon it with a high degree of success.

The Meteorological Office staff at Stonehouse returned to London in August 1945, but not to the South Kensington office which by then was too small. Instead, they went to another Government building near the Stationery Office establishment in Harrow which remained in use by the Office until the move to Bracknell in 1961.

Social life

Despite all the difficulties of wartime and having to live far from home in strange surroundings, the Meteorological Office staff at Stonehouse were able to live a full and varied life in addition to carrying out their official tasks. After the fall of France a number of the ladies set up a National Savings group and a knitting circle under the leadership of Miss M.E. Robinson (later to be Senior Cartographer at Harrow and Bracknell). Additional funds were raised from sporting events, concerts, and even a swimming gala. Staff played active roles in such general wartime activities as 'dig for victory' on rented allotments and took their turn at 'fire watching'. Several members helped to run a local hostel for servicemen on leave or in transit, and others joined first-aid groups. Later in the war, professional recitals sponsored by CEMA (Council for the Encouragement of Music and the Arts) were given in the school assembly hall; artistes included Astra Desmond, Herbert Sumsion and Joy Boughton. (It was important to ensure that the piano was properly tuned and correctly placed on such occasions.) Amateur musicians in the Office joined local choral and orchestral societies, as well as joining together to give amateur performances in the school, and in December 1943 a pantomime was put on entitled 'The Babes in the Wood: A Nightmare' by William Thykke Phogge (i.e. W.T. Hogg), featuring 'Dirty Weather with Two Cyclones', for which the music was directed by Gale Hardblow (i.e. Geoffrey Hartley).

A good picture of the way life appeared to those members of the Meteorological Office who worked there is given by the short collection of reminiscences in Appendix 1; some biographical details of the contributors are given in Appendix 2.

Summing up

The abiding impression produced either by reading reminiscences of the staff who worked at Stonehouse or by talking to them is that their wartime 'exile' was, on the whole, a happy one. Despite the difficulties of rationing and the black-out, and — for most staff — having to live in billets, there was a feeling that everybody was working hard for a common purpose; also, what was very important, people joined together to make their own entertainment, with tennis and swimming, choral and orchestral concerts, and dramatic performances. A member of the Meteorological Office who was not himself at Stonehouse has remarked that those who had been always seemed to be talking about it. Much of the credit for this must, of course, go to the senior staff at the time, and to none more than Dr and Mrs Goldie. As regards the contribution of the Goldies to the welfare of their staff, one cannot do better than quote the words of C.E.P. Brooks in his appreciation of Mrs Goldie written after her death in 1948:

'Most of the younger members [of the branches at Stonehouse] were billeted in strange homes, and Mrs Goldie invited them to tea on Sundays, sympathized with their troubles and generally mothered them. I recall with gratitude that in an emergency the Goldies gave me a home for a week, and the same kindness was extended to visitors from London who could not find hotel accommodation. When the canteen arrangements broke down and we decided to become our own caterers, the triumphant success of the experiment was largely due to the energy which Mrs Goldie put into it, in addition to the work which she was already doing in the British Restaurant at Stroud. In all these ways, the fact that our exile in Gloucestershire was on the whole pleasant and comfortable, was largely due to the efforts of Dr and Mrs Goldie to make it so.'

As to the rightful occupants of the buildings — the staff and pupils of Wycliffe College — it is probable that they suffered more inconvenience than the meteorologists did; the Headmaster had many worries and difficulties to contend with, not the least of which was the daunting task of putting the school buildings into some sort of decent shape ready for the return to Stonehouse in 1945. The centenary history of Wycliffe College records that for '... six weeks in September and early October a dozen masters with their wives, and twice as many boys, scrubbed floors and washed walls while local builders, carpenters and decorators repaired the damage'. (Financial compensation from the Ministry of Works was, of course, obtained later.)

Perhaps we may now, after forty years, pay some public tribute to our involuntary hosts.

Acknowlegements

As well as to the retired members of our own staff whose reminiscences are reproduced, or who are otherwise mentioned in the text, I should like to express my gratitude to the present Headmaster of Wycliffe College (Mr R.C. Poulton) and to Mr S.G.H. Looseley (Headmaster from 1947 to 1967) who have provided a wealth of valuable information including maps and photographs. Other photographs and useful information have been provided by Mrs Margaret Tunnell (née Shirley), Mrs Stephanie Smith (née Hart), and Mrs Helen Goldie (née Carruthers).

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Appendix 1 — *Reminiscences supplied by former Meteorological Office staff*

The following reminiscences are reproduced from the original texts submitted by the authors with the minimum of editing such as the elimination of redundant information, or removal of tentative statements offered on the basis of hazy memories which are known on independent evidence to be incorrect.

Miss E.E. Austin

Evacuation of the staff of the South Kensington branches of the Meteorological Office in 1939

(As remembered 45 years later so the details may not be reliable)

Just before the outbreak of war some (if not all) members of the staff were told that they must make arrangements to be able to get to the Office in any emergency and provision was made for some to sleep at the South Kensington offices (I don't think this lasted for more than a few days). The Office had cellars where the *Daily Weather Report* used to be printed but I never visited them (they accounted I believe for the fact that the underground passage from South Kensington Station, intended to go to the Albert Hall, stopped at the Meteorological Office) and I do not know where the staff were accommodated for the night.

We knew early on that we were to be evacuated but I was not myself responsible for making the arrangements except so far as the needs of my own work were concerned — I was working on Naval Handbooks at that time.

As far as M.O.3 were concerned the great problem was the Library on which much of their work depended. I think the method adopted was to stick a small red label on the books that were to be taken and though one or two may have fallen off I don't remember any difficulties arising. (Dr Brooks — with possibly Miss Sawyer were in charge.)

At some stage we were told to have a bag packed, presumably small enough to carry, with clothes for a week and rations for a day — but I'm rather vague about this.

After we had waited some weeks with no air-raids we all hoped to be at home for Christmas so the evacuation at the end of November was a great disappointment.

Two billeting officers (Cdr Hennessey of M.O.1 was one) had already visited Stroud and fixed up accommodation for us all in private houses. We were known I think as guinea-pigs as our hosts were paid a guinea a week to house us and give us breakfast and an evening meal with dinner on Sundays — we had our main meal at the canteen in the Office. The allowance must I think have been increased later — we did not pay it over ourselves.

On the day of evacuation we met (? at the Office or at Paddington) presumably on a special train or in reserved coaches. There had been strict secrecy as to where we were going but we knew by then that it was Gloucestershire.

On arrival we were taken to a hall somewhere in Stroud and given a 'pep' talk telling us how to behave as we were the first Civil Servants to be sent there! We were then put into single-decker buses, with windows blacked out I think, and with a billeting officer at the door we were dropped off one by one as we passed the house where we were to live, and presumably had to find our own way to Wycliffe College where the Office was situated.

M.O.3 and the Library were in the main school building and M.O.1 and M.O.4 were in neighbouring houses.

There was a canteen in the main building where we met for lunch and tea.

Office hours were ?9.0—5.0 but at one stage we were told that we were to work until 7.0 and for a period we did — to set an example.

In the first few months there was a bus at noon on Saturday to allow us to get home at the weekends, and we could be picked up on Sunday evenings (? at Hyde Park Corner or Exhibition Road) and taken back to Stroud. When that ceased we had to rely on the railway — there was a station at Stonehouse within a few minutes of the Office.

RAF personnel were on duty to guard us at the Office and when air-raids started our own staff took it in turns to sleep at the Office on fire-watch duty. When invasion was expected a unit of Home Guards was formed and we were given some training in how to throw a grenade and I think I even had one shot with a rifle but I don't expect it hit the target!

Dr Goldie was in charge of the Office at Stonehouse; for a time the Headmaster's room was kept vacant —?for DMO if necessary — but ultimately we were allowed to use it and, as Dr Goldie preferred not to move from his room on the first floor, it was given to me to share with one other member of the staff — previously I had had to share with three or four members of the junior staff of Naval Handbooks.

Return to London after war ended

I came up to London, on duty, at least every fortnight during the war and visited the Naval Meteorological Service (under Cdr Garbett) then housed in Fitzmaurice Place, Berkeley Square, and Mr C.S. Durst at the Air Ministry, returning on Monday evening to Stroud.

The staff had increased so much during the war that it was thought that the South Kensington building could no longer house us. I was given the job on one of my weekend visits of going over it — it was an eerie job as I was alone and did not know whether any of it was occupied or not, actually it was not though it looked as though it might have been vacated with very little notice. I was also told to go over a convent (somewhere in North London, I forget where) but there I had with me a member of the Air Ministry staff. As might have been expected nothing came of that visit. (I had wondered who would occupy the little chapel and whether it would have to be deconsecrated.)

A short time before we left Stonehouse some half-dozen of the staff came up to London to see the building at Wealdstone which we later occupied. It had, I think, been the building to which the Air

Ministry would have been sent if they had had to leave central London, it had two floors of cellars well underground. It was occupied by Air Force Officers in some special unit. We had lunch in the canteen there and were allowed coffee in the mess provided we left immediately after it — or perhaps it was the ladies only who had to leave.

Of the actual move from Stonehouse there is not much to tell. The Library again was the most difficult and someone had to stand at the top of the stairs to prevent the books or cartons from being thrown down the stairs! The Library was on the first floor.

We left Stonehouse I think on a Friday and were expected to (and did) report at Wealdstone on the Monday giving us little or no time to settle in at home after five years away. We were told to work as hard for peace as we had for war!

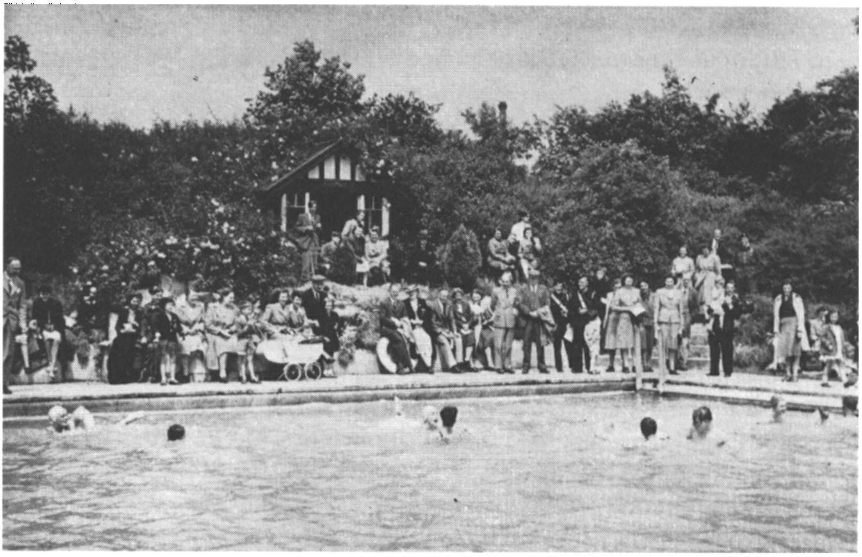
C.E.N. Franckom

I will try my best to tell you what I can remember of interest about Stonehouse days. Our location there was Wycliffe School; the boys had been 'evacuated' to somewhere in Wales. First of all it was Cdr Jack Hennessey, my assistant in M.O.1 who actually handled the move from Victory House (M.O.1) and South Kensington (M.O.3 and M.O.4) to Stonehouse; he was responsible for it all and an excellent job he made of it. I recollect that there were only six Divisions in the office then; M.O.1 — Marine, M.O.2 — Forecasting, M.O.3 — Climatology and Library, M.O.4 — Instruments and Stores, M.O.10 — Administration and Personnel, and M.O.6 — Royal Air Force, and there was only one Director, and three Assistant Directors as far as I can remember. M.O.2 were already at Dunstable, so only M.O.1, M.O.3 (Dr Brooks) and M.O.4 (Dr Scrase) went to Stonehouse, with one Assistant Director (Dr Goldie, one of nature's gentlemen) to keep us in order!

It is my recollection that Hennessey went down to Stonehouse several weeks before the move and more or less stayed there till we arrived and was able to welcome us! He had a lot to do; allocating office accommodation for each division, including stores and workshops for M.O.4, library for M.O.3 and Hollerith machines for M.O.1, arranging electric power supply, and black-out curtains for all windows. He also had to find billets or lodging for all those staff (of whom there were many who were very young) who didn't wish to make their own plans. With his Merchant Navy and Naval reserve background, Jack Hennessey was an efficient and versatile organizer and a good mixer, and he got on well with local authorities and local landladies. He had assistance at times from M.O.4 re workshops and stores, and Office of Works re electric and heating problems etc.

The move from London to Stonehouse went off very smoothly, as far as I can remember, and everybody settled in quite easily. I believe a representative from S2 (Air Ministry Secretariat) joined us for liaison duties and somebody from Office of Works, M.O.3 and the Library occupied the main building called School House, where the canteen was also located (previously the school dining room) and the kitchen. M.O.1 was rather select (!), being housed in the newest building, on the other side of the main road. We needed rather spacious self-contained premises because we were the only Met. Office Division that used machine methods for climatology (Hollerith machines). We were working on an urgent job of making climatological maps for certain ocean areas, on behalf of the Admiralty, in liaison with Naval Meteorological Office, important at a time when no weather reports or forecasts were available and there was radio silence at sea except in emergency. I had the pleasure of occupying the Headmaster's office; a very pleasant room with a nice outlook. M.O.1 had its own draughtsmen section of three people: a very convenient arrangement. Everybody seemed to settle down very well; Stonehouse and the neighbouring town Stroud, about 1½ miles apart, were pleasant country towns and the local people were very friendly. (There were the usual jokes about meteorologists bringing bad weather, but we were welcomed.) Shops were adequate (and pubs) both in Stonehouse and Stroud.

Railway communications were good with stations at Stonehouse and Stroud on the line connecting London and Gloucester, and with a fairly frequent local train service. Bus service was as adequate as practicable in wartime with fuel rationing. There were quite good recreational facilities; a very good cinema in Stroud, an excellent swimming pool in Wycliffe School grounds and, at Stroud, delightful countryside for rambling and plenty of interesting places nearby for sightseeing.



Private snapshot. Copy supplied by Mrs Stephanie Smith.

Swimming gala held by Meteorological Office staff at Wycliffe College.

Most of the junior staff in M.O.1 were young girls and they were accommodated in a large and quite pleasant boarding house near Ebley (about half-way between Stroud and Stonehouse). Most married staff rented furnished houses which wasn't difficult in those days. We had a furnished house at Ebley on the main road; I used to cycle to the office on an elderly (lady's) bicycle. Later we bought a largish terrace house in Stroud for £1000 (to avoid paying storage and furnished rental) and thought we were being very extravagant!

The Met. Office staff held occasional dances in the canteen, and the swimming pool was very popular in summer. A 'Swimming Gala' was held one weekend in the pool and included a water polo match with unlimited participants, and a fancy dress swimming race (both very exhausting items). I foolishly wore a tweed skirt of my wife's and nearly sank with the weight of it when it got wet. Proceeds went towards the 'Spitfire Fund'.

The winter of 1939/40 was extremely cold; one Saturday night there was a strong westerly wind and exceptional glazed frost, so bad that birds were frozen where they had perched and hundreds of telephone wires were brought down and branches from trees. Our back door faced west and in the morning it had a sheet of ice on it over an inch thick. It was almost impossible to stand up on pavements. We had a little river at the bottom of our garden, flowing through Stonehouse, and one morning I managed to skate to the office.

When Anthony Eden announced the formation of the Local Defence Volunteers (LDV, later re-christened 'Home Guards') on the 'wireless' one night several male members of the Met. Office staff joined at the local Police Station next morning. Some joined the Met. Office section but I joined the Ebley section as it was nearer to home. We had our headquarters in an old cloth factory and we were rather like 'Dad's Army' when we started. There were about thirty of us in the section and our arms were two shotguns (one of which was mine — an elderly 'hammer' gun). We were issued with our denim khaki uniforms and did a lot of drilling, marching and 'playing cowboys and indians' and eventually came the great day when we were each issued with an American '300' rifle and were able to do some limited target practice (but not much, due to ammunition shortage). One night (in the late summer of 1940, I believe) the phone rang at about 2 a.m. and my wife said 'Hurry up there is Hitler for you'. I went downstairs and on the phone was our LDV Captain, 'Get into uniform at once and report at HQ, Germans are reported to have landed'. I told my wife, 'You're quite right; it is Hitler'. 'Poor you and at this time of night', she said and went to sleep again! At our HQ, rifles were being issued in the light of a hurricane lamp, and six of us, with a Corporal in charge, were sent to man a trench we had previously dug alongside the main Stonehouse–Stroud road; all we did was to question the drivers of two cars and about 9 a.m. we were relieved and went home for breakfast. About 11 a.m. news came through on the 'wireless' that it was a false alarm; all very dramatic!

Soon after Dunkirk, Jack Hennessey and I asked the Director of the Office (Sir Nelson Johnson) for permission to volunteer for Naval Service afloat, as we considered that the best place for a seaman in real war (not 'phoney' by then) was at sea. Sir Nelson agreed that one of us could go, at the Admiralty's decision. I was selected, presumably because I was the younger. On 14 November 1940 I 'went back to sea' as a Commodore of North Sea Convoys. I got back to Stroud on various occasions and kept in touch with colleagues in the Office, but can only say that the general 'atmosphere' continued to be satisfactory.

I should mention that while I was in the Office in Stonehouse we had two air-raid warnings, one by day when some of us saw the aircraft and one at night; no bombs were dropped and we gathered the attack was on Bath or Bristol. Stonehouse could have been a target; Sperry's the gyro compass firm and Hoffman's who make ball bearings were there plus the Met. Office (all met. activities being of wartime value).

My wife's most vivid memory of Stonehouse days was of an open car passing our house one morning en route to the office with three elderly scientists in it with long wispy hair blowing in the breeze, thoroughly enjoying the informality of country life compared with London!

G.E.W. Hartley

Some memories of Meteorological Office, Stonehouse

I arrived at Stonehouse station at the end of January 1940 about 6 p.m. very cold after a six-hour train journey from Swindon (due to frozen points) and was lucky enough to find Mr Skelton who kindly directed me to a billet in Cainscross where I was made welcome by my hosts, Mr and Mrs Hewins. I had recently completed a forecasting course in Berkeley Square and was very relieved to be sent to M.O.4 to deal with instruments rather than forecasting. I began in Test Room, run by Mr Pace, but fairly soon moved to instrument design with special interest in wind measuring instruments — in this work I was concerned with the workshop, run first by Mr Stanley, and later by Mr Napier. I did a fair amount of travelling to visit firms and RAF establishments. I remember a trip to ICI in Cheshire, to be instructed (and later to instruct) in the use of a fog measuring device known as a Nubimeter, in connection with a project called FIDO, for dispersing fog by lighting petrol along the runway. I do not think the Nubimeter was very successful, but I do remember having bacon and eggs for breakfast at the ICI hostel. Later on I got involved in the design and construction of several wind-tunnels for anemometer testing, with help and advice from NPL and RAE Farnborough.

There was quite a lot of social occupation — such as tennis — I particularly remember a tennis match against Stroud Fire Brigade in which I partnered Dr Glasspoole; one of our opponents played in his fire-brigade headgear, which Dr Glasspoole was determined, but failed, to knock off.

Hair-cutting cost 3d at the Stonehouse barber who was also a bookmaker, and tended to leave his client in the chair while he telephoned for race results.

There was plenty of musical activity — some of us joined the Stroud Choral Society under Samuel Underwood; I played bassoon with the Gloucester Orchestral Society under Herbert Sumsion; I conducted an orchestra in Stroud and played in the Home Guard brass band. One Christmas we put on a pantomime in the library, in which all sections of the office in Stonehouse were involved — there was a small orchestra which included Mr Pace (cello) and Mr Napier (piano) and leading parts were taken by Dr Scrase and H.T. Smith.

I was fortunate to find a farmhouse near Painswick to live in with my wife and children — rather a long and hilly cycle ride, but well worth the trouble.

The move to Harrow meant leaving many friends behind, but fortunately Harrow was within commuting distance of my home 'Woodwind' at Ottershaw, Surrey.

O.M. Ashford

Recollections of Stonehouse — June 1943 to August 1945

I was posted to Stonehouse in June 1943 as head of M.O.4(a), the section responsible for the design and development of new and improved meteorological instruments. My 'office' was an enormous science laboratory, large enough for at least ten normal offices. Several attempts by other Branches to take over some of the space had been thwarted by arguing that the whole laboratory was needed for displaying a vast collection of meteorological instruments: few of these were in fact of any curent interest and several are now in the instrument museum.

Stonehouse was located in a billeting area and I therefore had to wait several months for a furnished house to be allocated. In the meantime, I went into 'digs' and my family stayed up in Scotland. In spite of the long working hours (48 hours a week, I seem to remember) I still had time on my hands and took the opportunity of enrolling in a Russian course and learning to play the oboe. For the latter I was encouraged by my colleague Geoffrey (Bill) Hartley, who needed an oboeist for the amateur orchestra which he directed in Stroud; he had a large collection of wind instruments and offered to lend me an oboe. As a Scotsman, I could hardly refuse such a generous offer. I used to cycle about 40 miles for my oboe lessons.

In due course I was assigned a house in Painswick, and later in Chalford, both of which were more than five miles from Stonehouse. I shall never forget the daily cycle ride to the office, downhill for the first mile or so and then along the valley. This meant that I did not get any exercise — apart from using the handbrake — on the initial stretch, which was especially trying in winter when I was often made painfully aware that cold air can be found in a valley.

As we only had a short break for lunch, few of the staff were able to go home in the middle of the day — perhaps I had been spoiled in this respect at my previous posting at Lerwick Observatory. I enjoyed the company in the canteen more than the food. After lunch I would often have a brisk walk with my boss, Dr Scrase or other congenial company; thanks to this, I got to know people from other branches, such as Dr Brooks, Dr Glasspoole and Cdr Hennessey.

The facilities at Wycliffe College, where the office was located, lent themselves readily to a wide variety of social activities. I enjoyed especially the tennis and swimming in the summer and the table tennis and badminton in the winter — also an occasional game of chess. We even had an annual athletics meeting, for which there was strong competition for the ladies' events but not so much for the men's — I was one of the few males under the age of thirty. To my amazement I had little difficulty in winning the 100 yards sprint against the only other competitor, considerably my senior; this is the only time in my life that I have won a race.

The office choir was ably led by Hartley who persuaded me, against my better judgement, to help to swell the thin ranks of the male voice section. I resigned in horror after finding that I was expected to sing a solo tenor part. It began: 'I hear the voice, I hear the voice of angels sing ...' I could hardly bear my own voice, let alone that of the angels. I had somewhat more success in the dramatic club — the Stonehouse Players, I believe. I played the part of a jingoistic politician in a very moving play with an anti-war message. I still remember my opening lines: 'My friends, this is a very solemn moment for all of us. The twin spectres of poverty and unemployment threaten the security of our fair land...' The Players were awarded first prize in a regional or county competition among amateur drama societies for this production, but before the end of the competition my part had been taken over by a much better actor, H.T. Smith. This story has an amusing sequel. Some years later I was invited to join the RAF dramatic group in Gibraltar. Imagine my surprise when I learnt that they wanted me to play the part of a jingoistic politician in an anti-war play! I readily accepted and the play once again won first prize in a local competition.

Other vivid memories of Stonehouse include trying to communicate with the three Polish assistants in the Test Room and with the office photographer who was stone deaf, the nights spent at the office on fire-watch duty, and the frequent visitors — there was even a Russian meteorologist with whom I was able to air my few phrases of Russian. But above all, it was a place of hard work and good companionship.

Appendix 2 — *Biographical notes on authors of reminiscences*

Miss E.E. Austin

Joined the Office in 1918. For many years Personal Scientific Assistant to Sir Napier Shaw and went with him to Imperial College, London on secondment from 1920 to 1935. The first woman Principal Scientific Officer. Retired in 1957, having been Head of the World Climatology and Upper Air Climatology Branches.

Commander C.E.N. Franckom, OBE

Marine Superintendent 1939–1969, but on active service with the Royal Navy from November 1940 to the end of the War. President of the WMO Commission for Maritime Meteorology from 1946 to 1956. Apart from his distinguished service in what may be called 'work', he participated enthusiastically in almost every aspect of Office social life.

O.M. Ashford

Resigned from the Office in 1952 to join WMO where he had a distinguished career, retiring in 1977 as Director of Programme Planning and UN Affairs.

G.E.W. Hartley

Joined the Office in 1939 after having been a schoolmaster. Spent his entire career dealing with instruments, particularly anemometers. A talented musician, with a gift for composing light music, he is an expert bassoon player. For many years until his retirement in 1971 he conducted the Office choral society.

Notes and news

The reopening of Ross-on-Wye

Thursday 16 May saw the reopening of the observing station at Ross-on-Wye after a gap of 10 years. Weather observations were first made at Ross in 1859 but the station is best known for the efforts of one man, Mr F.J. Parsons, MBE, the observer from 1914 to 1975 (when he retired at the age of 84). As well as providing climatological observations Ross-on-Wye was, under Mr Parsons, an important auxiliary synoptic station reporting at six of the eight synoptic hours. Station number 627 (or 140 for those with extremely long memories) was a key station in the network and its closure left a gap, not yet satisfactorily filled, on synoptic charts.

The Mayor of Ross for the year 1984/5, Councillor Arthur Clarke, made the reopening of the climatological station a mayoral project and was extremely fortunate in being able to acquire the site previously used by Mr Parsons. Accordingly, and because of the previous long record, the Meteorological Office took the unusual step of supplying all the necessary equipment and instruments on loan right from the start.

Observations will be made at 0900 and 1800 GMT for inclusion in the Health Resort bulletin published by the National Press. The data will also be validated and stored on the computerized data bank held by the Meteorological Office at Bracknell and, thus, form part of the National Weather Archive. As well as being the source of weather statistics this archive is much used by the Meteorological Office Advisory Services Branch to answer the very many and varied enquiries received from designers, planners, agriculturists, the legal and insurance professions as well as the general public.

The opening ceremony took place at the site at 1200 on 16 May with Ian McCaskill, one of the Meteorological Office team of BBC National TV weather forecasters, cutting the tape with the Mayoress of Ross. Also present were Mr F. Singleton, Assistant Director (Advisory Services) and Mr Denham representing the Bristol Weather Centre. Unfortunately Councillor Clarke was indisposed and could not be present. He was represented by the Mayor-Elect, Councillor Drew Lacey. Before and after the ceremony Ian McCaskill risked writer's cramp by signing autographs for at least, apparently, half of the several hundred people present and being photographed by the other half. The Meteorological Office representatives were introduced to the Principal Observer, Mr H.J. Ellis and his deputy, Mrs J. Swallow. Local interest is so great that there was a queue of people willing to be observers and the Local Council has now appointed a second deputy observer. The interest and commitment of the Council is evidenced by their willingness to pay the observers an honorarium.

In a short speech, Councillor Lacey paid tribute to the efforts of Councillor Clarke to reopen the station and he thanked the Meteorological Office for the loan of the instruments. In reply Mr McCaskill reflected upon the value of such observations, wished Ross-on-Wye all success for the future in this venture and faithfully promised to ensure that Ross-on-Wye received due mention in his television weather forecasts.

After the ceremony, and when the crowd had finally largely dispersed, the Mayoress, the Mayor-Elect and Town Clerk very kindly entertained Messrs Denham, McCaskill and Singleton in the reforging of the relationship between the Meteorological Office and Ross-on-Wye, a relationship which it is hoped will persist and prosper for many years to come.

Photograph by courtesy of The Ross Gazette

Ian McCaskill with Mr Howard Ellis, the Principal Observer at Ross-on-Wye.

Photograph by courtesy of The Ross Gazette

Ian McCaskill with the Mayoress of Ross, Mrs G.A. Clarke and the Mayor-Elect, Mr Drew Lacey.

Satellite photograph — 4 November 1985 at 0426 GMT

The satellite photograph opposite (Fig. 1) is from a NOAA-9 south-bound pass at 0426 GMT on 4 November 1985. The infra-red image shows the channel 4 (11 μm) data from the AVHRR received at the Lasham ground station and processed on the HERMES computer system. The photograph has been taken directly from the VDU screen. The synoptic situation at 0600 GMT is shown in Fig. 2.

Iceland can be seen clearly towards the top left-hand corner of the satellite picture. There was widespread convection in the polar air flowing across Iceland from the north-east, and a marked 'shadow' in the lee of the cold land surface. The reason for the 'streak' in the middle of this clear area is still obscure; however, it was still evident on the NOAA-6 pass later that morning.

Part of the north coast of France is visible on the extreme right of the picture (about half-way down) while the English Channel, much of Wales and northern England are also visible. The bright mass of cloud approaching the Channel is mainly cirrus and altostratus; however, rain did not reach the Brest peninsula until some 3½ hours later. This rain subsequently spread to some southern parts of England. A shield of stratocumulus can be seen over south-east England, which resulted in a gradual rise in temperature in those areas after local slight frost earlier in the night. A minor trough affected south-western parts of England, bringing light showers during the morning. Ireland is mostly cloud-covered, the cloud being associated with another trough; Valentia, in extreme south-west Ireland, reported thunder at about the time of the picture.

The cold front to the north-west of the British Isles was fairly weak at this time but the depression near Ocean Weather Station LIMA (57° N, 20° W) developed as it moved eastwards and subsequently deepened to 948 mb over the northern North Sea about 40 hours later.

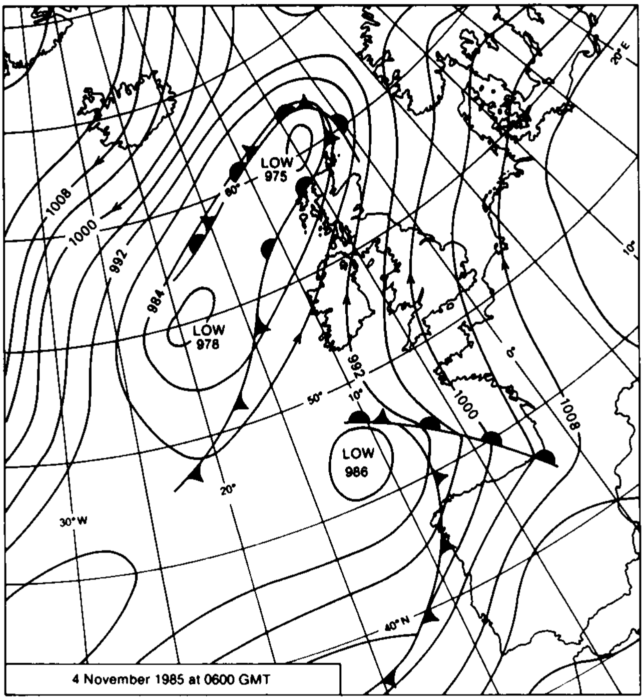


Figure 2. Synoptic situation at 0600 GMT 4 November 1985.

Figure 1. NOAA–9 infra-red image, 0426 GMT 4 November 1985.

Reviews

Air pollution by photochemical oxidants. Formation, transport, control and effects on plants, edited by R. Guderian. 170 mm × 248 mm, pp. xi + 346, *illus*. Springer-Verlag, Berlin, Heidelberg, New York, Tokyo, 1985. Price DM 158.

The dramatic and rapid decline in the health of forest trees which has developed over recent years in West Germany, and other countries of central Europe, has had a major political impact, and has stimulated measures to control emissions from various sources of air pollution in many European countries. Although most scientists accept that pollution in some form is of central importance in causing this forest decline, it has not yet been possible to directly link the damage to any particular pollutant, or combination of pollutants. The role of photochemical oxidants, primarily ozone, is now the focus of considerable interest; in addition to its direct effects on vegetation, ozone plays a key part in the conversion of sulphur dioxide and nitrogen oxides into the sulphate and nitrate of 'acid rain'.

The concern about ozone, and other photochemical oxidants, led the German Umweltbundesant (the federal environmental protection agency) to commission a review of their formation and effects, which was published (in German) in 1983. This English text, which is largely based on that publication, consists essentially of two long review chapters. The first of these is concerned with the formation, transport and control of photo-oxidants. There are brief summaries of the physical and chemical properties of the relevant molecules, together with sections on sources of the precursors, the chemistry and modelling of oxidant production, and methods of measurement. However, control is only discussed very briefly on the basis of model predictions. There is no mention of the technical means of controlling emissions, and it seems rather misleading to have included 'control' in the actual title of the book. The German origin of the book is most evident in this first chapter, over a quarter of which is devoted to measurements made in West Germany of oxidants and their precursors. The second chapter, which is about twice the length of the first, is concerned with effects of photo-oxidants on plants. This review covers their biochemical, physiological and ecological effects, factors influencing plant response, dose-response relationships and the effects of photo-oxidants in combination with other pollutants. There are also brief discussions of the use of bioindicators and of the experimental methods available to evaluate effects on plants.

This is definitely not a book to be read for pleasure. The information is densely packed and the style of writing is uniformly dull. The presentation often still resembles that of an official report, and little effort seems to have been made to rewrite the material for this book in a way which might attract a wider range of readers. Nevertheless, the book is thoroughly researched (there are 52 pages of references), and it contains what is undoubtedly the most detailed, authoritative and up-to-date review of the effects of photochemical oxidants on vegetation. As such, it will certainly be a valuable source of reference for specialists in this particular subject.

M.R. Ashmore

Meteorological Magazine

January 1986

Vol. 115
No. 1362

CONTENTS

Contributions: it is requested that all communications to the Editor and books for review be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For *Meteorological Magazine*'. Contributors are asked to comply with the guidelines given in the *Guide to authors* which appears on the inside back cover. The responsibility for facts and opinions expressed in the signed articles and letters published in *Meteorological Magazine* rests with their respective authors. Authors wishing to retain copyright for themselves or for their sponsors should inform the Editor when submitting contributions which will otherwise become UK Crown copyright by right of first publication.

Subscriptions: Annual subscription £27.00 including postage; individual copies £2.30 including postage. Applications for postal subscriptions should be made to HMSO, PO Box 276, London SW8 5DT; subscription enquiries 01–211 8667.

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.

ISBN 0 11 727829 7 ISSN 0026–1149

Printed in England for HMSO
Published by HER MAJESTY'S STATIONERY OFFICE
Dd. 738362 C13 1/86

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

February 1986

Met.O.971 No. 1363 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1363, February 1986, Vol. 115

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The Synoptic Data Bank

By J. Ballentine
(Meteorological Office, Bracknell)

Summary

The last 15 years have seen major changes not only in forecast models but also in the technology able to support them. Over this period the Synoptic Data Bank has kept pace, developing from a very simple system to a complex collection of software and data sets able to receive a wide assortment of data on a continuous basis, making it available to an ever-increasing and increasingly demanding range of users. From its original concept as a source of data for the forecast models it has developed into a major service, and this development seems likely to continue.

Introduction

In 1970, the decision that the Meteorological Office should extend its work in numerical forecasting required the creation of a data base to provide quality-controlled data in real time. This data base, now known as the Synoptic Data Bank (SDB), was designed to form a bridge between the data flow on the Global Telecommunication System (GTS) and the numerical weather prediction model.

Before the formation of the SDB, data from the GTS were transferred to five-hole paper tape and sent to the computer room for reading by slow paper-tape readers. The data requirement of the earlier numerical models was much lower than nowadays so that data consisted mainly of land and sea observations coded as SYNOPs (surface observations on land), SHIPs (surface observations at sea) and TEMPs (upper-air data). However, since the late 1970s the availability of satellite data and the collection of more reports from the southern hemisphere have led to vastly increased amounts of data in the SDB. When, in 1982, the forecast model was extended to become global the SDB was able to provide the required data. The need to achieve this without any major change in the design of the SDB has created many problems, but the system is now relatively stable and this is a convenient time to present an account of the SDB and its expanding role in the Meteorological Office.

Report types

The original SDB was set up to collect synoptic and upper-air reports for the numerical forecast model and for a limited number of other users. The design, a simple indexed structure, has been essentially retained despite the subsequent growth in the variety of data. Commercial software packages for handling data bases were not available when the SDB was developed and are not yet employed.

The growth of the SDB has been dominated by a continual demand for more, higher-quality data with a wider coverage for projects such as the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE) and the First GARP Global Experiment (FGGE), and, more recently, to meet the needs of a global analysis system for the larger forecast model. The number of report types has grown and now exceeds 50, consisting of surface, upper-air, satellite, and GRID (numerical output) codes, and TBUS data (satellite prediction information). Each new code often involves additional problems of storage, archiving, retrieval and error checking and so over the years has taken the SDB far beyond its original design.

As shown in Table I, the SDB still consists mainly of SYNOPs and SHIPs (now combined in code FM 12/13–VII) together with radiosonde information. However, the reason for the growing need for more data will be seen from Figs 1–4 which show the global distribution of reports. By far the greatest coverage is in the northern hemisphere, with only a small number of reports from land stations and a few ships in the southern hemisphere.

This distribution was satisfactory for a short-term forecast (1 to 3 days) confined to the northern hemisphere but for medium-range global forecasts the coverage of upper air data is insufficient, especially in the southern hemisphere. Even aircraft reports (AIREPs) of temperature and wind values at the aircraft's flight level tend to be infrequent and confined, like ship reports, to specific lanes.

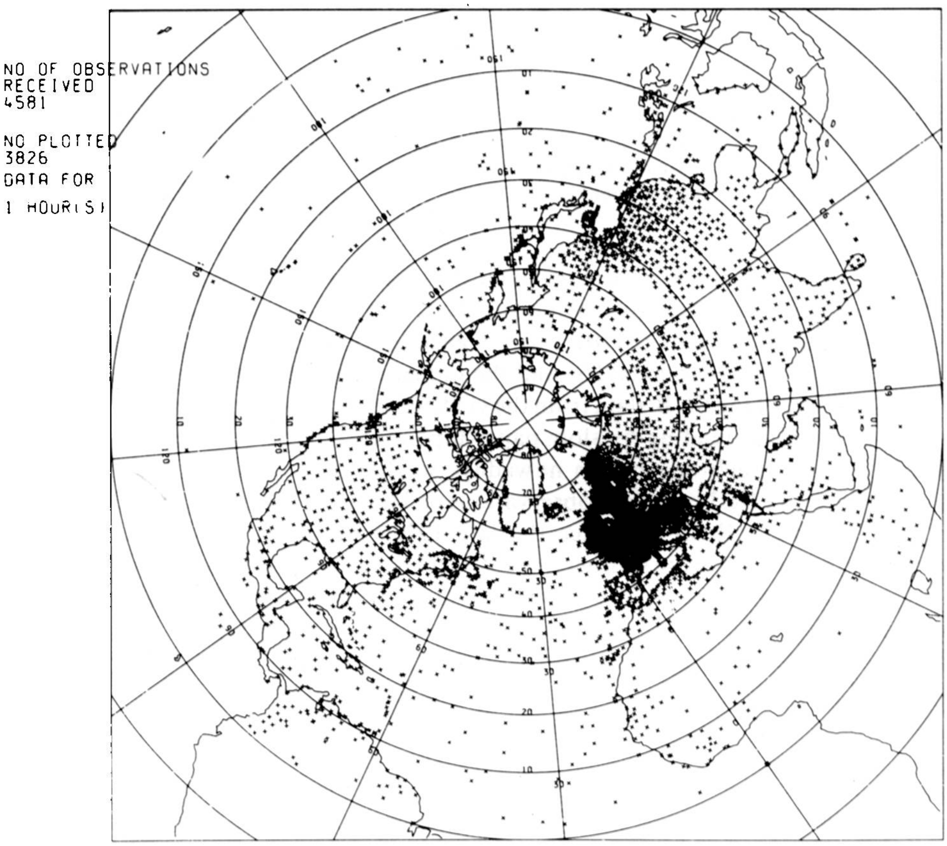


Figure 1. Surface observations (SYNOPs) in the northern hemisphere for 1200 GMT on 10 September 1985.

Table I. *The contents of one data bank, showing the main types of data stored in the data banks every 12 hours. Approximately 5×10^6 characters are processed every 12 hours.*

Type	No. of reports
SYNOPs	14 673
SHIPs	2 026
TEMPs (land and ships)	2 176
PILOTs (land and ships)	935
AIREPs	1 753
BATHY (bathythermal observation), TESAC (temperature, salinity and current report) etc.	772
NCM	126
METARs (aviation routine reports)	600
SATEMs[1]	4 350
SATOBs[1]	894
HERMES[1]	6 000
GRID[2]	155

Note [1] Stored in satellite banks
[2] Stored in GRID code banks

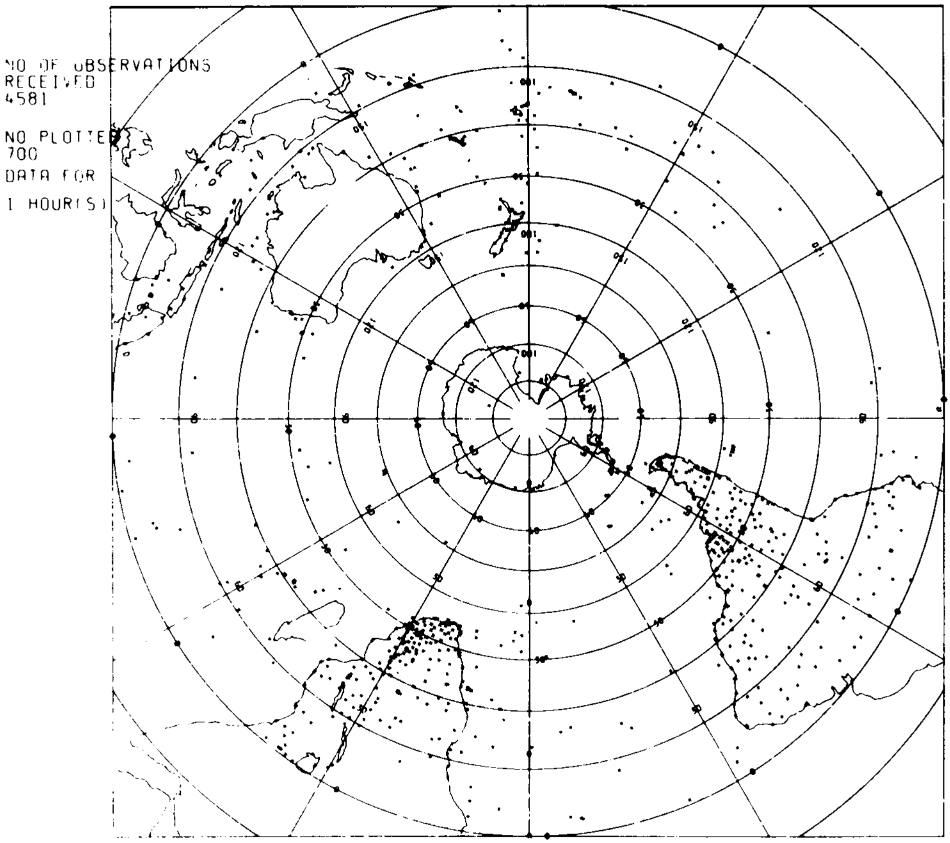


Figure 2. As for Fig. 1, but for the southern hemisphere.

In recent years, however, the imbalance between the coverage of data in the northern and southern hemispheres has been redressed by the availability of satellite reports. The series of geostationary satellites give SATOB reports of winds and temperatures, and the NOAA polar-orbiting satellites provide SATEM reports at about 500 km intervals of cloud cover, thickness of defined layers in the atmosphere, and water vapour. These reports are not yet accurate enough to replace other types of data but they provide very valuable additional information where other, conventional, types of data are sparse or non-existent.

The first major departure from the original SDB design occurred when it was realized that the large and growing number of satellite reports threatened to swamp the SDB. Since 1976, therefore, they have been stored in a separate set of Satellite Data Banks, designed with the same simple index structure as the SDB, capable of being increased in size, as necessary, without affecting any other data.

A similar policy was subsequently adopted with the GRID code reports from other Meteorological Centres. These data, consisting of heights, temperatures and wind vectors for standard pressure levels at fixed grid positions over the entire globe, are used by the researchers and, in plotted form, by the Central Forecasting Office (CFO). GRID data require a potentially large amount of on-line storage but have no archive value and so a third set of data banks was set up.

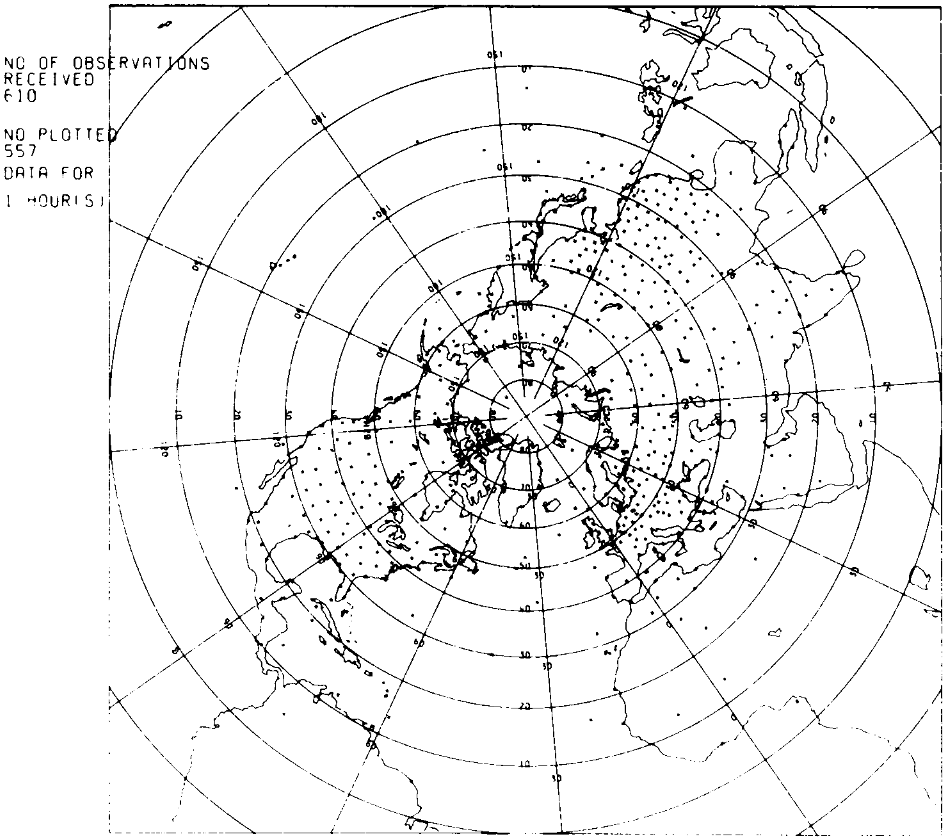


Figure 3. Upper-air soundings (TEMPs) in the northern hemisphere for 1200 GMT on 10 September 1985.

Data storage

Almost all the data stored in the SDB are received over the GTS via the Regional Telecommunication Hub (AUTOCOM) at Bracknell but, in addition, there are now also processed satellite data from the HERMES (High-resolution Evaluation of Radiances from Meteorological Satellites) minicomputer. The GTS data are passed via a Ferranti Argus system (Fig. 5) to the Meteorological Office central computer system (COSMOS) and processed by the permanently resident SDB software. These programs read and identify the data and, after checking and quality controlling, store the reports in the appropriate data banks.

The SDB programs must be sufficiently flexible to cope with large amounts of data at peak periods (bursts of around 1000 characters per second) while remaining inactive for periods when few data are arriving. The data flow (Fig. 6) determines optimum cut-off times for chart plotting. Information on the real-time flow of data is sent to World Weather Watch for forward planning of the GTS circuit.

The continuous availability of the SDB is of vital importance to the forecast so, in order to reduce the probability of loss, a dual system has been created in which two identical copies of the SDB are kept on separate discs and updated simultaneously. One set of banks is allocated for operational work and the parallel set for other users. When either disc is unavailable, all users are automatically switched to the

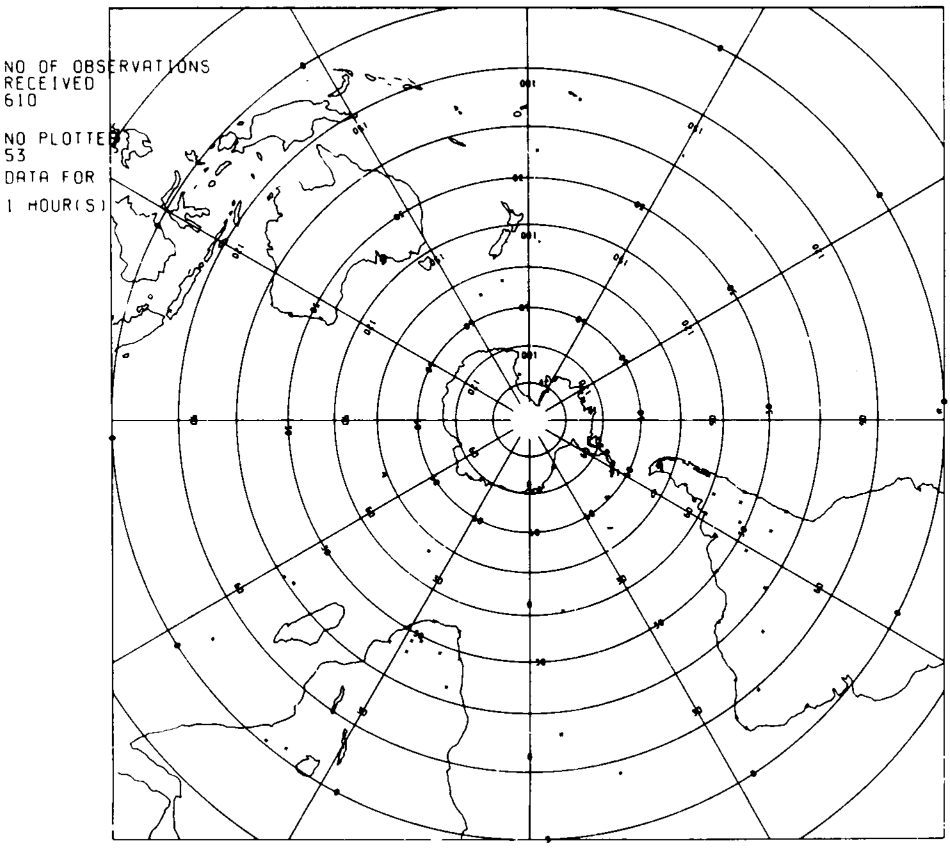


Figure 4. As for Fig. 2, but for the southern hemisphere.

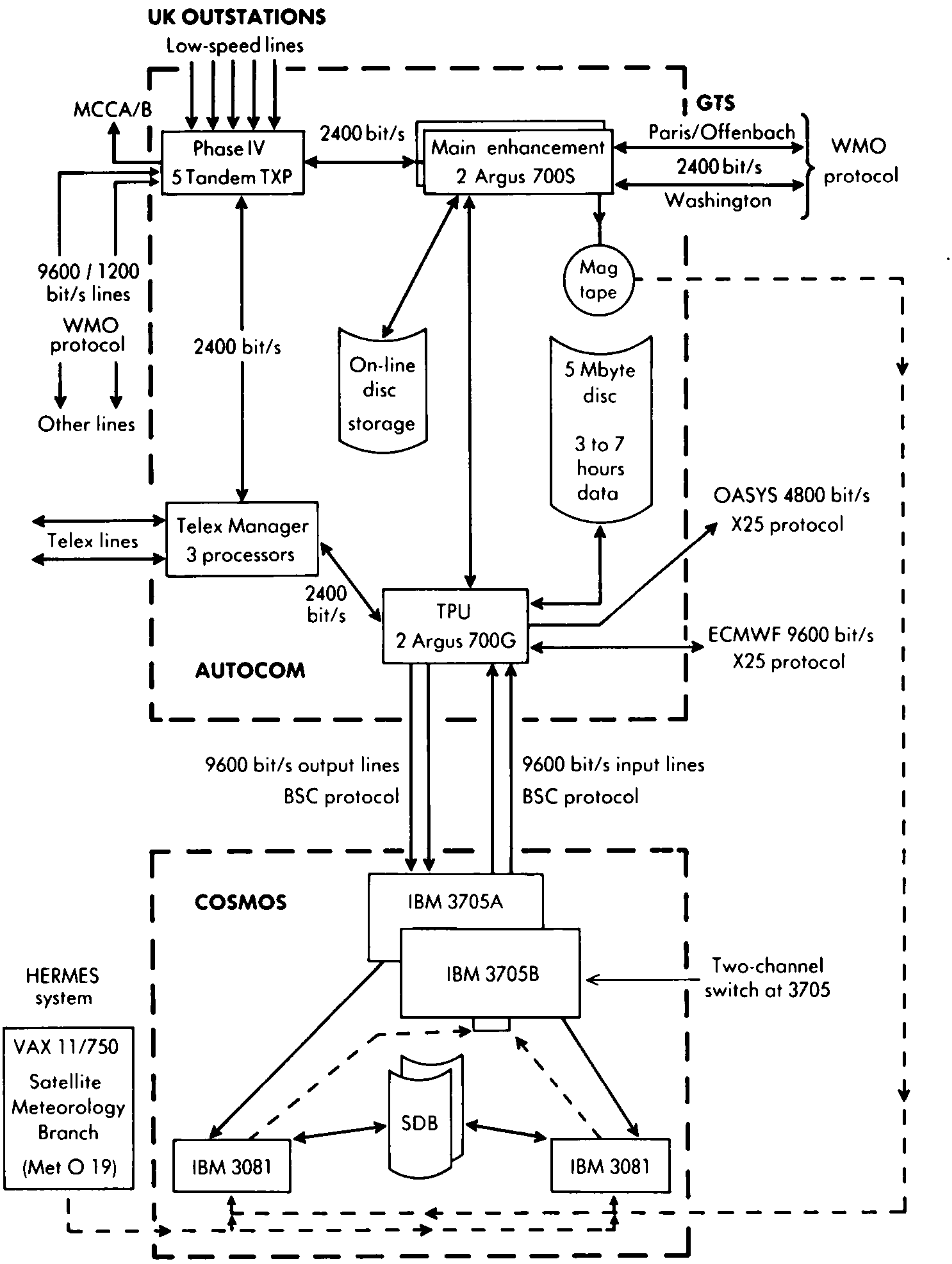


Figure 5. The international and UK data flow into the Bracknell Regional Telecommunication Hub and are then continuously passed to the Synoptic Data Bank. Processed satellite data from the HERMES system are passed to the Synoptic Data Bank shortly after the pass of the polar-orbiting satellite over the eastern Atlantic and western Europe. Line speeds given are in bits per second (bit/s); one byte is eight bits.

other which continues to accept and store data from the GTS. When the disabled disc is again available its data banks are automatically updated and dual storage is restored. This automatic switching is achieved, without programmer action, through the use of a 'housekeeping' data set which holds information about the data banks.

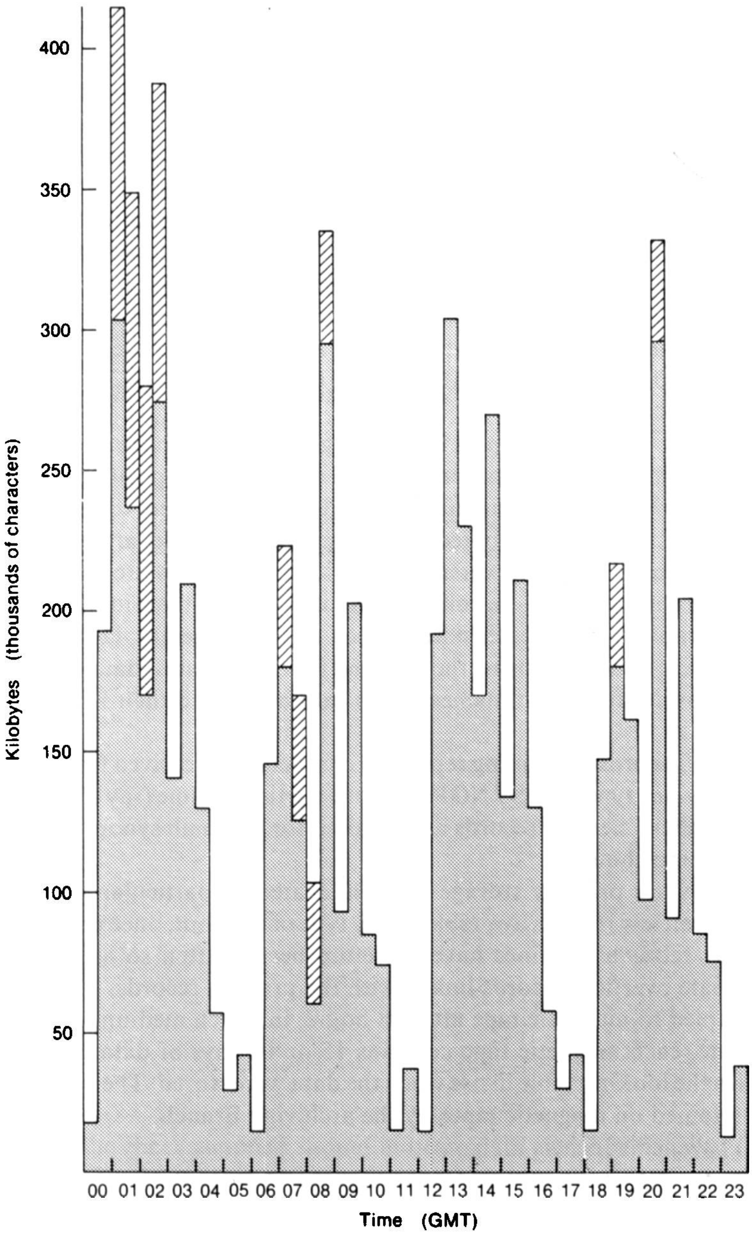


Figure 6. The peaks and troughs of data stored in the Synoptic Data Bank in a typical 24-hour period. The stippled histogram denotes the number of characters of surface, upper-air and satellite reports stored in the Synoptic Data Bank within each 30-minute period. The hatched areas at the top of the columns show the number of characters of GRID code data, received mainly from Washington and the European Centre for Medium Range Weather Forecasts, stored in the Synoptic Data Bank.

If the COSMOS system is unable to take data for short periods, the GTS data are held on a disc in AUTOCOM until the SDB is re-started. When there is a longer breakdown in communication, the data which are continuously written to a series of magnetic tapes by AUTOCOM are subsequently transferred to COSMOS for reading into the SDB, simulating the AUTOCOM–COSMOS link. The amount of data held on the tape will depend on the operational requirements at the time but tapes would usually be called for every 30 minutes.

In cases of a major breakdown in the system, AUTOCOM can store up to 6 hours of GTS data on disc and this, in conjunction with the GTS data from magnetic tape, can be read simultaneously into the banks when COSMOS becomes operational again.

Synoptic Data Bank data sets

The phrase Synoptic Data Bank is often used to refer to the 200 or so programs handling the storage and retrieval of the data. But, to be strictly accurate, the term SDB should only be applied to the data sets storing the data and a few others fundamental to the operation of the suite.

These comprise:

(a) The ten Synoptic and ten Satellite Data Banks. Each data bank stores meteorological reports for a 12-hour period (i.e. 0000 GMT to 1159 GMT or 1200 GMT to 2359 GMT), storage being by validity time rather than by time of receipt.

(b) The look-up table — a fairly complex index using the station number (or, for a ship, latitude and longitude), and the time and type of the observation, to determine the position for storage in the bank. This table has a particularly important function in that it enables changes to be made in the SDB layout without affecting the user. Any changes in record position, for example, are handled by changes in the look-up table. For this reason a current version of the look-up table is archived with each SDB.

(c) The abbreviated station index — a complete list of World Meteorological Organization (WMO) stations and some relevant details of each station, such as station height, latitude and longitude.

(d) Two housekeeping data sets storing the date and time of the latest data banks created. These two small data sets also provide the current names of the data banks and their location and availability.

Each SDB consists of records containing reports in characters as received from the GTS. Each record contains reports of only one type (e.g. SYNOPs) for one particular time (say 0500 GMT) and for one or more WMO block numbers. Several records are required for the main synoptic hours and very few for the intermediate and minor hours.

The first 800 records are primary storage areas allocated to particular types of data. These are accompanied by 220 overflow records available to any type of data but, once used, linked to the relevant primary records. The retrieval routines have therefore been written so as to search automatically through the appropriate overflow records linked with the primary records.

Data banks are copied to magnetic tape after 48 hours, in which medium they are retained for five years. When complete, each magnetic tape contains 15 or 16 days of data banks (depending on the month) together with the look-up table in use when the data were stored. The permanent Synoptic Data Bank archives are retained on magnetic tapes by the archiving Branch.

Bulletin recognition

When bulletins are received the first job of the software is to recognize the type of data by examination of the bulletin headings and allocate the appropriate Data Processing Branch (Met O 12) code type for future processing. For example, AAXX would indicate a land station SYNOP, and TTAA a TEMP part A. (If, however, the heading or content of a bulletin is unrecognizable it is stored in the 'dregs' records of the SDBs. These may be dealt with manually but this is a facility not readily available to users.) After the bulletin has been recognized the software then 'cleans up' the reports, removing all telecommunication characters, and investigates non-five figure groups for surface and upper-air reports. Groups with fewer than five characters are sometimes padded with slashes or re-formed if a space is in the wrong place; groups with more than five characters are split up and padded if necessary. The date and time are extracted from the bulletin heading and inserted in an information header preceding the bulletin contents. The bulletin heading is then discarded and the contents separated into individual reports which are then subjected to the quality-control routines.

Quality-control routines

These routines subject each observation (now that its format has been checked and standardized) to extensive tests on the data content. When an error is detected a quality-control 'flag' (a marker on the data set record) is set for that element. Tables II and III list quality-control tests for surface observations and upper-air data. These tests have been developed keeping in mind the main purpose of the SDB which is to provide a suitable source of data for the numerical forecast model in real time; hence a fully comprehensive set of tests is not possible at this stage of processing.

Table II. *Quality-control checks carried out at storage time.*

Code type		Valid Date/time	WMO block and station no.	Position groups lat./long. Marsden sq.	850 mb and 700 mb initial digit check	Max wind at standard levels	Wind shear check	Full hydrostatic check
TEMP	A	✓	✓	–	✓	✓	✓	✓
	B	✓	✓	–	–	✓	–	–
	C	✓	✓	–	✓	✓	✓	✓
	D	✓	✓	–	–	✓	–	–
TEMP SHIP	A	✓	–	✓	✓	✓	✓	✓
	B	✓	–	✓	–	✓	–	–
	C	✓	–	✓	✓	✓	✓	✓
	D	✓	–	✓	–	✓	–	–
PILOT	A	✓	✓	–	–	✓	✓	–
	B	✓	✓	–	–	✓	–	–
	C	✓	✓	–	–	✓	✓	–
	D	✓	✓	–	–	✓	–	–
PILOT SHIP	A	✓	–	✓	–	✓	✓	–
	B	✓	–	✓	–	✓	–	–
	C	✓	–	✓	–	✓	✓	–
	D	✓	–	✓	–	✓	–	–

The basic idea is that the checks applied should indicate data elements believed to be suspect when tested against some set of acceptable criteria — for example, an assumption that the atmosphere is approximately in a state of hydrostatic equilibrium. A flag does not necessarily indicate that the data are wrong, only that the allowed limits set in the SDB software have been exceeded or that consistency checks have failed. The basic philosophy adopted when the bank was established was that it was not the responsibility of the SDB to reject any meteorological information. Thus, if any element of a report is modified by the quality-control routines (for example as a result of the hydrostatic checks) the original data are stored in the 'quality control' records of the SDB, and may be retrieved by those who wish to make their own decisions about the questions raised by the flags. No quality-control flags are set when the hydrostatic equation shows a temperature or height error, and a new value has been substituted. However, a substitution flag is set in the information header and the user can decide if the original observation is to be seen.

Table III. *Some of the 250 quality-control checks carried out on a SYNOP. Internal consistency checks account for a large number of the quality-control checks.*

Check	SHIP	SYNOP
Valid date and time	✓	✓
WMO block no. and station no.	—	✓
Ocean Weather Ship position check	✓	—
Internal consistency	✓	✓
Background field pressure comparison	✓	✓
Pressure group checked for high-altitude station	—	✓
Movement check	✓	—
Pressure tendency sequence check	✓	✓
Temperature − dew-point consistency	✓	✓
Land or sea position	✓	—

Associated with every report with quality-control queries is a record of all the quality-control flags, corresponding to the data elements within the report; these indicate whether the data elements in question have been flagged.

In some cases reported values may be replaced by calculated values, for example:

(a) Marsden square/latitude, longitude/quadrant values are checked.

(b) Standard pressure level indicators in parts A and C of TEMP messages are corrected provided the indicator for the next level can be recognized. For example 70 05 40
becomes 70 50 40.

(c) Hydrostatic check for TEMPs part A and C ('standard levels' data up to 100 mb and above 100 mb, respectively).

The hydrostatic check is applied to all TEMPs part A and C. It is an extensive test of the temperatures and geopotentials of the standard pressure levels and is based on the hydrostatic equation which may be written thus, assuming the temperature varies linearly with pressure within each layer:

$$\text{Thickness} \simeq \frac{R}{2g}\left[\log_e P_N - \log_e P_{(N+1)}\right]\left[T_N + T_{(N+1)}\right]$$

If the difference between the thickness of each layer calculated in this manner and the thickness calculated from the reported geopotentials is less than 30 gpm for all layers the check is regarded as complete. If the discrepancy is larger than 30 gpm then further tests are performed to try to find the source of the error. A common source of error has been found to be an incorrect sign to a temperature value, and thus when errors are detected the first test entails reversing the temperature sign at the top of each layer and recalculating the thickness difference. (Surface pressure checks are used to check the lowest level, usually the 1000 mb geopotential). If the error persists further tests are made based on consideration of various lapse rates in successive layers. The whole series of these tests is worked through and elements are either corrected and substituted or, if a reasonable value cannot be found, then the suspect element is flagged.

Extensive internal consistency checks, about 250 in all, are made on surface reports.

If, during the passage through quality-control routines, some part of the observation is suspect, a flag is set in the information header attached to the beginning of every observation in the data bank. After quality control, the report, the information header and the quality-control record (if any) are finally stored.

Since the four parts of TEMP and PILOT (upper wind) reports do not usually arrive at the same time, full quality control on storage is not performed. Users are, however, provided with the option of using a second-level quality-control package on retrieval. This additional software combines all the available parts of the ascents, and, using some of the first-level quality control, can carry out additional detailed checks.

Retrieval

An important feature of the SDB is that any computer user may have easy access to the data whether either synoptic or satellite data are required.

A subroutine is therefore provided which acts as an interface between the users and the data sets without the user having to know where the data are stored. The user has to specify up to eight parameters to the subroutine and the correct routines are automatically loaded from the SDB libraries to search the data sets for the required information and supply them to the user. Retrieval routines may be called from FORTRAN or Assembler programs. The eight parameters, chosen to define fully the data and format required, are as follows:

1. Date and time of the reports to be retrieved.
2. Type of observation.
3. List of stations required.
4. The name of the user's retrieval area in which the retrieved data are placed.
5. Code type combination.
6. Element retrieval. To return only specified parts of an observation.
7. Option word. Type of retrieval: i.e. character, half-word integers etc.
8. Time slice: for data received within a time window.

The use of parameters 5, 6, 7 and 8 is optional. Quality-control information can be retrieved if required but it should be noted that only the preferred report is returned when using normal retrieval routines. On the GTS an observation can be received several times, not always in identical form, and hence the SDB software has to decide upon the best report available. Other versions are not rejected nor, in the past, have they been made available through normal retrieval software; however, during 1985 a further option was provided enabling all versions to be retrieved.

To decide upon the preferred report the following points are considered:

(a) Are the observations in question identical? If there are no differences detected the newest observation is not stored.

(b) Are the observations of the same length? If the new report is identical with the original as far as the original goes but the new report is longer, then the new report becomes the preferred report.

(c) A correction (CC or COR) report will always replace an old one independent of the data content.

(d) Two reports not identical are both stored but the preferred one is the longer or the one with the fewest quality-control flags raised.

Fig. 7 shows the three stages of a SYNOP through the SDB, ending with the final character retrieval of the observation displayed on a computer terminal.

DATA ON GTS:

↓ZCZCΩ
↓SMUKΩEGRRΩ↑110900<<≡
↓AAXXΩ↑11094<<≡
03318Ω41465Ω82435Ω11093Ω20085Ω49897Ω56057<<≡
77562Ω88511Ω333Ω82615Ω88622Ω90998Ω91149<<≡
91235Ω555Ω1//49=↓<<≡≡≡≡≡≡

CLEANED UP:

83 EGRR 541 0 4 0 83

11-byte information header
(as yet incomplete)

03318414658243511093200854989
75605777562885113333338261588
62290998911499123555555 1//49

PASSED TO QC ROUTINE — ERRORS FLAGGED:

VV and ww
TTT and $T_dT_dT_d$
4 added to 'L' as quality-control record is added to the end of the report

CHARACTER FORMAT RETRIEVAL:

87 ** EGRR ** 541 ** 00101001 ** 4 ** 00000000 ** 83
03318 41465 82435 11093 20085 49897 56057 77562 88511 33333 82615
88622 90998 91149 91235 55555 1//49
00000110 01000001 00000000 00000000 00000000 00000000

Figure 7. An example of a surface observation received from the Bracknell Regional Telecommunication Hub. The observation is recognized by the Synoptic Data Bank software as a SYNOP, quality controlled, and then stored in the data bank. When the SYNOP is retrieved in character format the user has available the 11-byte information header, the SYNOP WMO code, and any quality-control bits which are set during the quality-control process.

Data monitoring

Another operational use of the SDB is real-time data monitoring for three applications. First, telecommunication staff need to monitor the flow of data through the automated system to ensure that data for their area of responsibility are not corrupt and are transmitted correctly at the scheduled times.

The second need for real-time data monitoring is for the intervention team in CFO to be able to monitor reports used as input to the numerical forecast suite.

Third, an essential requirement of any data base is to monitor the volume of data received. In a system such as the GTS varies the number of reports received for any type of data varies from day to day. Even within each data type there can be fluctuations because the number of reports varies from hour to hour and even at the same hour from day to day from the same country.

Gross increases or decreases of any type of data can be noted. Synoptic and upper-air statistics are printed out for the whole twelve-hour period for the WMO blocks with a deficiency of 20% or more during any hour that they are expected to report. From this information it is possible, with the help of the Telecommunication Branch, to detect where international links have been cut for a period, and even where alternative links have the wrong bulletin routeing lists. In cases where this has occurred it is possible for telecommunication staff to request a recall of lost GTS data from other Regional Meteorological Centre data bases.

New applications

The Advisory Services Branch is now dependent on retrieving SYNOPs and National Climate Messages (NCMs) from the SDB for archival purposes and also for the preparation of daily plant disease and warning messages for farmers. Examples of these are potato blight, apple-scab and barley mildew warnings. The Meteorological Office Rainfall and Evaporation Calculation Service (MORECS) and other routine services also take and process data direct from the SDB.

To help achieve as complete a set of synoptic and climatological data as possible a monitoring program driven by a list of expected UK synoptic stations supplied by the Advisory Services Branch compiles bulletins of missing or flagged SYNOP reports every hour at HH+30 and at 1130 GMT and 2330 GMT for the 0900 GMT or 2100 GMT NCM reports respectively. These bulletins are sent to all outstations on the MCCA facsimile broadcast requesting them to send or repeat the missing report, or correct the flagged report. Generally it is expected that all missing reports will be re-transmitted within the 24 hours and stored in the current banks, but when this is not practicable the reports can be sent to the SDB up to the last day of the current month, and stored in a 'late' data set for direct accession by the Advisory Services Branch.

This monitoring is vital both to achieve, efficiently, completeness of the archive data banks and for the routine time-critical services to farmers and others.

The archiving staff have less pressing time-scales for their operations and can do considerably more detailed quality-control checks than can be done in the very short time available to the SDB. However, the continuous data flow means that time is not inexhaustible and there are real pressures to complete the archiving and quality-control process quickly.

New types of data

Much more difficult have been recent departures from the original system of transmitting data in character format over the GTS. HERMES satellite data, for example, providing a fine network of thickness and thermal wind information over the eastern Atlantic and western Europe are transferred to COSMOS by a smaller VAX minicomputer within the Meteorological Office. The SDB software operates a 'sideways' transfer from disc for storage in the SDBs.

Another radical departure is the use of a compressed code for SATEMs. These are of considerable importance because they provide a four-fold increase in the number of reports, giving improved coverage in both northern and southern hemispheres. In order to achieve the necessary compression the data are encoded in a complex way quite different from the standard character format.

An expanding service

Finally, there are plans to make the SDB part of a much wider system. Information on present weather conditions in the United Kingdom and Europe, together with gale warnings and reports of coastal and skiing conditions could be made widely available via Prestel and other videotext systems. It is also possible that with increasing automation the SDB could be used to provide global information to the Weather Centres for answering enquiries with little or no delay.

Acknowledgements

My thanks are due to Dr G.W. Bryant, Mr B. Edkins, Mr C. Long and Mrs A. Jackson for their valuable assistance in producing this article.

Appendix — A short glossary of computing terms used

Data set	An organized collection of records. Known as a file in many other computer installations.
Data base	A data set, or several data sets, which is not designed to satisfy a specific, limited application.
Subroutine	A logically subordinate routine that is arranged so that control can be passed between it and the master routine.
Half-word integer	An integer value contained in a two-byte area on the IBM system.

551.551.5:629.7

Transatlantic flight incident

By D.A. Forrester
(Meteorological Office, Bracknell)

Pan American flight PA125, London to San Francisco, experienced severe turbulence, and shot up 1000 feet, over Greenland just before 1700 GMT on 22 January 1985. Several passengers were injured.

The incident occurred as the aircraft was approaching the west coast of Greenland, close to 62° N 48° W. Just before the incident the aircraft measured a wind of 180° / 10 knots, and immediately after the incident the wind was 100° / 100 knots. The aircraft was cruising at 33 000 feet when it suddenly ascended to 34 000 feet, at which point the pilot assumed manual control, then dropped to 32 400 feet and subsequently recovered to 33 000 feet. The turbulence lasted for about 2 minutes.

From the appropriate 12 GMT and 00 GMT Central Forecasting Office 250 mb analyses (Figs 1 and 2) an interpolation was made to assess the likely situation at 18 GMT. This interpolated analysis has been transferred to the two charts containing plotted aircraft reports (Figs 3 and 4). The evidence indicates that the jet on the western side of the ridge, which extended to Greenland, is bifurcated near the area where the incident occurred.

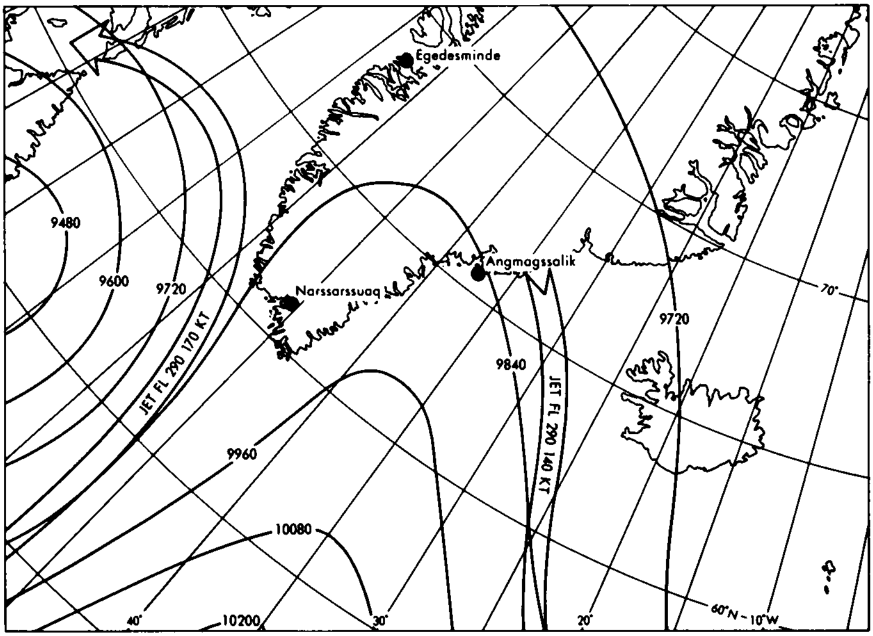


Figure 1. 250 mb analysis chart for 12 GMT on 22 January 1985. Contour values in geopotential metres. (Note: the terms KT for knots and FL for flight level are standard usage in aviation meteorology.)

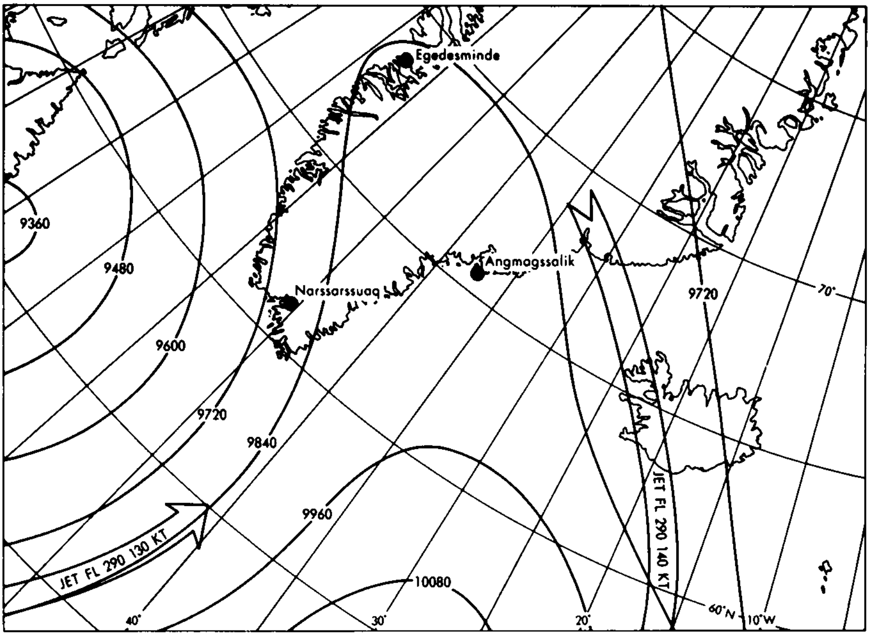


Figure 2. As Fig. 1 but for 00 GMT on 23 January 1985.

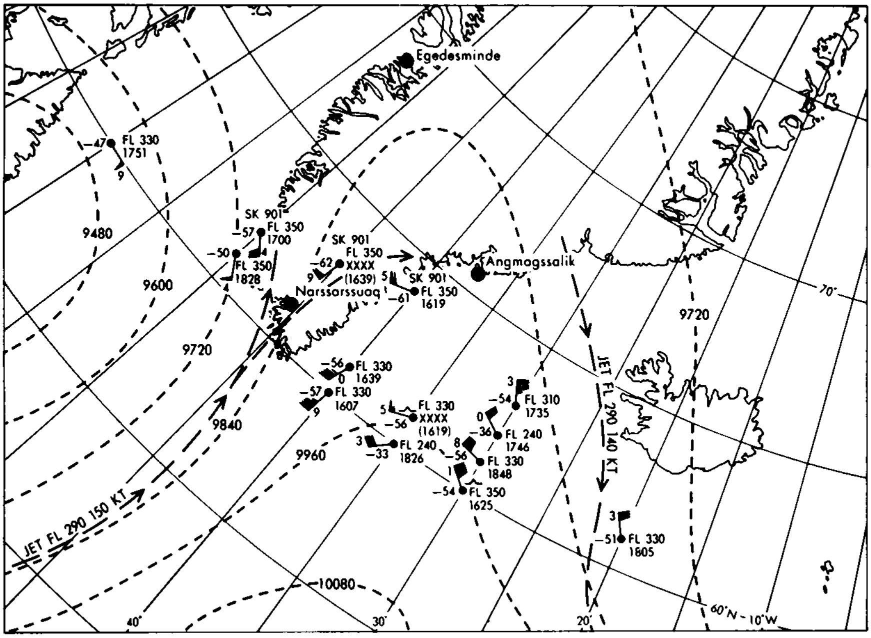


Figure 3. 250 mb contour chart for 18 GMT on 22 January 1985 interpolated from Figs 1 and 2. Aircraft reports are included giving flight level (FL), time of report (GMT), temperature (° C), and wind direction (tens figure is plotted beside the arrow) and speed (knots: long feather — 10, solid triangle — 50). The symbol ⌒ indicates moderate turbulence at time of report. (Note: Where the exact time of report is not known XXXX is plotted with the time of receipt in brackets below.)

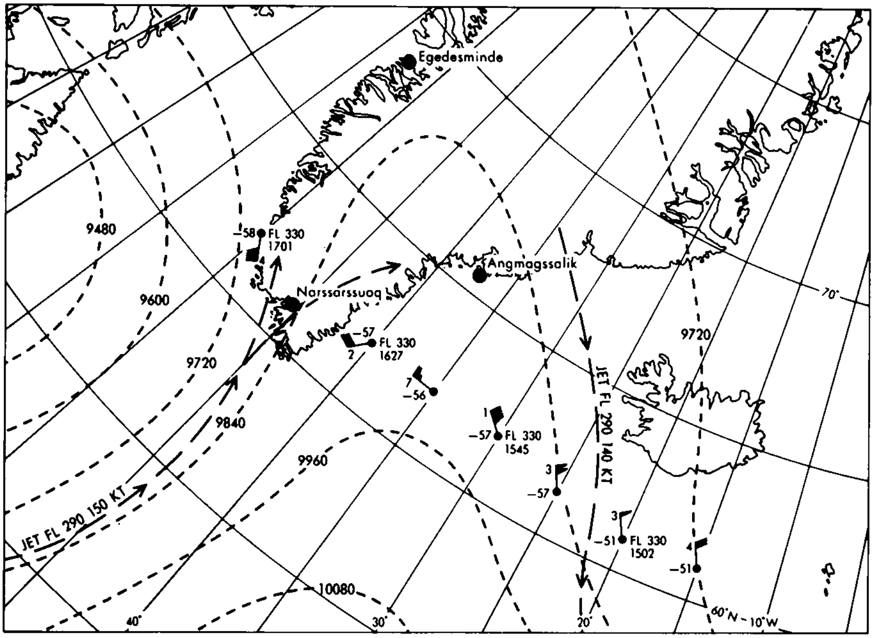


Figure 4. As for Fig. 3 but all aircraft reports are for Pan American flight PA125.

The computer Clear Air Turbulence forecast chart (Fig. 5) shows an area of 4% and 6% probability associated with the jet over south-west Greenland, and indeed the bifurcation can be seen quite clearly on this chart.

It is clear from the available aircraft reports and from the analysed charts, that the aircraft travelled from the eastern branch of the bifurcated jet through a zone of relatively light winds into the western branch of the jet. Thus it is not surprising that turbulence was encountered. Indeed this is a classic situation for the formation of clear air turbulence (Roach 1969). Moreover the tropopause was at about 260 mb and this may have intensified the vertical shear of the jet, thus increasing the chance of severe turbulence.

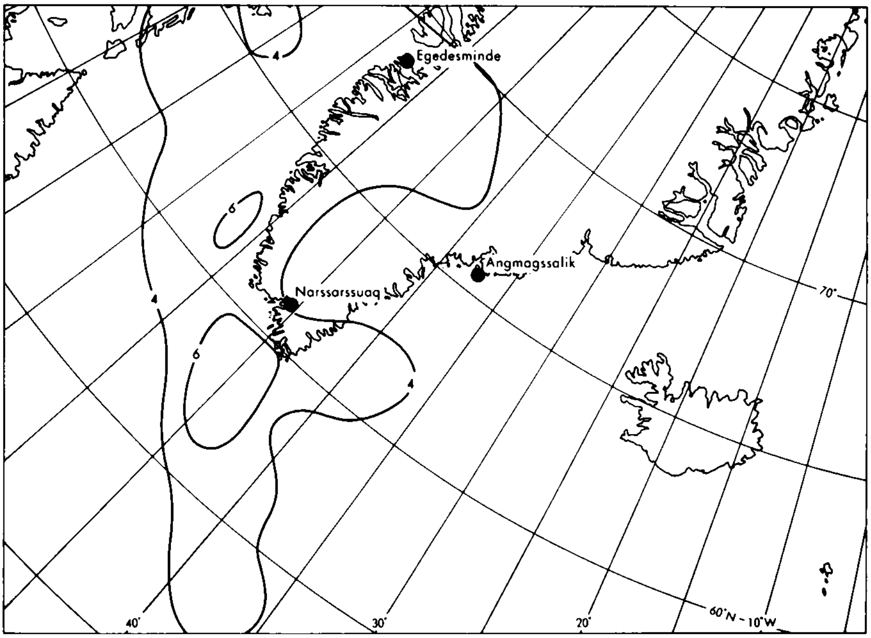


Figure 5. Computer 18-hour Clear Air Turbulence (CAT) forecast chart for 18 GMT on 22 January 1985 showing probability (%) of moderate or severe CAT at 250 mb.

Concerning the possibility of mountain waves, unfortunately ascents from the nearby upper-air station (Narssarssuaq) are not available for the day in question. The nearest ascents (Egedesminde and Angmagssalik) are to the north and not felt to be representative of the area in question. However, both these ascents do show some evidence of the possibility of mountain waves (stable layers with winds increasing with height). The available surface observations contain no firm evidence of cloud associated with mountain waves. However, although the presence of mountain waves cannot be discounted, it is felt that the incident can be explained satisfactorily without them.

Reference

Roach, W.T. 1969 Some aircraft reports of high-level turbulence. *Meteorol Mag*, **98**, 65–78.

551.509.52:551.509.53

Improved accuracy of international aviation forecasts of winds and temperatures

By N.D. Gordon
(New Zealand Meteorological Service)

In September 1980, a computer system providing forecasts of upper-level winds and temperatures for international aviation over the south-west Pacific was made fully operational in Wellington. This replaced a manual system where forecasts were produced for mid-latitudes in Auckland, and for the tropics in Nandi.

The manual and computer systems had been run in parallel for several months earlier so that their accuracy could be compared. As reported in Gordon and Purnell (1982), the root-mean-square (r.m.s.) vector-wind errors of the computer-derived forecasts at 250 hPa were reduced to about two-thirds of the errors of the manual forecasts. The computer and manual temperature forecasts were of comparable accuracy.

This computer system ran with little modification until the end of July 1985 when the new World Aviation Forecast System (WAFS) was implemented in New Zealand. Under this system, forecasts for the entire globe are produced in two World Area Forecast Centres (WAFCs) — Washington in the United States and Bracknell in England — and provided to Regional Area Forecast Centres (RAFCs) around the world. The Wellington RAFC receives data over most of the globe from the Bracknell WAFC, then distributes it in appropriate form to users.

For the month of August 1985, the old New Zealand computer system was kept in operation, without issuing any forecasts based on it, so that comparative verifications could be done. These verifications were against observations, as described in Gordon and Purnell (1982), with forecasts bilinearly interpolated from the centres of the four surrounding five-degree 'squares'. (This is the resolution on which the old forecasts were issued.) The WAFS forecasts are issued on a different grid of generally higher resolution, but for verification purposes have been bicubicly interpolated to the same points as the old system. The WAFS errors would probably be a little lower if the interpolation were from the original WAFS grid.

Verifications were done separately for the tropical south-west Pacific (north of 25° S from 145° E to 145° W), and for a mid-latitude area that corresponds to the old Auckland manual-forecast area — essentially from 25° S to 45° S and from 150° E to 160° W. Although five levels were verified at the four standard synoptic hours, for brevity Table I gives just two levels for 12-hour and 24-hour forecasts verifying at 00 GMT, the time of the most complete data coverage.

It should first be noted that, probably owing to the influence of the subtropical jet at this time of year, wind and temperature errors typically peak around August. Therefore, worst case errors are being considered here.

The table shows that the errors from the old system for August 1985 are almost all lower than the August average for the preceding five years. None the less, all the WAFS forecasts improve on the old system.

For winds, the percentage improvements are generally larger in mid-latitudes than in the tropics, larger at the higher level of 250 hPa, and larger for the longer-range forecasts of 24 hours. The best improvement is a reduction of 34% (from 28.7 to 19.0 kn) for 24-hour 250 hPa forecasts in mid-latitudes. Day by day values of the 250 hPa r.m.s. wind errors show that the WAFS forecasts have consistently lower errors than the old system, being bettered by it on only one day (August 29) in the entire month.

Table I. *Root-mean-square errors for 12-hour and 24-hour forecasts verifying at 00 GMT for winds (kn) and temperatures (°C) at two levels together with the percentage improvement of the WAFS forecasts over the old system for August 1985*

12-hour forecasts

	Tropics				Mid-latitudes			
	500 hPa		250 hPa		500 hPa		250 hPa	
	kn	°C	kn	°C	kn	°C	kn	°C
Original (unmodified)								
(Average for Augusts 1980–84)	14.6	2.05	19 5	2.34	17.2	2.37	27.7	3.70
Old system								
(August 1985)	12.4	1.60	17.9	1.91	15.7	3.11	25.1	3.74
WAFS 1985	11.6	1.47	16.4	1.75	14.7	2.68	18.6	3.13
Improvement (%)	6	8	16	8	6	14	26	16

24-hour forecasts

	Tropics				Mid-latitudes			
	500 hPa		250 hPa		500 hPa		250 hPa	
	kn	°C	kn	°C	kn	°C	kn	°C
Original (unmodified)								
(Average for Augusts 1980–84)	16.4	2.14	23.0	2.17	19.0	2.61	33.1	3.66
Old system								
(August 1985)	13.9	1.62	20.9	1.71	17.6	3.11	28.7	3.48
WAFS 1985	11.8	1.54	16.5	1.69	15.5	2.57	19.0	3.34
Improvement (%)	15	5	21	1	12	17	34	4

The percentage improvement of the WAFS temperature forecasts over the old system is generally smaller in the tropics and, if anything, decreases a little for the longer forecast period. This could be because the temperature errors for the old system were dominated by the statistical uncertainty of deriving temperatures from forecast height fields, with no systematic increase from 12-hour to 24-hour.

In conclusion, the wind and temperature forecasts based on data from the WAFC in Bracknell are an improvement over the previous computer system in New Zealand, with the largest increase in accuracy — 34% — coming in 24-hour forecasts of high-level mid-latitude winds. The old computer system was discontinued in early September.

Reference

Gordon, N.D. and Purnell, D.K. 1982 The aviation grid wind and temperature system. *Tech Note* No. 249. New Zealand Meteorological Service.

Notes and news

A Summer School on 'Mesoscale meteorology'

A residential Summer School is a new occurrence in this country. The first one ever to have been organized was held at the Meteorological Office College at Shinfield Park, Reading, during the week from 8 to 12 July 1985. The subject was 'Mesoscale meteorology' and over 75 people attended. They came from a variety of backgrounds, with the Meteorological Office and the Universities, notably Reading, providing equal inputs into the venture. In the planning, lecturing and in the numbers of participants involved, this was a new, combined operation, which it is hoped will be the forerunner of similar ventures in the future.

Many of the Office staff who attended were research workers, but there was also a significant contingent of active, operational forecasters. These were drawn from both the Central Forecasting Office at Bracknell and from the outfield, and others involved in the School had had similar experience in the past, so that the available forecasting expertise was quite large.

The University participants came from a dozen different Institutions. The University of Reading was well represented, as was Imperial College, and an international flavour was provided by a group of six from various centres in France. All of these were involved in mesoscale research in universities at some level, either in the forefront of scientific developments in the subject or as students doing advanced projects leading towards higher degrees.

There was therefore a numerical preponderance of research workers, but the presence of the practising forecasters was an element that was essential to the purpose and the character of the School. One of its central objectives was indeed the creation of an environment in which leading experts from both the theoretical and practical ways of meteorology could meet and talk together for an extended period, and enlarge each other's understanding. It is on this aspect, as seen from the forecaster's viewpoint, that this review concentrates.

Participants at the Summer School on 'Mesoscale meteorology' held at Shinfield Park, July 1985.

Sitting at the right-hand end of the front row are the Organizing committee (from the right: Dr K.A. Browning, Dr C.J. Readings, Prof. B.J. Hoskins, Dr B.W. Golding).

The daily timetable was straightforward. Lectures in the morning were followed by practical, mesoscale analyses of relevant case-studies in the afternoon. The lectures were delivered by acknowledged experts of whom it must suffice to mention a small number from the Meteorological Office (Dr K.A. Browning, Dr B.W. Golding and Dr M.J.P. Cullen) and the Universities (Prof. B.J. Hoskins, Dr A.J. Thorpe, Dr M.W. Moncrieff and Dr M. Miller). The lectures were good — authoritative and well-presented — and provoked some informed and interesting discussion. They formed a coherent series during the week; starting with Dr Browning's initial overview, and going on to cover the two broad areas of 'frontal mesoscale phenomena' and 'mesoscale organization of convection', which were the main topics of the School.

Individually, the lectures made varying demands on the audience. From the forecasters' point of view the straightforward ones were those which described observed phenomena, or models (either conceptual or numerical). Much of the material covered in this area has already been published (see Browning (1985), Golding (1984)). Even so there was great value in hearing it described by the authors and discussed by others at first hand. Much more demanding were those lectures which took us from the observations (the daily currency of forecasters) to physical understanding (the realm of theoreticians). Though the organizers of the School had imposed a moratorium on over-much mathematics, some inevitably crept in. This had predictable consequences for those who are not paid to spend their working lives using such concepts directly, but on the whole the cries of the drowning were relatively infrequent and resuscitation was available to all who needed it.

Certainly it was no easy matter to assimilate lectures which presented, perhaps for the first time, such heirarchies of ideas as 'vorticity — potential vorticity — isentropic potential vorticity'; or 'upright instability (CAPE) — slantwise instability (SCAPE)'. For many it was in something of an intellectual daze that concepts such as Q–vectors, density currents, Lagrangrian equations and much else came floating up from the front of the lecture theatre and over their heads. Looking back at the Summer School now, a need for improved preparatory literature can be seen. The *Lecture abstracts* which were available at the start of the School were not too helpful, in as much as they were concerned with generalizations rather than the particular concepts which became important in relation to the practical project work. It would have been helpful to many to have had some better record of these concepts.

But certainly it had been clearly recognized by the organizers that it would be hard work absorbing new ideas in the relatively short time available in the lecture periods. Complementary practical work was therefore carried out in the afternoons, in seven parallel groups. Each group was a carefully arranged mix of people drawn from a variety of backgrounds. In practice it took a day or two for the individuals within each group to learn to work and talk freely to each other, as there were considerable differences in both thinking patterns and working patterns between the forecasters and the researchers in each group. But it was in these groups that the meeting of minds slowly took place, catalysed and fertilized by the lecturers and other staff who were constantly available to encourage and discuss the work of individuals in each group.

To what extent the School succeeded in bringing the forecasters and the theoreticians together in any permanent sense is hard to say. The week passed all too quickly and just as it felt that real progress was starting to be made, it was time to disperse. It is hoped that no narrow assessment of its value will be made, for the School was a totally new venture and surely a very valuable one which should be repeated. It must be good for research workers to expose their ideas to the test of routine observations, and for forecasters (that most conservative group of people) to assimilate theoretically sound ideas into their pragmatic working routine. It is greatly to be hoped that Summer Schools of this kind become a regular occurrence, bringing the operational and research wings of meteorology in this country into close, regular contact.

P.G. Wickham

References

Browning, K.A. 1985 Conceptual models of precipitation systems. *Meteorol Mag*, **114**, 293–319.

Golding, B.W. 1984 The Meteorological Office mesoscale model: its current status. *Meteorol Mag*, **113**, 288–302.

Reviews

World-wide weather, edited by K. Takahashi. 160 mm × 242 mm, pp. xv + 252, *illus*. A.A. Balkema, Rotterdam, 1985. Price £17.50.

World-wide weather is a recently published translation of a Japanese text first published in 1975. It consists of a collection of 30 essays by 20 authors on various topics, ranging from the general circulation to ice-floes and icebergs. With such a diversity it is little surprise that each topic is treated superficially.

The book is neatly divided into three parts. The first sets the scene and deals with climatic change, solar energy and water. The next describes the meteorological characteristics of various regions and the last section briefly looks at the relationship of weather and human activity. The intention of the editors is to introduce to the general reader various world-wide weather phenomena of current interest and in this they have, by and large, succeeded. However, for today's reader, the ten years that have elapsed since first publication mean that the current problems of the sub-Sahara do not receive sufficient attention. It is good to see a chapter devoted to the widening of deserts but ideas on controlling and even making deserts fruitful are made to sound very simplistic.

Having been written for a Japanese readership many of the topics are concerned with meteorological phenomena of south-east Asia. The rest of the world, however, is not forgotten and there is, for example, a simple but good description of El Niño. Even so we are reminded that the 1972 occurrence eventually led to an astronomic rise in the cost of soya bean cheese in Japan! Several of the essays have been written from personal experience and reminiscences. Occasionally, this seems out of keeping in such a book when, for example, the author on tropical cold waves writes in a style more akin to travel journalism.

The editors, in their preface, state that there are some unresolved differences of opinion. One presumes they must be referring to some of the misleading statments such as 'big cities like Tokyo no longer have cold winters because of heat produced by human activities' or '... a computer can now (1975) forecast the occurrence of a tornado'. Unfortunately, an otherwise admirable book is spoilt by a number of minor errors and omissions. Too many of the diagrams are difficult to interpret because of their size and the one showing annual wind roses for a number of places in the British Isles has several errors. There are no photographs and in places, in the reviewer's copy, the printing is poor. Even in these days of high prices one would have expected rather better value for money.

This is certainly a book for the general reader and it brings together descriptions of a number of global weather features. However, even the most casual reader will probably be left at times wanting to know more and unfortunately the bibliography is poor — apparently because of the limited number of standard works translated into Japanese. As it stands, it is difficult to see this book finding a place on many western bookshelves.

C.H. Kensett

Climate and history, edited by T.M.L. Wigley, M.J. Ingram and G. Farmer. 150 mm × 230 mm, pp. xii + 530, *illus*. Cambridge University Press, 1985. Price £15.00, US $24.95.

It is good to see that this volume, which arose from a conference on 'Climate and History' held at the University of East Anglia in 1979, is now available in paperback at half the price of the hardback edition of 1981. It is not just a symposium volume; the editors have gone to a good deal of trouble to select the most important contributions to the conference and the result is a volume of immense value to those actively engaged in a wide range of related scientific disciplines.

The first part is a lengthy but excellent introduction which is very well balanced. The editors do not assume that climate has determined history to any great extent; indeed they emphasize the many pitfalls in any such assumption. Human communities vary considerably in how they adapt to environmental changes. For instance, the Norse colonization of Greenland which failed around AD 1500 was probably only subjected to a small deterioration of climate which did not greatly bother Eskimos living in the same area. Even the abandonment of marginal land may be due to changes in agricultural methods, prices or other social or economic changes rather than to changes of climate.

The second part of the book consists of nine chapters, six of which outline the various methods now used to reconstruct past climates. There are comprehensive chapters on: 'the use of stable isotope data','glaciological evidence', 'pollen analysis', 'tree rings', 'archaeological evidence' and 'documentary sources'. It becomes clear that all these methods face considerable difficulties in attempting to reconstruct past climates; it is essential to try to integrate the results from several methods before reasonably reliable conclusions can be reached.

The last three chapters of this section are specific examples of what can be achieved. The reconstruction of the Little Ice Age climate of Switzerland by Pfister forms an outstanding chapter while the other two chapters on 'the historical climatology of Africa' and 'droughts and floods in China (from 1470)' are interesting but of a somewhat lesser calibre.

The next five chapters form a section entitled 'towards a theory of climate–history relations'. There are contributions from H.H. Lamb and H. Flöhn who stresses the importance of short-term climatic fluctuations such as three successive cold winters. Flöhn also makes the point that persistent anomalies in one region will normally be accompanied by anomalous periods in other widely separated regions. The best contribution in this section is that by M.L. Parry who attempts to put matters on a scientific framework. He suggests, for example, that the relationship between the present yield of oats and climatic parameters can be used to estimate the climate when the crop failed in the past.

The fourth section of the book contains five so-called case studies of climate–history interactions. These make interesting reading but do not entirely support the idea of a strong connection between climate and history. Shaw, for instance, suggests that the decline of north African population since Roman times may be partly due to man's destruction of the forests and animals, while McGovern alleges that the decline of the Norse population in Greenland mentioned previously was caused primarily by a lack of adaptation to a small shift of climate. Sutherland shows that in Brittany during the period 1780–89 peasants were able to adapt to a run of poor harvests owing to bad weather although children suffered. In Maine, decline in agriculture between 1785 and 1885 seems to have been primarily due to movement of the population to better land elsewhere. Mooley and Pant follow with an interesting study of droughts in India over the last 200 years and conclude that they are random occurrences. The last chapter considers the effect of climatic fluctuations on human populations. It discusses population changes in the Tigris–Euphrates Valley from 6000 BP, the Sahel 1910–74 and the US Great Plains 1880–1979. It is suggested that populations can adapt to climatic events which occur more often than once in 100 years but rarer events may result in a catastrophe. The causes of the huge population changes (from less than 100 000 to about 2 million) which have taken place in the Tigris–Euphrates area over the last 8000 years remain uncertain but climate appears to have played a rather small part.

This excellent book is very readable, and the new cheaper paperback version should encourage those working in the many scientific disciplines concerned with climate and history to purchase their own copy. The delay of six years since the original conference has not made the volume out of date to any noticeable extent.

R.A.S. Ratcliffe

Books received

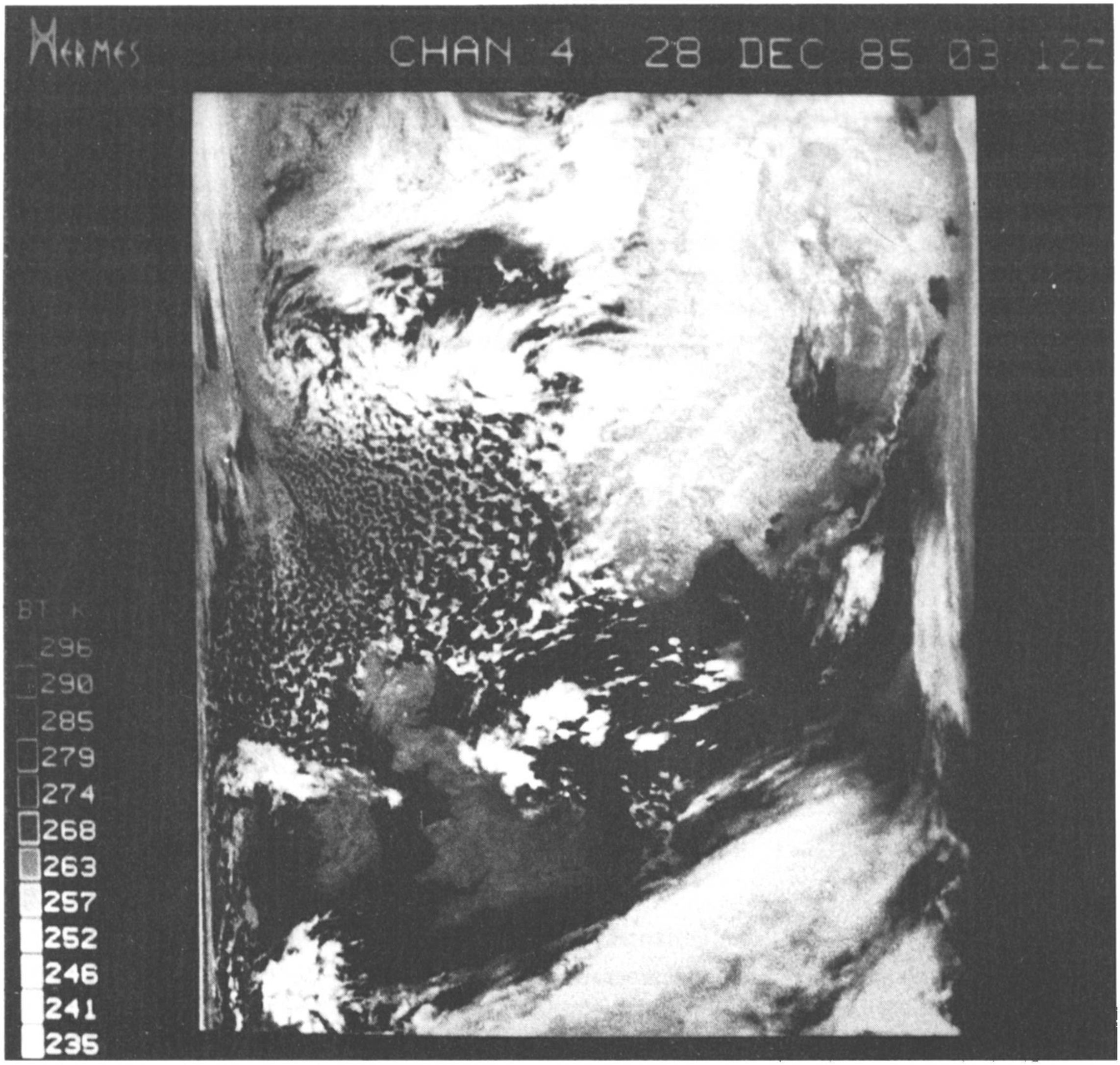
The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Climate and history, edited by T.M.L. Wigley, M.J. Ingram and G. Farmer (Cambridge University Press, 1985. £15.00) now published in paperback, is a collection of 20 papers including discussions of the climatic information obtainab le from the study of chemical isotopes, glaciers, pollen remains, tree rings, archaeological materials and documentary sources. Later chapters analyse the theoretical and methodological problems involved in assessing the impact of climate and climatic change on past societies, and then provide a series of case studies arguing for or against the importance of climatic factors in human affairs in specific economic, social and cultural contexts.

Intrinsic geodesy, by Antonio Marussi; translated from the Italian by W.I. Reilly (Berlin, Heidelberg, New York, Tokyo, Springer-Verlag, 1985. DM 160) is a collection of articles embodying Antonio Marussi's principal contributions to geodetic theory between 1950 and 1981, many translated into English for the first time. His objective was to turn geodetic theory away from its preoccupation with two-dimensional (spheroidal) geometry and to redirect it to the consideration of three-dimensional space. This change, made necessary by the coming of EDM and satellite techniques, was achieved by applying Gauss's differential geometry to the description of the earth's gravity field in terms of elements that are both intrinsic to the field and directly observable. The method was applied to both actual and normal gravity fields, and was extended to the study of the conformal representations between their respective equipotential surfaces, and further to the analogous problem of the propagation of light in a refracting medium.

Tornado! Proceedings of the first conference on tornadoes, waterspouts, wind-devils and severe storm phenomena, Oxford Polytechnic 29 June 1985, edited by G.T. Meaden and D.M. Elsom (Artetech Publishing Co. (54 Frome Road, Bradford-on-Avon, Wiltshire BA15 1LD), 1985. £10.00 hardcover, £3.00 softcover.) As the title indicates, this volume presents the proceedings of Britain's first national conference on tornadoes and other severe storm phenomena, held at Oxford Polytechnic on 29 June 1985. There are chapters on the Tornado and Storm Research Organization (TORRO) — by whom the conference was sponsored — and on the work of its divisions (Tornado, Thunderstorm and Hailstorm). There are other chapters on whirlwind types, the incidence of tornadoes in Britain together with accounts of the most damaging tornadoes known to have occurred, tornado damage to buildings, the spatial and temporal distribution of British thunderstorms, and ball lightning. The book concludes with several case studies of recent tornadic phenomena, including photographs and eye-witness accounts. This volume summarizes over a decade of painstaking and detailed research by TORRO into the distribution of tornadoes and allied phenomena in Britain, and contains much valuable information to workers in the field of severe convection studies.

Satellite photograph — 28 December 1985 at 0312 GMT



The satellite picture is an infra-red image from the NOAA-9 polar-orbiting satellite at 0312 GMT on 28 December 1985. The image has been processed on the HERMES computer system.

On 26 December the British Isles experienced a change of airstream from the mild west or south-westerly type which prevailed for much of December to a northerly type and this lasted for three days. The surface analysis for 0600 GMT (Fig. 1) shows the main synoptic features a little after the time of the satellite picture. There was a deep depression near the North Cape, Norway and a ridge of high pressure extended south-eastwards across Iceland towards southern Britain. The northerly flow between Iceland and Norway was very unstable to relatively high surface temperatures over the sea. Near the Norwegian coast, the cells had an open structure characteristic of deep convection whilst further to the west the cells were elongated owing to the stronger flow. A trough at about 65° N appeared to have circulations near the Norwegian coast and between 5° W and 10° W. The latter was probably a polar low and its circulation was still identifiable in the Irish Sea some 24 hours later.

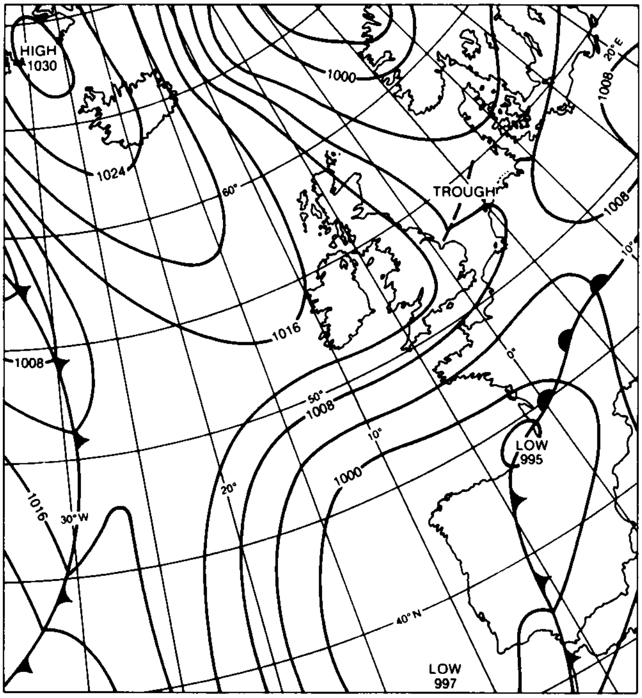


Figure 1. Synoptic situation at 0600 GMT 28 December 1985.

It was a very cold night with minimum temperatures in the range −5 to −10° C over many areas and as a result the British Isles contrast well with the relatively warm sea temperatures of around 7 to 11° C.

The trough approaching East Anglia was more active when it was over the north of Scotland early on 27 December although even here snowfall was variable, Invergordon reporting 35 cm of snow but Aviemore only 1 cm. The higher sea surface temperatures were required to maintain convection, and it was most intense just behind the surface trough. Sheltered areas to the north therefore remained dry whereas the north-east coastal strip of England experienced heavy snow showers. RAF Boulmer near Alnwick in Northumberland accumulated 21 cm of snow and the town of Whitby was reported to be cut off for a time. The satellite picture shows shallower cloud associated with the trough over and just to the east of Lincolnshire. The trough weakened further as it moved southwards but still gave light snow showers in East Anglia and parts of the south-east. Coastal regions on the western side of the country remained free of snow showers as convection was suppressed by the ridge of high pressure.

The following night the ridge had declined and the trough near 65° N brought snow showers to areas exposed to the northerly airstream, in the west as well as the east.

Letter to the Editor

Odd snowfall at Royal Air Force, Valley

Browning *et al.* in a paper *The use of satellite and radar imagery to identify persistent shower bands downwind of the North Channel (Meteorol Mag,* **114**, 325–331, 1985) state in the second sentence of their *Conclusions*: 'They can give rise to persistently adverse weather over rather narrow but well-defined paths when most other areas are enjoying relatively good weather'.

The forecaster on duty at Valley on the afternoon of 28 November 1969 would certainly agree with this statement! On that date an arctic air mass with record low thickness values moved southward over the British Isles. The gradient wind was from 350 degrees, the direction for 'North Channel showers at Valley'. The first showers of soft hail commenced at Valley around noon but the forecaster was not unduly concerned since records for the Holyhead area going back nearly 100 years gave no indication of lying snow in November. By midnight on that day a succession of heavy showers had deposited 10 cm of snow on the airfield! The snow cover ceased abruptly east of a north–south line on Anglesey about 10 miles east of the airfield. The occasion becomes all the more remarkable when it is realized that the fall on that date remains the record depth of snow recorded at Valley for *any* month during the last 25 years.

A.K. Kemp
(Senior Meteorological Officer)

Meteorological Office
Royal Air Force
Valley
Holyhead
Gwynedd LL65 3NY

Mr T.L. Hunt

It is with regret that we record the death on 25 October 1985 of Mr T.L. Hunt who had been the chief weather presenter at Anglia Television in Norwich for 22 years, until he retired in 1984.

Mr Hunt, who was usually known as 'Michael' or 'Mike', worked in the Meteorological Office from January 1939 to August 1961 when he resigned from his post as a Senior Experimental Officer at RAF Dishforth to begin a new career as a professional meteorologist presenting weather forecasts on commercial television.

He was immensely popular with his viewers for his cheerful, humorous and direct style. On going to Anglia TV he immediately began to set up his own network of 'weather correspondents' in the region, a network that was much denser than the official one, so that he could always give a truly 'up to the minute' report on the progress and development of rain, snow, or fog. In 1983 the Royal Meteorological Society awarded him a share of the FitzRoy prize for his work in applied meteorology. Mike Hunt was always a good friend to, and ambassador for, the Office, and his help in promoting awareness of the Norwich Weather Centre among the people of East Anglia was much appreciated.

Obituaries

Mr A.C. Nicholson

We regret to record the death on 30 October 1985 of Mr A.C. Nicholson, Scientific Officer, who was stationed at RAE Bedford.

'Nick' Nicholson joined the Office as a Scientific Assistant in 1947, and over the next two decades worked at several forecasting outstations including Manchester, Birmingham and London/Heathrow Airports; he was promoted to Senior Scientific Assistant in 1960. In 1969 he joined the staff of the Training School (as the Meteorological Office College was then known) to give instruction to the Assistant Courses on instruments. While there, he met Miss M.D. Pritchard, an Assistant Scientific Officer normally stationed at Gloucester, whom he married in 1979. From the College, he was posted in 1978 to RAF Cardington, moving to RAE Bedford in 1980.

Mr Nicholson enjoyed boating; while at Manchester he had a boat which he used on the canals, and later on he had one on the Thames. He was also keen on motor-cycling, and regularly took leave for the TT races. He was an amiable man, well liked by his colleagues.

Mr M.H. Lloyd

We regret to record the death on 24 November 1985 of Mr M.H. Lloyd, Senior Scientific Officer, of the Main Meteorological Office (MMO), RAF Upavon.

Max Lloyd joined the Office in 1953 as a Scientific Assistant; a period of national service in the RAF soon followed during which he was for a time stationed at Bahrain. From 1956 to 1964 he worked at South Cerney and Colerne; he then obtained promotion to Assistant Experimental Officer and began his career as a forecaster with a posting to Chivenor. Further promotion followed during the next few years, during which he had a tour of duty at Singapore, and in 1978 he was appointed Senior Meteorologial Officer at RAF Brize Norton.

In July 1983, Max Lloyd was appointed Officer Commanding (OC) the Mobile Meteorological Unit (MMU). On return from his first detachment to Ascension Island in December 1983, he was promoted to Wing Commander, OC MMU, and undertook three detachments to the Falkland Islands between February 1984 and September 1985; in addition, he moved to MMO Upavon in 1984 where he became deputy Principal Meteorological Officer.

Max Lloyd will be remembered for his amiable and practical approach to his work and also for his consideration for the staff under his command. His career within the Defences Service Branch brought him into regular contact with the Armed Forces who much appreciated his co-operation and enthusiasm as regards provision of meteorological support. His interests outside the Office were mainly concerned with sport. Indoors he enjoyed darts and snooker. Outdoors he played cricket to Minor Counties standard in the 1950s and more recently his golfing ability won him many friends whilst representing the Office and the Royal Air Force at station level.

His sudden death at the age of 49 came as a great shock to all who knew him.

Meteorological Magazine

GUIDE TO AUTHORS

Content

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

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Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

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 referred to 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.

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Meteorological Magazine

February 1986

Vol. 115
No. 1363

CONTENTS

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ISBN 0 11 727830 0 ISSN 0026–1149

Printed in England for HMSO
Published by HER MAJESTY'S STATIONERY OFFICE
Dd. 736047 C13 2/86

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

March 1986

Met.O.971 No. 1364 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1364, March 1986, Vol. 115

551.576.11

Stratocumulus: an introductory account

By D.A. Bennetts, E. McCallum, S. Nicholls,
(Meteorological Office, Bracknell)
and J.R. Grant
(Meteorological Office College, Shinfield Park)

Summary

This article on stratocumulus is one of a series of teaching papers on mesoscale meteorology developed at the Meteorological Office College. It describes the important physical and dynamical aspects of stratocumulus formation and dissipation, highlighting the roles of radiation, turbulence, subsidence and cloud microphysics. The aim is to provide simple conceptual models which will help meteorologists develop an understanding of this type of cloud.

1. Introduction

Stratocumulus is very common around the United Kingdom and usually occurs in large sheets, sometimes covering areas of about 10^6 km^2. Fig. 1 shows how often stratocumulus of some sort is present in the sky.

The presence of low-level layer cloud significantly affects the radiation balance of the lower atmosphere, thereby modifying both the structure of the boundary layer and the surface energy balance. Consequently, forecasts of boundary-layer phenomena, such as fog formation and dispersal, maximum and minimum temperatures, surface conditions, etc. are highly sensitive to the presence of stratocumulus.

It is difficult to forecast accurately its disperal and possible re-formation after a temporary clearance. In fact relatively little progress has been made towards developing reliable forecasting techniques, making it all the more important that forecasters should understand the physical and dynamical processes occurring in sheets of stratocumulus.

The object of this paper is to provide this physical insight without obscuring basic understanding with too much detail.

2. General features

Most data on the structure of stratocumulus have been obtained in the mid-latitudes from single cloud layers (e.g. stratocumulus near high pressure regions). Subtropical and arctic stratocumulus, as

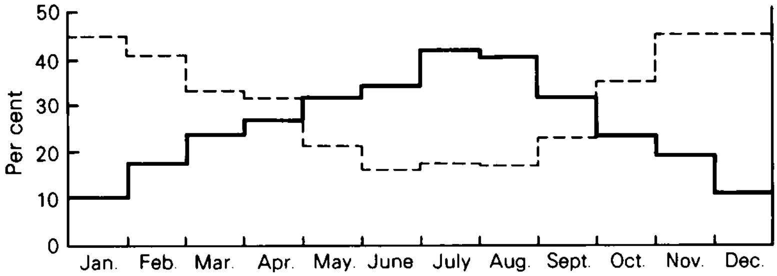

Figure 1. Frequency of occurrence of stratocumulus (pecked line) and stratocumulus mixed with cumulus (bold line) in daytime observations for Boscombe Down 1960–69.

well as multiple layers of stratocumulus, have been less well studied so some caution must be exercised in applying the present results to such cases.

Stratocumulus formation is usually associated with either (a) the cooling or moistening (or both) of the boundary layer, or (b) the spreading out of cumulus beneath an inversion. The general features are best illustrated by reference to an example. Fig. 2(a) shows vertical structure measured by the Meteorological Research Flight Hercules aircraft during a slow descent (solid lines) together with a simplified representation (dotted lines). There are five regions of interest, namely: just above cloud (region A), cloud top (region B), within cloud (region C), cloud base (region D) and below cloud (region E).

Region A – just above cloud

In this region the air is warm and dry, often through subsidence. The air is stable and there is little or no turbulence.

Region B – cloud top

At the top of the cloud layer there is a marked inversion and hydrolapse. This is particularly well defined by the temperature profile. The boundary between the cloud layer and the subsiding air (which is several degrees warmer) has been observed to be as little as a few metres thick, but more generally it is a few tens of metres. The consequent large temperature, and hence density, gradient makes the atmosphere very stable and local perturbations are strongly damped, so that the cloud top is usually fairly flat, although small-amplitude gravity waves are often present.

Wind shear is usually confined to the inversion layer at the cloud top, where it may be large.

Region C – within cloud

Within cloud the air is well mixed, as shown by the temperature profile in Fig. 2(b), (and hence there is little wind shear) and has a constant wet-bulb potential temperature. Since in this example there is negligible precipitation, the total water content of a parcel of air rising through the cloud is conserved.

In discussing the water content of the atmosphere there are two important quantities: the amount held as vapour and the amount held as cloud water. The relation between them is best seen by an example. Consider a parcel of air at the surface at 10 °C with 6 g kg^{-1} of water vapour. Lift this parcel of air, without entrainment, without loss of water through precipitation and without any exchange of heat to or from the environment, from 1000 mb to 800 mb. The cloud base is at 945 mb.

As the parcel rises through the atmosphere above the cloud base the amount of cloud water increases (roughly linearly) while the amount of vapour decreases. In fact the amount of cloud water increases at a value of about 0.7 g kg^{-1} km^{-1} or 1.0 g m^{-3} km^{-1} (the density of air at 1000 mb is about 1.2 kg m^{-3}). This value is referred to as the adiabatic liquid water content. In practice the liquid water content of stratocumulus is always slightly below this value owing to the entrainment of dry air at cloud top (this is

Height (mb)	Humidity mixing ratio of air (g kg^{-1})	Cloud liquid water content (g kg^{-1})	Total (g kg^{-1})
800	3.9	2.1	6.0
850	4.6	1.4	6.0
900	5.3	0.7	6.0
950	6.0	0.0	6.0
1000	6.0	0.0	6.0

revealed in Fig. 2(a) by the departure from the adiabatic value, shown by the dotted line, in the upper part of the cloud). Precipitation would also lower the liquid water content.

Icing on aircraft can be a major hazard in stratocumulus. This will occur with subzero temperatures (below about 10 °C if carburettor icing is considered) and high liquid water content. The latter reaches its maximum value near the cloud top. When temperatures fall below −20 °C most of the water is in the form of ice particles which bounce off the aircraft, i.e. there is little danger of icing. The main danger is in the temperature range 0 to −15 °C when there are many supercooled water droplets which freeze on impact with an airframe.

Region D – cloud base

The transition to clear air at the base of the cloud layer is poorly defined. In contrast to cloud top, the cloud base region has no strong temperature gradients and stability to vertical motion is weak. In consequence, the cloud base is diffuse and large perturbations can grow, as is evident from the rolls that are frequently observed at the base of stratocumulus sheets.

Region E – below cloud

Below cloud the air is also well mixed, with the same wet-bulb potential temperature as the cloud layer. In fact on many occasions the within-cloud and below-cloud regions may be treated as one, even though the potential temperature profile shows a discontinuity at the cloud base.

3. What controls the development of stratocumulus?

Stratocumulus results from interactions between processes having widely differing length and time-scales, in particular:

(a) Synoptic-scale subsidence maintains the inversion and tends to lower the cloud top.
(b) The stratocumulus lifetime of several days implies that radiative effects are important.
(c) Turbulent mixing raises the cloud top. ((a) and (c) are often in near balance.)
(d) The detailed structure of the cloud is defined by the microphysical processes.

We shall consider these four processes separately, then discuss their interaction.

(a) *Motion at the cloud top*

The cloud top is not an impenetrable surface — it merely marks the boundary between clear air and air containing drops. When cold air sinks away from the cloud top some air is drawn down from above the cloud and mixes with the cloudy air. In particular, the downdraughts formed at cloud top must entrain some warm dry air from above the inversion some of which would be replaced by air from within the cloud. It is difficult to observe this process (but see Fig. 2(a), humidity mixing ratio) as it takes place

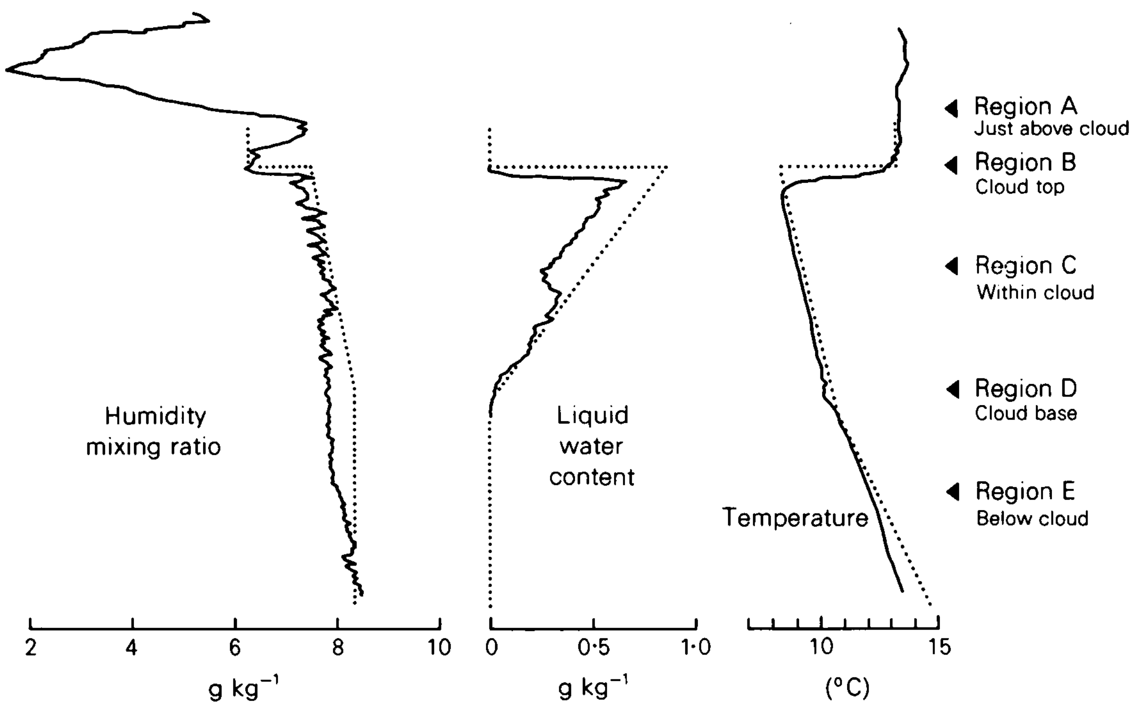

Figure 2(a). An example of the humidity mixing ratio, liquid water content and temperature profiles in stratocumulus. The solid lines show the structure as measured by the Meteorological Research Flight C130 aircraft. The dotted lines show an idealized representation for stratocumulus.

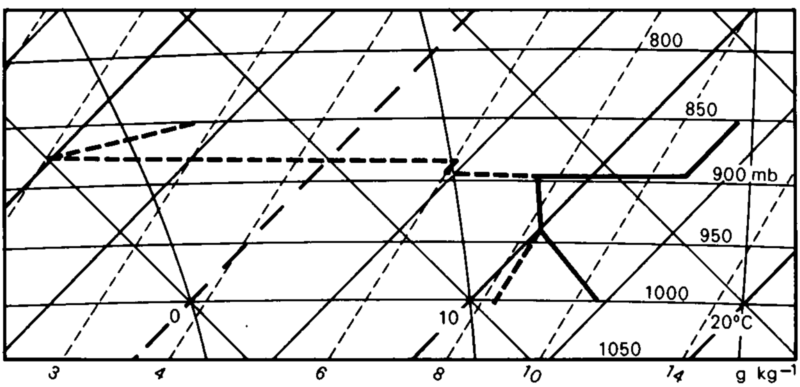

Figure 2(b). Plotted ascent corresponding to the idealized profiles in Fig. 2(a).

within a few tens of metres of cloud top, but over a period of time the effect is to deepen the mixed layer and the cloud top rises. Initially, the entrainment of dry air into the cloud top may decrease the liquid water content of the cloud while the injection of cloudy air into the above-cloud region will produce little visible difference. However, on a longer time-scale the process moistens the region just above cloud top and eventually, given a steady supply of moisture from the ground, the region will reach saturation and the cloud thicken. This effect is opposed by the large-scale anticyclonic subsidence, though the two need not be in balance. In consequence, the cloud layer will locally rise and fall, depending on whether one is stronger than the other. Aircraft observations show that frequently cloud top (and cloud base as well) slopes by 50–100 m per 100 km.

(b) *Radiative effects*

In general, radiative transfer takes place at all wavelengths but in the atmosphere we are primarily concerned with long-wave radiation (4–40 μm) and short-wave radiation from the sun (0.3–3 μm).

(i) Long-wave radiation

Once the cloud is sufficiently deep, typically about 150 m around the United Kingdom, the cloud layer acts approximately like a black body. The main long-wave properties can then be described by considering the radiative balance at cloud top, cloud base and within the cloud layer.

At cloud top, the cloud radiates (loses) energy according to its temperature (about 275 K) but receives very little from the overlying 'transparent' layers of the atmosphere. Cooling rates are therefore large, about 5–10 K per hour, and occur within the top few tens of metres of the cloud. Within the cloud there is little net radiative transfer as all the cloud droplets have a similar temperature, thus energy radiated away from a given volume inside the cloud is almost exactly balanced by that received from surrounding regions. At cloud base, since the ground temperature is usually a few degrees higher than cloud temperature, there is slight warming. Long-wave radiative transfer continues throughout the day and night, and its effect is summarized in Fig. 3(a).

(ii) Solar radiation

It is more difficult to summarize the role of solar radiation because of its variation with time of day, latitude, season, etc. In addition, the albedo of the cloud layer (i.e. the percentage of the incident flux reflected back to space) varies from 40–90%, depending on cloud thickness, drop size, solar elevation, etc. Of that which penetrates, some is absorbed by the cloud (13–15%) while the remainder reaches the ground. Another feature of the solar radiation is that, since it has a shorter wavelength, the depth over which it is absorbed by the cloud is much greater than that for long-wave radiation. Fig. 3(b)

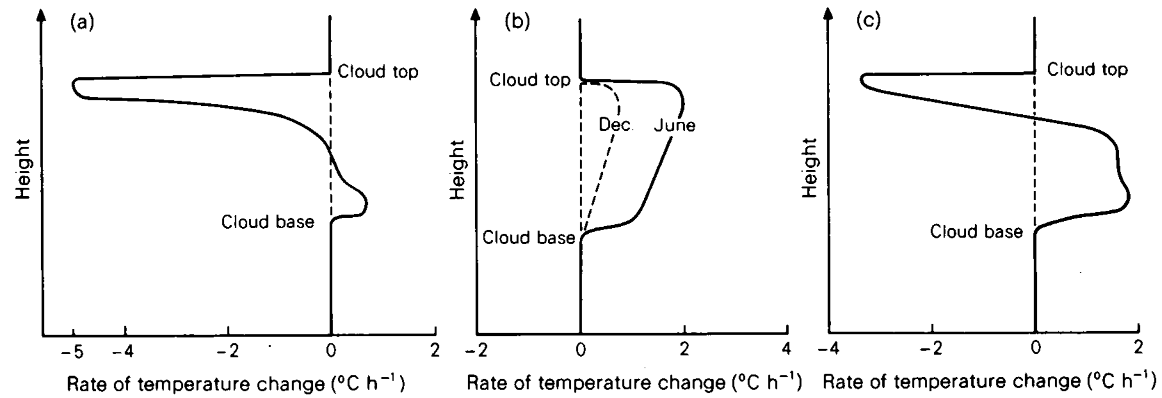

Figure 3. Typical rate of change of temperature profiles for stratocumulus showing (a) the net effect of long-wave radiation, (b) the net effect of solar radiation in the United Kingdom in June (solid line) and December (dashed line) and, (c) the combined effect of long-wave and solar radiation in the United Kingdom in June.

shows the net warming of the cloud in June at midday in the United Kingdom (latitude 52 °N). In winter this would be reduced by a factor of about four owing to the low elevation of the sun (dashed line in Fig. 3(b)) and at night would vanish. The combined effect of long-wave radiation and insolation (for the United Kingdom in June) is shown in Fig. 3(c). Note that in June at midday in the United Kingdom the amounts of solar radiation absorbed and long-wave radiation emitted by the cloud are nearly equal, although their spatial distribution is different. In consequence, stratocumulus may be expected to display significant diurnal changes, especially during the summer months.

(c) *Turbulence and entrainment*

The distribution of radiative heating and cooling, either by day or night, would, by itself, generate convective instability. This is released through turbulent motions which are observed to take the form of cold downdraughts descending from the vicinity of cloud top, with associated warm compensating updraughts. Thus cold air is brought down further into the cloud from the cloud top while warm air ascends. Since the rate of transfer of heat depends on the temperature difference within the cloud the system is self-regulating and, unless the cloud is dissipating or forming, effectively spreads the temperature changes due to radiation throughout the cloud.

However, as the long-wave cooling and solar heating will rarely be exactly in balance, in general the cloud experiences a net cooling. This will be discussed later, in more detail.

(d) *Microphysical structure*

As already stated, the liquid water content within stratocumulus increases roughly linearly with height at slightly below the adiabatic value. However, aircraft measurements show that there is usually little variation of droplet concentration with height (i.e. the number of cloud droplets stays the same but the drops become bigger towards the top of the cloud). The deeper the cloud layer, the larger the drops that form within it, and therefore there exists some critical depth at which drizzle (droplets more than about 100 μm) can form. It would be useful to derive a simple expression for this critical depth.

From microphysical theory there are two relevant facts:

(i) droplets less than about 20 μm radius grow only by condensation, and

(ii) droplets more than about 20 μm radius can grow by coalescence provided they are surrounded by droplets of different size.

Therefore, to produce drizzle, a few droplets must first grow, by condensation, to 20 μm. Thereafter growth by coalescence to produce drizzle is relatively rapid, although the process is complicated by the random nature of droplet collisions. Neighbouring droplets are not all the same size so it is helpful to define a mean droplet radius and to consider a size distribution about that radius. For example, if the mean radius is 10 μm then in stratocumulus one would expect to find drops ranging in size from about 5 to 15 μm, although these limits are not rigid. Thus a few 20 μm particles appear when the mean radius is about 15 μm. Therefore, knowing the critical mean radius (15 μm) at which 20 μm droplets first appear (i.e. the critical mean radius from which drizzle can subsequently form) and the liquid water content, the critical depth of cloud can be calculated provided that we know the number concentration of the cloud droplets.

For example, let the number of droplets be $N\,\mathrm{cm}^{-3}$. Then the liquid water within a cloud is given by $N \times$ (mean mass of the drops). Taking the mean radius as 15 μm the liquid water content equals

$$N \frac{4\pi}{3} \left(\frac{15}{10^6}\right)^3 \times 10^{12}\ \mathrm{g\,m^{-3}}. \qquad \ldots \quad (1)$$

Within stratocumulus the adiabatic liquid water content varies with height at a rate of about

1.0 g m^{-3} km^{-1} (section 2) therefore at the top of a cloud of depth *d* metres the liquid water content is:

$$d\,10^{-3}\ \mathrm{g\,m^{-3}}. \qquad \ldots \quad (2)$$

Equating (1) and (2) we have (very roughly)

$$d = 10N\ \mathrm{m}.$$

This relationship is summarized in Table I. Aircraft measurements have shown that N ranges from about 50 for clean maritime air to greater than 500 for industrial areas in continental regions. There is no way of measuring N from synoptic data but a good estimate can be made by considering the source of an air mass and its subsequent trajectory.

Table I. *An estimate of the depth of stratocumulus containing water droplets only required to produce drizzle at cloud base in a layer with cloud-top temperature above about −5° C*

Air mass	Number of water droplets (N cm^{-3})	Minimum depth of cloud to produce drizzle at cloud base (m)
Very clean maritime	50	500
Maritime	100	1000
Continental	200	2000
Industrial continental	250	2500

Whether or not the drizzle reaches the ground will depend on the humidity of the air below cloud base and local orographic effects that result in increased vertical motion.

Table I refers to stratocumulus cloud containing only water droplets. It provides only a very rough guide since droplet coalescence is a statistical process which has been poorly represented in the above calculations. In real clouds some drops, by chance, grow faster than others; also the effects of turbulence can 'recycle' certain drops allowing them a larger than average time in which to grow. In reality, rainfall production is a very complex process which is difficult to represent simply.

If the stratocumulus layer has a cloud-top temperature below about −5 °C, ice processes can become important and greatly enhance the production of precipitation, thereby reducing the depths in Table I. However, whether or not ice is present, maritime stratocumulus is always more likely to produce precipitation than continental stratocumulus.

Fig. 4 provides a summary of the processes discussed so far as well as indicating energy input from the surface.

4. The interaction of different scales of motion

(a) *Nocturnal effects*

Consider a sheet of stratocumulus in steady state during the day, with a radiation balance as shown in Fig. 3(c). At dusk the solar radiation ceases and the structure of the heating/cooling changes to that

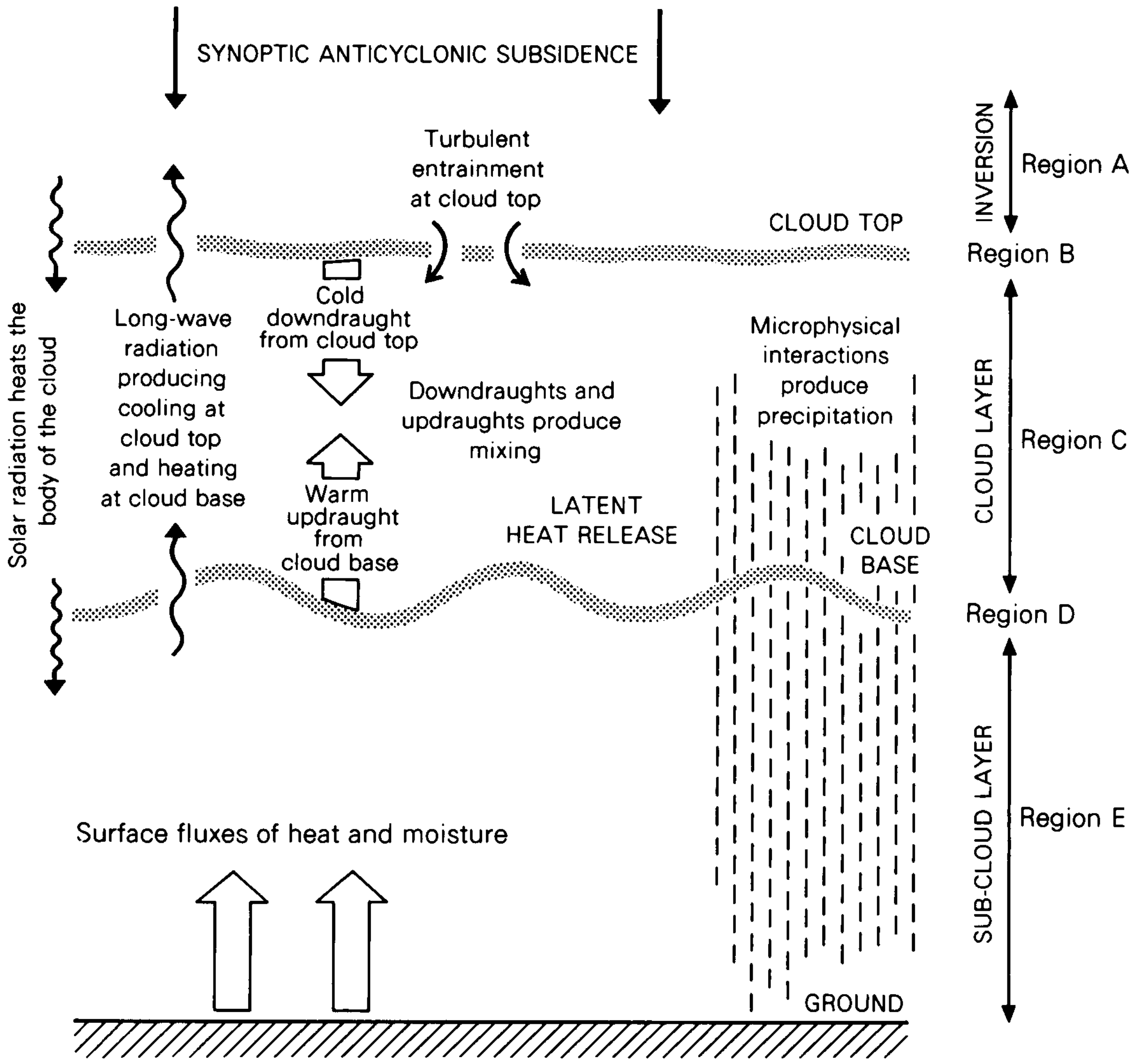

Figure 4. Summary of physical processes important to the development of stratocumulus.

shown in Fig. 5. Compared to daytime, nocturnal stratocumulus has enhanced cloud-top cooling and reduced heating (not zero as there is long-wave radiation from the ground) throughout the body of the cloud. What will happen to the cloud layer? Two competing processes may be considered (Fig. 5).

Process 1:

(i) At night there is a net cooling in the cloud layer.

(ii) Since the water vapour content remains essentially constant, cloud formation is enhanced (this has similarities to fog formation).

(iii) The net effect is that the cloud becomes denser and cloud base lowers.

Process 2:

(i) More cooling at the top and reduced heating at the base change the stability of the cloud layer leading to enhanced turbulence, principally through the presence of stronger downdraughts.

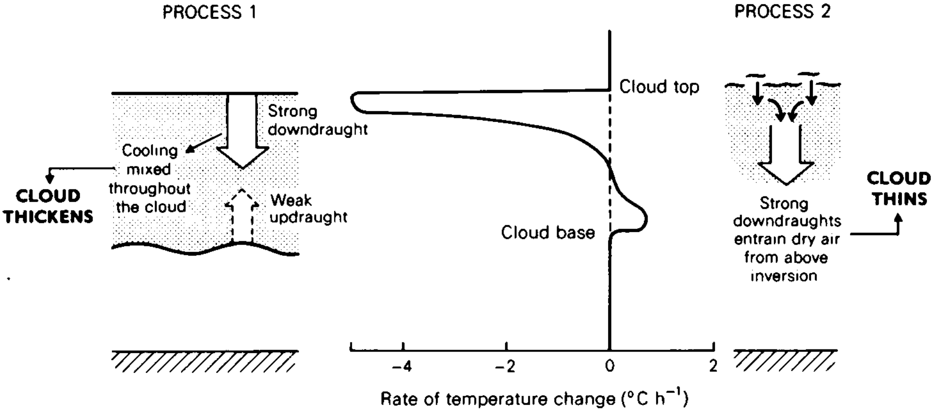

Figure 5. Outline sketch showing effect of the two competing processes on a sheet of nocturnal stratocumulus: Process 1 — radiative cooling at cloud top produces downdraughts which mix cold air throughout cloud layer and cause stratocumulus to thicken, and Process 2 — strong downdraughts entrain dry air which when mixed with cloudy air may disperse the stratocumulus.

(ii) Stronger downdraughts increase the entrainment of dry air from above the inversion.

(iii) If the air above the inversion is sufficiently dry the stratocumulus disperses through mixing.

Therefore at night there are two competing effects, one tending to thicken the stratocumulus and the other tending to disperse it. The outcome depends on the detailed structure of the cloud.

Little effort has been devoted to the investigation of Process 1 since, from a forecasting point of view, the precise details of a cloud layer are unimportant once persistence is assured. Process 2 is much more relevant since if the stratocumulus clears, surface conditions will markedly change. In fact Process 2 is the basis of James's rule (see Appendix 1). This technique was based on a statistical examination of station reports. James (1959) found two parameters to be important: D_m which measures the dryness of the air above the cloud and D_c which depends on the liquid water content and cloud thickness. If $D_m > D_c$ then the air above the cloud is dry enough to evaporate the cloudy layer completely.

James's rule is applicable over land only, mainly because the additional complications of sea surface temperature and the consequent flux of heat and moisture are too difficult to incorporate into a simple rule. It should also be remembered that James's rule is not very reliable because of the difficulty of making measurements accurate enough to distinguish between the two competing physical processes.

(b) *Daytime effects*

Consider now a sheet of nocturnal stratocumulus. As the sun rises, both the main body of the cloud and the ground warm up. At midday the radiation balance is as shown in Fig. 6. Again two processes can be envisaged.

Process 1:

(i) Both the main body of the cloud and the ground begin to warm, eventually achieving a balance.

(ii) The structure of the turbulence changes; updraughts are enhanced due to thermals, caused by the warm ground, penetrating the cloud layer from below, and downdraughts become weaker.

(iii) If the updraughts are sufficiently strong they may penetrate the inversion and induce compensating downdraughts which force dry, above-inversion air into the cloud layer.

This possibility involves a subtle balance. If the updraughts do not reach cloud top then no clearance is possible, indeed the cloud may thicken. Even if the updraughts penetrate the inversion, the air above the cloud top may not be either dry enough or warm enough to induce clearance. It is of crucial importance that the updraughts should be strong enough and the air sufficiently warm and dry to clear the cloud — or perhaps break it into small fair-weather cumulus. This balance of strength of updraught and state of the air above the inversion is reflected in Kraus's rule (see Appendix 2). Note, however, that Kraus's rule (Kraus 1943) only uses the change in temperature across the inversion. This is partly because he was more confident in measurements of temperature and partly because, in subsiding air, the hydrolapse and temperature inversion are often closely linked. Caution is necessary if the air above the cloud is unusually moist or dry.

As with James's rule, Kraus's rule is in practice less than perfect because of the delicate physical balances involved and the difficulty of making sufficiently accurate and representative measurements.

Process 2:

From Fig. 6 it is evident that sometimes the heating due to insolation and the cooling due to long-wave radiation will be of comparable magnitude within the cloud. As discussed earlier the cloud is destabilized causing turbulent motions which produce internal mixing and entrain potentially warmer air through the cloud top. The induced updraughts and downdraughts are now of equal strength and mixing is confined to the cloud layer. To put it another way, if the updraught and downdraught are of different magnitude, mixing takes place throughout the combined depth of the cloud and sub-cloud layers; if they are of equal magnitude, mixing is confined solely to the cloud layer. Thus the motions within the cloud are decoupled from those in the sub-cloud layer.

If this occurs then sub-cloud air no longer enters the cloud and the moisture supply is cut off. We have already seen that owing to entrainment at cloud top and possibly through precipitation there is a steady loss of moisture from the cloud and so if the supply is cut off, cloud base will rise and the cloud will thin and possibly disperse.

Observations show that under these conditions a weak inversion develops beneath the cloud base. If such a feature is observed during the day it suggests that there is evidence that the main cloud layer is beginning to thin and may, depending on its initial thickness, eventually clear. These ideas are discussed in much more detail in Nicholls (1984).

It is important to stress that throughout this section the discussion has concentrated on stratocumulus with radiatively driven convection. In many cases other forms of mixing (e.g. wind shear) may also be

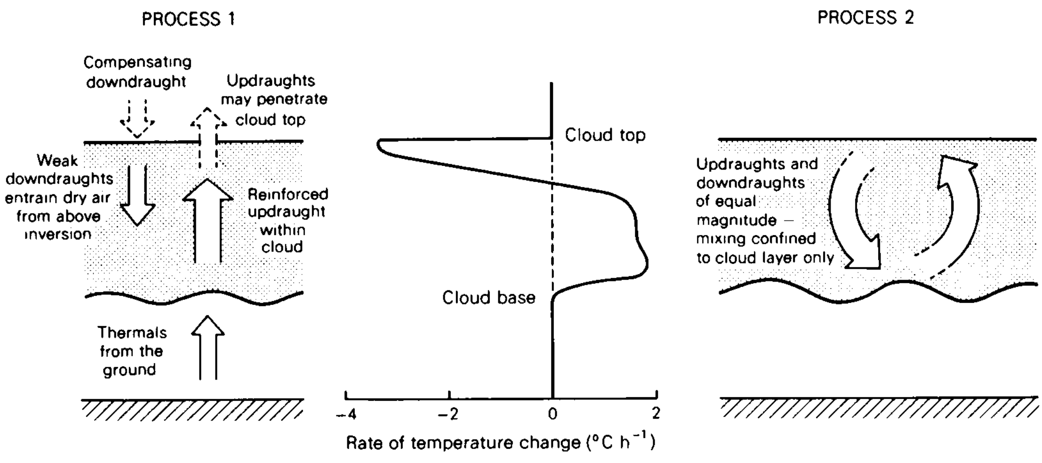

Figure 6. Outline sketch showing effect of the two competing processes on a sheet of daytime stratocumulus: Process 1 updraughts are enhanced due to warming and may penetrate the cloud top causing compensating downdraughts to entrain dry air, and Process 2 updraughts and downdraughts are of equal magnitude confining mixing to the cloud layer only.

important especially if the cloud is at low level or there are very strong winds. Then the cloud may have quite a different structure and behaviour.

5. Conclusion

This paper has attempted to summarize the main features of our current knowledge concerning the formation and dissipation of stratocumulus in simple terms. It acknowledges that stratocumulus remains a major forecasting problem, primarily because the evolution of the cloud is a response to subtle changes in the balance between a number of different, but interacting, physical processes. Forecasting rules are either completely empirical or are based on extremely simplified forms of this balance. Some progress has been made in recent years towards identifying and quantifying the important processes (see for instance the references in Nicholls, 1984). One of the aims of current research is to design numerical models which more accurately reflect these processes. Information from these models plus, it is hoped, more detailed data on an operational basis will result in better forecasts.

It is only by having a clear understanding of the processes involved that forecasters can make the fullest use of the rather meagre information available at present.

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Appendix 1 — *Nocturnal dispersal of stratocumulus over land*

James's Rule

The cloud will break if $D_m > D_c$ where D_m is the maximum depression (° C) of the dew-point below the dry-bulb temperature in the 50 mb layer above the cloud, and D_c is the value given in Table AI.

Table AI. *Values of D_c (° C)*

z (mb)	h (g kg^{-1}) 0.25	0.5	0.75	1.0	1.25	1.5
10	—		1.00	3.0	6.00	8.5
20	0.00	2.5	5.00	8.0	10.00	13.0
30	4.00	7.0	9.00	12.0	14.50	17.0
40	9.00	11.0	14.00	16.0	19.00	21.0
50	13.00	15.0	18.00	20.5	23.00	26.0
60	17.00	20.0	22.00	25.0	27.00	30.0
70	21.00	24.0	26.50	29.0	32.00	34.0

Where h is the difference (g kg^{-1}) between the humidity mixing ratios at the top and bottom of the 50 mb layer below the cloud, and z is the cloud thickness (mb).
Note: a linear hydrolapse in the layer is assumed.

The technique applies under the following conditions:

(i) The stratocumulus sheet is bounded at its top by a large hydrolapse, that is, a rapid decrease of humidity with height through the region of temperature increase.

(ii) There is no surface front within 400 miles of the locality of the cloud sheet.

(iii) The cloud base is above the condensation level of any convection from the sea (the rule applies only to stratocumulus over land).

(iv) The cloud sheet is extensive, covering several hundred square miles, and gives almost complete cloud cover, more than 6/8 for at least 2 consecutive hours. (The cloud was regarded as having dissipated if it broke to 2/8 or less for at least 2 consecutive hours.)

Failures of the technique in day-to-day forecasting can often be attributed to:

(i) inaccurate assessment of the cloud thickness (in the absence of reports from aircraft), and

(ii) uncertainties as to the magnitude and steepness of the temperature inversion and hydrolapse because of the lag of radiosonde elements.

Appendix 2 — *Dissipation of stratocumulus by convection*

Kraus's Rule

A cloud layer will not disperse by convective mixing with the air above if the pressure at the cloud top is less than P_c, as given below. (If the pressure at the top is greater than P_c the cloud may or may not disperse.)

$$P_c = P + a\,(P_o - 1000)$$

where P_o is the surface pressure (mb) and values of P and a are given in Table AII.

Table AII. *Values of P and a (mb)*

Temperature at cloud top (°C)		Magnitude of inversion containing the cloud layer (°C) 10		8		6		4		2	
		P	*a*	*P*	*a*	*P*	*a*	*P*	*a*	*P*	*a*
	20	833	0.80	861	0.83	891	0.87	924	0.90	960	0.95
Water	10	803	0.75	834	0.79	869	0.82	906	0.87	951	0.93
cloud	0	755	0.67	789	0.71	830	0.76	877	0.82	932	0.90
	−10	680	0.56	719	0.60	765	0.66	823	0.73	898	0.84
	0	779	0.71	812	0.75	850	0.79	891	0.85	941	0.91
Ice	−10	702	0.59	739	0.63	786	0.69	839	0.76	908	0.85
cloud	−20	586	0.45	628	0.49	679	0.54	747	0.62	841	0.74
	−30	451	0.30	489	0.34	540	0.38	613	0.45	728	0.58

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Controlling physiological age for maximum early potato production by the use of degree-day recordings

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Summary

This paper describes a graphical method devised to enable the farmer to monitor and control his potato-store temperatures in order to achieve optimum physiological age at the right time. The method is based on records taken in the farmer's store and compared with long-term records of degree-days from a suitable meteorological station.

1. Introduction

Potato growers have long recognized that seed potatoes which had sprouted before planting resulted in earlier crops. Research carried out at the University College of Wales, Aberystwyth and in ADAS over the last decade or so has demonstrated very clearly that the sprout lengths of the seed tubers were directly related to degree-days† above 4 °C. Researchers also found that the number of degree-days affected the yield of the ensuing crop (Hayes 1984). The effect of sprouting seed potatoes by exposure to increased temperatures is an ageing process, appropriately termed 'physiological ageing'.

Any technique which can bring forward the date of harvesting the early potato crop will have obvious financial rewards. The technique of physiological ageing of early potato seed was developed for this reason.

The physiological age (PA) of seed potatoes is measured in terms of degree-days above 4 °C over a certain stage of the life cycle of the seed potato. The optimum PA at planting varies according to potato variety and the intended date of planting. Agronomists have shown that achieving the optimum PA at planting time is an essential prerequisite to a successful crop.

1.1 *Definition of physiological age*

The PA of a seed potato is defined as the number of degree-days above 4 °C (measured in the vicinity of the potatoes) between the date of breaking dormancy and the date of planting. The date of breaking dormancy is said to occur when 50% of the seed tubers in a batch have sprouts of 3 mm or longer. The optimum PA, measured in degree-days greater than 4 °C, depends on the variety and planting date of the potatoes as shown in Table I.

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* ADAS Agricultural Development and Advisory Service the advisory branch of the Ministry of Agriculture, Fisheries and Food (MAFF)
WOAD Welsh Office Agriculture Department

† Degree-days are the integrated sum of temperatures above a given threshold (in this case 4° C) for a continuous temperature curve. A sine wave is used to estimate the daily temperature curve based on maximum and minimum temperatures. Empirical formulae incorporating maximum and minimum temperature and base temperature give the daily increment to the °C day total. The Meteorological Office preferred term is 'accumulated temperature', see the *Meteorological Glossary* (Meteorological Office 1972). However, industry, particularly heating engineers, prefers to use the traditional term of 'degree-days'.

Table I. *Optimum physiological age of potatoes at planting (degree-days above 4 ° C)*

Variety	Planting date	
	Early February	Early March
Arran Comet	500	700
Ukama	500	600
Estima	500	700
Manna	400	500

Note: an allowance of 50 either side of the optimum is acceptable. (Figures supplied by Agronomy Department, Trawsgoed for Dyfed development store.)

1.2 *Current research into the PA technique in Wales*

In studies carried out at Syke Farm in Pembrokeshire over the last 3 years, agronomists and mechanization specialists have investigated the commercial manipulation of PA for maximum early potato production. The results from this work are encouraging — giving improved yields and an earlier crop over the more traditional husbandry methods used by farmers (Birkenshaw 1984) — and are now being used more widely in potato-store management.

However, development work at Syke Farm required a purpose-built environmentally controlled potato store (Hull 1984) to optimize the PA process. At a cost of £7500, the store was far beyond the means of many farmers. Other factors, such as the novelty of microprocessor technology and the risk factor involved with a new technique, combined to discourage farmers from installing it. What they needed was a simple method of controlling PA (albeit not to the accuracy of the environmentally controlled store) using their existing store (normally a glasshouse or similar building).

1.3 *Controlling PA in a traditional store*

The management tactics adopted in any particular year to achieve optimum PA by planting depend on several factors:

(i) the date when dormancy breaks,
(ii) the optimum PA for the variety stored and the planting date aimed for, and
(iii) the season's weather.

The aim of the farmer is to reach target PA with the minimum of management input, energy use and, hence, cost. This can be done simply by recording the development of PA through the season in store, and advancing or retarding development according to the trend in previous years determined from records of degree-days over a number of years at a suitable meteorological station nearby.

This paper considers the likelihood of achieving a target of 500 degree-days by mid-February — a typical requirement in Wales — for various dates of dormancy break at Syke Farm. Long-term records from Dale Fort climatological station are used throughout with a temperature adjustment to simulate store conditions. A graphical method is devised to show when heating or cooling, to speed up or slow down the progression of PA, is required to reach optimum PA.

2. The probability of reaching optimum PA for selected dates of dormancy

The date when potato seed breaks dormancy depends on both its variety and the weather conditions. If the farmer buys his seed from a supplier he will have no control over this factor. However, home-grown seed can either be delayed by cool storage or speeded up by heating so that dormancy breaks at a certain time. It is often advantageous to do this.

Past weather records show the effect late or early breaks of dormancy will have on the probability (expressed as years in 20) of achieving target PA. Ideally many years of records within the store are required but in their absence, as is usually the case, records from the nearest suitable meteorological site must be used. These latter records must be compared with in-store temperatures to determine the temperature elevation in the store as a consequence of the building itself and the heat generated by the potatoes.

This was done by ADAS agronomists for Syke Farm where the temperature excess over Dale Fort climatological station, some 7 km to the south-west, was found to be on average 2 °C. Potatoes within the store are kept in trays stacked 20 high, with potatoes piled two or three layers deep. This allows air to circulate freely between the trays and prevents the high temperature rises associated with potatoes piled in heaps on the floor.

Fig. 1 shows the probability curves for various dates of dormancy break on the first day of the month

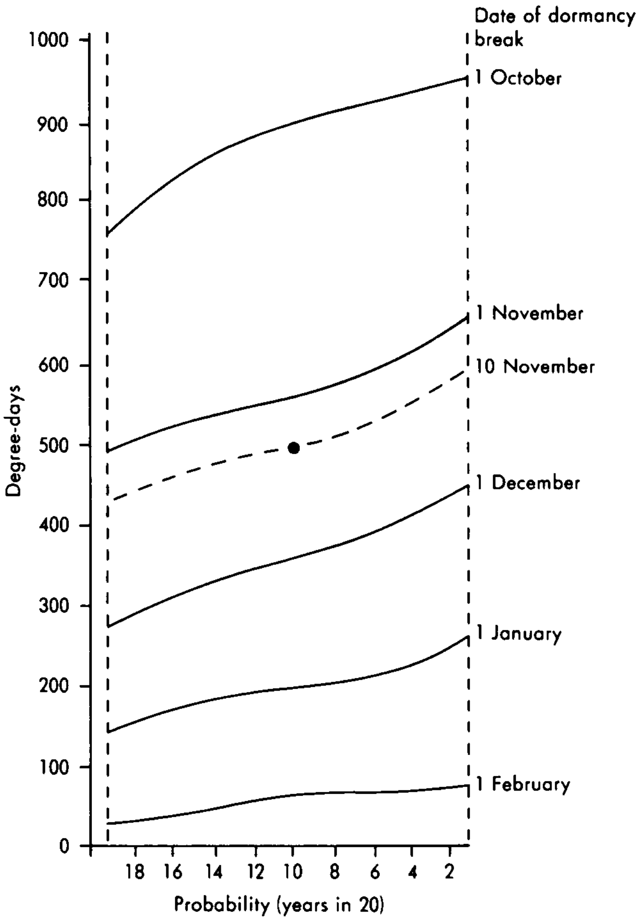

Figure 1. Probability curves for various dates of dormancy break for the years 1963–82 at Syke Farm, Dyfed showing the likelihood of achieving the optimum physiological age (500 degree-days) before planting in mid-February. The ideal date of dormancy break is indicated by the dashed line.

for the years 1963–82. (Intermediate dates can be estimated by eye from the existing curves.) If 500 degree-days are required by mid-February this will be achieved in all years if dormancy breaks in October; if dormacy does not break until December there is little hope of accumulating 500 degree-days by this date. A good time to break dormancy is early November (see curve for 10 November); this will give between 440 and 500 degree-days in the coolest 10 years (see • in Fig. 1). Thus the final degree-day total accrued will never be greatly divergent from the target and should be readily achieved with little management input.

3. Store management tactics to achieve optimum PA

In the majority of years, optimum PA will not be achieved without some management input in the form of advancing or retarding the progression of PA. Fig. 2 shows the median amount of heating or cooling needed to reach 500 degree-days by mid-February for selected dates of dormancy break. The dashed line was estimated by eye to show the seasonal accumulation required to achieve the target

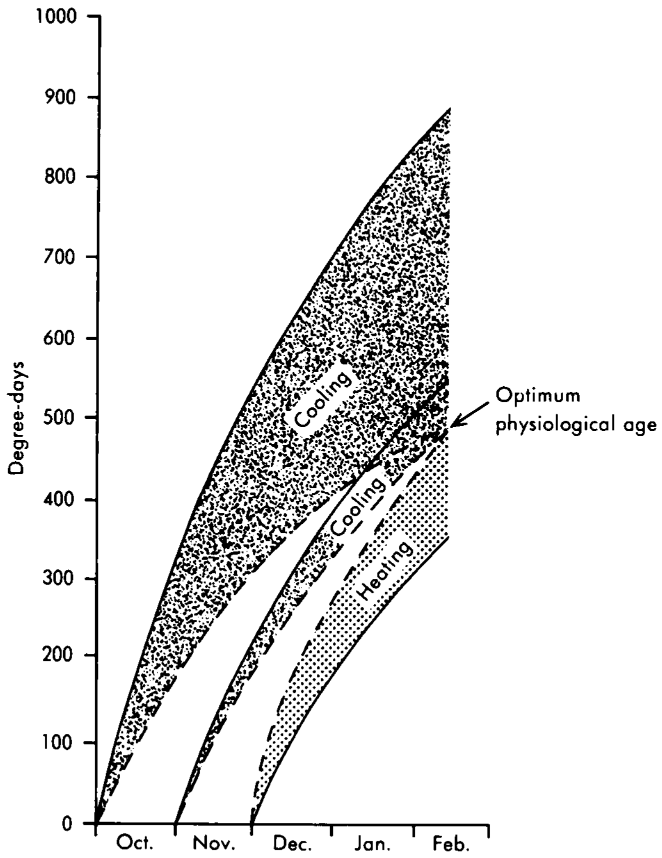

Figure 2. Requirement for heating or cooling (shaded areas) at Syke Farm, Dyfed to reach optimum physiological age (500 degree-days) by mid-February for three dates of dormancy break. The solid lines show the expected degree-day totals (10 years in 20) over the period 1963–82. The dashed lines show the optimum totals required to achieve the target.

exactly. The slope of the line reflects decreasing temperatures through the season. The solid lines represent the median year degree-day values over the 20-year period 1963–82.

Clearly if dormancy breaks early on during October, or if the winter is very mild, too many degree-days will accrue so a good deal of cooling will probably be required. Stores are cooled by opening all doors and keeping vents open; where fans are installed these can facilitate cooling.

If dormancy break is delayed until December, or if the winter is cold, the store must be kept as warm as possible. Some heating is provided by the potatoes themselves when the doors are closed, fans are turned off and some, but not all, vents are closed. However, in very cold weather additional heaters will be required to prevent frosting of the tubers and to boost the degree-day total.

4. Timing when to heat or cool

Long-term weather records show the likelihood that heating or cooling will be required — the store management strategy. Weather conditions in a particular year might dictate that the exact opposite action is required, so tactical management should consider each season on its own merit.

Decisions on when to heat or cool can only be made by comparing degree-day totals measured within the store (methods of doing this are described later) with the 'target lines' (i.e. dashed lines) shown in Fig. 2. One might then decide to heat the store whenever the actual total was more than a critical amount behind the target at a particular time. Similarly cooling might be applied when the actual total exceeded the target by this critical amount. A suitable value for the critical difference might be 50 degree-days. Agronomists have pointed out that the target PA is not a critical number and that provided the degree-day total at planting does not differ by more than 50 degree-days either side of the target, the performance of the potatoes will not suffer unduly once planted. 'Overcooking' the seeds will lower their performance as will planting under-developed seed.

Fig. 3 shows three actual seasons at Syke Farm compared with the target. In each season the potatoes broke dormancy on 1 November. In 1975/76 620 degree-days would have been reached by mid-February. The actual exceeded the target by 50 degree-days around the third week in December indicating that cooling was required. The low temperatures in December would allow this excess to be corrected but if action was delayed until 1 February, when the excess was 110 degree-days, it would have been impossible to prevent 'overcooking'. In 1966/67 a similar situation occurred but corrective action was not necessary until the middle of January. In 1976/77 the maximum difference between target and actual was only 30 degree-days so no corrections were required.

Fig. 4 is similar to Fig. 3 except that dormancy broke one month later. 1981/82 was an exceptionally cold winter and the degree-day total fell more than 50 degree-days behind the target almost straight away. In a season like this, the doors should be opened as little as possible and extra heaters would be needed overnight. The 1967/68 winter was less severe and corrective action was not required until mid-December. It is likely that in this year closing the doors would have provided sufficient warming to get back on target. 1974/75 was exceptionally mild and no corrective action was needed.

The above examples suggest that most stores in south-west Dyfed will require some form of heating or cooling over the winter. Provided the farmer keeps a close eye on the degree-day totals within his store he should be able to stay on course.

5. Methods of recording degree-days within a potato store

The only accurate way to monitor PA in-store is to record degree-days within the potato bulk. These recordings will indicate both the current age of the tubers and also enable the temperature excess over

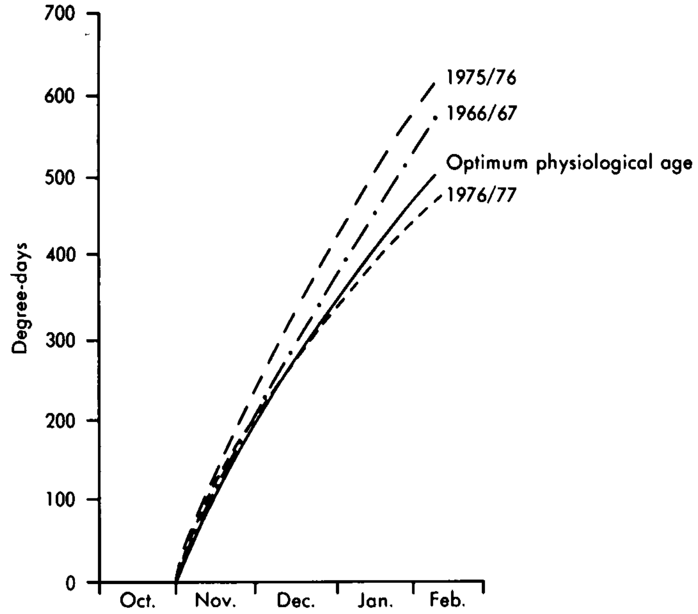

Figure 3. Comparison of recorded degree-days for three individual seasons at Syke Farm, Dyfed with the optimum value of 500 degree-days, where the dormancy break in each case was 1 November.

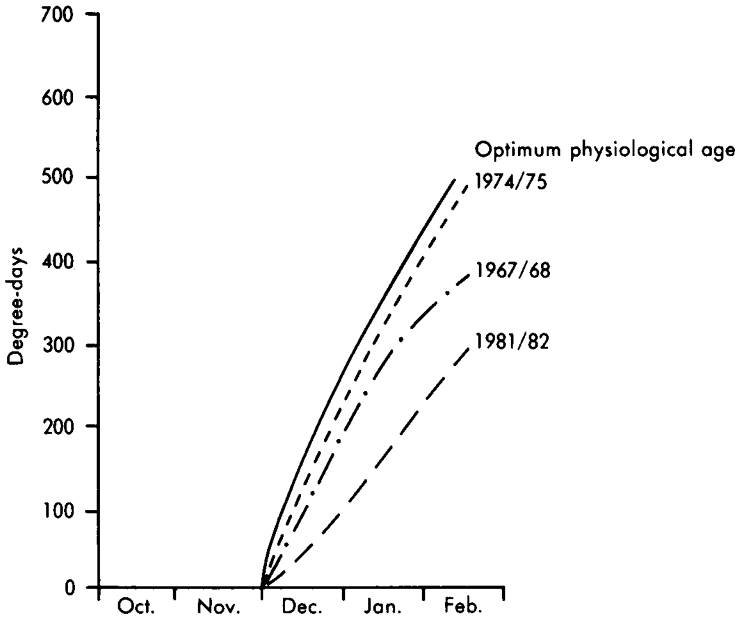

Figure 4. As Fig. 3 but for a dormancy break of 1 December.

ambient conditions at a nearby meteorological station to be established. One of two methods is available to the grower:

(a) High-quality maximum and minimum thermometers can be placed in the air spaces between the potatoes and read daily at 0900 GMT. The daily increment to the degree-day total is then read off from tables and noted each day. A form prepared to enable growers to log these recordings is shown in the Appendix. (A good deal of effort has been devoted at shows by the Agrometeorological Department in persuading growers that the Six's thermometer as marketed by many agricultural suppliers is not sufficiently accurate for this type of work.)

(b) A battery or mains-operated temperature integrator, as described by Roe (1981), can be installed consisting of a thermistor which is exposed within the potatoes, and a counter which clocks up the degree-days from the date the counter was last reset. Once set up, the integrator (Fig. 5) will run unaided

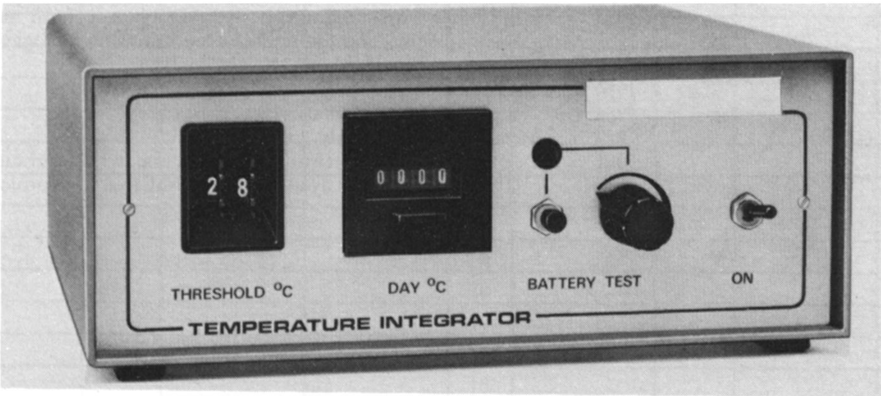

Figure 5. Electronic digital temperature integrator.

for many months and can be read whenever the farmer chooses, therefore saving valuable time.

An integrator is more accurate than the thermometers because it continuously integrates the temperatures and does not rely upon empirical formulae. Also the instrument is reliable and not easily broken. However, the cost of the integrator is four times that of two thermometers and the method is not, as yet, in general use.

6. Conclusions

This paper outlines a simple method whereby growers can monitor and control PA in their potato using meteorological data. Provided careful attention is given to routine checking of PA levels, and additional heaters are available, there is no reason why optimum PA cannot be achieved successfully. The following list itemizes the steps a grower would have to follow using this technique:

(i) Determine the date of dormancy break and decide on a planting date. Obtain optimum PA for variety of potato from ADAS agronomists.

(ii) Record degree-days above 4 °C within the potatoes from the date dormancy is broken.

(iii) Request target line from the Regional Agrometeorological Department of ADAS and plot the graph (see Figs 3 and 4).

(iv) At weekly intervals plot the in-store degree-day total from the date of dormancy break on the graph. If this value differs by more than 50 degree-days from the target, heat or cool as required. (Delaying corrective action makes getting back on course more difficult.)

(v) Having reached optimum PA (within 50 degree-days), plant as soon as soil and weather conditions are suitable.

Acknowledgements

The guidance provided throughout this work by Dr J. Starr, Agrometeorological Department, Trawsgoed and Mr J. Nield and Mr R. Finch, Agronomy Department, Trawsgoed is gratefully acknowledged.

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Appendix — *Form for recording physiological ageing of store potatoes over a two-month period*

Recordings of the physiological ageing of store potatoes

taken at .... during 19 ....

Date of dormancy break: ....

Month: .... Month: ....

Day	Max (thrown back)	Min	Today's degree-day total	Degree-day from dormancy	Day	Max (thrown back)	Min	Today's degree-day total	Degree-day from dormancy
1					1				
2					2				
3					3				
4					4				
5					5				
6					6				
7					7				
8					8				
9					9				
10					10				
11					11				
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30					30				
31					31				

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Rainfall investigations at Cardington and Winchcombe 1954–67

By R.P.W. Lewis

(Meteorological Office, Bracknell)

Summary

An account is given of the setting up and operation of two investigations carried out by the Meteorological Office into the fine-scale structure in space and time of heavy downfalls of rain using networks of synchronized open-scale rain recorders, one in flat and one in hilly country.

Introduction

During the period 1954–67 the Meteorological Office set up and ran two investigations into the fine-scale structure in space and time of heavy falls of rain, principally in connection with the problems of urban storm-water drainage; one investigation was near Cardington in Bedfordshire, and the other near Winchcombe in the Cotswolds. Holland (1967) has given a general survey of the work at Cardington, but the work at Winchcombe has received little publicity, although the results have long since been incorporated into the Office's store of data and have been used in such important publications as the *Flood studies report* (Natural Environment Research Council 1975). The present article attempts to put both investigations into perspective as part of the work planned and co-ordinated by the Joint Committee on Rainfall and Run-off (JCRR), and to give an account of how both were set up; it is in no way intended to be a scientific assessment of the results.

Formation of the JCRR

The Meteorological Office has for many years had a close working relationship with engineers and officials concerned with designing and installing systems of storm-water sewers to alleviate the nuisance caused by local flooding following heavy thundery downpours. (All who worked at the Meteorological Office at Harrow between 1945 and 1961 will recall that the main road near the entrance to the drive would become impassable from time to time.) Between 1948 and 1954 the British Climatology Branch (M. O. 3) was represented on the Rainfall, Run-off and Floods Committee of the Institute of Civil Engineers (ICE), the Hydrological Research Group of the Institution of Water Engineers (IWE) and had regular contact with the Inland Water Survey and the Road Research Laboratory (RRL). In 1954 the JCRR of the Ministry of Housing and Local Government and the Road Research Board was formed on which the Office was initially represented by Dr J. Glasspoole. The Committee met for the first time on 11 September 1954 and, after surveying the contemporary state of knowledge, put forward a program of research and investigation. The RRL were tasked with investigating how heavy falls of rain produced run-off from urban catchments of varying sizes and shapes, and with elucidating the principles of designing networks of sewers to improve drainage and alleviate nuisance. The Office was tasked with (a) revising and improving the classical Bilham formula for predicting the return periods of heavy falls of rain in short periods at a point and (b) relating observations of such falls to the spatial and temporal structure of the whole downpour over the surrounding area. The general economic criterion at that time for the effective design of a storm-water sewerage scheme was that flooding should not occur more frequently than once every ten years on average, i.e. a return period of ten years; more recently, a five-year return period has been adopted.

The Cardington experiment

Before the first meeting of the JCRR, the rainfall section of the M.O.3 had already planned and begun to set up a suitable dense network of recording rain-gauges. It was necessary for the chosen area to be fairly flat (because hills or mountains with steep slopes and narrow valleys would produce complicated orographic effects untypical of most of the urban areas to which the results would be applied); it was desirable for electricity to be made easily available to all the gauges; and it was also extremely desirable for trained Meteorological Office staff to be already within easy reach to run the investigation. All these conditions were found to be satisfied over an area of some 20 hectares on and adjoining the meteorological office at RAF Cardington, near Bedford. Some of this area was already on Government property, but most of the gauges had to be sited on private land, including farms, and there were at times difficulties in reconciling the layout of a scientifically suitable network with the necessary avoidance of inconvenience to farmers and other occupiers.

While sites were being chosen and leases and way-leaves negotiated, the Instrument Development Branch (M.O.16) at Harrow devised an 'open-scale' chart mechanism which could be attached to the normal Meteorological Office tilting-siphon (T/S) rain recorder in place of the daily drum. This open-scale device would feed a strip-chart from one drum to another at a speed which was about 14 times that of the movement of the ordinary daily chart, thereby enabling a detailed analysis of heavy rainfall to be made much more easily; the mechanism was worked either by clockwork or electricity (battery or mains), and a chart would last for four days.

By the end of the summer of 1956 sixteen open-scale rain recorders had been installed at Cardington, all powered by mains electricity and producing records that were in theory synchronized. The strip-chart mechanism did, however, give a certain amount of trouble, and the charts were liable to jam or slip. A fundamental snag in this simple adaptation of the standard rain recorder was that the chart had to be pulled horizontally from one vertically mounted spool to another; gravity thus tended to act at right angles to the desired direction of motion and small defects in the sprocket holes or the driving mechanism, or some other minor irregularity, had exaggerated consequences. There were additional adverse effects due to bird droppings, dust and leaves, and the net result was that seldom if ever were all the recorders in the network serviceable simultaneously, although for most of the time the majority would be. Another hazard was that during thunderstorms — which produced exactly the sort of rainfall that the network had been devised for — the electricity supply was likely to fail.

All recorders were visited every day, and a quarter of all the charts were changed. Although a Land Rover would have been ideal for getting round the network, for some years the transport officer was able to supply only one-ton or (worse) three-ton lorries which were naturally more difficult to manoeuvre through gates and tended to churn up the tracks very badly, much to the annoyance of the local farmers. One recorder was in the middle of a pig farm and the enclosure was defended against meteorologists by a guard of ferocious pigs. During the summer of 1959 three extra recorders were installed near the meteorological office to form a particularly dense cluster, and during the following winter three more were installed on sites stretching away in a north-easterly direction near the villages of Cople, Mogerhanger and Sandy. (These last three were powered by batteries, not mains electricity.) The locations of all the recorders used at Cardington, except the last two mentioned, are shown in Fig. 1.

Use of statistical methods

Towards the end of 1958 a small meeting was convened at Dunstable by Mr J.S. Sawyer (later to become Director of Research) to discuss methods of handling and analysing the Cardington data; the meeting was attended by the author. Mr Sawyer remarked that the variability of areal falls of rain might

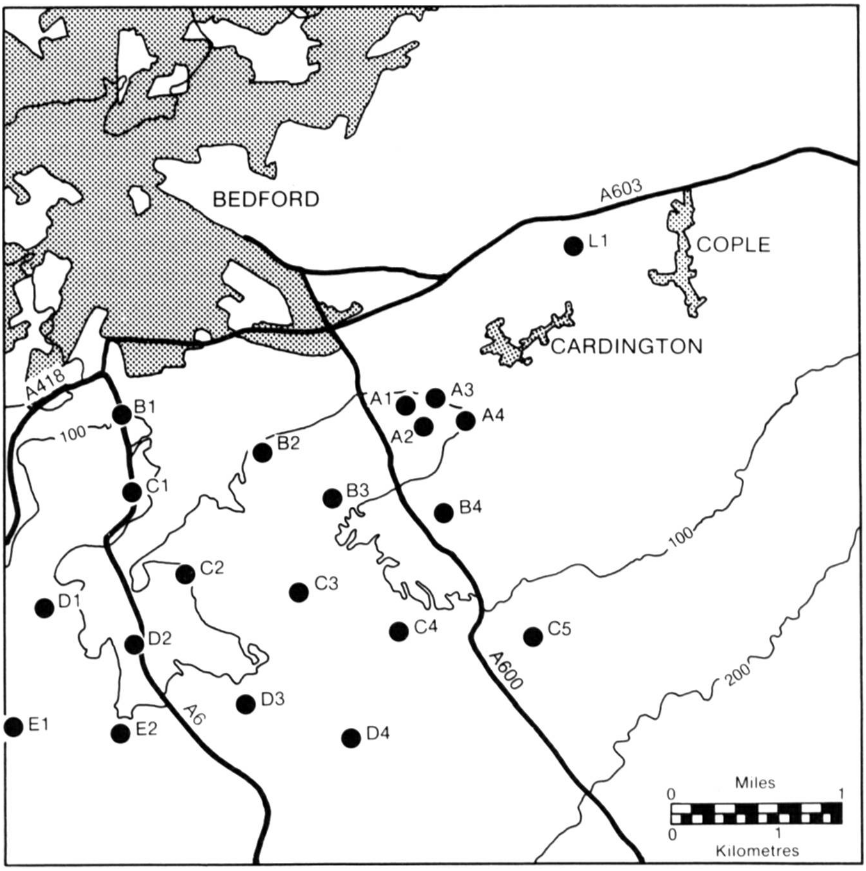

Figure 1. Open-scale rain recorder sites at Cardington. The identifiers (A1, B3, etc.) are those used during the investigation. Sites L2 and L3 lie outside the figure, about 3.4 km east and 6.3 km east-north-east of L1 respectively.

profitably be investigated by an extension into two dimensions of the methods he had employed on the variability of mean upper winds along a one-dimensional track (Sawyer 1950), and that the somewhat intractable frequency distributions that had been found for the Cardington two-minute rainfalls could be treated by 'Monte Carlo' methods using computer simulation with a pseudo-random-number generator. The author's request for official expenses to study these new methods at Monte Carlo was rejected out of hand; however, he was able to provide the necessary extension of Sawyer's formula to a circular area on the assumption — later to be verified for the special case of the Cardington network — that the correlations between two-minute rainfalls at two points were independent of direction. (Later, D.J. Holland provided analogous formulae for the more awkward case of a square.) The discovery that measurements along a line could to a large extent replace measurements over an area led to the extension of the network along a line to the north-east as described previously.

Liaison with local authorities

Once M.O.16 had devised an open-scale strip-chart mechanism for attachment to the standard T/S recorder, arrangements were made for the production of several hundred by a commercial firm, and by

1958 letters were being sent out by M. O. 3* to local authorities in England and Wales inviting them to co-operate in making much more accurate records of rates of rainfall than had hitherto been available. The response from local authorities was enthusiastic — indeed, embarrassingly so, because various troubles that arose in the course of manufacture of the mechanisms led to unforeseen delays in supply. These troubles were overcome, however, and by the early 1960s a considerable number of authorities as well as official Meteorological Office stations were taking part in supplying open-scale records for analysis. The data from these analyses were, before long, incorporated in the long series of records of 'heavy falls in short periods' that began in the nineteenth century and continues, in modified form, to the present day. Some results (which can never, of course, be regarded as final) can be found in the papers by Holland (1964), and Jackson and Larke (1974) and have gone some way to dealing with the first task laid upon the Office by the JCRR in 1954. This aspect of the work, however, seems likely to continue for a very long time to come, with more and more information becoming available on regional and local differences in the incidence of heavy falls; unlike the specific investigations at Cardington and Winchcombe it has no definite end, and will not here be considered further.

Extension of investigation to a hilly area

Now that the Cardington investigation was well under way and beginning to produce results, it was thought desirable to mount another investigation on a similar scale in an area that was hilly (but not mountainous), and reasonably possible for urban development, to see if there were systematic differences between it and Cardington in the way that violent falls of rain varied in space and time. If the differences were small, or could be clearly related in an obvious fashion to the topography, then advice relevant to the design of storm-water sewers could be tendered fairly confidently for a wide range of urban sites in southern Britain. A sub-committee recommended one or two suitable areas, and by early 1959 one had been selected about ten miles south-west of Dorchester in Dorset covering a height range from about 350 to 700 feet and consisting largely of rough uncultivated ground. A suitable network of rain recorder sites was planned using large-scale maps, and by the middle of the summer plans were sufficiently advanced for a field excursion to take matters further. On a hot sunny day in July 1959, therefore, L.H. Watkins of the RRL (Secretary to the JCRR) and the author set out from London by car to meet an Air Ministry Lands Officer and local farmers and landowners to explain the scheme and negotiate leases and way-leaves; they were looking forward to an enjoyable, busy, and useful couple of days in pleasant country. However, by tea-time that afternoon they had all been sent packing with a few brusque phrases from the first farmer they met. He would be delighted for them to put down their gauges, he said. How long did they want them there? A fortnight? Three weeks? *Three years?* He had, it seemed, been busy pushing upward the level of cultivation and one of the two dense arrays would have been in the middle of a cornfield. He stamped off angrily and the Dorset investigation was strangled at birth; Mr Watkins and the author returned, crestfallen, to London the following day. The title of the relevant file was promptly changed from 'Rainfall investigation in Dorset' to 'Rainfall investigation in hilly country'.

The Winchcombe experiment

The lesson of the Dorset fiasco — namely, that the people on the spot should have been consulted in advance — was immediately absorbed. The JCRR sub-committee was reconvened, and before long put forward two more areas which might be suitable for an investigation in hilly country, both in the

* By then called 'Climatological Services'.

Cotswolds. The rain-gauge inspector at the time (I.H. Chuter) was despatched in early May 1960 to survey these areas and talk informally to all the local people who might be involved — landlords, tenant farmers, and so on — so that they understood the purpose of the investigation and could raise any likely difficulties and objections. Mr Chuter's visit was successful, and he returned to Harrow with a firm proposal for an investigation in the area south of Winchcombe. Three weeks later he went round the area again with the author, and the Winchcombe investigation was under way.* The sub-committee visited the site in August, and during the following autumn and winter firm planning began. Whereas at Cardington the meteorological office was already staffed to carry out special observational and research work, and the demands of the rainfall investigation could be met by the addition of a couple of Scientific Assistants, for the Winchcombe experiment it was necessary to establish a separate small unit of a Senior Scientific Assistant and two Scientific Assistants which would be attached for convenience to the meteorological office at RAF Little Rissington; additionally, an Assistant Experimental Officer was to be stationed at Little Rissington for a few months to supervise the initial arrangements, liaising with M.O.3, the Meteorological Officer at Little Rissington, local works services and contractors, and so on. Because the provision of mains electricity to all the sites at Winchcombe would have been prohibitively difficult and expensive, it was decided to operate the strip-chart mechanisms there by electric batteries and use clocks fitted with a crystal control system for accurate timing. The network as originally planned should have contained 34 recorder sites including two dense clusters of 5 sites each. In the event, for various reasons including shortage of equipment, some objections raised by the farmers (though the relationship between the meteorologists and the farming community was on the whole excellent) and the sheer operational difficulty of coping with so many sites, the number was reduced to 24. Later on, in 1964, three more sites were added to the north-west at the request of the radar meteorologists working at Malvern; in addition to open-scale rain recorders these sites were equipped with radar reflectors to help provide estimates of attenuation. All sites that were actually used during the investigation are shown in Fig. 2.

Difficulties in supplying the clocks and crystal control units unfortunately led to considerable delays in making the network operational. Although the sites had been prepared and fenced and the recorders installed by the summer of 1961, it was the summer of 1962 before the network was working even at half strength, and 1963 before all the sites came into operation. The appalling weather of the 1962/63 winter posed severe problems for the rainfall unit, and in January 1963 an urgent rescue operation had to be mounted to bring indoors as many accumulators as possible lest the acid should freeze and damage the plates beyond repair. For many weeks a considerable number of sites were totally inaccessible, but when the thaw came it was found that the recorders had survived unscathed. The network was finally closed down in October 1967 after data had been collected for over 130 storms. The Reports of Work of the unit show that, as at Cardington, the provision of transport was an unexpected worry; at Winchcombe, the main difficulty was over the provision of drivers to cover various holiday periods.

Analysis of data

While the Winchcombe investigation was in progress, the earlier one at Cardington was deemed to have run its course and the network there was closed down in June 1963, data from some 150 storms having been collected; after September 1961 data collection had been confined to the summer half-year. Both at Cardington and Winchcombe, a good deal of the analysis of the strip-chart records was carried out by the Assistants on the spot. Further analysis was carried out at Headquarters (first at Harrow and

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* It is gratifying to be able to record that the Winchcombe site was, in the event, much better than the one in Dorset would have been.

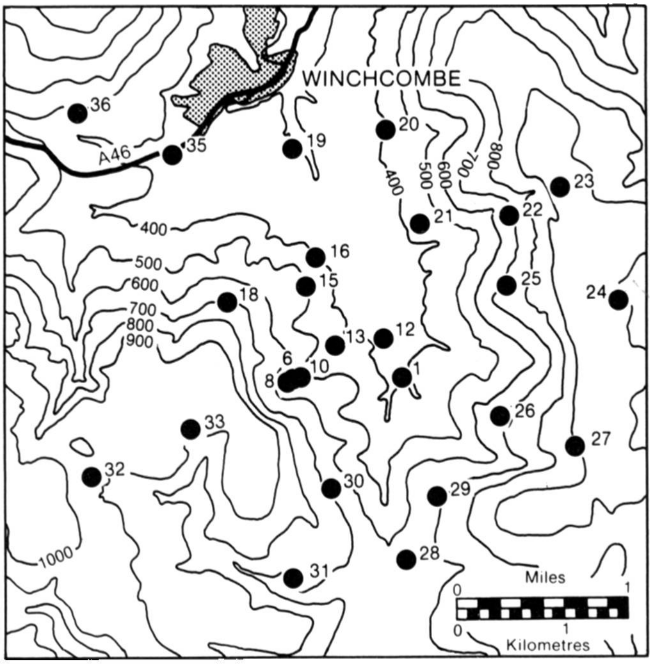

Figure 2. Open-scale rain recorder sites used at Winchcombe. Some additional sites were prepared but did not come into operation.

then at Bracknell) and two pieces of apparatus of distinctly Heath Robinson design were constructed known as 'OSCAR' Marks I and II, OSCAR standing for 'Open-Scale Chart Analyser (Reversing)'. OSCAR possessed drums with sprockets, cog-wheels and an electric motor. At Cardington, however, the apparatus consisted of two smooth stones for holding a strip chart flat on a table-top, together with a perspex scale. By the late 1960s, all two-minute rainfalls, for every occasion of interest, from every serviceable recorder at Cardington and Winchcombe, had been transferred to magnetic tape. Considerable care was taken to allow for losses in catch during the siphoning process, an important matter for intense falls of rain. Much attention was also given to the relative efficiency of catch of the various gauges by comparing long-term totals, and to the elimination, as far as was humanly possible, of the inevitable errors of synchronization introduced into the records by the way in which the strip charts tended to jump sprockets, or slip, or pull alternately too taut and too loose. To quote the words of D.J. Holland from an unpublished report: 'the field workers and analysts were soon connoisseurs of these mechanisms' foibles and became adept at interpreting what were sometimes very puzzling inconsistencies; but a good many such inconsistencies have had to remain unresolvable to the requisite degree of timing-accuracy and have therefore had to be very circumspectly interpreted when put on to maps'. (It is safe to say that these inconsistencies are only important for comparison between the records of *different* recorders, and not between different portions of the record of one shower at the *same* recorder.) It is almost certainly true — even if saying so is somewhat pointless — that if the instrumental technology of 25 years later had been available the results of the investigations would have been much more reliable.

Visit by representatives of the Joint Committee on Rainfall and Run-off (JCRR) to Winchcombe in October 1961. From left to right: D.J. Holland (Meteorological Office), D.J. MacLean (Road Research Laboratory), L. Evans (Meteorological Office) in local charge of the investigation, and L.H. Watkins (Road Research Laboratory) secretary to the JCRR.

Site No. 10, Winchcombe area (grid reference SP027256), looking towards the east, May 1962. This view gives a good idea of the general characteristics of the area.

Results of the investigations

As stated above, it is not the intention of the author to give a full scientific assessment of the results of the Cardington and Winchcombe investigations. Rather unfortunately, the Meteorological Office was not able to provide such an assessment immediately after the program of data extraction had been completed, probably because of the necessity to divert staff and other resources into other, more pressing, work such as the Dee Weather Radar Project. Also, the attention of hydrologists at that time was turning towards considerably bigger catchments than those of which the Cardington and Winchcombe networks were representative. The data have, however, been discussed in some detail by Marshall (1980) in relation to the movement and shape of storms, and he showed that there were indeed systematic differences, related to topographical features, between Cardington and Winchcombe.

For more immediately practical purposes, the data have been used in design studies for storm-water sewers (Department of the Environment 1976) and for the pattern of urban run-off (Kidd and Lowing 1979).

Some current applications

Later and more elaborate programs of investigation into rainfall distribution, such as Project Scillonia, the Dee Weather Radar Project (Central Water Planning Unit 1977) and FRONTIERS (Browning 1979) might be thought to have few, if any, points of contact with the work at Cardington and Winchcombe. These more recent studies have been concerned either with deepening our scientific understanding of the processes of rain formation or with developing the use of radar to provide detailed very-short-range forecasts of rainfall ('nowcasting') to help in controlling river flow and in alleviating flooding; at Cardington and Winchcombe, on the other hand, the purpose was to provide long-term statistical information for the design of fixed networks of sewers. Recently, however, it has become apparent that the radar estimates of rainfall, which are averaged over 5 × 5 km squares, can be much too smooth and that some remarkable variations on scales of 1 km or less can occur; the Cardington and Winchcombe data provide a wealth of valuable information on these fine-scale effects, in particular the relationships between point and areal rainfalls.

Difficulties in the field

It should not be thought by the reader that people mentioned by name in the present article were the only ones to make a significant contribution to the success of the Cardington and Winchcombe investigations, still less that they were the only ones involved at all. In such an extended piece of work, lasting well over ten years, important contributions were made by many Meteorological Office staff of all grades from Assistant (Scientific) to Assistant Director, the dirtiest and toughest tasks being undertaken by the Assistants and Senior Assistants who performed the daily round of inspecting and adjusting the rain recorders and changing the strip charts, whatever the weather. For example, the entry in the daily log at Cardington for 13 February 1960 finished with the remark, written in red ink, 'ITS SNOWING LIKE HELL!!' (Examination of the more official synoptic record shows that it was.)

At Winchcombe, life was harder still. The terrain was rougher, with gradients of up to 1 in 3 in places. The standard round involved opening and closing some 140 gates, and each site had about six or seven locks (for the entrance gate, the rain recorder, the 'black box' timing device, the battery case, and so on), each lock being operated by a different key. Several times meteorologists had to take cover to avoid being fired on by hunters shooting duck, once they became involved with a fox-hunt, and once they had trouble with an obstreperous bull. The weather was frequently appalling, and in the Report of Work for

February 1966 it is recorded that 'parts of the Winchcombe area are waterlogged, and under-foot conditions are sometimes atrocious. Occasionally the staff more often resemble participants in the Eton wall game than Civil Servants'. The typical enthusiasm and dedication shown by the meteorologists in making sure the job was done, and done well, whatever the circumstances, seems not to have been shared to anything like the same extent by the drivers of the RAF vehicles who doubtless considered the whole operation to be completely mad.

Acknowledgements

Thanks are due to I.H. Chuter (now at Napier College of Technology, Edinburgh), B.H. Cole, A.B. Turner, L. Evans and L.H. Watkins (formerly of the Transport and Road Research Laboratory) who were able to give the author information additional to that contained in official records and his own memory.

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Awards

L.G. Groves Memorial Prizes and Awards

The presentations of the L.G. Groves Memorial Prizes and Awards for 1984 were made on 16 October 1985 at the Main Building, Ministry of Defence, Whitehall. Air Vice-Marshal A.G. Skingsley, CB (ACAS) presided, and Commander Michael Peer Groves RN (retd) made the presentations. Commander Groves is a nephew of the late Major Keith Groves who, with his wife, founded the L.G. Groves Memorial Fund in memory of their son. Among the several members of the Groves family who were present were Mr Nicholas Abbott, Miss Margaret Groves and Mr Robin Wight who have all acted as presenters of the prizes on various occasions in the past.

Air Vice-Marshal Skingsley opened the proceedings by welcoming all the guests and prize-winners. He reminded the audience that the L.G. Groves Memorial Fund was established in memory of Sergeant Louis Grimble Groves who lost his life in 1945 while serving as an Air Meteorological Observer with No. 517 Squadron of Coastal Command and remarked that since their inception in 1946 the awards had stimulated many ideas of great theoretical and practical value. He explained that the changes in the titles of three of the Prizes and Awards forecast by his predecessor in the role of president of the ceremony (Air Marshal Sir Peter Harding) had now been put into effect. He gave a brief account of the current awards and offered his own congratulations to the winners.

Air Vice-Marshal Skingsley then introduced Commander Groves and called upon him to say a few words before making the presentations. In response, Commander Groves expressed his pleasure in being present and related an amusing story about flight safety based on his own experience of early naval aviation.

The citations were then read by Air Commodore P. King, OBE (Inspector of Flight Safety, RAF), and Commander Groves presented the winners with their prizes and certificates, adding his own personal congratulations.

The 1984 Air Safety Prize was awarded to Sergeant T. Meechan, then of the Survival Equipment Section, RAF Cottesmore (now serving at RAF Coningsby) in recognition of his initiative and inventiveness in designing a gauge to measure the cutter movement in life-saving jacket operating heads. The gauge, which is applicable to all survival equipment inflation systems, facilitates accurate checking of cutter movement and should ensure the correct inflation of life-jackets and life-rafts. The gauge is cheap, easy to produce and has Service-wide applications. It is being introduced as part of a Servicing Instruction.

The 1984 Meteorology Prize was awarded to Dr J.F.B. Mitchell of the Meteorological Office. Dr Mitchell is the leader of a highly successful group within the Dynamical Climatology Branch which uses complex numerical models of the climate system to understand, and ultimately predict, climate variations. Recent events in Africa have demonstrated that, in an increasingly sensitive world, climatic variations can have consequences that go far beyond their area of origin to affect the whole global community. To an increasing extent they may have to be taken into account in strategic planning, both civil and military. Under his enthusiastic leadership the group has considerably enhanced our appreciation of the physical basis of climate and climatic variability.

Dr Mitchell's personal research has been concerned mainly with estimating the effects of increased atmospheric carbon dioxide concentrations, the primary cause of which is the burning of the Earth's supply of fossil fuels. It is a problem which has been causing growing international concern. Dr Mitchell's work has been wide-ranging and notable for its detailed assessment of the physical causes

Dr J.F.B. Mitchell, winner of the Meteorology Prize, receives his prize from Commander Michael Peer Groves.

Mr G.J. Day, winner of the Meteorological Observer's Award, is congratulated by Commander Michael Peer Groves.

L.G. Groves Memorial Prize and Award winners with Commander Michael Peer Groves, Air Vice-Marshall A.G. Skingsley and Air Commodore P. King, left to right: Air Commodore King, Flight Lieutenant R.P. Minards, Dr J.F.B. Mitchell, Air Vice-Marshall Skingsley, Commander Groves, Mr G.J. Day and Sergeant T. Meechan.

of the changes. In particular, he has analysed and elucidated the tendency in a number of estimates for parts of the subtropics and middle latitudes, already comparatively dry, to become even drier.

His expertise is widely recognized at home and abroad and he has contributed not only to the work of the Meteorological Office but also to research programs under the European Economic Community and the US Department of Energy.

The 1984 Meteorological Observer's Award was presented to Mr G.J. Day, now retired but formerly Assistant Director (International and Planning) in the Meteorological Office.

The collection of wind, temperature and aircraft position data from the main air routes and around the airfields of the world will make a significant contribution to flight safety and economics in guiding weather forecasting and warning methods. In some data-sparse areas and on flight paths inbound and outbound from airfields the identification of strong shear zones, regions of turbulence and significant icing potential could be vital. The so-called Aircraft to Satellite Data Relay (ASDAR) facility provides just such a data collection method.

As Assistant Director, Mr Day had no particular responsibility to encourage the development of observing methods. In practice, and almost single-handed, he has devised a method of funding an ASDAR development program through an international consortium, cajoled other nations to take part, encouraged British industry to bid (successfully) for the development contract, nursed development through all the normal, and some unique, shoals and persuaded international airlines and satellite authorities to collaborate, to the point where flight certification units are being fitted to wide-bodied jets in the fleets of British Airways, British Caledonia, Trans World Airlines and United Airlines. The RAF is giving the equipment serious consideration with a view to equipping some of their aircraft. Plans have been laid to install and maintain 40 to 50 such units in airlines around the world in the next few years. He has been the driving force behind all this activity, much of it conducted in his spare time, whilst earning the gratitude, friendship and respect of those around him.

The 1984 Ground Safety Award was awarded to Flight Lieutenant R.P. Minards, then Station Flight Safety Officer (SFSO) at RAF Bruggen (now undergoing refresher training at the Central Flying School) for his initiative and effort in producing the flight safety video film *Safeguard*. The film, shown to all new arrivals at RAF Bruggen, emphasizes the potential flight safety hazards on a busy front-line station. The film is used by the Inspectorate of Flight Safety on their flight safety course and a number of SFSOs are considering the idea.

Obituary

Mr I.J.W. Pothecary, Assistant Director (Defence Services), died suddenly on 27 November 1985. He was aged 57 and had served for 34 of those years in the Meteorological Office.

Ivan Pothecary was born and brought up in Wiltshire and attended the grammar school in Chippenham through the years of the Second World War. In 1945 he joined the Royal Engineers, took the Engineers' short course at the University of Birmingham and was commissioned as Second Lieutenant. Three years later he returned to the University to complete a degree in Mathematics, Physics and Geography, qualified as a glider pilot and became a Pilot Officer (General Duties) in the Royal Air Force Volunteer Reserve.

Ivan Pothecary joined the Office in October 1951 and, after taking the Scientific Officers' Course at the Meteorological Office Training School in Stanmore, he was posted to the Meteorological Research Flight at the Royal Aircraft Establishment, Farnborough. He was there for only one year, the idea then being that, in their first few formative years in the Office, the young scientists should sample a wide variety of the work being undertaken. He enjoyed the flying, of course, but he also laid the foundations for scientific papers, which later appeared in print under his name, on clear air turbulence, the use of aircraft to measure wind shear by observation of vertical smoke trails, gravity waves, and pressure surges. After Farnborough, he spent nine months at the Main Meteorological Office at Gloucester, where he showed himself to be a proficient forecaster, before moving on to M. O. 21 at Dunstable, then the Short Period Forecasting Research Branch, to work under R.C.Sutcliffe and J.S.Sawyer in the Napier Shaw Laboratory. Here, he impressed his superiors not only with his thoroughness and industry in tackling scientific problems but also with his personality and strength of character, and he found himself appointed in September 1955 as scientific aide-de-camp in the office of the Director of the Meteorological Office, Dr (later Sir Graham) Sutton at Victory House in Kingsway, London.

He was promoted to Senior Scientific Officer and returned to Dunstable early in 1957 but he soon applied, and was accepted, for a post on secondment as Principal Scientific Officer in the British Caribbean Meteorological Service in Piarco, Trinidad, which he took up in November 1957. There he was Assistant Director in charge of the Eastern Division of what shortly became the West Indies Meteorological Service. Qualities already displayed elsewhere quickly came to the fore, in particular a gift for office organization and an ability to handle staff firmly whilst still remaining popular with them. Not unnaturally, he came to grips in Piarco with the problems of hurricane forecasting and, as ever, his enthusiasm and interest in this new area were such that he soon made his mark. He received a commendation for his work from the Federal Minister of Communications that referred to the several occasions on which he had stayed on duty for 24 hours or more when a hurricane threat developed. In hurricane forecasting there was a need for close co-operation with the US Weather Bureau in San Juan, Puerto Rico and when he left for the United Kingdom in November 1960, the Meteorologist-in-Charge, Ralph Higgs, wrote that co-operation between the two offices had reached heights never before achieved.

It may have been another comment made in the West Indies — that he had shown a refreshing interest in instruments and an ability to keep them in working order — that led immediately on his return from the tropics to a midwinter posting to Eskdalemuir Observatory in the Southern Uplands of Scotland. There he was Superintendent for the best part of three years doing an excellent job in a post that he would not have chosen for himself. At Eskdalemuir he was concerned not only with meteorology but, in liaison with the Royal Observatory, Herstmonceux and the Blackford Hill Observatory, Edinburgh, was responsible for magnetic and seismic observations. In his term of office there was constructed a new seismic vault and a surface laboratory and Eskdalemuir became the leading UK Seismic Observatory. He also experimented with the *in situ* calibration of daylight recorders and with proton magnetometers.

Ivan Pothecary's career took another eventful turn when he was sent from Eskdalemuir towards the end of 1963 to become a Senior Forecaster at London/Heathrow Airport. He was given a special responsibility there for developing the use of satellite data in aviation forecast. Within a year he had mastered the forecasting job and had paid a visit to the US Weather Bureau Satellite Meteorology Laboratory to build on the new interest. He also found time to write a book, *The atmosphere in action*, which was published by Macmillan in November 1965 as No. 4 in the Quantum series of text-books. (This was translated into Danish.) He also contributed articles on satellite meteorology to the *Meteorological Magazine*. There was a natural progression in 1965 to the Senior Forecaster roster in the Central Forecasting Office at Bracknell and this was followed by a last spell in the Research Directorate of the Office, as deputy to the Chief Meteorological Officer at the Meteorological Research Flight, during 1967–69. There he was involved in a number of projects including the testing and use of an airborne infra-red radiation thermometer and a design study for a projected quartz crystal hygrometer but his main interest centred on the organization of the work of the Flight as a whole and the development of workable solutions to the many problems encountered.

In 1969 he joined the Defence Services Branch (Met O 6) in which he served with distinction for the remainder of his career. His first posting in this area was as deputy to the Chief Meteorological Officer at Headquarters, RAF Strike Command and in 1971 he was selected to join the National Defence College course in Defence Studies at Latimer. This he enjoyed immensely, his instructors noting that his intellectual curiosity led him to ask awkward questions when others hesitated. The course strongly coloured his attitude to his work thereafter. He returned to Strike Command but in September 1973, and with temporary promotion to Senior Principal Scientific Officer, he took up the appointment of Chief Meteorological Officer at the Headquarters, Near East Air Force in Cyprus with responsibility for the organization and administration of meteorological offices serving the RAF over an area extending from Gan (Addu Atoll) in the Indian Ocean to Gibraltar. In Cyprus he was faced at first with the problems of the military emergency of the time and later with the need to streamline his resources very substantially in meeting the needs of the smaller Command which came into being. He drew praise from the Commander British Forces, Near East for his able direction and objective thinking and for his wide military interests.

Returning to the Meteorological Office Headquarters at Bracknell in 1975 he was soon appointed Assistant Director (Defence Services) and headed Met O 6 for the next decade. He was very well suited for this role and became deeply committed to the military requirement. This was quickly recognized by the many within the British and foreign military services with whom he came in contact. He was a member throughout of the NATO Military Committee Meteorological Group, the present chairman, Captain John R. Lincoln, US Navy writing 'The meteorological community of all of NATO is richer by far for Ivan's contributions. He served an outstanding term of three years as our Chairman. His abilities for working with and providing the guiding light of leadership in this international forum were unique ...'. At the same time he worked to maintain the closest possible understanding with the Air Staff at home and strove to develop a similar relationship with Army Staffs. Liaison with the Directorate of Naval Oceanography and Meteorology was never better, a circumstance that paid handsome dividends in respect of the quality of the meteorological support that was given to all the armed services in the South Atlantic during the Falklands campaign and after.

He was elected to the Council of the Royal Meteorological Society in 1969 and became a member of the Finance and General Purposes Committee. He had been a member of the Committee of the Scottish Branch of the Society while at Eskdalemuir. His interest in military matters lead to his regular attendance at meetings of the Royal United Services Institute for Defence Studies. He was always on the look-out for details of historic military occasions in which the weather had played a significant part and had planned to write a book on the subject after his retirement. We have surely been deprived of an original and entertaining work. His last public talk was given on the *Effects of Weather on the Persian Wars 492–480 BC,* to the History Group of the Royal Meteorological Society.

Ivan Pothecary's social life was very much bound up with his profession. His closest friends were from within the Office, and the house guests of himself and his wife Anne were often acquaintances, old and new, from amongst the many overseas meteorologists with whom he came into contact throughout his career. He was interested in archaeology and spent many happy hours in trenches at digs throughout the country and in Cyprus, fishing out bits of pot and bone with brush and trowel. He also discovered in himself a gift for water divining and an outdoor party-piece was the location of wells, drains or water-mains beneath his host's lawn.

Ivan Pothecary had a very personal style of management. He showed great loyalty to the Office and inspired the same in his staff. As he was apt to say, he did not run his Branch by committee. His leadership was felt throughout. Not surprisingly, his untimely passing has left a great gap and a strong sense of personal loss to his very many professional friends and colleagues at home and abroad.

Correction

Meteorological Magazine, January 1985, p.27, caption to Figure 3. ('How the meteorological reconnaissance flights began' by E.B. Kraus.)

Several knowledgeable readers have written to us pointing out that the tail-fin shown in the figure cannot possibly belong to a Blenheim but is that of a Hudson. We can but apologize.

Meteorological Magazine

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Meteorological Magazine

March 1986

Vol. 115
No. 1364

CONTENTS

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ISBN 0 11 727831 9 ISSN 0026–1149

Printed in England for HMSO
Published by HER MAJESTY'S STATIONERY OFFICE
Dd. 736047 C13 3/86

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

April 1986

Met.O.971 No. 1365 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1365, April 1986, Vol. 115

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Discrimination in the use of radar data adjusted by sparse gauge observations for determining surface rainfall

By B.R. May

(Meteorological Office, Bracknell)

Summary

Dense radar observations of a rainfall field can be adjusted by sparse gauge observations to estimate the surface rainfall at an ungauged location as an alternative to a direct interpolation between the gauge observations. It is demonstrated that it is possible to choose which of the estimates — gauge-only or adjusted radar — is closest to the unknown true gauge value with a success rate of correct choice of more than 50%. The purpose of choosing is to prevent the indiscriminate use of radar observations and to reduce the possibility of them being used under circumstances in which it would be non-beneficial.

1. Introduction

The Advisory Services Branch (Met O 3) of the Meteorological Office has a requirement for estimating surface rainfall amounts at ungauged locations for a range of durations from five minutes to a year. In the past this has been carried out by direct interpolation between gauge observations, for instance using the CARP procedure (Shearman and Salter 1975). This process is essential for deriving isohyetal fields, i.e. the spatial distribution of rainfall amount for a specified duration.

For studies of daily or longer period rainfalls well after the event, observations from the climatological network of rain-gauges are usually adequate. The inter-gauge spacing in this network ranges from 3 km to over 30 km depending on locality with an average of about 8 km. For more pressing requirements for daily rainfalls the only observations which are reported in near real time are those available from the synoptic network with gauge spacings ranging from 20 km to 100 km and an average of about 40 km. For observing sub-daily rainfalls, whether reported in real time or historically, the rain recorders are again separated by about 40 km on average with a large range of spacings as above.

Recently, quantitative measurements of rainfall by radar have become available (Palmer *et al.* 1983) and because of their regular and dense coverage (5 km spacing) they have potential as an aid to interpolation especially between widely spaced gauges. Their availability in real time every 15 minutes, and every 5 minutes historically, increases their potential for a range of advisory and research purposes.

The strategy has been adopted in Met O 3 that radar data should be used to aid in estimating by interpolation the surface rainfall which would have been observed by gauges rather than acting as an

Notation

g	gauge measurements
r	radar measurements
g_t	adopted true gauge observation
r_t	adopted true radar observation
g_i	gauge values at corner (i) of square
r_i	radar values at corner (i) of square
g_e	estimate from gauge observations only
r_e	estimate from radar observations only
a_e	r_t adjusted by gauge observations
o_e	optimum estimate, i.e. the better of g_e and a_e
p_e	estimate chosen (either g_e or a_e) by the practical choice method
$\bar{g}$	constant — average g of whole array
S	operator indicating 'standard deviation of'
E_{rg}	$S\{\log(r_t/g_t)\}$
E_{gg}	$S\{\log(g_e/g_t)\}$
E_{ag}	$S\{\log(a_e/g_t)\}$
E_{og}	$S\{\log(o_e/g_t)\}$
E_{pg}	$S\{\log(p_e/g_t)\}$
E_{rr}	$S\{\log(r_e/r_t)\}$
I	inter-gauge spacing
I_a	I at which $E_{rr} \approx E_{rg}$
I_b	I at which $E_{ag} \approx E_{rg}$
I_c	I at which $E_{gg} \approx E_{ag}$
F_1, F_2	parameters for exponential transformations of data
V_g	$\Delta E_{gg}/\Delta I$
V_r	$\Delta E_{rr}/\Delta I$
N_g	percentage of occasions on which g_e is the better estimate
N_{pc}	percentage of occasions on which the better estimate is chosen correctly

entirely independent measure of an 'unknown' true surface rainfall in competition with gauges. However, the indirect way that radar rainfall estimates are produced (May 1983) suggests that a field of radar observations will inevitably deviate from the corresponding field of gauge observations; comparisons of co-located gauge (g) and radar (r) measurements reveal considerable differences in absolute amounts and, more important, in the ratio r/g at neighbouring locations (Collier *et al.* 1983).

Radar observations of rainfall amounts are averages over contiguous 5×5 km squares which need to be ascribed to specific locations. By symmetry the locations are chosen to be the centre of the squares and so the rainfall field as seen by radar is described by a regular array of grid-point values with a spacing of 5 km as in Fig. 1.

Fig. 1 also shows the typical positions of widely-spaced interspersed gauges. Met O 3 has developed a procedure for estimating the point rainfall that would have been measured by a gauge, at any grid point (such as X in Fig. 1), from the radar rainfall at X adjusted by rainfalls observed by a selection of surrounding gauges. The procedure, called PRAGED (Spalding 1984), involves fitting by a least-squares process a suitable two-dimensional surface to the adjustment factors g/r at the selected gauges and interpolating to estimate g/r at X. This factor multiplies the r at X to give the adjusted radar estimate (a_c).

A simple interpolated estimate (g_c) of the gauge rainfall at X can also be obtained from the selected gauge observations without the use of radar data at all. Two estimates of the rainfall at X are now available and so it is reasonable to ask which of g_c and a_c is the better estimate. The problem is that the true gauge rainfall at X is not known so that a precise objective decision cannot be made (if it was known then the question would not arise anyway).

The requirement then is to develop a practical method of choosing the better estimate, g_c or a_c. Restrictions are adopted so that the method should be entirely objective using no information other than is contained in the radar grid-point and sparse-gauge values of the particular rainfall field for the specified duration. This means that there is no consideration of the type of rainfall involved — localized, uniform widespread, orographic, etc. — and so the method can be applied to any duration in principle.

For the method to be developed it is necessary that suitable detailed rainfall fields are available to act as truth fields. This means that the investigation is limited to the use of daily rainfall fields. There is a difficulty in finding a selection of suitable homogeneous gauge and radar fields to represent the wide range of conditions under which a method of choosing the better estimate would be required to be used. As a consequence only one example of real r and g fields is chosen but it is transformed in a plausible way to simulate a wider range of conditions. Since there is a need to obtain the maximum amount of information from the limited data, the processes of making gauge-only and adjusted radar estimates at X are simulated for networks with a range of gauge spacings positioned around all grid points in the field.

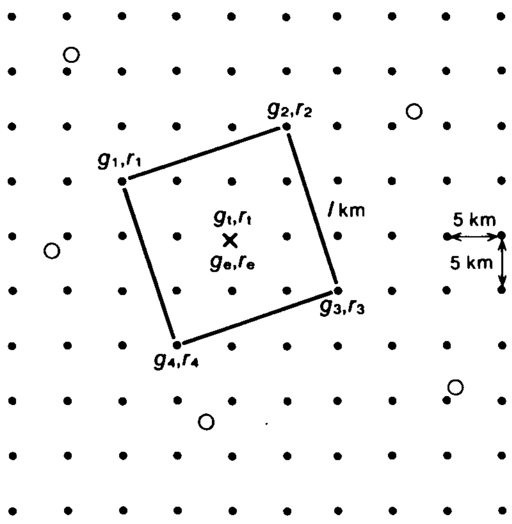

Figure 1. An example of the grid used for radar rainfall data showing simulated interspersed gauges (O). Also shown is a square of sides l km centred on X with the four corner positions used for gauge (g) and radar (r) rainfall values. For explanation of other symbols see text.

2. The data

The radar data used in this investigation are authentic 5 km grid-point daily rainfalls as described previously covering an area of 80 × 80 km (a 16 × 16 array of points) for one day. These radar data have been corrected at source by an on-site calibration but in Met O 3 they are treated as unadjusted data. The corresponding co-located gauge rainfalls are accurate interpolations to each grid point from a carefully drawn isohyetal pattern based on all gauge observations in the area (amounting to about 100) with a spacing of about 8 km. Since on average the gauges are spaced further apart than the grid points there must be a small degree of correlation between adjacent grid-point values arising from the interpolation involved in contour drawing. It is believed that this is negligible compared with the correlation which exists anyway because of the structure of the rainfall field and does not invalidate the results of this study. In contrast, the radar values at each grid point are independent observations but again are correlated because of the field structure.

These radar and gauge values are referred to as the original values. The isohyets only are plotted in Figs 2 and 3 for clarity. Both radar and gauges showed a well-defined area of heavier rainfall near the centre of the field. In comparison the ratio g/r in Fig. 4 shows a pattern of maxima and minima not obviously related to the rainfall pattern.

3. The analysis

The aim of the first part of the analysis is to use the g and r values in Fig. 1 to simulate the estimation of rainfall by direct interpolation within gauge observations and by the gauge adjustment of radar observations, and to investigate the accuracy of these estimates.

As an example, consider gauge-only estimates. Four grid points ($i = 1,2,3,4$) at the corners of a square of side l km centred on the grid point X are chosen where l is identified with the inter-gauge spacing in a sparse network as in Fig. 1. At any grid point within the square it is possible to make an estimate, using the four corner values (g_i), of the rainfall which would have been observed by a gauge for comparison with the true gauge rainfall (g_t). The smallest square of interest has only one internal point and this is at the centre, so all comparisons are limited to the centre point of all squares of whatever size. This has the

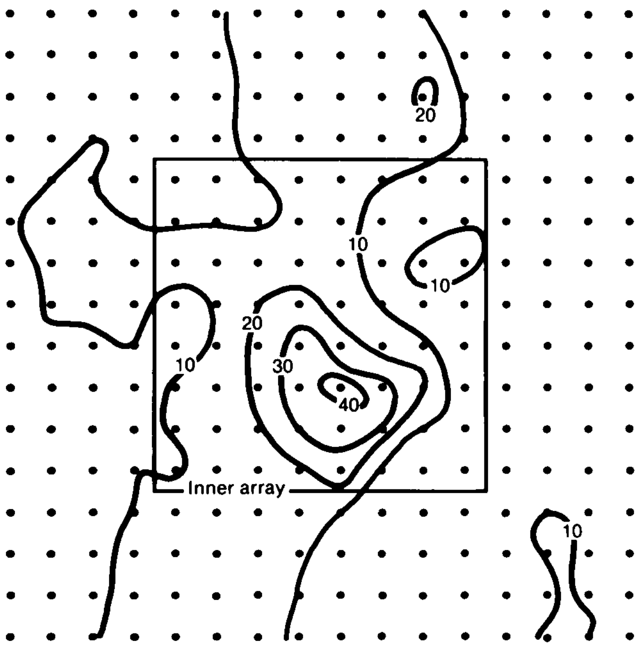

Figure 2. Original rainfall field as recorded by gauges with isohyets at 10 mm intervals.

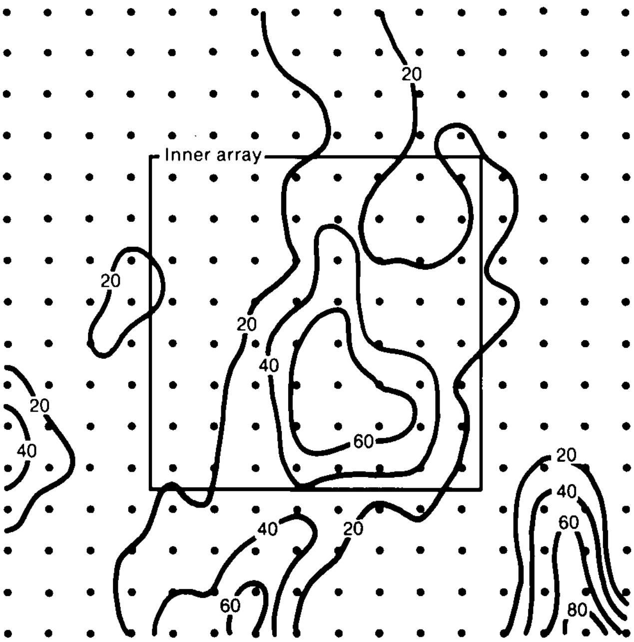

Figure 3. Original rainfall field as recorded by radar with isohyets at 20 mm intervals.

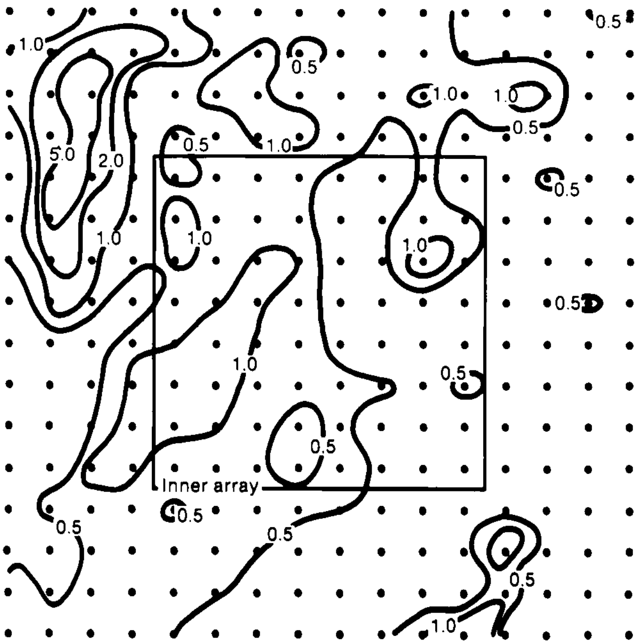

Figure 4. Field of original adjustment factors (g/r).

effect of simplifying the interpolation procedure, reducing it to taking a simple average of the corner values. The gauge-only estimate is then

$$g_c = 0.25 \sum^{i=1,4} g_i$$

compared with the co-located observed true value g_t. The square of side l and fixed orientation is moved over the array of g values so that the centre point occupies the 64 positions in the inner 8 × 8 array as outlined in Figs 2 and 3. This provides a sample of 64 comparisons of g_c and g_t for a square of that particular size and orientation and for that rainfall distribution.

We introduce the notation S(q) to represent the standard deviation of a general variable q. Following May (1983), the mean (m) and standard deviation (s) of the sample of 64 $\log(g_c/g_t)$ values represents the bias and variability of g_c values relative to g_t such that approximately 68% of the g_c/g_t ratios are within the range $10^m \times 10^{\pm s}$. In this paper the variable component $S\{\log(g_c/g_t)\}$ is used exclusively as a measure of the error of g_c values. For brevity $S\{\log(g_c/g_t)\}$ is denoted by E_{gg} and represents the error resulting from observing with widely spaced gauges a rainfall field which would have been observed by infinitely close gauges.

The l value of the squares used to represent the network of gauges ranges in size from 7.1 to 40 km. Where squares of the same size but different orientations are used the resulting two values of E_{gg} are averaged.

Estimates from adjusted radar observations are produced in a similar way, where

$$a_c = 0.25\, r_t \sum^{i=1,4} (g_i/r_i)$$

the g_i/r_i being the adjustment factors at the corners of the square and r_t the radar value at the centre. Again the a_c values are compared with the co-located g_t values giving an E_{ag}, $S\{\log(a_c/g_t)\}$, for each sample of 64 a_c/g_t ratios for each square. E_{ag} represents the error of adjusted radar estimates. Estimates from radar-only observations (r_c) are also required in this paper giving values of E_{rr}, $S\{\log(r_c/r_t)\}$, where,

$$r_c = 0.25 \sum^{i=1,4} r_i$$

the r_i being the radar values at the corners. E_{rr} is the radar analogue of E_{gg}.

Finally the single value of E_{rg} is calculated which is the $S\{\log(r_t/g_t)\}$, where r_t and g_t are co-located, for the sample of 64 ratios from the inner array. E_{rg} represents the error of adjusted radar rainfall values and is independent of l, but since $\log(r_t/g_t) = -\log(g_t/r_t)$ and $S\{\log(r_t/g_t)\} = S\{\log(g_t/r_t)\}$, E_{rg} also represents the variability of g/r over the inner area. (To enable log ratios to be evaluated in these processes all zero values of g and r in the original arrays are replaced by 0.1 mm.)

4. Comment on the data analaysis

It should be noticed that the isopleths of g/r in Fig. 4 are fairly smooth which implies that the individual grid-point values (not shown) must be correlated with each other. As a consequence E_{rg} is only an estimate of the random variability of $\log(g/r)$ which would be difficult to define and cumbersome to determine, but nevertheless is a measure of the change in r/g or g/r with position. The same remarks apply to g_c/g_t, a_c/g_t, and r_c/r_t ratios at adjacent grid points.

It is the spatial pattern of rainfall depicted by radar observations and how well it agrees with the pattern depicted by the gauges which is important; the absolute values of radar data are not important because biases in them with respect to gauge values are reduced by adjustment. For instance, if all the original radar values in Fig. 5 are multiplied by a constant factor then E_{rg}, E_{ag} and E_{rr} all remain unchanged and conclusions about the impact of radar data are unchanged. There is no reason why g/r values encountered in a practical adjustment process should be rejected simply because they are outside specified limits; neighbouring r values can also be much smaller or larger (in absolute units) than gauge values but can still depict the correct pattern of rainfall. Also g/r values should not necessarily be rejected because they are calculated from small values of g and/or r with the risk that rounding errors produces an increased variability in the g/r ratios; this can be regarded simply as less accurate radar data, with a larger E_{rg}.

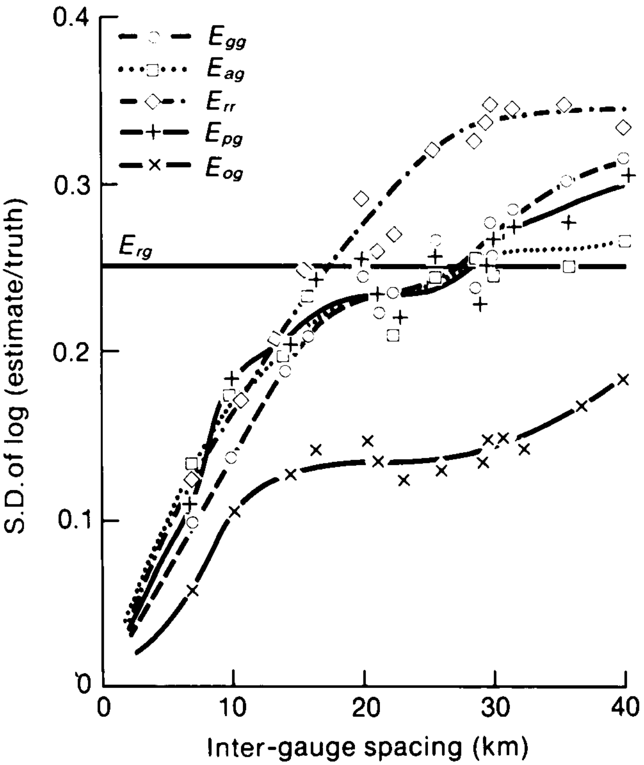

Figure 5. Variation of errors (standard deviation (S.D.) of log estimate/truth) of estimates for original rainfall data. For explanation of symbols see text.

5. Results from the original data

In Fig. 5 the values of E_{gg}, E_{ag} and E_{rr} for the original data are plotted against l with smooth curves being fitted by eye. $E_{rg} = 0.25$ for the error of radar data implied by these rainfall fields and is represented by a horizontal line.

E_{gg} increases smoothly for values of l increasing from 7.1 to 40 km and can be extrapolated naturally to a zero value for $l = 0$. This is consistent with more widely spaced gauges recording less accurately and infinitely close gauges recording without error at all. The magnitude of the spatial change of isohyetal gradients in Fig. 5 determines the shape and particularly the steepness of the E_{gg} versus l curve; for convenience the average gradient $\Delta E_{gg}/\Delta l$ for the l range 0 to 40 km is denoted by V_g. This is a measure of the 'peakiness' of the field, a small V_g indicating a nearly flat field and a large V_g a very non-uniform field. For this original gauge field $V_g \approx 0.012\ \text{km}^{-1}$.

E_{rr} also increases smoothly from an assumed zero value for $I = 0$ with V_r (the average gradient $\Delta E_{rr}/\Delta I) \approx 0.014\ \text{km}^{-1}$.

E_{ag} also tends to zero for $I = 0$ because with decreasing distance between gauges the corner values of g/r in Fig. 1 all tend to g_t/r_t and hence a_c to g_t. E_{ag} appears to be converging to a value a little larger than E_{rg} for large values of I. This is reasonable since the wider apart the gauges are the less influence they have in comparison with radar in determining the adjusted radar field.

For these original data there is little difference between E_{gg} and E_{ag} curves in Fig. 5 although there is a critical inter-gauge spacing (I_c) $\approx$ 25 km such that for $I < I_c$, $E_{ag} > E_{gg}$ and the use of radar data increases (slightly) the error of estimates, and for $I > I_c$, $E_{ag} < E_{gg}$ giving a slight decrease.

For this one example it is not possible to demonstrate how E_{ag} and E_{rr} are related to the two basic factors E_{gg} (or V_g) and E_{rg}. It is possible, though, to transform in a plausible way the original rainfall fields to simulate changes in E_{gg} and E_{rg} and the accompanying changes in E_{ag} and E_{rr}. An assumption is involved here that the behaviour of the radar observations is reasonable — for instance, if the gauge rainfall field in Fig. 2 had a peak of larger rainfalls than originally then the radar would still have observed a peak and not, say, a minimum.

The results of transforming the original data to simulate changes in E_{gg} and E_{rg} are described in the next section. This is the second part of the analysis.

6. Transformation of the data

(a) Gauge rainfall unchanged, radar data accuracy varied

To do this the original g values in the array are left unchanged, which preserves the original E_{gg} and V_g, but each original r value is replaced by $g \times (r/g)^{F_1}$, where g is co-located with r. For $F_1 = 1.0$ the r values also remain unchanged so that E_{rg} keeps its value of 0.25. From the definition of E_{rg} and the form of the transformation it follows that for any F_1, $E_{rg} = 0.25 \times F_1$ for this gauge field. Using this relationship, radar fields with specific required values of E_{rg} can easily be produced, and these fields still retain some influence of the pattern of the original radar field.

The calculation of E_{ag} and E_{rr} has been carried out as before for the range of E_{rg} values from 0.0 to 0.55. Figs 6(a), (b) and (c) show the results for $E_{rg} = 0.15$, 0.25 and 0.35 which are sufficient to demonstrate the main effects of changes in the radar data (the trend lines only of E_{gg}, E_{ag} and E_{rr} varying with I are shown for clarity). These values of E_{rg} are typical for real data.

For the most accurate radar data shown, i.e. where $E_{rg} = 0.15$, the curves of E_{rr} and E_{gg} nearly coincide (and V_r tends to V_g) because the simulated radar field is very similar to the gauge field. As the radar data degrade in accuracy the radar field is an increasingly inaccurate image of the gauge field and the E_{rr} curve steepens. As suggested previously, for large values of I, E_{ag} tends to a value determined by E_{rg}; as a consequence, since the E_{gg} curve is fixed, for more accurate radar data $E_{ag} < E_{gg}$ over the whole range of I but for less accurate radar data $E_{ag} > E_{gg}$. For the less accurate radar data it is the E_{rr} and E_{ag} curves which converge.

(b) Radar data error unchanged, gauge rainfall field varied

This requires two transformations of the arrays of data. Firstly, each original g is replaced by $\bar{g} \times (g/\bar{g})^{F_2}$ where $\bar{g}$ is a constant, chosen to be the average g over the whole array. By itself this would change the g values, E_{gg} and V_g, as required but also the r/g ratios, so to retrieve the original $E_{rg} = 0.25$ the original r values are also replaced by $r \times (g/\bar{g})^{(F_2 - 1.0)}$. For $F_2 = 1.0$ the original r and g values are

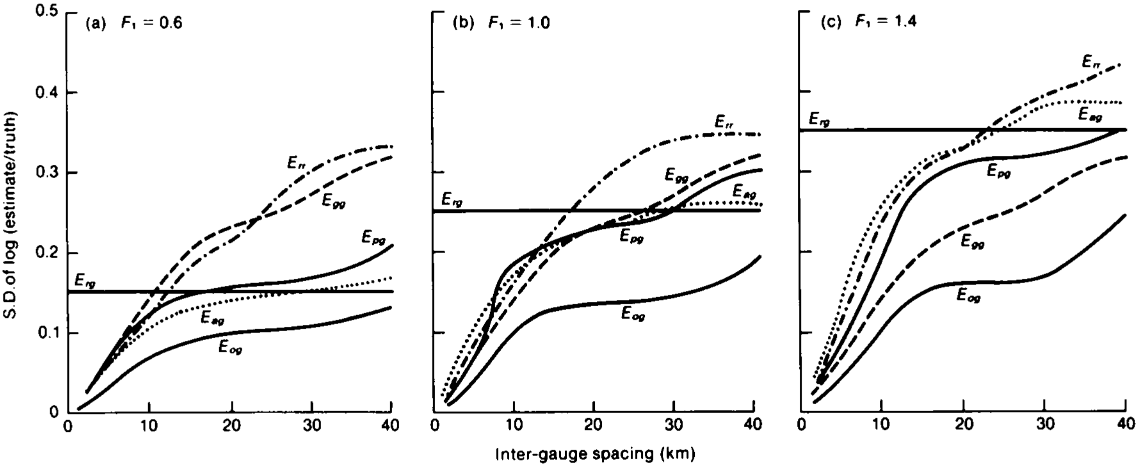

Figure 6. Variation of errors (standard deviation (S.D.) of log estimate/truth) of estimates when original gauge rainfall remains unchanged but radar field is varied to simulate changes of rainfall data accuracy.

unchanged; as F_2 tends to zero the g values all tend to $\bar{g}$ and the rainfall field pattern flattens, but for $F_2 > 1.0$ the gauge field is more non-uniform than originally.

The calculation of the errors has been made as before for simulated fields for a range of F_2 from 0.0 to 3.0. Figs 7(a), (b) and (c) show the results for $F_2 = 0.5$, 1.0 and 1.5 which give a practical range of values of V_g from 0.006 to 0.018 km^{-1}.

Again irrespective of the flatness of the rainfall field the E_{rg} strongly determines the variation of E_{ag} with l. Since the E_{ag} curve is nearly fixed the change in V_g results in $E_{gg} < E_{ag}$ for all gauge spacings for the flatter field and $E_{gg} > E_{ag}$ for the more variable field. As the rainfall field becomes less flat the E_{rr} curve departs from the E_{ag} curve and approaches the E_{gg} curve.

Figs 6 and 7 show how estimate errors change with different gauge rainfall fields and errors of radar data. In the next section the implications of these results are discussed.

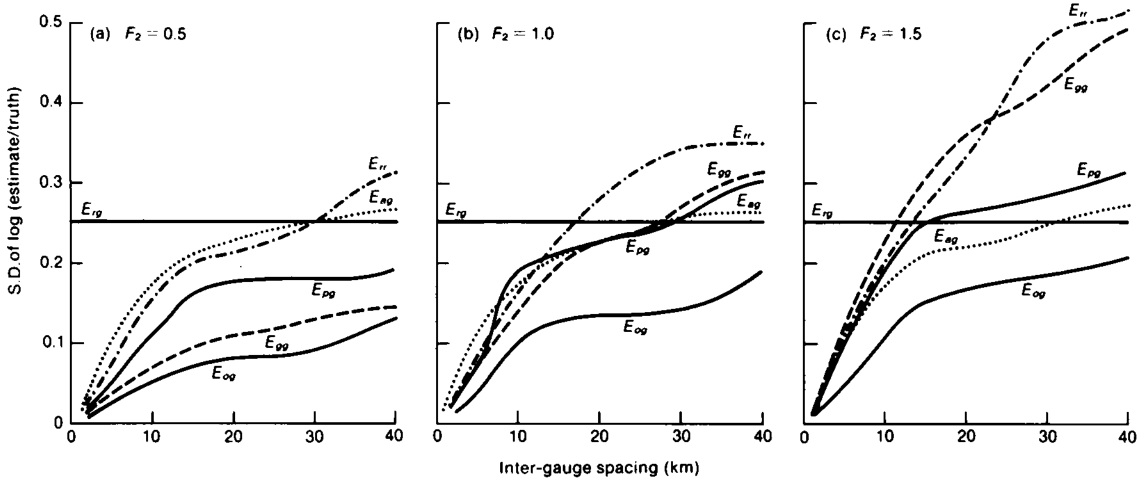

Figure 7. Variation of errors (standard deviation (S.D.) of log estimate/truth) of estimates for simulated changes of uniformity of rainfall fields as recorded by gauges but keeping the original g/r field unchanged.

7. Discussion of results from changing E_{rg} and V_g

(i) Figs 6(a) and 7(c) are similar in the relative positions of the E_{gg}, E_{ag} and E_{rr} curves which differ only in the vertical scale, and the same is true for Figs 6(c) and 7(a). This suggests that an important factor is the relative magnitude of the error of radar data and the variability of the gauge field.

(ii) For a particular rainfall field, accuracy of radar observations, and inter-gauge spacing the use of radar data to estimate rainfall can be regarded as beneficial if $E_{ag} < E_{gg}$ and non-beneficial if $E_{ag} > E_{gg}$. The concept of a critical inter-gauge spacing l_c as in Fig. 5 is not very relevant in practice. For a particular E_{rg} a small change in V_g (or vice versa) appears to produce a large change in l_c, as demonstrated by the entries in Tables I(a) and (b), and when $l_c \approx 20$ km E_{gg} and E_{ag} are nearly identical

Table I. *Transformation of original data to simulate changes in E_{gg} and E_{rg}*

(a) Gauge rainfall field unchanged, radar data error varying

F_1	E_{rg}	V_g	V_r	Gauge spacing at which: $E_{rr} \approx E_{rg}$ (l_a)	$E_{ag} \approx E_{rg}$ (l_b)	$E_{gg} \approx E_{ag}$ (l_c)	Effect of radar data: beneficial (b) or non-beneficial (n)	Test of choice methods: Optimum % number of g_c N_g	Practical % correct choices N_{pc}	mean ratio E_{pg}/E_{og}	Comments
		km⁻¹			km						
0.0	0.00	0.012	0.012	0			b	0	100	1.0	For $F_1 = 0.0$, the
0.2	0.05	0.012	0.012	4	33	0	b	14	82	1.2	r/g field is flat,
0.4	0.10	0.012	0.012	8	28	0	b	24	63	1.5	radar and gauge
0.6	0.15	0.012	0.012	13	28	0	b	35	57	1.6	fields are not.
1.0	0.25	0.012	0.014	18	27	≈ 25	neither	50	50	1.8	As F_1 increases,
1.4	0.35	0.012	0.016	23	25	> 40	n	63	51	1.9	the radar data
1.8	0.45	0.012	0.019	26	23	≫ 40?	n	70	54	1.9	gradually
2.2	0.55	0.012	0.026	30	20	≫ 40?	n	76	56	1.9	deteriorate

(b) Radar data error unchanged, gauge rainfall field varying

F_2	E_{rg}	V_g	V_r	l_a	l_b	l_c	Effect	N_g	N_{pc}	E_{pg}/E_{og}	Comments
0.0	0.25	0.000	0.012	15	30	--	n	100	61		For $F_2 = 0.0$, gauge
0.1	0.25	0.001	0.012	22	30	≫ 40?	n	87	59	5.4	rainfall field is
0.5	0.25	0.006	0.012	30	30	≫ 40	n	68	50	2.0	flat, radar and
0.8	0.25	0.009	0.012	22	28	> 40	n	58	50	1.9	r/g fields are
1.0	0.25	0.012	0.014	18	27	≈ 25	neither	50	50	1.8	not. As F_2
1.2	0.25	0.015	0.016	15	28	0	b	44	52	1.7	increases, the gauge
1.5	0.25	0.018	0.017	13	29	0	b	36	57	1.6	field becomes
2.0	0.25	0.025	0.025	9	28	0	b	32	64	1.5	more variable
3.0	0.25	0.039	0.039	6	28	0	b	18	77	1.3	

with little benefit or harm resulting anyway. The more interesting conditions are when $l_c \approx 0$ or > 40 km and V_r and V_g are very different as in Figs 6(c) and 7(a) and Table I.

(iii) It is convenient to regard radar data which result in $E_{ag} < E_{gg}$ as being 'accurate', and 'inaccurate' if $E_{ag} > E_{gg}$. However, a particular value of E_{rg} cannot be accurate or inaccurate on an absolute scale because the effect of using radar data depends on the field (V_g) being observed and, to a lesser extent, the gauge spacing. For instance, in Fig. 7(a) for $E_{rg} = 0.25$ the radar data are inaccurate because a uniform rainfall field is being observed and gauge estimates have less error than adjusted radar estimates (non-beneficial use) whereas in Fig. 6(c) the same quality radar observations of a much more variable field lead to poorer gauge estimates than adjusted radar ones (beneficial use). Cases of beneficial and non-beneficial use of radar data are also indicated in Table I.

(iv) There is no automatic beneficial trade-off between radar observations and numbers of gauges to maintain a specified error of estimates — beneficial in this case meaning that l can be increased when radar data are used. For instance, in Fig. 7(c) an error of estimates equal to 0.25 can be achieved by gauges only with $l = 12$ km but l can be increased to 30 km (a reduction in gauge numbers per unit area by a factor of 0.16) when the gauges are used to adjust radar observations and so there is a positive trade-off. From Fig. 6(c) for the same error, $l =$ 26 km for gauge-only estimates but is 10 km for adjusted radar estimates and there is now a negative trade-off. In the first case the radar data are capable of contributing useful information to the radar and gauge combined field so reducing the need for gauges; in the second case the radar contributes misleading information and so more gauges are needed to compensate. Positive trade-offs are associated with the beneficial use of radar data and negative trade-offs with non-beneficial use.

(v) There appears to be a strong association between the distance (l_a) at which $E_{rg} \approx E_{rr}$ and whether the radar data are beneficial or non-beneficial. From Table I it can be seen that beneficial radar data result in values of l_a less than about 20 km and non-beneficial data with l_a more than about 20 km. It is thought that this change-over value of l_a is not absolute but is characteristic only of the particular rainfall pattern used here.

(vi) The approximately constant distance (l_b) at which $E_{rg} \approx E_{ag}$ (from Table I) is associated with the strong control by E_{rg} of the limiting value of E_{ag} for large values of l. For very sparse gauges then (a practical circumstance) the error of adjusted radar estimates is determined almost completely by the error of radar data and not by the variability of what is being observed.

(vii) For perfect radar data, i.e. $F_1 = 0.0$, the 5 km grid of radar observations behaves like a 5 km network of gauges. If the real gauges are distributed uniformly with a spacing of l km then the combined network of observations would have an average spacing of

$$\left(\frac{1}{5^2} + \frac{1}{l^2}\right)^{-1/2} \text{km}$$

giving an error of estimates which can be read off the E_{gg} versus l curve for the rainfall field being observed.

(viii) With so much variety encountered in the variability of rainfall fields and the accuracy of radar observations it is impracticable to specify gauge spacings to cater for all circumstances. Irrespective of whether the radar data are used or not it is advisable to use as many gauge observations as possible since all the figures show that E_{gg} and E_{ag} both decrease continuously with l.

In summary, radar data can be beneficial or non-beneficial so that if used indiscriminately and inappropriately there is a risk of an increase of errors of rainfall estimates.

The next section deals with the possibility that for the rainfall fields, radar data errors and sparse gauge spacings met in practice, an objective decision can be made whether or not to use radar data.

8. Development of a practical method of deciding when to use radar data

In simulation there is no difficulty in deciding when to use radar data or not because g_t is available for direct comparison with a_c and g_c. In practice g_t is not available so the problem is to develop a method of deciding between g_c and a_c without knowing g_t exactly. This is the third part of the analysis.

Before going on to consider how to make this choice it is necessary to establish the desirable features of a practical method.

(i) The simulations suggest that the beneficial or non-beneficial use of radar data depends on the rainfall field variability and the accuracy of radar observations such that accurate observations and variable fields favour the use of adjusted radar estimates, and inaccurate observations and flat fields favour the use of gauge-only estimates. The method should contain elements which represent the competition between these two factors.

(ii) The rainfall field variability and radar data accuracy vary continuously from one grid point to the next so the choice of using g_e or a_e should be made independently at each grid point. It should not be inevitable that the choice at adjacent grid points is the same since in practice this could lead to hard-edged areas containing either all g_e or all a_e estimates. This may arise by chance but should not arise by design. This suggests that the method must involve 'local' (to the grid point) estimates of field variability and radar data accuracy.

(iii) No method of choosing g_e or a_e can be 100% correct since g_t is not known; however r_t is known and can be used but is an imperfect estimate of g_t. The choice between g_e and a_e must inevitably depend on probability considerations.

(iv) The method must be effective in preventing as far as possible the obviously incorrect choice of g_e or a_e being made.

(v) It would be useful if the method could be integrated into the operational procedures described in section 1 used for obtaining g_e and a_e in practice.

The practical circumstances are as pictured in Fig. 1. The accuracy of radar observations at X can be estimated only from the sparse gauge measurements in the vicinity, and the variability of the gauge rainfall field judged from the inaccurate radar observations.

To test the effectiveness of a method of choosing, a rule is required to determine which is the better of g_e and a_e as an estimate of g_t when g_t is known. The rule follows naturally from the use of $S\{\log(g_e/g_t)\}$ and $S\{\log(a_e/g_t)\}$ to measure errors in the samples of g_e and a_e values — being that g_e is the better estimate if $|\log(g_e/g_t)| < |\log(a_e/g_t)|$, otherwise a_e should be chosen. The absolute values are used, there being no concern as to whether g_e and a_e are greater or smaller than g_t.

9. The optimum solution

At this point it is useful to derive by simulation the errors to be expected for the hypothetical situation in which the correct choice of g_e and a_e can always be made — the optimum solution. Using the data arrays described previously, for each sample of 64 values the $S\{\log(o_e/g_t)\}$ (denoted by E_{og}) can be calculated where o_e is the better of g_e and a_e determined by the rule above. In addition, from each sample the number of occasions out of 64 that g_e is the better estimate (N_g) is counted and expressed as a percentage; a_e is then the better estimate on $(100 - N_g)$% of occasions. The value of simulated estimates of E_{og}, for the optimum solution, is that they can act as a standard for the performance of practical methods of choosing g_e and a_e.

By definition, for a particular rainfall field, E_{rg}, and value of l, E_{og} must always be less than both E_{gg} and E_{ag} which can be seen from Figs 6 and 7 where E_{og} is plotted against l. N_g appears to be nearly independent of l for a particular gauge and radar rainfall field and so the mean values of N_g averaged over all l values in the range 7.1 to 40 km are given in Table I.

For the original gauge data and $E_{rg} =$ 0.0 the r/g field is flat, giving error-free adjusted radar estimates, but the g field is not flat resulting in erroneous gauge-only estimates so that $N_g = 0$%. As E_{rg} increases the radar estimates become progressively less accurate and some values of g_e are chosen in preference to a_e, so N_g increases. In contrast, for a flat rainfall field and a non-flat r/g field, g_e is always chosen so $N_g = 100\%$, but as the rainfall field becomes variable values of a_c start to be chosen and N_g decreases. These values of N_g are consistent with E_{gg} and E_{ag} in Figs 6(a) and 7(c) — when $E_{gg} > E_{ag}$ (i.e. beneficial radar data), N_g is $< 50\%$ and vice versa. For the original data $N_g \approx 50\%$ so that neither g_c nor a_c is strongly preferred. This is consistent with the E_{gg} and E_{ag} curves being nearly coincident in Fig. 5.

10. A practical solution

Referring to the practical circumstances in Fig. 1, an estimate of $S\{\log(r/g)\}$ at X can be found from the surrounding gauges selected in the operational process to adjust the radar value at X. This estimate is inevitably based on only a few values of r/g but it is the best local area estimate that can be made of the error of radar data. The gauge observations can be used to estimate g_c at X but there is no observed g_t for comparison. An alternative is to calculate r_c at X from the radar values at the gauge locations for comparison with r_t at X, which is available. The radar equivalent of g_c/g_t, r_c/r_t, is a measure of the flatness of the rainfall field in the same local area surrounding X as that for $S\{\log(r/g)\}$. Because of the inaccuracy of radar data r_c/r_t is a less reliable index of flatness than g_c/g_t which decreases the precision of the test.

The practical test then becomes — choose g_c if $|\log(r_c/r_t)| < S\{\log(r/g)\}$, otherwise choose a_c.

As before, the results to be expected from this method of choosing g_c or a_c can be simulated. From Fig. 1, the $S\{\log(r/g)\}$ estimate is derived from the four corner values of r/g and the r_i values at the corners give r_c at the centre to form the $\log(r_c/r_t)$ estimate. The test is applied for each particular size and orientation of the square, at the 64 positions of the centre point, and the chosen a_c or g_c (denoted by p_c) is used to calculate $S\{\log(p_c/g_t)\}$ (denoted by E_{pg}). A count is also made of the number of occasions out of 64 on which the test chooses the better estimate correctly and this is expressed as a percentage (N_{pc}). It is found that for a particular E_{rg} and rainfall field, N_{pc} is nearly independent of l and so only mean values of N_{pc} over the l range 7.1 to 40 km are quoted. The results of simulating the operation of this practical choice method are given in Table I.

From Table I(a) it can be seen that with the original gauge rainfall field and a uniform r/g field (i.e. $E_{rg} = 0.0$) the correct choice of estimate (a_c) is always made and as a consequence the accuracy of estimates chosen reaches the limit E_{og} set by the optimum choice method. As the radar data deteriorate in accuracy the success rate of correct choice falls to a value of 50% — by coincidence for the original data. At first this appears to be a poor success rate, being no better than the random choice rate, but it is consistent with the E_{gg} and E_{ag} curves in Fig. 5 which show that there is little to choose between g_c and a_c on average in these conditions. Even if the method preferred one kind of estimate to the total exclusion of the other the success rate would still be 50% because one half of the correct estimates are g_c ($N_g = 50\%$ in Table I) and one half are a_c. However, the penalty for being unable to choose the correct estimate on no more than 50% of occasions is that $E_{pg} = 1.8 \times E_{og}$. As the radar data deteriorate even further the success rate increases again with g_c now more often being the preferred value but E_{pg}/E_{og} continues to increase slightly. In contrast, from Table I(b) it can be seen that for the original radar data error but varying rainfall field a 61% success rate of correct choice is obtained for a flat gauge field with g_c being preferred more often. The ratio E_{pg}/E_{og} loses its significance under this condition because both E_{pg} and E_{og} are close to zero. As the field becomes more variable the success rate reaches a minimum of 50% and then increases again with a_c now being preferred more often but the ratio E_{pg}/E_{og} continues to improve, apparently to a limiting value of 1.0.

The significant features of Table I are that the choice method works well in terms of a favourable N_{pc} (i.e. $> 50\%$) in circumstances when one or other of the estimates is clearly better, and particularly well with good radar data. When radar data are beneficial the efficiency ratio E_{pg}/E_{og} is less than 1.8.

11. Some practical considerations

The advantages of simulation in this work are that conditions can be altered and results for perhaps unrealistic circumstances can be produced, these being useful for revealing the underlying processes. However, simulation as used here only results in the calculation of the statistics of errors of fields and not actual fields of g_e, a_e, o_e and p_e. The next phase of this work is to investigate whether these results are reproduced, even approximately, with real fields.

Retrospectively, procedures described in the introduction can be used to derive grid-point value fields of g_t from the full gauge network, g_e from a sparse gauge network and a_e from radar data adjusted by the sparse gauges. Four further fields can then be derived — the optimum choice and an accompanying field indicating whether g_e or a_e is the optimum choice at each point, and the practical choice of g_e or a_e and its field of indicators of correct or incorrect choice. It would be expected that the following features would be exhibited by these fields:

(i) With decreasing distance from a gauge in the sparse network the probability that g_e is the optimum estimate should increase. This should result in a concentration of g_e choices around the gauge, possibly to the total exclusion of a_e choices.

(ii) With increasing distance from the gauges the probability that a_e is the preferred estimate should increase. It is possible, though, that for a very non-uniform r/g field, a very flat gauge field or close gauges in the sparse network, a_e values are still not the better even at the remotest points between gauges.

(iii) If the practical choice method is used, then close to the gauges there should be a concentration of correct choices (of g_e). More remotely from the gauges incorrect choices should occur but if the radar data error is small then the relative number of incorrect choices should also be small and the number of correct choices (now a_e) should be large.

A point of interest concerns the appearance of hybrid rainfall fields which are represented by grid-point values of interspersed g_e and a_e estimates. No restriction can be imposed that g_e or a_e should be smaller, or larger, than g_t because g_t is not known. At one point an estimate which is larger than g_t can be chosen while at the neighbouring point an estimate which is smaller than g_t can be chosen. This may lead to the introduction of spurious features into the practical choice field even though there is a bona fide better estimate at each individual point. Comparisons of p_e and g_t fields should show whether this is likely to be a problem in practice.

The errors of radar data depend on a variety of factors including the distance from the radar installation, the types of rainfall occurring during the duration involved and, therefore, on the duration itself, topography, and the sampling interval used to derive the radar rainfalls. The variability of rainfall fields would depend mainly on rainfall type and duration. It would be possible to investigate accuracy of radar data and variability of rainfall for durations of a day or longer with existing data but it would be difficult for sub-daily durations because of a lack of dense recorder networks to provide g_t fields.

In principle these methods can also be applied to areas as well as points. It is likely that for areas both the errors of radar data and the variability of rainfall fields are smaller than for points because of the reduction due to areal averaging. Figs 6(a) and 7(c) indicate that if the data error and field variability reduce in the same proportion then the error curves retain their relative pattern and E_{ag}, E_{og} and E_{pg} also reduce. This is a matter of real practical interest because there is a requirement to develop a method to decide when radar observations are beneficial in estimating daily rainfalls averaged over 40 × 40 km squares, with sparse gauges and no truth field, for application in the Meteorological Office Rainfall and Evaporation Calculation System. A possible method is to produce the p_e field as described above and average the 64 p_e values to form the 40 × 40 km square values required; this keeps the decision of whether to use radar data at the 5 km spacing level and so changes in the conditions within each large square can be accounted for.

12. Conclusions

Fields of rainfall amount for a specified duration can be derived by interpolation within sparse gauge observations (g_e) or from dense radar observations adjusted by the gauge observations (a_e). Over an area the gauge-only field can be a better estimate of the true gauge field than the adjusted radar field or vice versa; it depends on the relationship between the accuracy of radar observations (compared with co-located gauge ones) and the variability of the rainfall field being observed. At specific locations it is not possible to determine with 100% success which of g_e and a_e is the better estimate but a method has been developed which embodies the two competing factors above and which gives a success rate of choice better than the 50% from chance.

Without such a choice being made it is possible for radar data, used indiscriminately, to be non-beneficial.

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An occasion of high absolute humidity in England: 1 July 1968

By R.P.W. Lewis

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Summary

Occasions of high absolute humidity are worthy of study in view of their importance for the proper functioning of air-conditioning plant at large computer installations. On 1 July 1968, dew-points reached at least 18 °C for several hours over almost the whole of southern England and at least 20 °C over smaller, though still considerable, areas. This was the most extreme occasion of widespread high humidity during the period 1957–80.

Bilham (1938), in his book *The climate of the British Isles*, included a section entitled 'Extremes of absolute humidity' which was in part based on earlier work by Dight (1934). Dight had prepared a table of all occasions from 1900 to 1933 when temperature exceeded 85 °F at Kew Observatory, together with the associated humidity data, from which Bilham extracted occasions showing 'a notably high value of the absolute humidity'. The criterion used by Bilham, to judge by the values he quotes, was a vapour pressure of at least 19.9 mb, i.e. a dew-point of at least 17.4 °C (63.3 °F); the highest value at Kew was 23.9 mb (dew-point 20.4 °C). Such occasions of high absolute humidity have assumed a new interest in recent years with the development of elaborate computer installations, the proper functioning of which is crucially dependent on the proper environmental conditions of temperature and humidity; if the dew-point in the ambient air is too high for the air-conditioning system to cope with, the computers will have to be closed down, an important consideration for real-time systems or those working to a tight schedule, such as weather forecasting. Knowledge of the most unfavourable conditions possible is therefore important.

Climatological Memorandum No. 103 (Meteorological Office 1976) indicates that over the whole of England (except the extreme north) and South Wales the maximum dew-point during the years 1961–70 equalled or exceeded 19.0 °C (equivalent to a vapour pressure of 22.0 mb). Use was therefore made of a series of climatological data tapes of hourly values, mainly for the years 1957–80, available in the Special Investigations Branch, to search for occasions when vapour pressure ⩾ 21.5 mb (or dew-point ⩾ 18.6 °C). The stations surveyed were Boscombe Down (1957–80), Dungeness (1957–79), Exeter (1957–80), Filton (1957–79), Gloucester (1960–80), London/Heathrow Airport (1957–80), Waddington (1957–80) and Watnall (1957–80) for the months June to September. Of these eight stations, 1 July 1968 came out as top of the list at six and was also selected at another station leaving only one (Dungeness) where it failed to qualify. Very high absolute humidities were therefore exceptionally widespread over southern England on 1 July 1968 and the occasion was thought to merit more detailed examination.

The occasion, 1 July 1968, has been studied in detail by Stevenson (1969) because on that day there were extensive outbreaks of thundery rain which deposited large amounts of red Saharan dust over a wide area. Stevenson's paper analyses the synoptic situation and presents detailed isentropic analyses. She does not, however, comment on the high absolute humidities, and these are shown in Figs 1(a), (b) and (c).

Of individual stations, Watnall is remarkable as having recorded at 12 GMT a dry-bulb temperature of 29.9 °C and a wet-bulb temperature of 24.9 °C, yielding a dew-point of 22.7 °C. This value of dew-point compares with values of 21.4, 21.2 and 20.7 °C at 10, 11 and 13 GMT respectively and might possibly, therefore, be due to an error in reading the wet bulb, although at an official station this is most unlikely. (The evidence of the hygrogram is inconclusive.)

The winds over England were relatively light, though by no means calm. The reported dew-points might therefore have been too high by a degree or so. Regrettably, aspirated psychrometer records were not available at Kew or any other station known to the author. Nevertheless, we may draw the conclusion that on one occasion in the period 1957–80 (24 years) dew-points over almost the whole of southern England reached values of at least 18 °C for several hours and of at least 20 °C over smaller though still considerable areas. Whether this occasion qualifies as the most notable this century for widespread and persistant high absolute humidity cannot be judged without painstaking investigation of the records from before the era of the machinable data set; almost certainly, however, it must be near the top of the list, and forms a useful benchmark for assessing similar occasions in the future.

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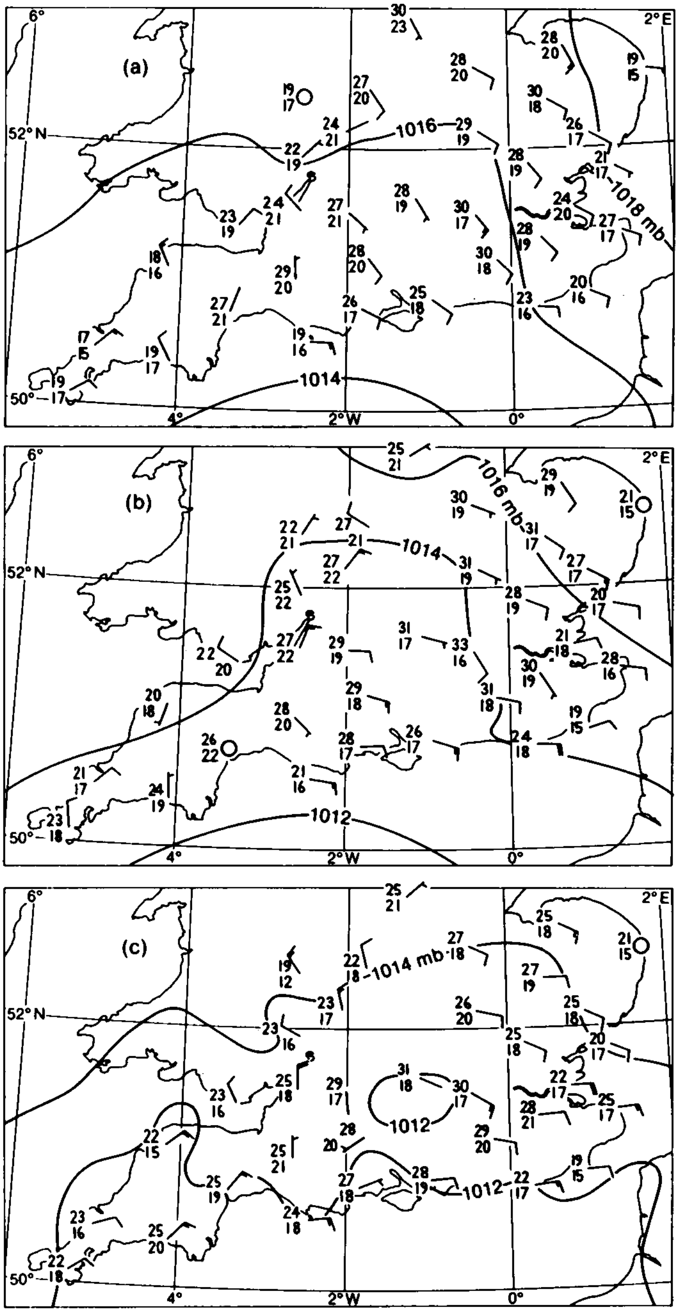

Figure 1. Wind direction and speed (one long feather = 10 kn), and dry-bulb and dew-point temperatures over southern England on 1 July 1968 at (a) 12 GMT (b) 15 GMT and (c) 18 GMT. Isobars are shown at 2 mb intervals.

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Royal Meteorological Society

The title of the meeting of the Society held on 18 December 1985 was 'Climatic impact of nuclear war', a topic now often referred to as 'nuclear winter'. The meeting, held in the Department of Mechanical Engineering at Imperial College, London, attracted a large audience; the President of the Society, Mr A. Gilchrist, was in the Chair. After a few brief remarks the President called on Dr A. Slingo of the Meteorological Office to take general charge of the meeting and introduce the principal speakers.

Dr Slingo began by giving a brief historical sketch of a subject which, as he said, did not exist five years ago. During this time, a single paper published in 1982 in a Swedish environmental journal had led to a substantial international research effort into the so-called nuclear winter. As with previous environmental issues (for example, 'acid rain', the effects of supersonic transport, chlorofluoromethanes, and carbon dioxide and other trace gases) the subject had attracted wide interest from non-meteorological scientists, environmentalists, politicians and the general public at a time when the subject was still growing rapidly and new research was being undertaken. It was appropriate, therefore, that the Royal Meteorological Society should take the opportunity to review the scientific arguments in the nuclear winter hypothesis, to discover where (if anywhere) there was consensus, where there were uncertainties and disagreements, and if possible to identify where new work was needed. Dr Slingo briefly sketched the standard scenario for the nuclear winter as follows:

1. Extensive nuclear exchange (about 5000 Mt).
2. Immediate effects — blast, radiation, oxides of nitrogen, thermal pulse.
3. Thermal pulse ignites material over wide area — city and forest fires.
4. Smoke palls contain large quantities of carbon aerosol of size ≤ 1 μm. Some removed by precipitation — black rain.
5. Remaining smoke absorbs sunlight very effectively — atmosphere warms.
6. Surface insolation falls — surface cools.
7. Smoke plumes rise and merge.
8. Heated atmosphere above cooled surface. Convection suppressed so smoke resists further scavenging.
9. Changes induced in general circulation.

The typical result is that surface temperatures will fall by about 20–30 °C in summer and remain low for several weeks.

Dr R. Harrison, of the University of Essex, then described the relevant properties of different aerosols. There were three major sources: industrial fires, forest fires, and dust (as distinct from aerosols generated by combustion) raised by winds or produced by volatilization. Important properties of aerosols are their size distributions, chemical composition, rates of coagulation, rates of loss to various sinks, and optical characteristics. (Examples of 'sink' processes are sedimentation, scavenging, and diffusion.) Dr Harrison showed how different ways of expressing size distribution, for example by number, surface area, or mass per unit volume, led to very different formulae. In the discussion following Dr Harrison's paper, Professor Percival of Queen Mary College, London said that the *shapes* of the aerosol particles had a marked effect on several of the properties described, and more work was needed on this.

Dr K.P. Shine (Department of Atmospheric Physics, University of Oxford) gave an account of the relevant radiation physics. He showed how relatively simple models could demonstrate the sorts of effects that could occur when a large mass of particulate absorbing matter was injected into the atmosphere. As more and more 'soot' is added, the balance between radiative and convective equilibrium leads to a progressive lowering of the tropopause until it reaches the earth's surface, and the effect on surface temperature moves from a possible slight warming to a strong cooling. However, while discussing a slide showing various predicted values, Dr Shine warned his audience that a mathematical model of the type he had described was little more than an educational toy which illustrated certain physical processes that *might* occur on the basis of sweeping assumptions and numerous approximations; results from such a model were open to very serious misinterpretation. Dr Shine concluded by describing some of the important characteristics of an aerosol that determine its effect on radiation, how complicated they were, and how uncertain was the derivation of bulk parameters for use in any radiative–convective model simple enough to be handled mathematically.

From the floor, Professor Scorer remarked on the apparent unreality of the current discussions. Why should something like a classic local smog situation persist for a long period over a huge area subject to normal atmospheric processes on the synoptic scale? Dr Slingo said that later speakers would be discussing this very point.

Mr D.E. Parker (Meteorological Office) described work he had carried out on the effects of major volcanic eruptions over the past 100 years. After remarking that volcanic eruptions were by no means good analogues for a nuclear war, he showed that their effect on surface temperatures was too small to be disentangled from the natural variability always present.

Dr J.F.B. Mitchell (Meteorological Office) described some modelling experiments that had been carried out in the Meteorological Office. Because of the speculation that smoke from fires following an extensive nuclear war could lead to changes in climate, several sensitivity studies had been carried out using existing three-dimensional atmospheric general circulation models. Preliminary experiments indicated that a full-scale nuclear war would produce a reduction of surface temperature over the northern mid-latitude continents of about 25 °C in summer with substantially smaller reductions at other times of the year. In a later study, in which the advection of smoke and scavenging by precipitation were parametrized, the surface cooling was less severe. Dr Mitchell emphasized that these results were crucially dependent on enough smoke being released into the atmosphere and on the assumption that the smoke is uniformly mixed in the troposphere on a continental scale. As at present these assumptions are largely a matter of speculation, there was little point in carrying out more elaborate experiments using general circulation models until the initial conditions could be specified with more confidence. Dr Mitchell also pointed out that the general circulation models now in use had been developed to take account of perturbations of a size occurring naturally; the perturbation introduced by the type of smoke cloud assumed to be produced by a nuclear winter was so very much larger, that the physical reality of the model results was questionable.

Dr P.M. Kelly (University of East Anglia) discussed the application of the results of various model experiments to the United Kingdom. It seemed that effects on temperature were likely to be relatively small in winter, but could be large and very serious in summer. There was some discussion from the floor, in which Dr A.F. Tuck and Dr P. Jonas (both of the Meteorological Office) took part, on the influence of the assumptions made involving wash-out of smoke.

Mr B.W. Golding (Meteorological Office) discussed the possible effects of mesoscale perturbations on the nuclear winter hypothesis. Calculations of possible widespread and long-term atmospheric effects from a massive nuclear exchange had so far been carried out using models with rather coarse grids, equivalent to about 5° of latitude, suitable for normal synoptic-scale forecasting. This meant that effects due to the initially patchy nature of the smoke could not be modelled properly. He described recent work using a mesoscale model extending over the area of the British Isles which had a horizontal grid length of 15 km and 16 levels in the vertical. The model was modified to include advection of smoke and also a parametrization of short-wave radiative heating by smoke. A smoke source was inserted in a column of radius 75 km near Manchester, and the initial conditions were for a real day of anticylconic weather in summer. The results showed that a direct circulation set up by heating of the smoke could lead to cloud formation near its top. This might have important consequences for the subsequent evolution of the smoke pall. Further work was needed to determine the sensitivity of the model to the approximations made and to the initial conditions. More detailed treatment of the source region was desirable and so was the inclusion of the interaction between winter and smoke.

Professor Scorer asked why a simpler case had not been studied, such as a circular island with symmetrical orography; this might have revealed all that was significant in the results. Mr Golding replied that a suitable model already designed for mesoscale forecasting over the United Kingdom was available, and use was made of it.

Dr A.F. Tuck (Meteorological Office) began his talk on the effects of nuclear war on ozone by saying, echoing Robert Boyle, that his discourse might well have been entitiled 'A sceptical chymist looks at nuclear winter'. He pointed out that the direct chemical products of nuclear fire-balls included large quantities of NO_2, a gas which absorbs strongly in the near ultraviolet and visible spectrum. The effect of this on the transmission of solar radiation should be considered, since it would affect the amount of radiation which could be absorbed in any soot clouds which might subsequently develop beneath. NO_2 and HNO_3 also have infra-red spectral features in the 'atmospheric window' region (7–14 μm) and so do other gases which are products of complete or partial combustion of organic and fossil fuel material; SO_2, C_2H_6, C_2H_4, and any molecule containing a C–O vibration for example. Very crude order-of-magnitude estimates suggest that the 'greenhouse' effect from these gases (which will be present in the smoke) should be studied with better radiative transfer calculations than those hitherto employed. To give an accurate quantitative assessment of all the chemical reactions that might take place following the incineration of a large industrial city was a matter of extreme difficulty.

Professor Sir Frederick Warner, FRS (Scientific Committee on Problems of the Environment (SCOPE) and the University of Essex) who is Chairman of the Steering Committee of the SCOPE project on Environmental consequences of NUclear WAR (ENUWAR), gave a brisk and professional presentation of the main conclusions contained in the ENUWAR report which had been presented in September 1985 to the SCOPE General Assembly in Washington DC, USA. These conclusions were based on the results of a variety of modelling experiments and much other evidence. It seemed that the indirect environmental effects of a nuclear war, though perhaps not so extreme as early studies had predicted, would nevertheless be no less serious for non-combatant than for combatant nations. Sir Frederick did not, however, discuss the implications for these conclusions of the views put forward at the current meeting.

Dr Slingo, in drawing the meeting to a close and in response to various questions from the floor, emphasized his misgivings that excessively sweeping conclusions were being drawn from the results of model experiments by people who did not fully understand, and were not in touch with, the actual work. Experience in the Meteorological Office had shown that large-amplitude atmospheric waves were excited by the dust cloud perturbation, and the origins and reality of these waves were still not properly understood.

Notes and news

Summer school at Dundee University

A postgraduate summer school on *Remote Sensing Applications in Meteorology and Climatology* will be held at the University of Dundee, from 17 August to 6 September 1986. The summer school is intended for meteorologists, postgraduate students, fresh postdoctoral research workers and other workers in the field and will concentrate on recent developments and active areas of research work. The topics to be covered in the school are expected to include the following: Introduction to atmospheric physics and remote sensing; Data acquisition; Pattern recognition and image processing; Satellite data as input to numerical weather prediction models; Satellite data and hurricane prediction; Use of radar and satellite data for estimation of precipitation; Observations of the middle atmosphere from satellites; Studies of synoptic and mesoscale systems from satellites; Cinematographic methods for the study of atmospheric motions; Multispectral classification of clouds, fog and haze; Remote sensing of sea-surface winds; Atmospheric moisture and oceanic latent heat flux; Climatological data set and climatological modelling; and Earth–atmosphere radiation budget and climatology from satellites.

In addition to the formal lecture programme, a number of less formal seminars will be held and there will be practical exercises based on photographic imagery, video, film and slide material, and digital printouts organized in the laboratory. Practical exercises to illustrate to participants the important digital image processing operations are also expected to be available.

Some bursaries may be available to assist students to attend.

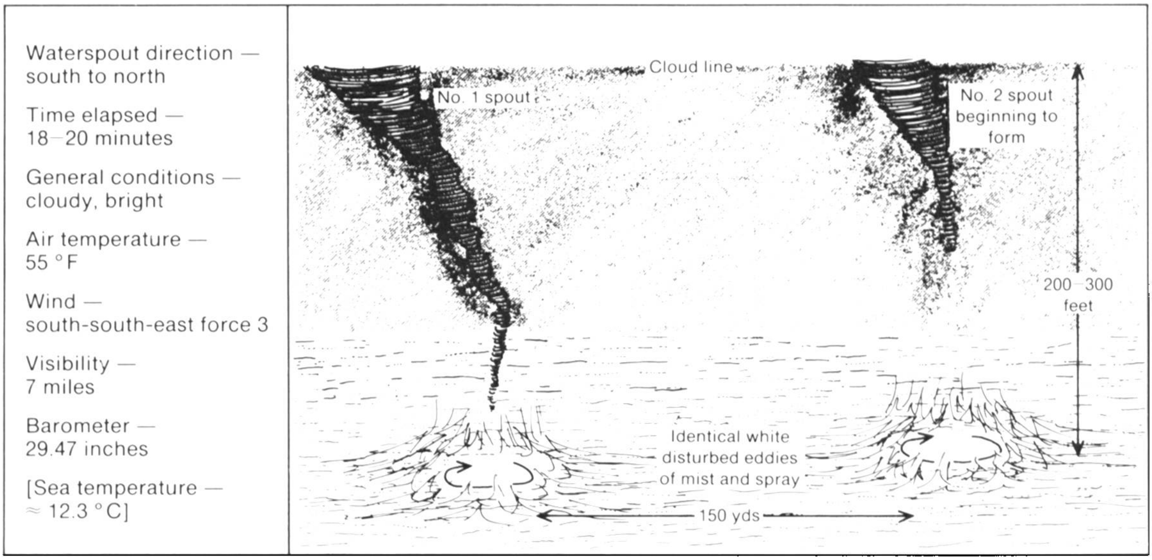
There will be sufficient free time to allow excursions to nearby places of interest.

Further particulars and application forms are available from Dr W. M. Young, 1986 Summer School Secretary, Carnegie Laboratory of Physics, University of Dundee, Dundee DD1 4HN, Scotland.

Waterspouts off the Farne Islands

The account that follows is taken from a letter to the editor from Mr Gordon Medlicott, a keeper at the Longstone Lighthouse on the Farne Islands off the coast of Northumberland. At 12 GMT on the day in question a mature depression extending up through the troposphere was slow moving off north-west Ireland with a central pressure of 984 mb. An unstable south-easterly airstream covered the area of the Farne Islands and showers were widespread over the whole of the British Isles. A thunderstorm was reported at Aberdeen at 12 GMT.

When I observed the event I was very excited to be able to witness such an event at close quarters. I have seen waterspouts in the Southern Oceans whilst in the Merchant Navy some 25 years ago but ships always give these things a wide berth and they are only seen from a distance. However here is an account of what was observed by myself and two colleagues at the Longstone Lighthouse on 2 October 1984. The general weather conditions were, a fine bright day with only a slight sea swell. Our attention was drawn by a rather unexpected heavy rain shower which lasted only about 90 seconds, it was then observed that a very black cloud was to the south of us at about 800 yds and a small disturbance was dancing on the water, this continued to grow until a large localized area of about 10–12 yards of mist and spray could be seen spinning about. We then realised we were about to see something unusual. This disturbance was of course the birth of the eventual waterspout. My colleagues went off to fetch their cameras and during the next 15–18 minutes took several shots of the event, unfortunately the resulting photographs do not show the event too well, but it was worth the attempt. A second swirl of water began to form about 150 yards south-east of the first and this did eventually form into a very thin spout, but the first one was of the main interest. The spout began to form, originating from a cone at cloud level (this was most surprising as I'd



Sketch of waterspouts observed near the Longstone Lighthouse, Farne Islands, on 2 October 1984 (drawn from a rough sketch made by the author) together with readings made at the time.

assumed they started at sea level and climbed upwards), it was now about 400–600 yards away, and we then had visible two waterspouts, these were travelling in a northerly direction (I wouldn't like to hazard a guess at the speed) and eventually disappeared. After reading up on waterspouts I now realise that what we had seen was a textbook phenomenon.

Photograph taken by Mr Turney, Assistant Keeper, of one of the waterspouts observed near the Longstone Lighthouse, Farne Islands, on 2 October 1984.

International assessment of the role of carbon dioxide and of other greenhouse gases on climate variations and associated impacts

We think our readers will be interested in the following 'conference statement' which we print as received.

A joint United Nations Environment Program (UNEP)/World Meteorological Organization (WMO)/International Council of Scientific Unions (ICSU) conference was convened in Villach, Austria from 9 to 15 October 1985, with scientists from 29 developed and developing countries, to assess the role of increased carbon dioxide (CO_2) and other radiatively active constituents of the atmosphere (collectively known as greenhouse gases and aerosols) on climate changes and associated impacts. The other greenhouse gases reinforce and accelerate the impact due to CO_2 alone. As a result of the increasing concentrations of greenhouse gases, it is now believed that in the first half of the next century a rise of global mean temperature could occur which is greater than any in man's history.

The conference reached the following conclusions and recommendations:

1. Many important economic and social decisions are being made today on long-term projects – major water resource management activities such as irrigation and hydro-power, drought relief, agricultural land use, structural designs and coastal engineering projects, and energy planning — all based on the assumption that past climatic data, without modification, are a reliable guide to the future. This is no longer a good assumption since the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century. It is a matter of urgency to refine estimates of future climate conditions to improve these decisions.
2. Climate change and sea-level rises due to greenhouse gases are closely linked with other major environmental issues such as acid deposition and threats to the Earth's ozone shield, these being mostly due to changes in the composition of the atmosphere caused by man's activities. Reduction of coal and oil use and energy conservation undertaken to reduce acid deposition will also reduce emissions of greenhouse gases; a reduction in the release of chlorofluorocarbons (CFCs) will help protect the ozone layer and will also slow the rate of climate change.
3. While some warming of climate now appears inevitable due to past actions, the rate and degree of future warming could be profoundly affected by governmental policies on energy conservation, use of fossil fuels, and the emission of some greenhouse gases.

These conclusions are based on the following consensus of current basic scientific understanding:

- The amounts of some trace gases in the troposphere, notably CO_2, nitrus oxide (N_2O), methane (CH_4), ozone (O_3) and CFCs, are increasing. These gases are essentially transparent to incoming short-wave solar radiation but they absorb and emit long-wave radiation and are thus able to influence the Earth's climate.
- The role of greenhouse gases other than CO_2 in changing the climate is already about as important as that of CO_2 itself. If present trends continue, the combined concentrations of atmospheric CO_2 and other greenhouse gases will be radiatively equivalent to a doubling of the amount of CO_2 from pre-industrial levels, possibly as early as the 2030s.
- The most advanced experiments with general circulation models of the climatic system show increases of the global mean equilibrium surface temperature for a doubling of the atmospheric CO_2 concentration, or equivalent, of between 1.5 and 4.5 °C. Because of the complexity of the climatic system and the imperfections of the models, particularly with respect to ocean–atmosphere interactions and clouds, values outside this range cannot be excluded. The realization of such changes will be slowed by the inertia of the oceans; the delay in reaching the mean equilibrium temperatures corresponding to doubled greenhouse gas concentrations is expected to be a matter of decades.
- While other factors such as aerosol concentrations, changes in solar energy input and changes in

vegetation may also influence climate, the greenhouse gases are likely to be the most important cause of climate change over the next century.

- Regional-scale changes in climate have not yet been modelled with confidence. However, regional differences from the global averages show that warming may be greater in high latitudes during late autumn and winter than in the tropics; annual mean run off may increase in high latitudes; and summer dryness may become more frequent over the continents at middle latitude in the northern hemisphere. In tropical regions, temperature increases are expected to be smaller than the average global rise, but the effects on ecosystems and humans could have far-reaching consequences. Potential evapotranspiration will probably increase throughout the tropics whereas in moist tropical regions convective rainfall could increase.
- It is estimated on the basis of observed changes since the beginning of this century, that global warming of 1.5 to 4.5° C would lead to a sea-level rise of 20–140 cm. A sea-level rise in the upper portion of this range would have major direct effects on coastal areas and estuaries. A significant melting of the west Antarctic ice sheet leading to a much larger rise in sea level, although possible at some future date, is not expected during the next century.
- Based on analyses of observational data, the estimated increase in global mean temperature during the last one hundred years of between 0.3 and 0.7° C is consistent with the projected temperature increase attributable to the observed increase in CO_2 and other greenhouse gases, although it cannot be ascribed in a scientifically rigorous manner to these factors alone.
- Based on evidence of the effects of past climate changes, there is little doubt that a future change in climate of the order of magnitude obtained from climate models for a doubling of the atmospheric CO_2 concentration could have profound effects on global ecosystems, agriculture, water resources and sea ice.

RECOMMENDED ACTIONS

1. Governments and regional inter-governmental organizations should take into account the results of this assessment in their policies on social and economic development, environmental programs, and control of emissions of radiatively active gases.
2. Public information efforts should be increased by international agencies and governments on the issues of greenhouse gases, climate change and sea level, including wide distribution of the documents of this conference.
3. Major uncertainties remain in predictions of changes in global and regional precipitation and temperature patterns. Ecosystem responses are also imperfectly known. Nevertheless, the understanding of the greenhouse question is sufficiently developed that scientists and policy-makers should begin an active collaboration to explore the effectiveness of alternative policies and adjustments. Efforts should be made to design methods necessary for such collaboration.

Governments and funding agencies should increase research support and focus efforts on crucial unsolved problems related to greenhouse gases and climate change. Priority should be given to national and international scientific program initiatives such as (a) the World Climate Research Programme (WMO–ICSU), (b) present and proposed efforts on biogeochemical cycling and tropospheric chemistry in the framework of the Global Change Programme proposed by ICSU, and (c) National Climatic Research Programmes. Special emphasis should be placed on improved modelling of the ocean, cloud–radiation interactions, and land surface processes.

Support for the analysis of policy and economic options should be increased by governments and funding agencies. In these assessments the widest possible range of social responses aimed at preventing or adapting to climate change should be identified, analysed and evaluated. These assessments should be initiated immediately and should employ a variety of available methods. Some of these analyses should be undertaken in a regional context to link available knowledge with economic decision-making and to characterize regional vulnerability and adaptability to climate change. Candidate regions may include the Amazon basin, the Indian subcontinent, Europe, the Arctic, the Zambezi basin, and the North American Great Lakes.

4. Governments and funding institutions should strongly support the following:
   (i) Long-term monitoring and interpretation with state-of-the-art models of radiatively important atmospheric constituents in addition to CO_2 (including aerosols), solar irradiance, and sea level.
   (ii) Study and interpretation of the past history of climate and environment, specially regarding interactions among the atmosphere, oceans and ecosystems.
   (iii) Studies of the effects of atmospheric composition and of changing climate and climatic extremes on subtropical and tropical ecosystem, boreal forests, and on water regimes.
   (iv) Investigations of the sensitivity of the global agricultural resource base with respect to:
      (a) direct effects of increases in atmospheric CO_2 and other greenhouse gases;
      (b) effects of changes in climate; and
      (c) probable combinations of these.
   (v) Evaluation of social and economic impacts of sea-level rises.
   (vi) Analysis of policy-making procedures under the kinds of risks implied by a significant greenhouse warming.

5. UNEP, WMO and ICSU should establish a small task force on greenhouse gases, or take other measures, to:
   (i) help ensure that appropriate agencies and bodies follow up the recommendations of the conference;
   (ii) ensure periodic assessments are undertaken of the state of scientific understanding and its practical implications;
   (iii) provide advice on further mechanisms and actions required at the national or international levels;
   (iv) encourage research in developing countries to improve energy efficiency and conservation; and
   (v) initiate, if deemed necessary, consideration of a global convention.

Presentation of award to Sir Arthur Davies

Sir Arthur Davies, KBE, Secretary-General Emeritus of the World Meteorological Organization (WMO), was presented with the thirtieth International Meteorological Organization (IMO) Prize on 20 January 1986 at a ceremony held at the premises of the Royal Society, London. (See *Meteorol Mag*, **114**, 1985, 323.) The proceedings were opened by the Parliamentary Under-Secretary of State for Defence Procurement (Mr John Lee, MP) who spoke of Sir Arthur's achievements and gave official expression of the pleasure of HM Government that Sir Arthur had been honoured in this way. Professor G.O.P. Obasi, the current Secretary-General of WMO, outlined the history of the IMO Prize and gave an account of Sir Arthur's career including personal memories of the latter's courtesy and helpfulness. Both Mr Lee and Professor Obasi referred to the remarkable fact that the United Kingdom had already provided four recipients of the IMO Prize, and said how pleased they were that two of this number — Professor R.C. Sutcliffe and Mr J.S. Sawyer — were present at the ceremony. Dr R.L. Kintanar, President of the WMO, then formally presented the Prize to Sir Arthur Davies.

In his speech of thanks, Sir Arthur said how privileged he felt to have his name added to the list of distinguished scientists from all over the world who had been similarly honoured, and himself paid tribute to the presence of Dr Sutcliffe and Mr Sawyer. He stressed the importance of the international and co-operative nature of meteorological science, of which the IMO Prize was itself a symbol.

Sir Arthur Davies receiving his award from Dr R.L. Kintanar.

Letter to the Editor

Comments on 'Satellite photograph — 4 November 1985 at 0426 GMT' (*Meteorol Mag*, **115**, 1986, 34–35): the explanation of the obscure streak in the middle of the clear area off southern Iceland.

An analysis of 20 synoptic observing stations over Iceland at 00 and 09 GMT on 4 November suggests that the origin of the streak is due to low-level convergence near and off the coast of south-east Iceland. Coastal observations along the east and south-east coasts suggest that the north-easterly air flow splits on approaching Iceland, the bulk of the flow passing south-east of the land mass and blowing strongly along the south-east coast. However, part of the flow crosses the land to go round the northern part of the vast upland ice sheet Vatna Jökull (mostly 1000 to 2000 m above sea level) before turning south to reach the south coast of Iceland in the region of the cloud streak. Additionally, it is possible that a strong katabatic from the ice sheet also aids the northerly flow off the land in that area. Thus, as shown in Fig. 1, there is marked surface convergence in the region of cloud formation. Interestingly, surface observations also suggest a second convergence line originating near the eastern-most tip of Iceland, and extending downstream. Close examination of the satellite picture does suggest a continuous line of cloud corresponding to this convergence zone.

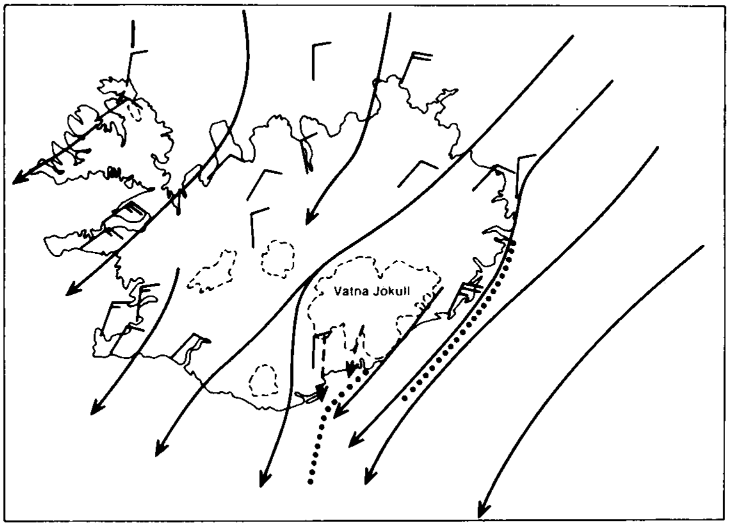


Figure 1. Surface wind direction and speed (one long feather = 10 kn) and streamlines at 09 GMT 4 November 1985. Significant ice sheets are depicted by pecked lines, these generally covering high ground above about 800–1000 m. The convergence zones referred to in the text are shown by dots and the katabatic flow from the Vatna Jökull ice sheet by dashed lines.

Cloud bands such as these are frequently seen in satellite imagery when cold air masses stream out to sea in regions where the immediate land area is hilly or where there are distinct kinks in the coastline. Such bands have been documented by Mass and Dempsey (A topographically forced convergence line in the lee of the Olympic mountains, *Mon Weather Rev*, 1985, **113**, 659–663) when cold air streams westwards into the Pacific from Washington State. Readers may even spot such bands over the British Isles, notably in north-westerly airstreams when cold air reaches the Irish Sea from the region of the Mourne Mountains (County Down), and also over the North Sea downwind from the Aberdeen or Berwick-upon-Tweed (Northumberland) areas.

G.A. Monk

Meteorological Office
Bracknell

Reviews

The climatic scene, edited by M.J. Tooley and G.M. Sheail. 155 mm × 240 mm, pp. xxi + 306, *illus*. George Allen and Unwin, London, Boston, Sydney, 1985. Price £23.00.

In his opening lectures to postgraduate courses at Imperial College in the mid-1950s Professor Sheppard used to say that meteorology was an observational science. That was, of course, before the advent of large computers and the development of dynamical modelling techniques transformed a major part of the subject. Nowadays, major advances in the understanding of the atmosphere can come from, often unsung and by many people not understood, formulations or reformulations of sets of equations or improvements in the parametrization for numerical modelling purposes of the physical processes that dominate atmospheric dynamics.

To many young, and perhaps not so young, meteorologists, even to discuss the accomplishments and achievements of Gordon Manley may seem anachronistic and those who bother to read his papers may all too easily dismiss them as being the speculative writings of a geographer somewhere on the fringes of meteorology. What then did Manley achieve? Why should his memory and work be honoured by a distinguished group of meteorologists, climatologists and biometeorologists? In a very few words, Manley simply made maximum effective use of the main tools available to meteorologists of his era. He observed and recorded what he saw perceptively, he described accurately and, above all, he understood much of what he saw. He concentrated much of his interest upon geographical and topographical variations of the weather within the United Kingdom and, particularly, over and around his much loved Pennines. Although essentially empirical, his work on lee waves — especially that particular phenomenon known as the helm wind of Crossfell — was the springboard from which the definitive theoretical contributions by R.S. Scorer and others gained much of their impetus. As a meteorological journalist Manley stood the critical test of the *Manchester Guardian* (nowadays *The Guardian*) editorship and readership.

Manley graduated, first, as an engineer and then proceeded to read for a degree in geography at Cambridge. There, his boyhood interest in meteorology began to bloom when he was introduced to polar and high-level environmental problems. His engineering training gave him the feel for basic and accurate measurements while his Cambridge studies indicated how this might best be applied to his particular interests.

This book in paying tribute to Manley discusses and extends his work in various fields. In order to determine whether or not climatic changes are occurring or have occurred during the few centuries when instrumental observations are available it is necessary to be able to compare past and present data. Such procedures are bedevilled by changes in instruments, instrument exposures, sites, observing practices, and so on. A major and important component of his work is the creation of homogeneous data sets such as the Central England Temperature Series.

After a brief biography of Manley, three chapters by Kenworthy, Harris and Shaw discuss the creation and use of such homogenized data series for the United Kingdom. Flöhn discusses the derivation of proxy series — a technique that owes much to Manley. Lamb also shows how proxy data can be used and produces synoptic maps for some famous historic storms. Notable must be that for the Spanish Armada in 1588 for which Lamb has produced charts of isobars and fronts before the barometer was even invented!

Chapters by Grove and Pfister discuss such matters as snow cover and glaciers over Scandinavia and central Europe, subjects both dear to Manley's heart. Long-term climatic changes are discussed by Barber in a study of peat stratigraphy. Oldfield and Robinson discuss geomagnetism and palaeoclimate while the last three chapters in the book all point to the reasons for investigating climate and climatic change at all. Tooley discusses sea-level and coastal changes, Carter and Prince discuss the effects of climate on plant distributions while Bourke writes about climatic effects on diseases and pests of agriculture. These last three papers would have been received by Manley with particular enthusiasm. He was always aware of the principal reasons for studying climate as shown by his contributions to the *Report of the land utilisation survey of Britain*.

In these days of sophisticated climatic modelling it could be very easy for the incautious to derive solutions for the many integrations of sets of equations but yet have no idea either as to the likelihood of occurrence or the consequential effects upon humanity. There is a need for the type of work undertaken by Manley to continue, a need to be able to validate data whether these are derived from current observations, proxy historical or model output. There is a need to be able to understand the possible effects of climatic change. The economic and social consequences of not so doing could be traumatic.

We owe it to future generations — and no one as yet knows just how far in the future — to understand the atmosphere and, particularly, its long-term variability.

This book should be read by all those, of whatever meteorological discipline, who are striving to understand climate. May the work of Manley, all he stood for as a meteorologist and as a warm, understanding, concerned human being, continue to prosper.

F. Singleton

Atmospheric ozone, edited by C.S. Zerefos and A. Ghazi. 155 mm × 230 mm, pp. xxxi + 842, *illus.* D. Reidel Publishing Company, Dordrecht, Boston, Lancaster, 1985. Price Dfl 275, US $99.00, £69.95.

International Ozone Symposia have been held every four years since the International Geophysical Year, the first being at Albuquerque in 1964. There has been a considerable expansion in (and funding for) atmospheric ozone research since the publication of papers in the early 1970s suggesting that there could be a reduction in stratospheric ozone as a result of man's activities. The decrease in the number of papers, from 185 in 1980 to 138 in 1984, probably reflects the decision of the organizers to restrict the sessions to four and a half days rather than five.

The papers are photographically reproduced with some reduction in size from the author's camera-ready copy, to form a single manageable volume. Rather little editing or sub-editing seems to have been done so that, in the paper by Evans *et al.* (page 680) on the use of the automated Brewer ozone spectrophotometer to produce whole-sky maps of ultraviolet intensity, the text refers to the colours used for shading, and makes quite a point of their spectral order, while the figures (obviously produced on the same PET microcomputer) use 'chunky' graphic symbols in black and white. Again, on page 583, N^z is printed where N^2 was clearly intended, and on pages 256 and 257 Figs 1 and 3 have been interchanged. In view of the method of reproduction, it could be argued that the fault lies more with the authors than with the editors, but it remains a fault. With the exception of just two one-page abstracts, the contributions are presented as short papers of between two and six pages. The actual variation in content of the work presented is far greater than this — while some papers might have appeared elsewhere as letters others are in effect extended abstracts of much larger papers, even though formally they forego the claim to *be* abstracts by *having* them. Both types of presentation are useful, and it is convenient to have them assembled in one place.

The topics covered by the papers largely follow the pattern set by previous Ozone Symposia, and the reader desiring an outline of each of the nine sessions will find the Editors have provided just that in their introduction. I shall confine myself to noting what seemed to me to be the main areas of growth. In 1980 there was just one paper reporting preliminary results with the Total Ozone Mapping Sounder (TOMS), and more on the nadir-viewing Solar Backscattering Ultraviolet (SBUV) instrument. In 1984 the Symposium heard reports of improved algorithms for calculating total ozone columns from TOMS and SBUV, and vertical profiles from SBUV. An extensive set of maps of total ozone is available from TOMS, and has been used to check the ground-based ozone spectrophotometer network. The relationship between upper-atmosphere circulation patterns and total ozone as observed by Dobson decades ago is now seen in far greater detail. Difficulty in reconciling TOMS and SBUV values with the Dobson network has resulted in a number of new determinations of the absorption cross-section of ozone, which seem to have largely removed the disparity. The essentially downward-looking infra-red and ultraviolet satellite instruments have been joined by a new generation which view the Earth's limb, using either thermal emission (Limb Interferometer Monitor of the Stratosphere and the Stratosphere Mesosphere Explorer) or solar occultation (Stratospheric Aerosol and Gas Experiment). These are able to measure other minor species of importance in ozone photochemistry, as well as ozone. As far as computer modelling is concerned, the move away from one-dimensional models to two and three dimensions has continued. Two major balloon measurement programs aimed at comparing different measurement techniques for both ozone and related minor species are reported. They are the Balloon Intercomparison Campaign, in Texas in 1982, and the Middle Atmosphere Program/Globus, at Aire-sur-l'Adour in 1983. Finally there was an increase in the number of papers on ozone in the troposphere, even though the section heading implies that papers on polluted urban atmospheres had been excluded. The general impression is of an area of research which is active within its own borders and a stimulus to neighbouring areas.

E.L. Simmons

Global change, edited by T.F. Malone and J.G. Roederer. 180 mm × 252 mm, pp. xxviii + 512, *illus*. Cambridge University Press, Cambridge, London, New York, New Rochelle, Melbourne, Sydney, 1985. Price £35.00, US $59.50.

This volume, published on behalf of the International Council of Scientific Unions (ICSU), comprises the proceedings of a multi-disciplinary symposium held in Ottawa in September 1984. The specific objective of both the symposium and this book was to explore the need for, and the possibility of, an international research program 'to illuminate the complex and synergistic physical, chemical and biological processes in the Sun–Earth system that determine its change'. As with so many recent environmentally-orientated proposals, the underlying justification is posed in terms of pressures both from society and upon society. However, although the preface quotes with approval from the ICSU General Assembly of 1982 that 'This will not only present a challenge to all the disciplines now represented in ICSU but will require increasing contact with the human and social sciences', there is limited evidence of such societal-based contact — the final paper on human activities and global change (W.C. Clark and C.S. Holling) plus 2½ pages from R.W. Kates as 'extended comment'.

The book is thus a statement of the science involved in such a geosphere–biosphere program, and is structured to provide authoritative summary reviews on the major areas of concern. After four general policy-type presentations, there follows a section on the atmosphere and hydrosphere (although the latter does not seem to involve hydrology!). The structure of this section is not too clear, however. Following papers on atmospheric chemistry (P.J. Crutzen and M.O. Andreae) and physics (G.S. Golitsyn), there is a brief review of recent global climatic change studies presented by T. Yeh and C. Fu. Then two papers introduce the role of the oceans and their interaction with the atmosphere (R.W. Stewart and F.B. Bretherton, and D. Lal and W.H. Berger), before returning to the climatic change theme again with an account of the World Climate Research Programme by its Director, P. Morel. This section concludes with what to the reviewer was the most stimulating contribution, namely a palaeoclimatic research plan by T. Webb, J. Kutzbach and F.A. Street-Perrott. For atmospheric scientists this section overall provides a useful review of ongoing enquiries in areas with which one is, in general, familiar. The critical issue, however, is its impact on other scientists, as it is interaction and integration of research interests and understanding which is the whole purpose of the exercise.

For atmospheric scientists, therefore, the major value should be in the succeeding sections — seven papers on life systems, two on the solid earth, and four on sun and space. It is at this stage that the very real diversity of interests, objectives and expertise involved becomes apparent to any reader. Individuals will find different sections the most stimulating and informative the several papers on ecosystems appealed most to this reviewer. Critical gaps also appear, such as virtually no reference to change in the detailed form of the land surface itself, i.e. the whole field of geomorphology.

There is then a brief section on the theme of tools and technology, which may well prove to be the most critical theme if integrated work at a truly global scale is to be attempted seriously. As a result, merely two fairly brief papers on monitoring change by satellites (S.I. Rasool) and on data management (W.W. Hutchinson and S.W. Bie) seemed to under-represent the vital role that these areas must play, though there is also a valuable extended comment on a world digital data base by D.P. Bickmore. Finally, an equally brief section of human activity is still partially concerned with the impact of society on the science of the environment, so that the critical issue of society's ability to adjust to change receives scant attention — despite the incontrovertable assertion that 'managing global change is not the same as predicting it' (p. 478).

Overall, this volume is both stimulating and disappointing. All readers will find informed guidance to ideas and developments beyond, yet essentially related to, their own area of interest and expertise. Yet the evidence of real research integration — as distinct from assertions of faith — is not as great as one might have hoped. Perhaps the very existence of this volume, and the encouragement for integration from ICSU that it implies, will enable such integration to develop further.

S. Gregory

Books received

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

Reviews of United Kingdom statistical sources, Vol. XVII; Weather, by B.W. Atkinson, and *Water,* by E.C. Penning-Rowsell and D.J. Parker for the Royal Statistical Society and the Economic and Social Research Council (Oxford, Pergamon Press, 1985. £27.00) is the latest volume in this series, which details the availability and form of statistical information on a wide variety of topics. The primary aim of the series is to act as a work of reference to the sources of statistical material of all kinds, both official and unofficial. This volume covers the availability (or otherwise) of a wide variety of meteorological and hydrological data sources.

Safety of dams: flood and earthquake criteria, by the Committee on Safety Criteria for Dams, the Water Science and Technology Board, the Commission on Engineering and Technical Systems, and the Natural Research Council (Washington, National Academy Press, 1985. £18.50) is a report concerning the levels of safety to be provided at dams to withstand extreme floods and earthquakes. In the opening chapter of the book an attempt is made to take a broad look at the problems of coping with extreme floods and earthquakes at dams from the viewpoint of society as a whole. Other chapters describe the technical methods that have evolved to estimate the magnitude of extreme floods and earthquakes, the limitations of the methods, and some possible improvements in the methods.

Sea fog, by Wang Binhua (Berlin, Heidelberg, New York, Tokyo, Springer-Verlag, 1985. DM 215) describes many aspects of sea fog, with particular reference to fogs over the East Asia Sea region. The author started compiling and summing up the materials and experience concerning sea fog as far back as the 1940s. In recent decades data from marine meteorological observatories, research ships and, in particular, meteorological satellites have made possible the development of a general concept for sea fog distribution and the mechanisms of its generation and dissipation. The present book contains chapters on the generation and classification of sea fog, its distribution and variations around the world, hydrometeorological characteristics, sea fog analysis in the East Asia Sea region, the physical properties of sea fog, and sea fog forecasting.

Ice shelves of Antarctica, by N.I. Barkov (Rotterdam, A.A. Balkema, 1985. Hfl.85.00, £20.75) examines the large volume of observational data collected and published by the many expeditions to Antarctica before 1968. The author describes the special conditions of existence of ice shelves, their movement, morphology, charging, the structure of the thermal regime, and their contribution to the development of glaciation on the continent. Particular attention has been paid to the study of the floating, most representative, part of such ice formations. Considerable space has been devoted to the author's own observations made during 1960–61 in the West, Shackleton, Lazarev and Novolazarevskii ice shelves when he was a member of the glaciological section of the Fifth Soviet Antarctic Expedition.

Atmospheric chemistry and physics of air pollution, by John H. Seinfeld (Chichester, John Wiley and Sons, 1986. £61.35) is intended to serve as a textbook for a course in the atmospheric aspects of air pollution. Its object is to provide a rigorous, comprehensive treatment of the chemistry of air pollutants in the atmosphere, the formation, growth, and dynamics of aerosols, the meteorology of air pollution, and the transport, diffusion, and removal of species in the atmosphere.

World survey of climatology, Vol. 1A: General climatology, by A. Kessler (Amsterdam, London, New York, Tokyo, Elsevier Science Publishers, 1985. US $55.50, Dfl. 150.00) summarizes the current knowledge of the heat and radiation budget of the Earth's surface and includes many of the important contributions made in the last decade. The text is, however, more than just a summary as the author has taken into consideration the climatological impact of the budget, thus providing a particularly profound treatment of the topic.

Mr G.A. Bull

We record with regret the death on 27 February 1986 of Mr G.A. Bull who was Editor of the *Meteorological Magazine* from 1947 to 1960. He joined the Office in 1926 and, after the usual early career in forecasting, both before and during the war, began his long association with the National Meteorological Library and the Editing Section. From 1953 to 1959 he was the United Kingdom member of the World Meteorological Organization Technical Commission on Bibliography and Publications and was for some time the Vice-President of the Commission. He played a major part in planning the Library at Bracknell and in setting up the Meteorological Office Technical Archives as a consequence of the Public Records Act of 1958. In 1960 he was promoted to Assistant Director (Support Services), later becoming Assistant Director (Data Processing).

He was Honorary Librarian of the Royal Meteorological Society from 1960 to 1964. After retiring from the Office in 1966 Mr Bull became Administrative Secretary of Reading University Library, an appointment he held for the next two years.

Mr Bull will be remembered by all his colleagues as a friendly, enthusiastic and hard-working man who won the respect of all who knew him. He, more than anyone else, made the *Meteorological Magazine* what it is today.

Meteorological Magazine

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Meteorological Magazine

April 1986
Vol. 115
No. 1365

CONTENTS

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ISBN 0 11 727832 7 ISSN 0026–1149

Printed in England for HMSO
Published by HER MAJESTY'S STATIONERY OFFICE
Dd. 736047 C13 4/86

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S
STATIONERY
OFFICE

May 1986

Met.O.971 No. 1366 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1366, May 1986, Vol. 115

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Monitoring the homogeneity of UK climatological data

By Frances A. Crummay

(Meteorological Office, Bracknell)

Summary

UK temperature and sunshine data have been monitored for homogeneity during the period 1951–80. Of the stations investigated 34% were flagged as containing inhomogeneities, the majority being gradual changes for which corrections could not easily be made. These findings have implications for the World Meteorological Organization concept of Reference Climatological Stations and the use of individual stations for the monitoring of climatic trends.

Introduction

The need to monitor climatic change has increased in importance in recent years because of interest in the possible impact of man on the environment. The study of climatic trends requires long records of representative climatological data with any inhomogeneities eliminated, while the production of long-period statistics also requires homogeneous series of data.

The World Meteorological Organization (WMO) has recommended the nomination of Reference Climatological Stations whose data could be used to determine climatic trends. The *Manual on the Global Observing System* (WMO 1981) states that such stations require at least 30 years of homogeneous records, where man-made environmental changes have remained, or are expected to remain, at a minimum. In the United Kingdom the original reference stations were based on Principal Climatological Stations, mostly Meteorological Office-staffed synoptic observing stations, where high observing standards would be maintained. In 1982 this list was revised to comprise 21 long-period stations, both voluntary and officially manned, with minimal changes in site. The homogeneity of none of these reference stations was checked at the time owing to the difficulties of analysing such long periods of data by hand. However, daily climatological data are available in machinable form for most stations from 1959 and, for the purposes of creating the 1951–80 averages, monthly data were entered in the computer archives for 214 stations from 1951 to 1958. The aim of this paper is to describe a routine to monitor the homogeneity of stations with at least 10 years' data in the period 1951–80. There were 577 such stations for temperatures and 391 for sunshine.

Detection of inhomogeneities

Estimated values of climatological data at a station may be derived using regression techniques with selected near neighbours or by performing Principal Component Analysis (Crummay 1985). The latter technique was selected for this application since the near-neighbour approach may place too much weight on individual stations, which may themselves contain inhomogeneities.

Principal Component Analysis, as described by Kendall (1975), enables fields of correlated data to be represented by a set of orthogonal patterns, or eigenvectors, each explaining the greatest part of the remaining variance. The leading components represent systematic differences between the variables while random differences are consigned to higher-order components. This application of Principal Component Analysis is discussed by Spackman and Singleton (1982) and in more detail by Spackman (1979, 1980). By selecting an optimum number of components, it is possible to isolate the systematic differences and use these as estimates for comparison with the genuine observations.

The complete, self-consistent correlation or covariance matrix required was derived from a data set of monthly values created as part of the preparation of averages for the period 1951–80, any missing values having been estimated using the near-neighbour technique described by Tabony (1983).

The optimum number of components to use was determined by an investigation of known inhomogeneities identified by Done (1980). The majority of these were detected when the number of components equalled 8% of the number of stations for temperature and 12% for sunshine. The higher percentage for sunshine is a reflection of the lower inter-station correlation compared to that observed for temperature.

Residuals (observations minus estimates) were derived and divided into two subsets whose means were compared using 'Student's' *t*-test. Simply dividing the residuals into two halves would not permit the detection of inhomogeneities near the beginning and end of the record. The *t*-test was therefore performed five times with the data divided as follows to identify the approximate location of any changes:

	Subset 1	Subset 2
(i)	First 5 years (60 residuals)	last 25 years (300 residuals)
(ii)	First 10 years	last 20 years
(iii)	First 15 years	last 15 years
(iv)	First 20 years	last 10 years
(v)	First 25 years	last 5 years

Only genuine observations (as opposed to estimates) were used and queries raised when the difference in mean values of the two subsections exceeded the 95% confidence limit. To identify the specific years in which inhomogeneities occurred and to aid clarity, the annual means of the residuals were plotted, as shown in Figs 1 and 2. This application of the *t*-test is relative rather than absolute, however, as illustrated by the following points:

(i) The level of statistical significance is dependent on the amount of data available, e.g. a difference of 0.01 °C can become significant with a long enough record. The testing will therefore preferentially 'pass' stations with a short series of observations.

(ii) The routine is more likely to identify inhomogeneities in the middle of a record than those at the end.

(iii) Stations with a poor standard of observations, and hence a large 'noise' level, are more likely to be passed by the routine than a station with high observing standards and a small but steady trend.

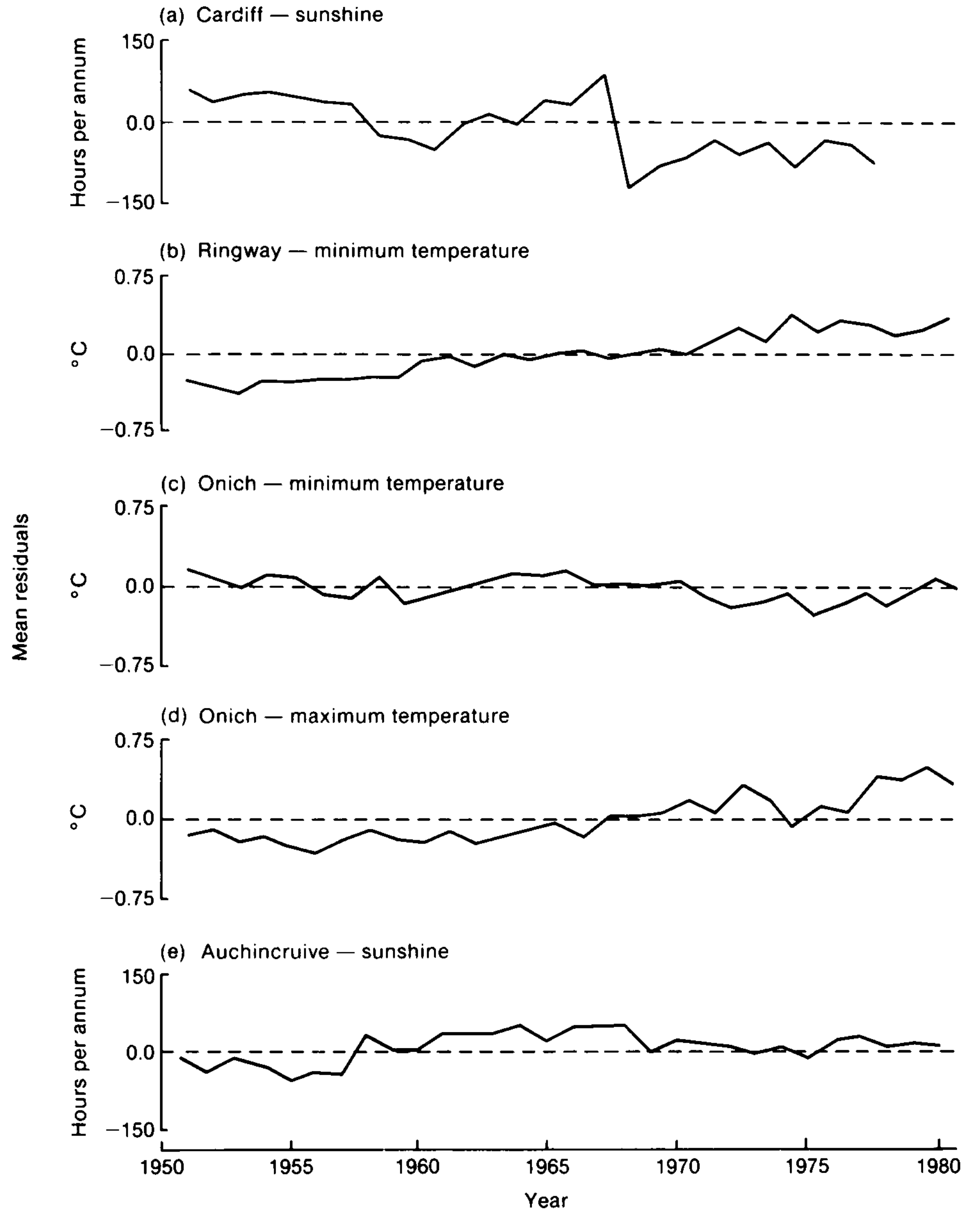
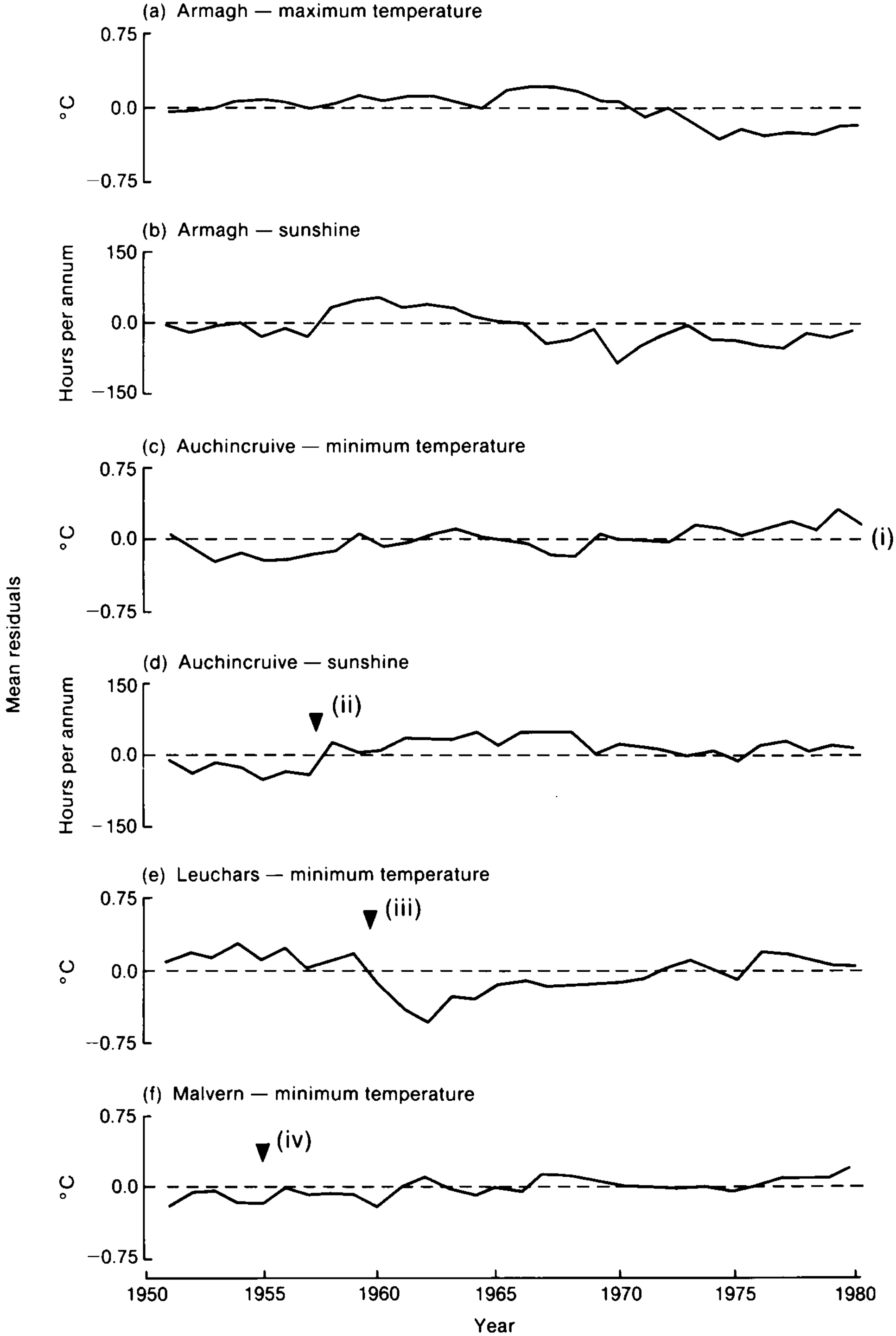


Figure 1. Annual mean residuals (observations minus estimates) for selected stations showing examples of inhomogeneities identified during the period 1951–80: (a) step inhomogeneity caused by change in site, (b), (c) and (d) changes in site exposure or character, and (e) deterioration of screen or instrument.

Figure 2. Annual mean residuals (observations minus estimates) for some of the Reference Climatological Stations listed in Table I showing inhomogeneities identified during the period 1951–80. The reference numbers (i)–(viii) refer to the possible causes of inhomogeneities listed in Table II. (The station at Cambridge is at the National Institute of Agricultural Botany (NIAB).)



(a) Armagh — maximum temperature
0.75
0.0
−0.75
°C
(b) Armagh — sunshine
150
0.0
−150
Hours per annum
(c) Auchincruive — minimum temperature
0.75
0.0
−0.75
°C
(i)
(d) Auchincruive — sunshine
150
(ii)
0.0
−150
Hours per annum
(e) Leuchars — minimum temperature
0.75
(iii)
0.0
−0.75
°C
(f) Malvern — minimum temperature
0.75
(iv)
0.0
−0.75
°C
Mean residuals
1950
1955
1960
1965
1970
1975
1980
Year

Figure 2.

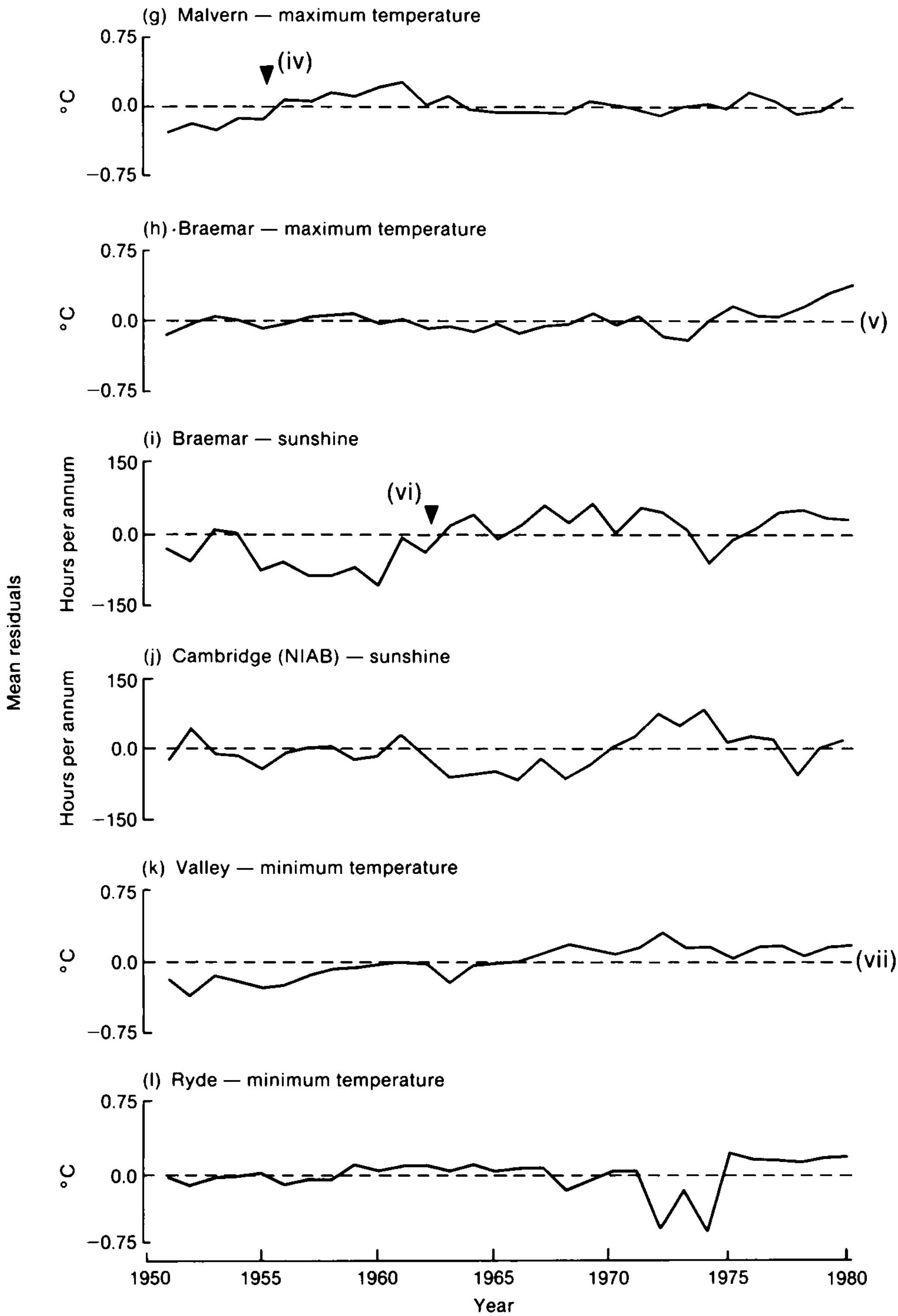


Figure 2 continued.

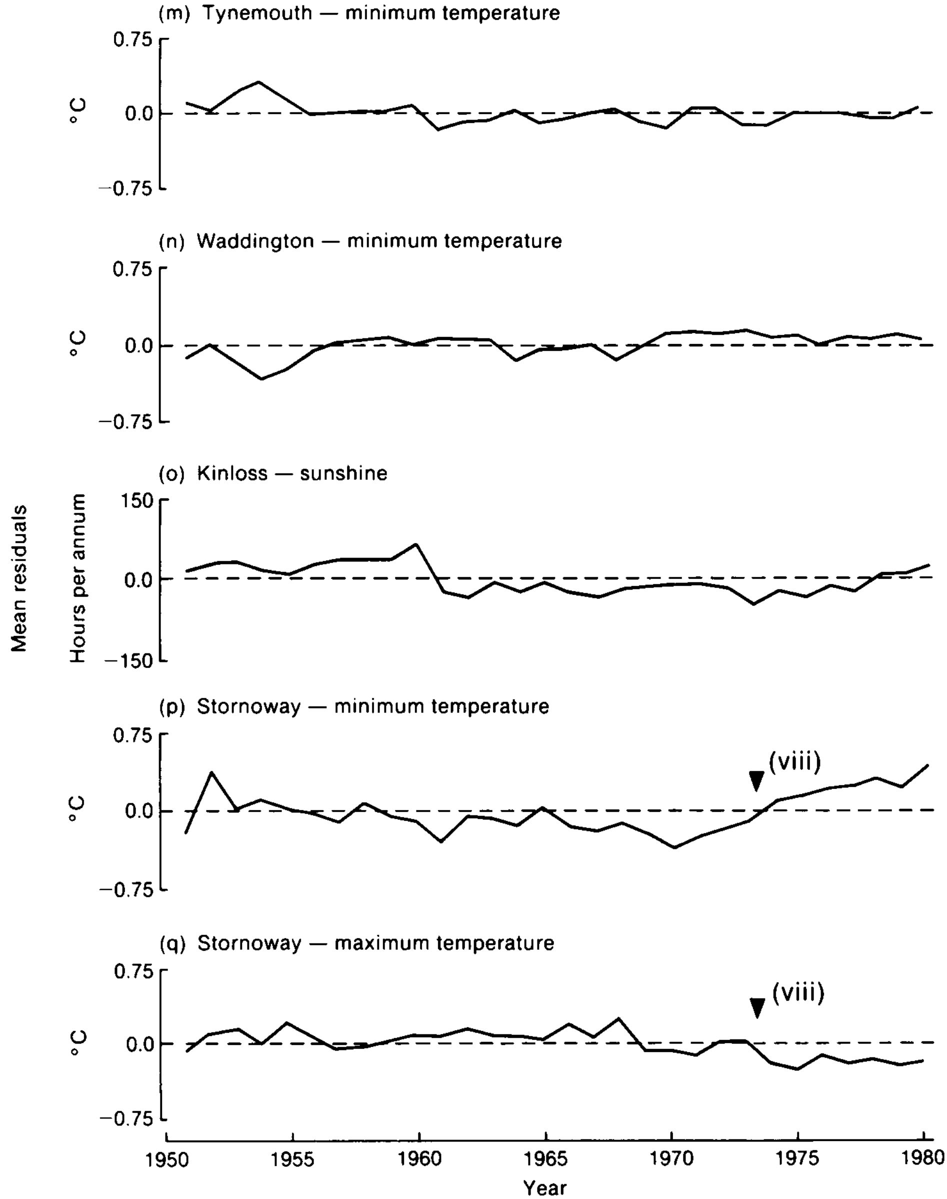


Figure 2 continued.

As a result, some level of inhomogeneity must be defined to be of practical as well as statistical significance. From an examination of the residuals it was decided that a level of ± 0.2 °C for temperature and ± 50 hours per annum for sunshine would be suitable.

Examples of inhomogeneities

Queries were raised for 34 stations (9%) for sunshine, 89 stations (15%) for maximum temperature and 116 stations (20%) for minimum temperature. From plots of the residuals it was apparent that the majority of inhomogeneities consisted of gradual changes in recorded temperatures and sunshine. The inhomogeneities may, however, have several causes:

(i) Step inhomogeneities caused by changes in site: observations of sunshine at Cardiff (Fig. 1(a)) clearly illustrate this feature. In 1960 the growth of trees at the initial site led to a decrease in observed sunshine of approximately 80 hours per annum. The recorder was moved and values returned to their previous levels. However, in 1967 the recorder was again moved, to Ty Twyn, a poor site obscured by trees. The level of sunshine recorded fell by approximately 150 hours per annum (25 minutes per day) until the station closed in 1976.

(ii) Changes in site exposure or character: for example, by the growth of trees or urbanization. Since most of the long-period stations are in urban sites it is important that the latter feature be identified. Fig. 1(b) illustrates the residuals for Ringway where increased urbanization has resulted in a gradual increase in minimum temperatures by 0.5 °C over the 30-year study period. Onich (Figs 1(c) and (d)) also exhibits the effects of changing site characteristics. Here, the growth of trees increased the shelter around the site and resulted in a gradual increase in the diurnal temperature range.

(iii) Deterioration of screen or instruments: a notable example of this is apparent in the residuals of sunshine at Auchincruive (Fig. 1(e)). An amber sphere, in use until 1957, was replaced and the residuals show a clear increase in the sunshine recorded.

(iv) Small changes in site and instrumentation, or varying accuracy between observers: these would usually result in very small changes which would not normally reach the 0.2 °C or 50 hours per annum thresholds. Occasionally, however, successive events may become significant.

In the 1951–80 study period, 231 (60%) of the 390 stations reporting all three elements were considered homogeneous. Of the 186 stations not reporting sunshine, 146 (78%) were deemed homogeneous for the temperature elements.

Homogeneity of the Reference Climatological Stations, 1951–80

The results previously illustrated indicate the problems associated with the identification of specific stations as Reference Climatological Stations. The requirement of a long homogeneous record is difficult to attain with small changes sometimes having a major effect on the observations recorded whilst major changes of site may have little effect. In addition, changes in site exposure, instrumentation and even observers have been shown to have some influence.

A list of the 21 reference stations selected in 1982 is provided in Table I together with the list of prospective stations suggested for future consideration. From an examination of the graphs produced it was apparent that ten of the current stations contained at least one inhomogeneity. Some of these could be considered negligible, but others showed clear discontinuities. One of the most notable was a site change in 1959 at Leuchars which adversely affected the minimum temperature record (Fig. 2(e)). However, a further site change in 1969 appeared to have little effect.

A complete list of the inhomogeneities identified within the 30-year period for both present and prospective reference stations is displayed in Fig. 2, with some possible causes postulated in Table II.

It is suggested that for the current reference stations flagged by the testing routine, several alternatives exist:

(i) To recognize that some may meet WMO Reference Climatological Station criteria for only one element.

(ii) To select a new reference station in the same area, for all elements.

(iii) To select a new reference station for the elements flagged as inhomogeneous.

(iv) To apply corrections, where possible, to the data series before any climatological study is undertaken.

Table I. *Reference Climatological Stations selected in 1982 (list (a)) together with prospective stations suggested for future consideration (list (b)). (Year of first observation at present site is given.)*

(a) Current

Aldergrove	1926	Leuchars	1921
Armagh	1851	Malvern	1890
Auchincruive	1932	Mount Batten	1920
Benbecula	1942	Ryde	1914
Braemar	1857	Squires Gate	1942
Cambridge	1950	Tynemouth	1914
Dale Fort	1950	Valley	1941
Eskdalemuir	1911	Waddington	1946
Falmouth	1869	Wick	1941
Ilfracombe	1912	Wye	1934
Lerwick	1921		

(b) Prospective

Aviemore	1982	Hurn	1951
Aughton	1978	Kinloss	1951
Boulmer	1975	Leeming	1965
Camborne	1978	Manston	1961
Elmdon	1949	St. Mawgan	1955
Exeter	1978	Stornoway	1942
Hemsby	1978	Tiree	1942
Herstmonceux	1978		

Site changes are clearly not the only influence on the climatological record of a station. A detailed examination of data records is needed to ascertain the homogeneity of any particular station series. 1950, however, there are insufficient data in machinable form to carry out this type of analysis.

Table II. *Possible causes of some of the inhomogeneities shown in Fig. 2*

Reference number	Cause
(i)	Thermometer changes throughout period
(ii)	Amber sunshine sphere replaced 1957
(iii)	Site change 1959
(iv)	Site change 1955
(v)	Thermometer changes throughout period (5 in 10 years)
(vi)	Site change 1963
(vii)	New site 1963, moved enclosure 1966
(viii)	Site change 1973

Implications for detecting climatic trends

What then should determine the choice of Reference Climatological Stations? Clearly the future continuation of a station must still be considered a major aspect in its selection but a knowledge of past fluctuations, not of climatic origin, is also necessary. It is apparent that a large percentage of the present reference stations, previously considered to contain long, homogeneous records of climatological observations, do in fact contain inhomogeneities.

The majority of inhomogeneities identified are not clear discontinuities caused by changes in site, but more gradual trends caused by changing site conditions and instrumentation. Although this study does not consider wind or rain, similar conclusions were reached by Tabony (1980) after studying rainfall data for the period 1911–70. He showed that trends ranged from −4.0 to +5.9% per decade, three times the range that might be expected by chance. These trends are difficult to correct but may become significant.

As a consequence, it is suggested that the use of single stations to monitor climatic change may result in the inclusion of unrepresentative trends and inhomogeneities. Two alternatives are suggested:

(i) The calculation of a regional series to monitor climatic trends: the use of several stations will reduce the impact of inhomogeneities in any one of the records. This is similar to the approach developed by Manley (1974) although the current high density of stations permits the nomination of smaller study regions.

(ii) A thorough investigation into the homogeneity of stations for different time-periods: this will assist in the construction of a composite series of data from sections of individual station records which have been shown to contain representative trends for specified periods of time.

This present work has been used to suggest suitable Reference Climatological Stations for the period 1951–80 for the variables studied and these are identified in Fig. 3. They include Malvern, homogeneous after 1955, and Edgbaston, which closed in 1979. Further investigations of other periods will be continued to assist in the selection of stations which can be used to monitor climatic change before 1951.

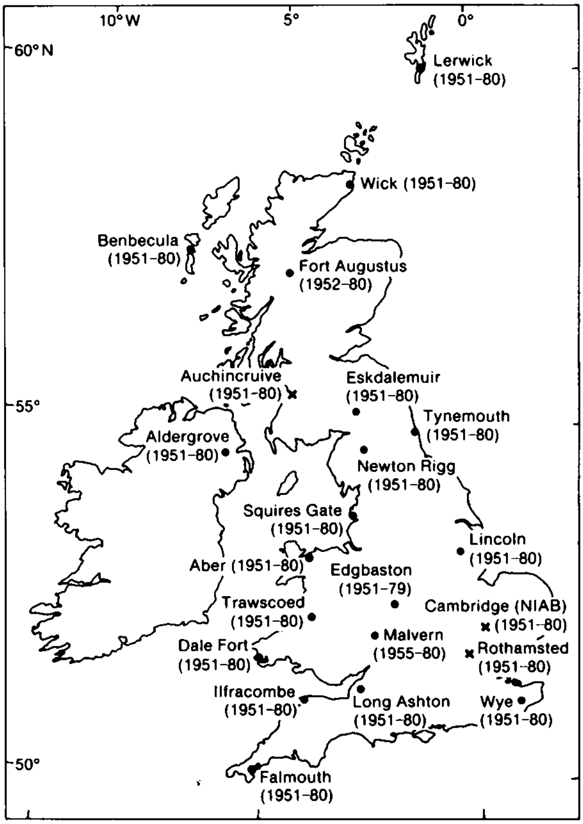


Figure 3. Suggested Reference Climatological Stations for the period 1951–80 suitable for minimum and maximum temperature and sunshine records (●) or temperature records only (X). (The station at Cambridge is at the National Institute of Agricultural Botany (NIAB).)

Conclusions

Of stations investigated for the 1951–80 period, 34% contained inhomogeneities. These included more than 45% of the reference stations currently being used to monitor climatic change. Several different types of inhomogeneity have been observed with the majority consisting of gradual trends in the values recorded. Corrections can be suggested for any clear step discontinuities caused by site changes but the gradual trends cannot easily be corrected.

Instead of using specific reference stations to monitor climatic change, it might be preferable, assuming a sufficiently dense station network, either to

(i) calculate regional series (the use of more than one station would reduce the dependence on any particular station which might contain inhomogeneities), or

(ii) set up a composite series of data based on sections of individual station records considered to contain representative trends for specific periods of time.

Suitable stations for the period 1951–80 are suggested and work is in progress to select representative stations for other periods. The implementation of the monitoring routine at regular intervals will help to ensure that stations selected for reference purposes continue to meet the criterion of the WMO.

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The Cyprus tornado of 29 May 1985

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Summary
A rare inland tornado in Cyprus is discussed.

1. Introduction

While winter waterspouts of varying intensity are not uncommon around the southern shores of Cyprus, some occasionally even crossing the coast, inland rotational phenomena on the island are rarely reported and appear in the main to be relatively minor events (McGinnigle 1970). However, the tornado which occurred between 1100 and 1200 GMT (1400–1500 Local Time) on 29 May 1985 in the Kornos/Pyrga area (see Fig. 1) was a frightening and destructive one. This article examines the event through observations, satellite pictures and eyewitness reports of damage.

2. Observations

Fig. 2 shows the 300 mb chart for 1200 GMT. The upper trough was moving slowly eastwards and, at the time of the tornado, was positioned just to the west of Cyprus. The progression of the trough over the past 48 hours is indicated on the chart. Tornadoes and waterspouts in the Cyprus area are often associated with such patterns and the present case is strikingly similar to that reported by Hardy (1971).

The infra-red satellite picture for 1055 GMT (Fig. 3) shows the convection associated with the upper trough and, of particular interest, the prominent cluster of convective cloud over the eastern part of Cyprus.

Although from the satellite picture the area of cloud appears widespread, there was nevertheless a strong orographic influence exerted by the Troodos Mountains. All the convective precipitation was confined to the east of Mount Olympus and north of a line from Mount Olympus to Larnaca (see surface

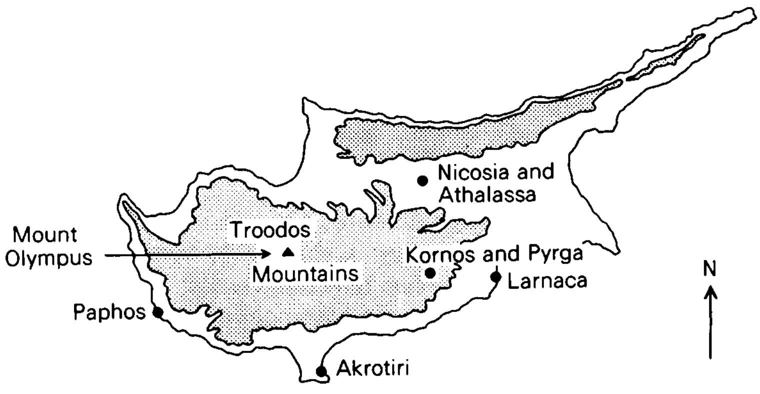


Figure 1. Map of Cyprus showing places mentioned in the text.

*Now at Royal Air Force Leuchars

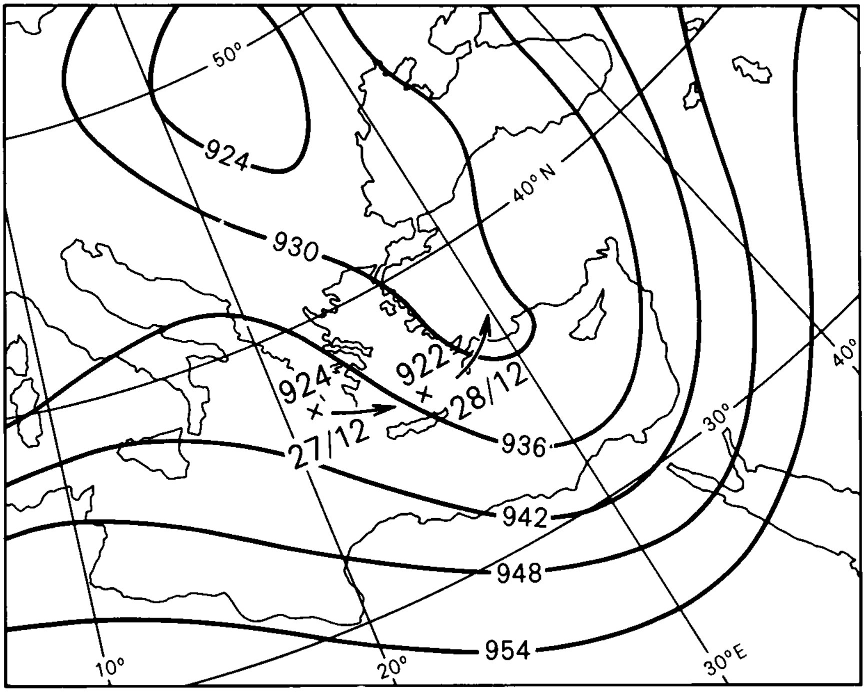


Figure 2. 300 mb chart for 1200 GMT on 29 May 1985. Crosses indicate estimated centres of low geopotential at 1200 GMT on 27 and 28 May. Heights are in decageopotential metres.

observations, Fig. 4). The long spell of thundery rain at Nicosia probably resulted from the interaction of the orographic influence of the mountains and the south-westerly upper winds. This is partially confirmed by cloud base reports of high- and medium-level cloud lowering towards the mountains throughout the period.

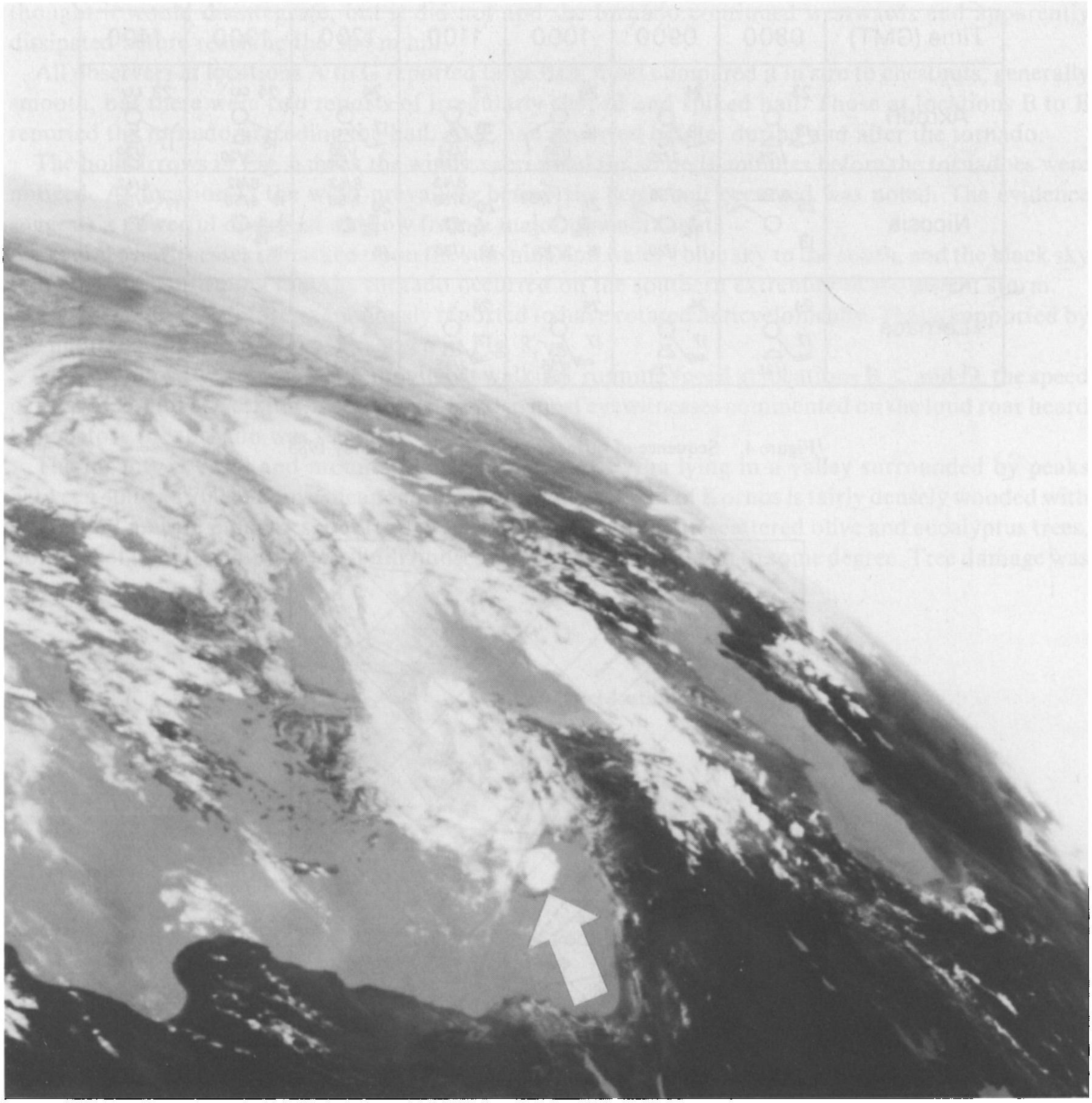
Unfortunately, lightning put the wind-finding radar at Athalassa out of action. However, the other sensors continued to function and the data are shown in Fig. 5. It is clear that, once the surface layer is lifted above 875 mb, the air is very unstable. This is consistent with the strong influence of the mountains discussed above. (The upper-level winds from the 0600 GMT ascent are also shown in Fig. 5.)

3. Eyewitness reports

Fig. 6 shows the probable path of the tornado (or tornadoes) based on eyewitness reports and a study of the damage. The following story emerges.

At about 1400 Local Time a lady at location A noticed a strong rotational whirl which swept through her apricot trees. At the same time a subdued roaring noise to the north (behind a nearby hill) passed from north-west to south-east. At about the same time observers at B saw three 'hooks' (presumably funnel clouds) developing downwards from the cloud base to the north, and tracking south-east towards Kornos. Two of these merged into one, and the remaining closely spaced pair eventually touched ground close to a house at C, and stripped off part of the roof. The inhabitant of the house saw only one tornado at this stage, and said that it was about 30 m wide. However, he was somewhat confused and frightened and quickly sought refuge indoors.

Eyewitnesses at D were adamant that two tornadoes, 'not very wide', passed one each side of the 364 m hill immediately to the south. Workmen laying a new road at E heard a roaring noise coming from the



Photograph by courtesy of European Space Agency

Figure 3. Infra-red satellite photograph for 1055 GMT on 29 May 1985. Arrow indicates the cluster of convective cloud over the eastern part of Cyprus.

direction of that hill, and saw just one tornado, approximately 100 m wide. It was at about this point that the electricity pylon (Fig. 7) was twisted and brought down, and a tractor was overturned, causing the only fatality. The tornado continued to approach the men at E and passed about 100 m to the south. According to people at F, it crossed Pyrga village and then curved sharply westwards, slightly north of its previous track. This brought it back directly over the new reinforced concrete and breeze-block building at E in which the workmen were sheltering. The building was so violently shaken that they

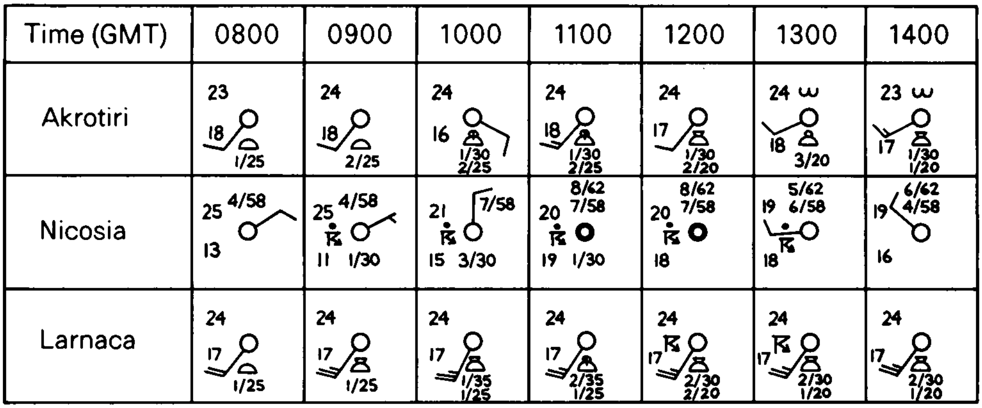


Figure 4. Sequence of surface observations for 29 May 1985.

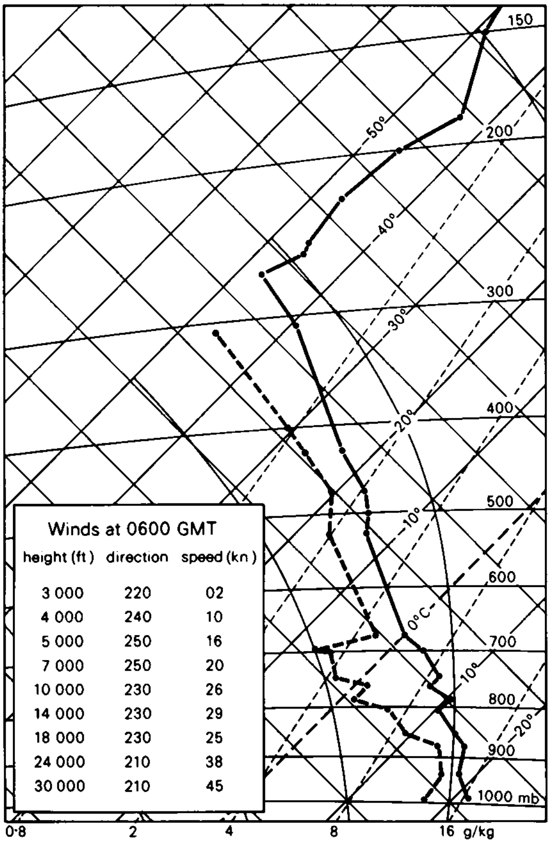


Figure 5. Upper-air ascent for Athalassa at 1200 GMT on 29 May 1985. Winds are for 0600 GMT on same day.

thought it would disintegrate, but it did not and the tornado continued westwards and apparently dissipated before reaching the 364 m hill.

All observers at locations A to G reported large hail; most compared it in size to chestnuts, generally smooth, but there were two reports of irregularly shaped and spiked hail. Those at locations B to E reported the tornado preceding the hail. At F hail occurred before, during and after the tornado.

The bold arrows in Fig. 6 mark the wind experienced for some 10 minutes before the tornadoes were noticed. At location G the wind prevailing before the large hail occurred was noted. The evidence suggests a powerful divergent outflow from a major downdraught.

Several eyewitnesses remarked upon the sunshine and watery blue sky to the south, and the black sky to the north, confirming that the tornado occurred on the southern extremity of the parent storm.

The tornado was almost unanimously reported to have rotated anticyclonically. This is supported by the nature of the tree damage, as shown in Fig. 8.

The tornadoes were reported as moving at walking/running speed at locations B, C and D, the speed of a car at E, and at walking pace again at F. Also most eyewitnesses commented on the loud roar heard long before the tornado was seen.

The locality is rural and mountainous, Kornos and Pyrga lying in a valley surrounded by peaks between 400 and 700 m above mean sea level. The area just east of Kornos is fairly densely wooded with young and mature pine trees, but further east it is more open with scattered olive and eucalyptus trees. Some 60 of the 110 mainly stone-built houses in Pyrga were damaged to some degree. Tree damage was

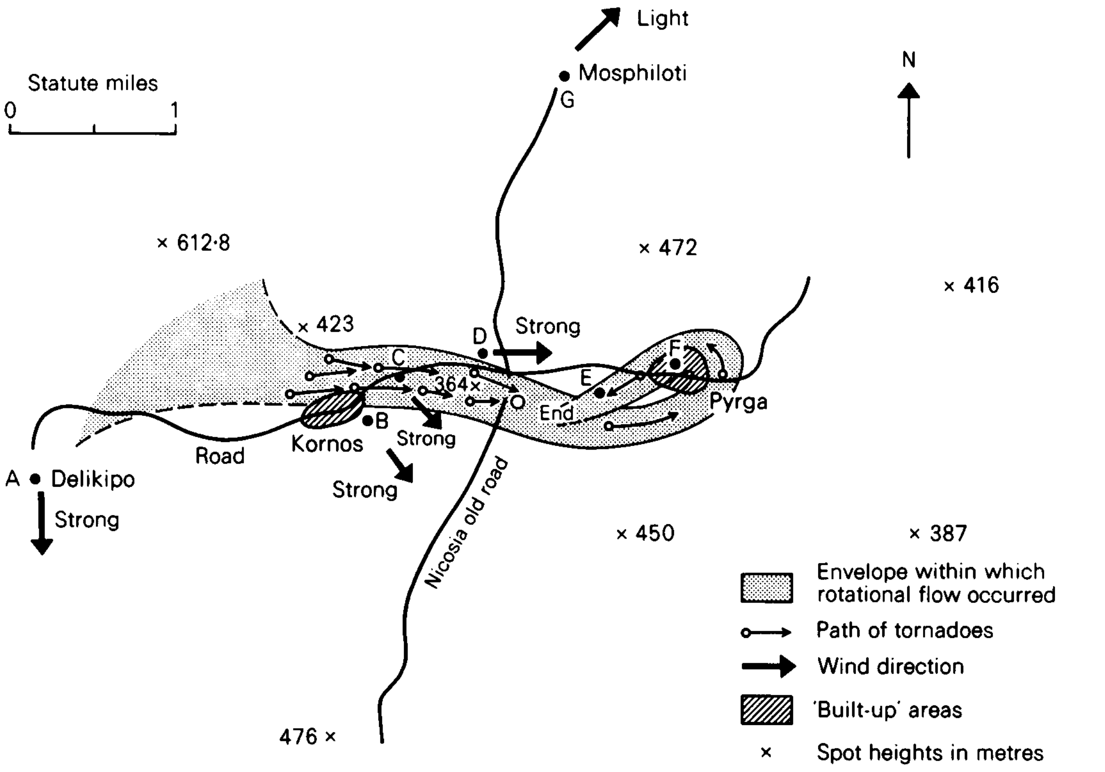


Figure 6. Sketch map showing probable path of the tornadoes based on eyewitness reports and reported damage.

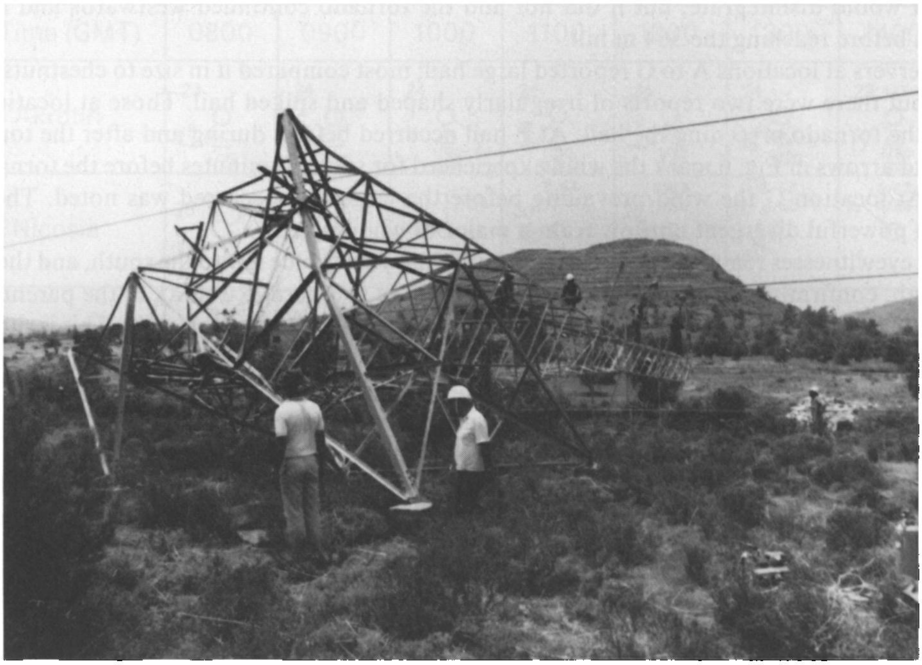


Figure 7. The electricity pylon near location E in Fig. 6.

Figure 8. Damaged pine tree near location D in Fig. 6.

extensive — scores of mature trees were uprooted but some, near the tornado touchdown area, were snapped or twisted off some 5 m above the ground.

4. Classification of the tornado

The structural damage, path length and path width suggest that the tornado should be classified as 1,2,2 on the Fujita–Pearson (FPP) scale (Fujita 1973); the evidence of structural damage was, however, confined to the time that the tornado passed over Pyrga. Alternatively, comparison of the rural damage with the categories of the TORRO scale (Elsom and Meaden 1984) would suggest force T4, denoting a severe tornado with wind speeds of 54–63 m s^{-1}. The description for the T4 category is 'large well-rooted trees uprooted, snapped or twisted apart'; the evidence for this clasification comes mainly from the area east of Kornos.

5. Conclusions

The severe local storm which shed this tornado occurred over the eastern part of the Troodos Mountains, a known preferred area for such storm development. Contributory factors were assessed to be:

(i) The upper trough which crossed Cyprus eastwards as a relaxing but well-marked feature.

(ii) The moist layer up to 880 mb, evident from the Athalassa radiosonde ascent, and from the coastal low-level cumulus. More usually the moist layer is capped by an inversion much nearer sea level.

(iii) The high value of wet-bulb potential temperature in the lowest 1000 m resulting from the upper trough overriding the lower levels (Carlson and Ludlam 1968). Note also the directional shear measured at Athalassa at 0600 GMT and shown in Fig. 2 for 1200 GMT.

(iv) The isolated trigger of intense local heating over the central massif of an island surrounded by relatively cool seas. This is to be coupled with the orographic effects generated as the low-level boundary-layer air was forced over the mountains.

There was little in the synoptic data to indicate that a severe storm would develop in the area. The strong surface wind at Larnaca is a characteristic event at this time of year, as is the high surface temperature and relative humidity. Perhaps the 300 m wind over the south-eastern part of the island was more veered than usual, but not sufficiently to arouse particular interest. The one indicator that may presage such events appears to be the presence of a plume of cirrus cloud spreading several hundred kilometres north-eastwards away from a 'hot-point' source. This is evident in the satellite picture of this event, the plume starting over Cyprus. However, convection must have already begun to form before such a signature becomes evident. Nevertheless, a combination of the characteristic upper-level contour pattern coupled with a close monitoring of the satellite pictures may give at least a few hours warning.

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ECMWF — ten years of European meteorological co-operation

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Summary

An account is given of the objectives of the Centre which was formally established in 1975, its organization and control by the various countries that support it (the Member States), the forecasting model and data-assimilation system, the computer system, the schedule of operational forecasts, and the way the forecast products are disseminated. There has been a steady increase in forecast skill over the past six years with a corresponding increase in use of the products by the Member States, and further progress is expected.

Background

The European Centre for Medium Range Weather Forecasts (ECMWF) was formally established on 1 November 1975, a date when its Convention had received sufficient ratification to come into force. However, as described by Knighting (1978), this followed a long period of careful planning and preparation which started as long ago as October 1967, when the council of Ministers of the European Communities adopted a resolution to promote a common program for scientific and technical research. The problem of extending useful weather prediction into the medium range was singled out as one of several projects where a joint European effort was regarded as essential, and where, according to different assessments, the benefit would by far outweigh the cost.

John von Neumann had already outlined an overall strategy in atmospheric modelling and prediction in 1955 (von Neumann 1960). He considered that the prediction problem could conveniently be divided into three categories depending on the time-scale of the forecast. In one category came short-range prediction of motions, determined mainly by the initial state of the atmosphere. The second comprised much longer-term prediction of characteristics of motion that are largely independent of the initial state, and thus include the problem of climate simulation. In between these two extremes there was another category for which it was necessary to consider the details of both the initial state and of external forcing. The logical approach was to attack these problems in that order.

In the early 1970s there was enough experience in both short-range prediction and climate simulation by numerical models to justify a serious attempt to tackle the medium-range forecast problem which falls into the third, and perhaps most difficult, of the categories listed above. In the planning documents leading up to the creation of the ECMWF, medium-range forecasting was considered to imply a period from four to ten days ahead, but a more natural time interval is perhaps two days to two weeks.

Medium-range forecasting was in many ways an ideal candidate for co-operation. The scientific and technical problems are formidable, and only very few countries have enough scientific and technical experts to tackle them. Moreover, the computer and other resources needed exceed those normally practicable at the national level. Medium-range forecasts are less time-critical than short-range ones, and there is little disadvantage from an operational point of view if they are made at a distance from the national forecast offices, on condition that fast and reliable telecommunication links exist.

The Centre's objectives and organization

It is convenient to recall the objectives of the Centre as laid down in its Convention. They are:

(i) To develop dynamic models of the atmosphere with a view to preparing medium-range weather forecasts by means of numerical methods.

(ii) To prepare, on a regular basis, the data necessary for the preparation of medium-range weather forecasts.

(iii) To carry out scientific and technical research directed towards improving the quality of these forecasts.

(iv) To collect and store appropriate meteorological data.

(v) To make available to the meteorological offices of the Member States in the most appropriate form, the results of the studies and research provided for in the first and third objectives above, and the data referred to in the second and fourth objectives.

(vi) To make available to the meteorological offices of the Member States for their research, priority being given to the field of numerical forecasting, a sufficient proportion of its computing capacity, such proportion being determined by the Council.

(vii) To assist in implementing the program of the World Meteorological Organization.

(viii) To assist in advanced training for the scientific staff of the meteorological offices of the Member States in the field of numerical weather forecasting.

The governing body of the ECMWF is a Council composed of not more than two delegates per Member State. The Council has three advisory bodies on financial, scientific and technical matters. The Council and its advisory bodies meet once or twice a year. The Centre is organized in three departments, and its director is appointed by the Council.

There are at present 17 Member States (see Table I) and, in addition, a special co-operation agreement has been signed with Iceland. The Centre is financed by contributions proportional to the Gross National Product of each Member State, a figure which is reviewed every third year. Member States' contributions for the year 1985 total £8 465 000, almost 95% of which goes on staff, computer equipment and associated expenditure.

Table I. *Percentage budgetary contributions to the ECMWF for the period 1985–87*

Member States	Contribution %
Belgium	3.06
Denmark	1.82
Federal Republic of Germany	22.41
Spain	5.96
France	18.43
Greece	1.23
Ireland	0.53
Italy	11.33
Yugoslavia	2.16
Netherlands	4.64
Austria	2.17
Portugal	0.72
Switzerland	3.17
Finland	1.51
Sweden	3.44
Turkey	1.76
United Kingdom	15.66

The Centre's headquarters are in Shinfield Park, near Reading and about 15 kilometres from Bracknell. The building, covering more than 6000 square metres, and the land were provided by the United Kingdom, and occupied from 1979 (Wiin-Nielsen 1979), the same year that the Centre started to do operational forecasts.

The forecasting system

The Centre's forecasting system consists of two components: a general circulation type model and a comprehensive data-assimilation system. From the very start the Centre set out to develop a model which could describe the evolution of weather on all time-scales; in fact the same model (but with different horizontal resolution) has been used to predict intense small-scale weather phenomena (such as typhoons) as well as to simulate climate for periods of up to ten years. In the same way, the data-assimilation system was built in order to use not only conventional observations such as radiosonde data, but also asynoptic information from satellites and aircraft. The ECMWF data-assimilation system was successfully used to produce global analyses four times a day for the Global Weather Experiment. This data set, consisting of more than 70 000 global fields, has been used extensively by scientists all over the world.

The first numerical model used by the ECMWF was a grid-point model with 15 vertical levels and a horizontal resolution of 1.875 degrees of latitude and longitude. This model served for operational forecasting from September 1979 to April 1983. The finite-difference scheme conserved potential enstrophy during vorticity advection, a condition which is important when extending a prediction beyond several days. In April 1983 the grid-point model was replaced by a model using a spectral representation in the horizontal and a so-called triangular truncation at wave-number 63. The spectral technique was found to be more accurate than the grid-point model for the same computational cost. The number of vertical levels was increased to 16. Finally, in May 1985, a very-high-resolution spectral model was put into operation, whereby the spectral truncation was extended to wave-number 106. By and large this is equivalent to a grid-point model having a horizontal resolution of about 100 km.

Very substantial efforts have gone into developing a detailed description of the different physical processes which become more and more important as forecasts extend into the medium range.

The fundamental process driving the earth's atmosphere is heating by incoming short-wave solar radiation and cooling by long-wave radiation to space. The heating is strongest at tropical latitudes, while cooling predominates at polar latitudes, especially in the winter hemisphere. The bulk of the net incoming solar radiation is absorbed by the underlying surface rather than the atmosphere. However, evaporation of moisture and surface heating lead to much of this energy being transferred to the atmosphere as latent and, to a lesser extent, sensible heat. Thus the dominant direct heating of the atmosphere is found to be the latent heat released with deep tropical convection.

Radiative fluxes in the ECMWF model are calculated for five spectral intervals — two for solar and three for terrestrial radiation. The effects of water vapour, ozone, carbon dioxide and selected aerosols are included. The model predicts the cloud cover as a function of humidity, static stability and convective activity. The Centre's cloud scheme has gradually developed, and several Member States are using predicted clouds as a direct model output parameter. The prediction of boundary clouds and the outflow of cirrus from deep convective clusters were introduced in May 1985 with the new very-high-resolution spectral model.

The treatment of physical processes in the boundary layer deserves considerable attention in medium-range forecasting. The calculation of boundary-layer fluxes is based on the Monin–Obukhov similarity theory, which assumes that the gradients of wind and internal energy are universal functions of a stability parameter to be determined from empirical data. The roughness length over land depends on vegetation and sub-grid-scale orography. Over the sea the roughness length is given by the Charnock formula (Charnock 1955).

The model deals separately with deep and shallow convection. A correct handling of convection is essential, not only for tropical forecasting *per se* but also for the overall maintenance of the large-scale tropical circulation systems, which are important for the large-scale circulation at higher latitudes.

Medium-range weather prediction requires global observations of high quality, coverage and resolution. Thus a continued improvement in medium-range forecasts is strongly dependent on the Global Observing System. Good observations through the depth of the atmosphere over remote ocean areas are as important as good observations over land, so that observing systems providing a homogeneous data coverage for large areas are of particular importance.

For this reason the ECMWF has devoted considerable research efforts to develop a four-dimensional data-assimilation system in order to make efficient use of temperature and moisture soundings from the polar-orbiting satellites and to use wind observations from the geostationary satellite platforms.

The computer system

The ECMWF's first generation computer, installed in 1978, had a Cray 1-A mainframe, with a performance of about 100 MFLOPS (million floating-point instructions per second). This was replaced in 1983 by a Cray X-MP dual processor, which in turn was replaced at the end of 1985 by a four-processor version (the Cray X-MP/48). The throughput of the Cray X-MP/48 is about ten times that of the Cray 1-A.

The Cray X-MP is connected via a data link, the Loosely-Coupled Network. It is also directly coupled to two front-end processors, a Cyber 835 and a Cyber 855. A dedicated VAX 11/750 minicomputer takes care of graphical applications, and an IBM 4341, with an attached mass storage, is needed for archiving the Centre's data. In-house connection to the Cyber computers is via a Gandalf system, and external communication via an RC 8000. It is through this machine (to be replaced by a VAX-oriented system later this year) that the Centre acquires its observational data from the Global Telecommunication System (GTS), via links to the Regional Telecommunication Hubs at Bracknell and Offenbach, and transmits its analyses and forecasts to Member States. Details of the ECMWF computer system are shown in Table II.

Table II. *Details of the ECMWF computer system*

Computer	Memory	Disc or tape storage	
Cray X-MP/48	64 Mbytes 256 Mbytes (SSD)*	21 disc units	10.300 Gbytes
Cyber 835	4 Mbytes	26 disc units	10.700 Gbytes
Cyber 855	12 Mbytes	10 tape units	
IBM 4341	8 Mbytes	10 disc units	12.500 Gbytes
		cartridge tapes	105.000 Gbytes
		6 tape units	
4 × VAX 11/750	18 Mbytes each	7 disc units	2.100 Gbytes
		1 tape unit	
2 × RC 8000	576 Kbytes each	1 tape unit	
		2 disc units	0.132 Gbytes

* Solid-state storage device

Production and dissemination of forecasts

On its general operational schedule, the ECMWF makes one forecast each day for ten days ahead, starting from the 1200 GMT analysis. No other operational forecast is currently run. At about 1700 GMT each day an analysis valid for 1800 GMT the previous day is carried out, thus providing the first guess for the 0000 GMT analysis which is carried out at about 1800 GMT each day. Similarly, analyses for 0600 and 1200 GMT are carried out at around 1830 and 2000 GMT, the final analysis having a data cut-off time of about eight hours. It is from this that the ten-day forecast is run.

Forecasts are distributed to the Member States in digital form. The present distribution amounts to over 10 000 products each day from the Centre. A product is defined as one parameter (e.g. geopotential) for one level (e.g. 500 hPa) for one time-step (e.g. forecast time 240 hours) for one area (e.g. a European area). A selection of ECMWF products is distributed daily to users all over the world via the GTS (Table III).

Table III. *A selection of ECMWF products disseminated on the Global Telecommunication System*

Product	Northern hemisphere (from latitude 20°)	Tropics (35° N to 30° S)	Southern hemisphere (from latitude 20°)
Mean-sea-level pressure	Analysis to day 6	—	Analysis to day 5
500 hPa geopotential	Analysis to day 6	—	Analysis to day 5
850 hPa temperature	Analysis to day 6	—	Analysis to day 5
850 hPa wind	—	Analysis to day 3	—
200 hPa wind	—	Analysis to day 3	—

Results of operational forecasts

Since the Centre started operational forecasting in September 1979 there has been a considerable improvement in the quality of the forecasts. This has been confirmed by both objective assessment and by subjective evaluation by users in Member States and elsewhere. The intercomparison study undertaken by the Commission for Atmospheric Science (Lange and Hellsten 1984) clearly demonstrated this, also that the Centre's forecasts were the most accurate among those participating in the intercomparison.

The improvements are due to continual development of the forecasting procedure, including both the model and the data-assimilation system. The greatest change to the model took place in May 1985; the effect of that change has led to a further significant improvement in predictive skill as can be seen from Fig. 1.

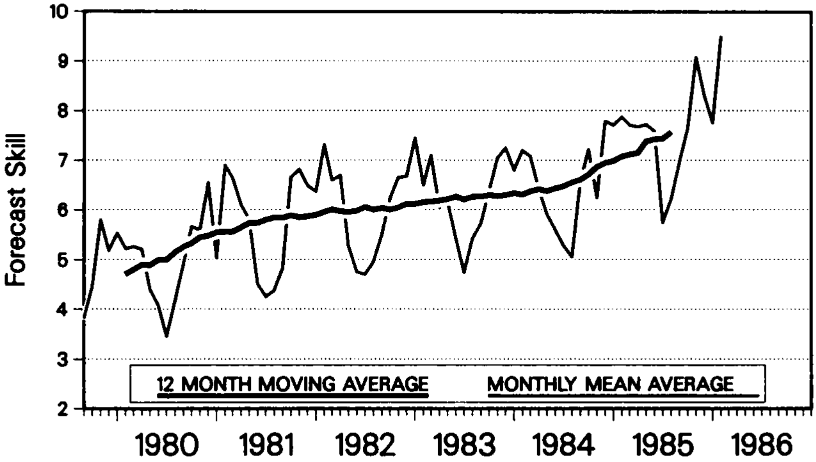

Figure 1. ECMWF forecast skill between September 1979 and February 1986. Forecast skill is based on 'days of predictability' derived locally at ECMWF.

Similar improvements have taken place in respect of forecasts for the southern hemisphere and the tropics, but from a much lower starting point. While the limit for useful forecasts for the northern hemisphere is six to seven days, corresponding values are four to five days for the southern hemisphere and three days for the tropics.

Usage of forecasts in Member States

While the operational forecast is being produced on the Centre's computer system, forecast products in the form of coded fields are being disseminated via dedicated telecommunication lines to the computer systems of the 17 Member States which support the ECMWF. The medium-range products have now become an integral part of the prediction routine in European forecast offices. Member States use the Centre's forecasts not only as an additional reference source, but also often as part of objective (statistical) interpretation schemes, as boundary values for their own limited-area models, or to drive other models (for example, sea and swell models for use in ship routeing). The primary end users of the medium-range forecasts interpreted by Meteorological Services of Member States are in the sectors of agriculture, marine, construction and heavy engineering, energy planning, leisure and tourism, land transport, environment and pollution (see Fig. 2).

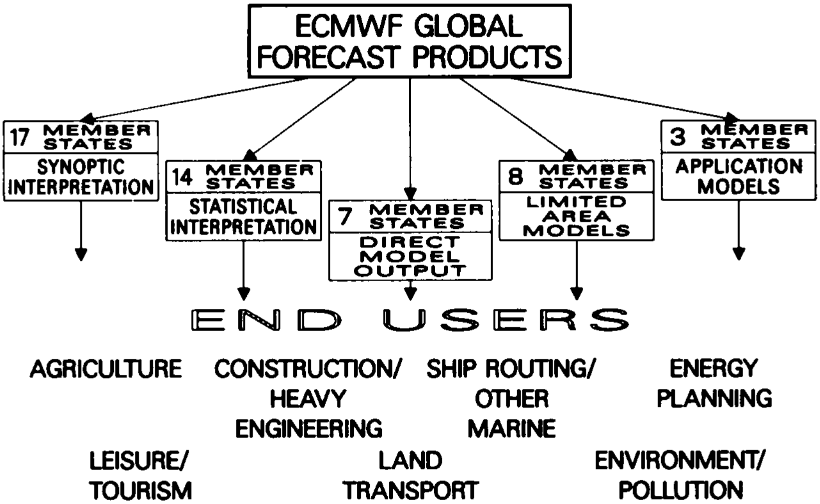

Figure 2. Application and use of ECMWF products in the Member States.

As well as standard operational products, the Centre's forecasting system also produces a range of products which are experimental in nature, such as cloud amounts, winds interpolated to the 10-metre level above the model surface, temperatures interpolated to the 2-metre level, fields smoothed by filtering to remove small-scale features (which cannot be well predicted at the later stages of the forecasts), time-averaged fields, and so forth. These additional products are also made available to Member States, and may be presented directly to forecasters or used in other ways (for example, as input parameters to statistical forecasting schemes). Thus, the Centre is assisting its Member States to improve the 'user interface' between numerically produced fields and the requirements for forecasts of actual weather elements by the end users of the forecasts.

Other services

Twenty-five per cent of the Cray computer resources and ten per cent of the Cyber resources are available for use by Member States. Computer time is distributed among the countries according to a special formula and is only partly proportional to the Gross National Product. Ten per cent of the time allotted to Member States is available for special research projects. Scientists may forward requests for this through any Member State.

The Centre is gradually building up an archive of raw and processed data (global analyses and forecasts). A special data set including selected basic observations and global analyses for seven standard levels has been developed covering a period of five years. The World Meteorological Organization (WMO) has contributed financially to the development of the data set which is currently being sent to a large number of users all over the world. The Centre is also in the process of re-analysing the Global Weather Experiment data using the most recent version of its data-assimilation system. As the Centre's archives are gradually developed, their value for the scientific community will increase more and more.

The Centre provides a two-month training course every year in advanced numerical weather prediction. The course is also open to scientists from non-Member States, 16 of whom participated over the past two years.

The Centre also gives an annual scientific seminar and organizes workshops in different subjects.

Future plans

Predictability studies recently carried out by Lorenz (1982) have indicated that the limit of predictive skill can be extended by between two and four days just by model improvements alone. Further amelioration of approximately two days can be expected due to the positive feedback of the model from the data assimilation. The Centre will maintain its successful 'brute force' strategy by continued enhancements to the complete forecasting system. Major problems are related to the treatment of orography, the parametrization of the boundary layer, and of deep and shallow convection. Continued progress in the performance of supercomputers will probably make it possible to run a global model with a resolution around 50 km before the end of this decade.

The quality of the Global Observing System is crucial for medium-range prediction. In a project supported by WMO, the Centre has recently developed a system for monitoring it. By intercomparisons of very-short-range forecasts (first guess to the analyses) with specific observations over periods of a month or so, systematic errors can be identified in the observations. Several cases of radiosonde observations with large systematic errors have been identified and the operators informed so that corrective action can be taken. It is believed that by instituting systematic quality control of observations with feedback to the producers, we shall achieve better-quality observations and consequently better forecasts.

This article is a revised version of the one that appeared in the *WMO Bulletin* for October 1985 and is published by permission of the Director of ECMWF.

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Reviews

Safety of dams: flood and earthquake criteria, by the Committee on Safety Criteria for Dams, the Water Science and Technology Board, the Commission on Engineering and Technical Systems, and the Natural Research Council. 150 mm × 227 mm, pp. xvi + 276, *illus*. National Academy Press, Washington, 1985. Price £18.50.

The safety of dams, particularly that of existing dams, presents major policy problems. Many existing dams do not meet current safety criteria whilst the consequences of their failure can be catastrophic. The US Natural Research Council were therefore asked by the United States Department of the Interior to prepare an inventory of currently used safety criteria for dams in respect of extreme floods and earthquakes, and to evaluate alternative criteria for the safety of Federal dams. The resultant report is thorough but is limited both in that the question they were asked to address is not a very useful one, and by the very limited time, seven months, they were given to answer it.

Given these constraints, the Report has focused on the choice of the design-magnitude events as criteria — the extreme flood event for spillway design, and earthquake magnitude for seismic safety. Unlike other fields of engineering, such as the nuclear and chemical industries, the design safety objective for major dams is that they should not fail under any foreseeable event, although a less stringent criterion may be appropriate for dams presenting a less serious hazard. The discussion in the Report on design criteria for flood events therefore revolves around the estimation of the Probable Maximum Flood. The Report recommends the continued use of this method as a criterion, but also states that less strict criteria may be appropriate both to existing dams and to dams presenting a minor hazard.

To this reviewer, these conclusions are not terribly useful, particularly in regard to safety criteria for existing dams. Currently dams are, as the Report notes, categorized in terms of a 'hazard classification'. This classification is based upon the potential energy stored and the nature of the downstream developments at risk. If the application of less rigorous criteria is acceptable for existing dams and for minor dams, then it seems reasonable to base these upon a rigorous analysis of the potential consequences of failure. However, the existing system seems crude; it does not include, for example, the time before peak for flood events. The longer this lead time, then the greater the opportunity to ameliorate the consequences of a failure. Similarly, very cursory consideration is given to the mode and speed of dam failure: this can vary greatly according to the type of dam. Equally, the Committee draws attention to the problem of classifying a dam in terms of the potential hazard it represents when, in the future, development may take place downstream. However, it fails to note that some flood protection dams, notably those on the Ganges system, are intended specifically to permit the intensification of use of the flood plain.

The Committee reports that some of its members would have wished to have attempted to formulate a hazard classification standard, but that they did not have time to do so. Seven months is obviously an inadequate time for a Committee to carry out such a task. However, given the coarseness of the existing hazard classification and the large number of existing dams which do not meet current criteria, a refined classification system is needed as a basis on which to decide when to relax current criteria. More especially it is needed to determine which dams should be given priority for remedial works. Such a classification would also be useful where the inadequacies of an existing dam arise, not from inadequate spillway capacity or seismic resistance, but for other reasons. It would therefore have been more useful to have asked the Natural Research Council to address this issue, and to have given them adequate time to do so, than to consider design criteria events. The difficulty in deriving such a hazard classification is that such generalized predictions as to the likely consequences of a failure are best derived from very detailed analysis of the consequences of the failure of specific dams.

Within the restrictions given to the Council, the Report makes a number of good points. Some of the discussion of economic issues is, however, ambiguous; the measurement of damages in terms of compensation being an example. Although the Report recommends that, in any benefit–cost analysis of dam safety, the potential loss of life should not be evaluated in money terms, it does note that capitalized values for lives lost have been so used. This approach is now regarded in the United Kingdom as being theoretically unsound.

C. Green

Climatic hazards in Scotland: Proceedings of the Joint Royal Scottish Geographical Society and Royal Meteorological Society Symposium, University of Stirling, June 1984, edited by S. John Harrison. 153 mm × 212 mm, pp. ix + 81, *illus*. Geo Books, Norwich, 1985. Price £8.00, US $14.00.

This small 81 page book details the proceedings of a joint Royal Scottish Geographical Society and Royal Meteorological Society Symposium held at the University of Stirling. As only nine papers are involved I will briefly attempt to describe each in turn.

A.H. Perry from the Department of Geography, University College of Swansea, opens the proceedings with a professional view of climatic hazards and their status in the hazard spectrum. This is followed by a conventional discussion of meteorological parameters and the hazards they can cause. Section three discusses in some detail extreme rainfall events and the Meteorological Office's apparent inability to forecast them. The fourth paper deals with floods as a hazard. The fifth contribution discusses the effect of wind on commercial forestry. It was this and subsequent papers that I found the most interesting. K.F. Miller described how the rate of attrition (measured in square centimetres per day) of unhemmed cotton flags provides a cheap and reliable guide to tree growth potential in relation to site exposure. It is thought that the rate of attrition of these cotton flags is determined largely by wind speed and wind gustiness. In his paper K. Smith, from the Geography Department at the University of Strathclyde, uses press reports to assess climatic hazards. He points out that while climatic extremes can occur anywhere, climatic hazards only happen where man and his works get in the way of these extremes. How better to assess man's perception of climatic hazards than to analyse press reports of weather-related events for a major conurbation, in this case Glasgow. In the seventh paper G. Edmond, from the Department of Roads and Transport, Highland Regional Council, looks at the problems associated with road maintenance and snow clearance in the Scottish Highlands. He states, 'although Meteorological Office forecasting has reached a considerable degree of accuracy, there is still a fair amount of forecasting of icy conditions which do not materialize'. He goes on to describe how ice detection systems could be a cost-effective solution to the problem of unnecessary salting. A representative from the insurance industry discusses, in chapter eight, the insurance aspects of extreme weather events. The general tenor of his article can be summed up with the quote, 'What has to happen for an event to qualify as extreme is perhaps debatable, but whatever the definition, they are occurring far too often and much more frequently than they did two or three decades ago'. S.J. Harrison in the final paper attempts to draw together many of the points raised and, considering the diversity of approaches, this was not an easy task.

I hope the above résumé gives some indication of the diversity of the papers presented at this meeting. Indeed it is the variety of opinion, approach and perception that makes this book readable. I feel the organizers have succeeded in their attempt to draw together those people whose work brings them into direct contact with the hazardous aspects of climate, and the resultant flow of ideas across disciplinary boundaries will, I hope, produce some answers to the many questions that this Symposium raised.

W.H. Moores

Tornado! Proceedings of the first conference on tornadoes, waterspouts, wind-devils, and severe storm phenomena, Oxford Polytechnic 29 June 1985, edited by G.T. Meaden and D.M. Elsom. 145 mm × 210 mm, pp. 72, *illus.* Artetech Publishing Company, Bradford-on-Avon, 1985. Price £10.00 hardback (£3.00 paperback).

These conference proceedings are published under the sponsorship of the Tornado and Storm Research Organization (TORRO) founded by Dr Meaden in 1974 as 'a privately-supported research body, serving the national public interest'. It publishes its findings mainly in *The Journal of Meteorology* (not to be confused with the defunct American publication of the same title) and subscribers will have received these proceedings as its 100th issue.

After a message of welcome from Professor H.H. Lamb, the work of the various divisions of TORRO is explained and papers are presented by the leading researchers. The divisions are: tornadoes (M.W. Rowe and G.T. Meaden), thunderstorms (K.O. Mortimore), hailstorms (D.M. Elsom), ball lightning (M. Stenhoff), and weather disasters (A. Thomas). There is also an article on building damage caused by tornadoes by P.S.J. Buller. The only Meteorological Office contributor is R.J. Pritchard of the London Weather Centre on 'The spatial and temporal distribution of British thunderstorms'. There then follows a number of case studies of recent tornadic phenomena and a joint statement from the TORRO directors on 'The tornado threat in Europe'.

There is little sign here of unscientific jumping to the wrong conclusions, though perhaps the Wiltshire whirlwind watchers may care to investigate the effect of a military helicopter hovering low over a cereal field. The professional meteorologist can only be amazed and impressed by the wealth of data on British severe storm phenomena accumulated by amateur and university enthusiasts and described here. It would be wrong to ignore their challenge to 'responsible authorities' to 'include tornado forecasting as part of national meteorological services, and issue tornado warnings on occasions of possible severe tornadoes'. TORRO has shown us that tornadic damage is more common in England than was thought a few years ago, but we must not assume that as much effort is needed to combat the threat by issuing warnings as in the USA. It is instructive to compare these proceedings with those of the 14th conference on severe local storms, published by the American Meteorological Society in 1985, where the 113 papers, many on radar, satellite and computer studies, indicate the amount of money being spent over there.

Has the Meteorological Office a role in combining the findings of the Americans, from R.C. Miller onwards, with the British data being collected by TORRO? We have good numerical models, a dense land surface observing network, and now radar, satellite and accurate SFERIC data. There would be a market in continental Europe as well as in Britain for more-detailed severe weather warnings.

K. Grant

Photograph by courtesy of Captain G.V. Mackie

The current and two former Presidents of the North Atlantic Ocean Stations Board (NOAS), photographed after the ceremony at Hull on 18 December 1985 when the Dutch vessesl *Cumulus* was handed over by the Netherlands Secretary of Transport and Public Works to the Parliamentary Under-Secretary of State for Defence Procurement for a nominal sum of £1.

From left to right, with terms of office in brackets, are: Dr Udo Gärtner (Federal Republic of Germany) (1986), Dr D.N. Axford (United Kingdom) (1982–85) and Mr Bert Kamp (Netherlands) (1978–81).

Meteorological Magazine

May 1986

Vol. 115
No. 1366

CONTENTS

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ISBN 0 11 727833 5 ISSN 0026–1149

Printed for HER MAJESTY'S STATIONERY OFFICE
by Delco Printing Co Ltd 5/86 Dd 739131 C13

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S
STATIONERY
OFFICE

June 1986

Met.O.971 No. 1367 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1367, June 1986, Vol. 115

551.509.313

The Meteorological Office fine-mesh data assimilation scheme

By R.S. Bell
(Meteorological Office, Bracknell)

Summary

The initial fields for the Meteorological Office operational forecast models are provided by a data assimilation scheme which uses a repeated insertion technique to adjust model fields towards the observations. This paper describes how the scheme is used in the limited-area fine-mesh version of the model. The results of several studies are presented which illustrate the beneficial aspects of fine-mesh analyses compared with analyses which have been interpolated from a coarser-mesh global data assimilation.

1. Introduction

Fine-mesh limited-area forecast models have been an important tool to the forecaster for more than a decade now, but for much of that period little attention has been paid to the problem of analysing fine-scale detail. The initial conditions for the fine-mesh model have generally been determined by interpolation from a coarser-mesh hemispheric or global analysis. The reasons for this reluctance to tackle the problem of objective analysis of small-scale features are not difficult to understand. Primarily the problem is one of data sparsity. It has long been thought that attempts to analyse on a scale which is smaller than that provided by the observing network would be doomed to failure. The introduction of high-resolution satellite data from the HERMES (High-resolution Evaluation of Radiances from MEteorological Satellites) system (Turner *et al.* 1985) has, however, provided one impetus for the development of a fine-mesh analysis system.

Another difficulty, which has slowed the development of fine-mesh analysis systems in operational numerical weather prediction centres, is the problem of initialization. Conventional non-linear normal mode initialization schemes have proved to be rather difficult to apply to limited-area models because their solution is complicated by the presence of lateral boundary conditions. Bourke and McGregor (1983) have developed techniques for overcoming these problems, but such complications do not in fact arise with the scheme adopted by the Meteorological Office. The repeated insertion scheme, which was first developed by Lyne *et al.* (1982) for global data assimilation, has been designed to minimize the excitation of spurious gravity waves. Small observation increments are added to the model fields, which are assumed to be sufficiently in balance, at each time-step, so that the model is not forced too far from a 'balanced state' and the requirement for any further initialization is eliminated. It is relatively simple to adopt such a scheme for use with a limited-area fine-mesh model.

Apart from the observations, the other component of any analysis scheme is, of course, the forecast model itself. The detail provided by fine-mesh forecasts is very impressive (Woodroffe 1984) and although spurious features are occasionally developed, there is now sufficient confidence in the fine-mesh fields to use them as the basic starting point of the analysis in preference to the smoother coarse-mesh fields. The fine-mesh forecast structure should be retained in subsequent analyses, especially in data-sparse regions. Better quality control of observations which define intense features might also be anticipated if those features were present in the first guess for the analysis. The important detailed structure of frontal regions cannot be determined from observations and can only be analysed using a fine-mesh first guess. By achieving a frontal analysis on a scale which is consistent with the forecast model being used, the 'spin-up' time during which the fields adjust to the scale of the model is much reduced. The elimination of this spin-up period implies that useful rainfall fields may be obtained from the early stages of a forecast and also that features which may be developing rapidly in those early stages would not have their development retarded.

The fine-mesh data assimilation scheme also allows the inclusion of a more detailed orography at the analysis stage. This makes the analysis of surface reports which are influenced by orographic effects more meaningful and also allows the full effects of a more detailed representation of a mountainous area to be felt from the start of the forecast. The alternative way of including a finer-mesh orography is to insert it gradually during the early stages of the forecast which, as well as generating 'noise', means that the full benefits are lost.

2. The fine-mesh data assimilation scheme

The techniques used for the analysis and assimilation of data for limited-area fine-mesh modelling are closely allied to those developed for the operational global data assimilation scheme, to the extent that both data assimilation systems share the same core computer code. Atkins and Woodage (1985) have given a brief descriptive account of the data assimilation scheme and Gadd (1985) has outlined the 15-level weather prediction model which is used for both data assimilation and forecasts. Full details of the coarse-mesh scheme can be found in Bell (1985) and to avoid undue repetition only a brief outline of the basic scheme is given here. Additional detail is given where the fine-mesh scheme differs from the global scheme.

(a) Intermittent assimilation

The first point to note is that the fine-mesh data assimilation is not a continuous cycle. The starting point for making a fine-mesh analysis of time T is an interpolated coarse-mesh analysis valid at T−12 hours. This uses a simple bi-linear interpolation to the latitude–longitude fine-mesh grid which has twice the resolution of the coarse-mesh model and has the same 15 levels and the same terrain-following vertical coordinate system. The fine-mesh domain is enclosed by longitude lines 80° W and 40° E and by latitude lines 80° N and 30° N. There are 129 grid points east–west and 67 north–south giving a horizontal resolution of about 75 km in the vicinity of the United Kingdom. Lateral boundary values are required to allow for the movement of synoptic features through the edges of the forecast region. The boundary tendencies for the prognostic variables are derived from a coarse-mesh forecast starting from the same coarse-mesh analysis at T−12 which is used to provide the interpolated fine-mesh field. These tendencies are applied throughout the assimilation period as well as the subsequent forecast. Fuller details of the boundary update scheme are given in Dickinson (1985), which also describes the integration scheme and the physical parametrizations. The necessity for lateral boundary updating is one reason why this intermittent assimilation cycle has been adopted for the fine-mesh model in preference to a continuous cycle. The boundary updating scheme involves the specification of interpolated coarse-mesh values at the fine-mesh boundary points and a continuous assimilation cycle would involve using boundary values from a succession of coarse-mesh forecasts. This procedure would introduce a shock to the fine-mesh model whenever the boundary values were introduced from a new coarse-mesh forecast since they would be incompatible with previous values. The gravity waves generated would make quality control of observations for the fine-mesh analysis rather difficult since the first-guess fields would be contaminated by noise. The intermittent assimilation cycle also makes the subjective monitoring of the analyses by the forecasters in the Central Forecasting Office rather easier because the coarse-mesh and fine-mesh solutions cannot diverge too far from one another.

The assimilation cycle consists of four separate 3-hour assimilation periods as illustrated in Fig. 1.

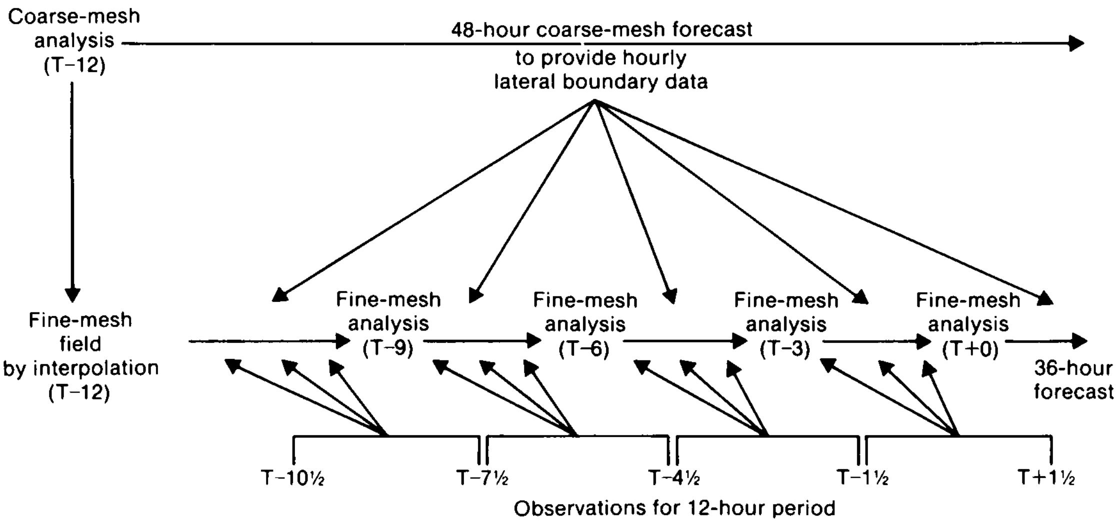


Figure 1. Schematic diagram of the operational fine-mesh data assimilation scheme.

The observations used in each period are those which are valid at T−9, T−6, T−3 and T+0 hours. An observation time window of ±1½ hours allows all observations which fall within that 3-hour window to be used, with the exception of surface data which are included only if verifying at the analysis time. This contrasts with the coarse-mesh assimilation cycle which is based on 6-hour assimilation periods each with a 6-hour time window for the observations. Thus, in the fine-mesh scheme, the asynoptic data, such as aircraft reports and satellite soundings, are used at a time which is closer to the observation time and also the surface observing network can be used at the intermediate hours (03, 09, 15 and 21 GMT). The adjustment of the model orography to fine-mesh values in the first period (03 or 21 GMT) does, however, preclude the use of surface pressure information at these stages. This more frequent insertion of data with a smaller time window is likely to be particularly beneficial when the observations are able to identify small-scale, rapidly moving features. The fine-mesh analyses also make use of a more comprehensive surface station network in Europe, whereas in the coarse-mesh analyses only a subset of the network is used for reasons of economy. To avoid unnecessary disturbance near the boundaries of the domain, observations are excluded from a zone near the boundary, where an enhanced diffusion is applied.

A single cycle of the assimilation is illustrated schematically in Fig. 2. The quality control, selection and weighting of observations for a fine-mesh analysis uses the same three-dimensional univariate optimum interpolation procedure as the coarse-mesh analysis, with only a few small modifications.

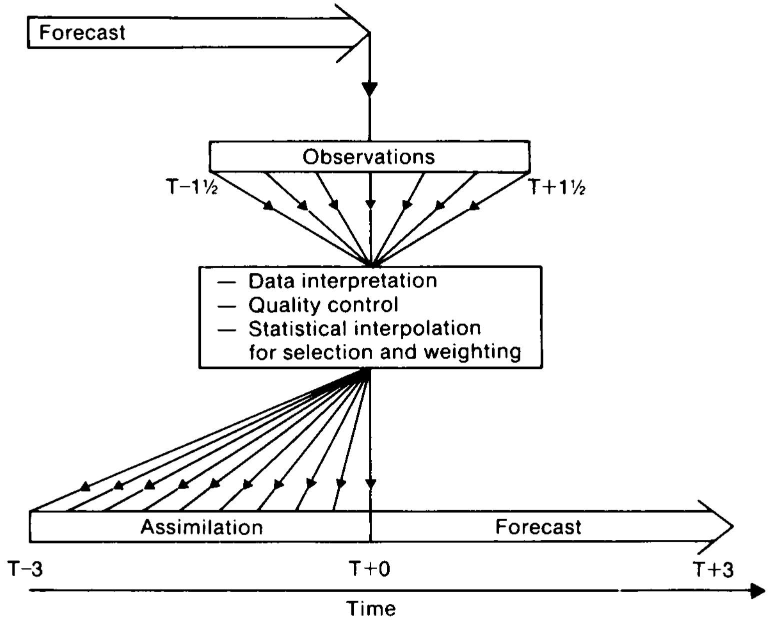


Figure 2. Schematic diagram of one data assimilation cycle (time in hours).

(b) Quality control

The first of two complementary quality-control checks involves the raising of a flag on every observation that departs substantially from the first-guess field, which in the fine-mesh scheme is a 3-hour fine-mesh forecast verifying at the observation time.

An observation ψ_{OB} is suspect if the inequality in the equation

$$(\psi_{OB} - \psi_{FG})^2 \geqslant N_1^2 (\epsilon_{OB}^2 + \epsilon_{FG}^2)$$

is satisfied, where ψ_{FG} is the first-guess value at the observation point, and ϵ_{OB} and ϵ_{FG} are the assumed errors for observation and first guess respectively.

The suspect observations are not allowed to quality control other observations in the second check, which consists of comparing an observation with the interpolated analysis ψ_{INT} using neighbouring observations. However, they may be reinstated if their departure from the interpolated analysis does not exceed a predetermined level as given by the equation

$$(\psi_{OB} - \psi_{INT})^2 \geqslant N_2^2 (\epsilon_{OB}^2 + \epsilon_{INT}^2)$$

where ϵ_{INT} is the expected analysis error. Conversely observations which satisfy this equation are rejected.

The parameters N_1 and N_2 in the above equations have been chosen in order that the scheme gives realistic quality-control decisions (values of 3 are typical). Optimum interpolation is used to calculate ψ_{INT} and ϵ_{INT}. The interpolated analysis is given by

$$\psi_{INT} = \psi_{FG} + \sum_i W_i (\psi_{OB} - \psi_{FG})_i$$

where the observation weights W_i are found by solving the set of equations determined by minimizing the expected analysis error variance ϵ_{INT}^2. To solve these equations the error characteristics of the observation and first-guess fields (i.e. the error covariances) have to be specified. Once the W_i have been found, ϵ_{INT}^2 is known. The summation in the above equation is taken over all selected data. Ideally all data should be used to interpolate to the analysis point, but for reasons of computational economy a selection of the best data is made. The best data are defined as those which, when taken singly, reduce the expected analysis error by the greatest amount.

(c) Interpolation increments for the analysis grid

The optimum interpolation procedure is performed twice. Once to provide an analysis at observation points for the purpose of quality-control checks as discussed above, then a second time to select the data and calculate the required weights for determining increments appropriate to the analysis grid. At this stage only those data which passed the two quality-control steps are available for selection. The optimum interpolation procedure is modified to allow for the higher resolution of the model in two respects. Firstly, the observation errors are reduced by 10% from the values used on the coarse mesh, on the basis that the component of the error which caters for the unrepresentativeness of the observation as an area average may be reduced; this implies a higher weight for the observations. Secondly, a narrower structure function is used as the basis for calculating the first-guess error covariance. The width of the Gaussian structure function is reduced by a factor $\sqrt{2}$ compared with that used on the coarse mesh. This achieves the aim of analysing small-scale features which are identified by the observations. An interpolation analysis is not actually required for the analysis grid, all that is needed are details of the selected observations and their weightings for use in the following assimilation stage.

(d) Assimilation of increments

During the assimilation stage, interpolation increments are recalculated for each time-step using the optimum interpolation weights W_i which have already been calculated. This is done during a 3-hour integration starting at the previous analysis time, using a repeated insertion technique. At each model time-step, the weighted average $\Delta\psi$ of the difference between the forecast values at that time-step ψ_M and the observed values ψ_i is calculated using the equation

$$\Delta\psi = \sum_i W_i (\psi_i - \psi_M)$$

and a small fraction of this is added into the model.

The assimilation equation is represented by

$$\psi_{n+1} = A(\psi_n) + D(\psi_n) + \lambda_n (\Delta\psi_n + G(\Delta\psi_n) + H(\Delta\psi_n))$$

where operator A represents the forecast equations, including all the physical parametrization processes, and operator D represents a damping term which is required to suppress gravity waves generated during the assimilation process. These gravity waves generally have a larger divergent wind component than meteorological motions, and divergence diffusion, which has no effect on the vorticity, is used to control them. A damping coefficient of $2.5 \times 10^6\ m^2\ s^{-1}$ is used. The other three terms, which are all scaled by the relaxation coefficient λ_n, are the assimilation increment $\Delta\psi_n$ together with further increments (denoted by operators G and H) which are derived using geostrophic and hydrostatic relationships. During the assimilation period λ_n increases linearly with time. As indicated in Fig. 3, at the

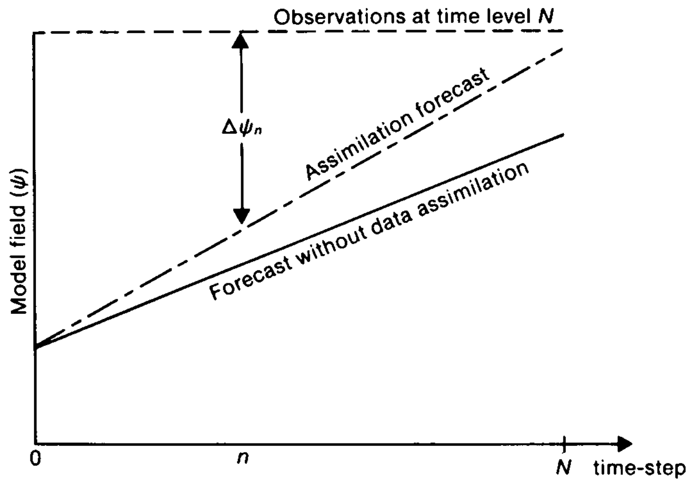


Figure 3. Variation of assimilation increment with time.

start of the assimilation period the assimilation increments may be large and are therefore given a small weight. As the fields adjust towards a state defined by the observations during the assimilation period, the assimilation increments become smaller and a larger relaxation coefficient may be used without generating too much noise. For mass field information the final value of λ is 0.175, but for wind data a smaller value is used during the last few time-steps of the period in order to suppress undesirable surface pressure oscillation at the start of the subsequent forecast. The geostrophically derived wind increments (operator G) and hydrostatically derived temperature increments (operator H) are designed to hasten the fit of mass field data and are fully described in Bell (1985). Geostrophic wind increments are easier to use in the fine-mesh scheme, because the narrower structure function for the first-guess error correlation gives a smoother temperature increment field upon which the geostrophic wind increments are based.

3. Some results of the scheme

(a) Direct impact of additional data

The same basic set of observations is used in any analysis whether coarse mesh or fine mesh. Both aim to make the best use of all available data. Two components of the observing network do, however, produce information on a scale which is equivalent to the fine-mesh model grid. These are the Local Area Sounding System (LASS) data (the locally retrieved satellite temperature soundings produced on the HERMES computer facility) and the European surface observation network. Unfortunately the potential for more detailed analyses based on the direct impact of such data has yet to be realized. Bell and Hammon (1985) have discussed the problems associated with LASS data in some depth. Although a lot of detail is evident in the observed thickness fields, it has proved difficult to identify what detail is real and what is spurious. Significant biases have been noted at low levels and near the tropopause, caused by cloud clearing problems and also the use in the retrieval process of a poor climatological first guess. All these factors contribute to the problem of analysing and adequately assimilating the information from LASS data. Lorenc *et al.* (1985) have described methods by which these weaknesses may be overcome.

The problem of extracting fine-scale information from the surface observing network is equally intractable. It is uncertain how representative the reports are of grid-box mean fields, particularly where local orographic effects may be large. It is also uncertain how to spread the surface information into the lower troposphere. Ideally one might wish to confine the influence of surface information to the boundary layer, but the required flexibility to do this has not yet been established. At the present time the only use made of surface synoptic reports is the surface pressure information. The indirect impact of the data is more significant. When one considers how the data interact with the fine-mesh forecast model and the fine-mesh orography the benefits are more obvious as the following sections will show.

(b) Impact on analysis of using a more detailed orography

Much fine-scale detail at the surface over land is a result of orographic influences and even if this detail is evident from observations on a 75 km fine-mesh scale, it is unlikely to be analysed correctly if a coarse orography is used. Fig. 4 illustrates the mean height for the coarse-mesh orography (150 km grid mesh) for western Europe. It is clear that only the largest features are resolved on this scale. The United Kingdom is only identifiable by a single high value representing the Scottish Highlands and another representing North Wales. The Alps are identified as a single high value of 1800 metres in Switzerland and there is no detail at all in France and Germany. In contrast the fine-mesh (75 km mean) orography in Fig. 5 shows substantially more detail. In particular, the Alps reach up above 2400 metres and four separate high points are clearly resolved, as is the Rhône valley between the Alps and the Massif Central.

The Alps present a considerable barrier to flow from a northerly direction as the example in Fig. 6 clearly shows. The subjective analysis in Fig. 6 has ignored many of the smaller features in the observations which have been influenced by orography on a scale much smaller than 75 km and which are essentially noise as far as the objective analyses are concerned. Even with small features ignored, it is clear that there is a substantial distortion of the flow around the Alps and through the Rhône valley with associated troughing in the region of the Po valley. Fig. 7 shows the objective analysis for the same data time after four cycles of the fine-mesh data assimilation with a coarse-mesh representation of the orography. The flow has only been disturbed slightly by the model Alps in this case and pressure is much too high in northern Italy where the model has been unable to adjust to the observations because of the inappropriate orographic forcing. Fig. 8 is similar to Fig. 7 but in this case a fine-mesh representation of the orography has been used. This shows a surface pressure field which more closely resembles the subjective analysis in terms of the flow around the Alpine barrier and the low pressure to the lee of the Alps.

(c) Aspects of quality control

Another potential advantage of the fine-mesh data assimilation scheme is the greater detail that may be available in the first-guess field which is used for quality controlling the observations. This is especially important at the surface, but may also be valuable near upper jets. An interesting example illustrating this point is an intense surface low which moved north-eastwards across Ireland and Scotland on 18 October 1984. The intensity of this low was not evident until it reached land, where pressure falls in excess of 20 mb in 3 hours occurred in south-west Ireland. The lowest observed pressure

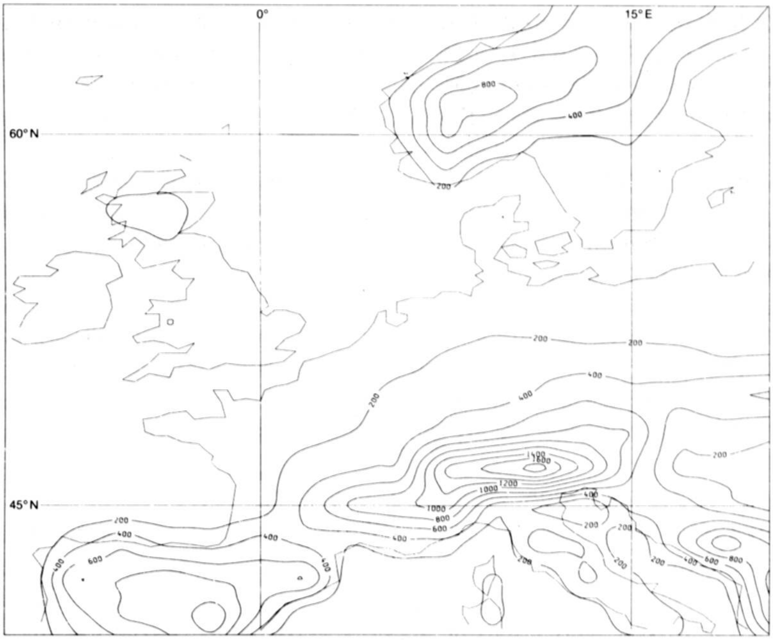


Figure 4. Coarse-mesh orography over north-west Europe. Contours are at 200 m intervals.

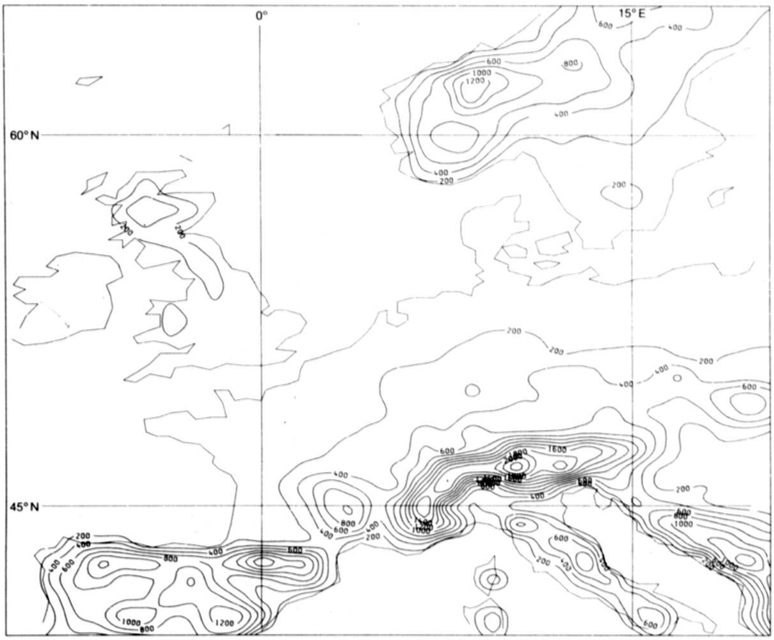


Figure 5. As Fig. 4 but for the fine-mesh.

was 966 mb at Valentia, but the coarse-mesh analysis (Fig. 9) could only achieve 979 mb with the centre shown as nothing more than a trough extending from the main Atlantic low and too far north. Part of the problem was a poor first guess which caused the rejection of several observations and made the fitting of the remaining observations more difficult. The fine-mesh data assimilation of the same case is illustrated in Fig. 10. Although the fine-mesh scheme was unable to adjust towards the Valentia observation which was still rejected, two other previously rejected Irish observations were accepted and the resulting analysis was 6 mb deeper with the centre correctly placed further south. At 18 GMT the low had moved to the north of Scotland and central pressures in the fine-mesh forecasts were 963 and 959 mb from coarse-mesh and fine-mesh analyses respectively, compared with an observed value of 956 mb. The track of the low in the forecast based on the coarse-mesh analysis (Fig. 9) was much too far west of the observed track whereas the forecast and observed tracks in Fig. 10 almost coincide and, perhaps more important, the forecaster could place more credence in this solution because the analysis was better.

(d) Impact of a higher-resolution assimilation model

In addition to making the assimilation of observations rather easier, as the previous example has shown, it would be hoped that a higher-resolution model would provide more detail in data-sparse areas. An example of this is the analysis based on data for 00 GMT on 10 October 1985. The subjective analyst's chart for that date is given in Fig. 11. The main feature of interest is the system in the Atlantic where surface reports are completely lacking. The analyst has drawn a low of central pressure 998 mb at 30° W, based on continuity and satellite imagery, with a warm front extending towards Ireland. Figs 12 and 13 show objective analyses for the same data time from the coarse-mesh and fine-mesh data assimilation systems respectively. The fields of surface pressure, 1000 mb wind and 700 mb vertical velocity are superimposed. The fine-mesh solution is closer to the truth in several respects. It correctly puts the centre of gravity of the system back near 30° W and it has a sharper definition of the frontal structure as indicated by the vertical motion field. The wind vectors match the subjective analysis with regard to the sharp trough which marks the cold front at 30° W, the sudden decrease in strength of the south-westerly flow at 15° W at the surface warm front and also south-westerly flow in the warm sector which is rather too anticyclonic in the coarse-mesh analysis. The different characteristics of the two analyses are very obvious in Fig. 14 which shows cross-sections through the system along the 52° N line of latitude. The horizontal wind shear is much greater in the fine-mesh analysis (Fig. 14(a)) at 28° W near the cold front. At 850 mb the northerly component of the wind changes from northerly 10 m s^{-1} to southerly 20 m s^{-1} across the frontal zone in the fine-mesh analysis, whereas the comparable values for the coarse-mesh analysis are northerly 5 m s^{-1} changing to southerly 15 m s^{-1}. There is a much stronger thermal contrast in the fine-mesh analysis, as indicated by the pecked contours, especially at low levels. The fine-mesh solution also gives much stronger vertical motions as indicated by the arrows.

The best test of the analyses is to determine how good the subsequent forecasts are. Figs 15 and 16 show the evolution of two fine-mesh forecasts one starting from an analysis produced by the fine-mesh data assimilation system (a) and the other starting from an interpolated coarse-mesh analysis (b). Fig. 15 shows T+0, T+6 and T+12 surface pressure charts for the two forecasts, the left-most charts corresponding with Figs 12 and 13. The centre pair of charts indicate a 6 mb difference in the central pressure of the Atlantic low by T+6 and the two forecasts diverge further by T+12 so that (a) is 9 mb deeper than (b) with a correspondingly more vigorous circulation. This trend continues in the later stages of the forecasts, shown in Fig. 16, with differences in central pressure of 12 mb, 12 mb and 8 mb at T+18, T+24 and T+30 respectively. The speed and track of the forecast low is similar in both runs. In fact, as regards position both runs verified very well, as indeed did a coarse-mesh forecast from the

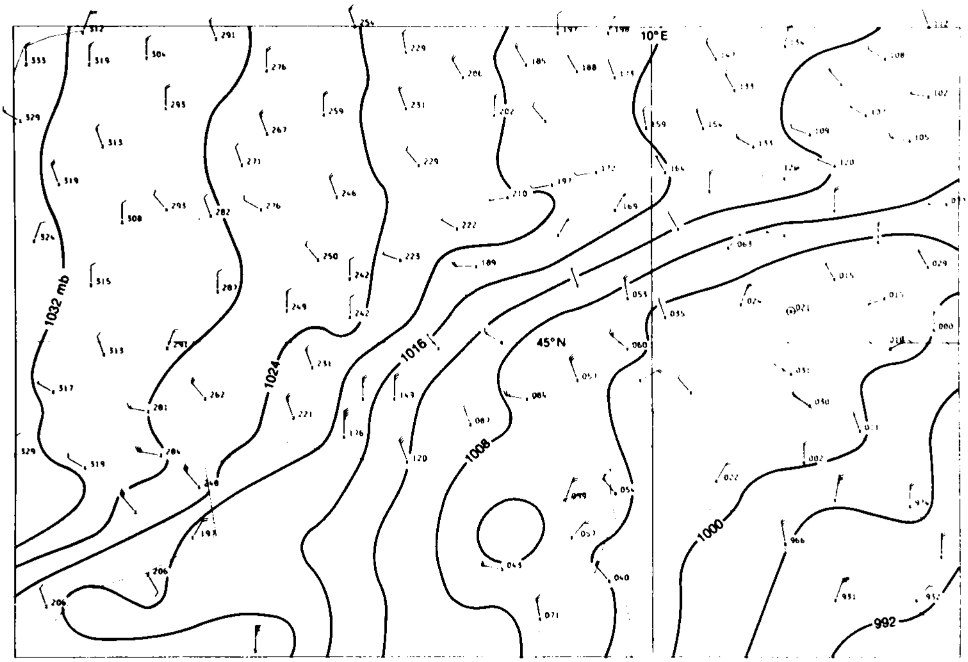


Figure 6. Subjective analysis of surface pressure at 12 GMT 9 February 1984.

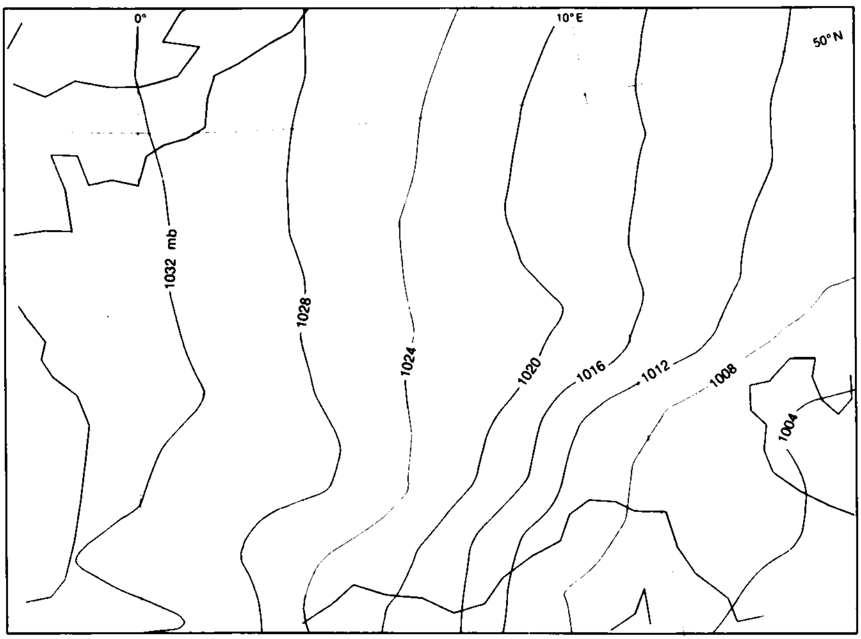


Figure 7. Objective analysis of data in Fig. 6 using fine-mesh data assimilation scheme with coarse-mesh orography.

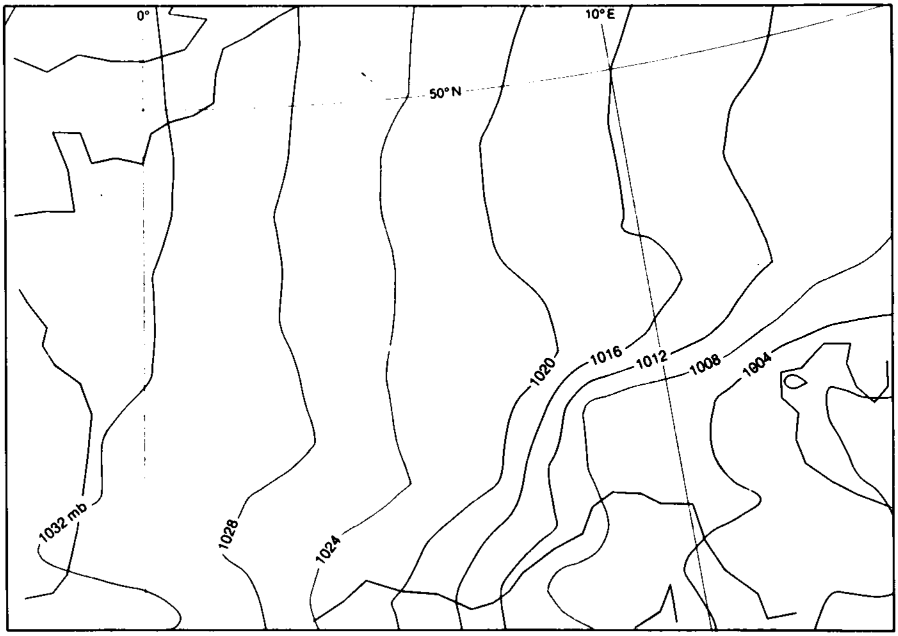


Figure 8. As Fig. 7 but using fine-mesh orography.

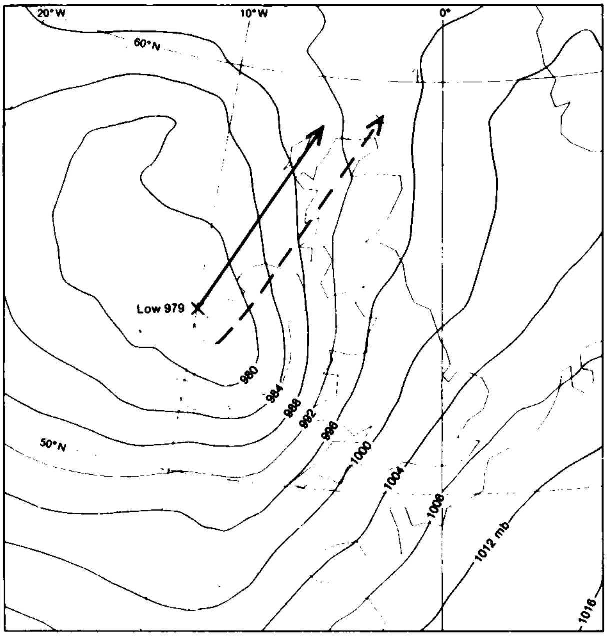


Figure 9. Objective analysis of surface pressure at 00 GMT 18 October 1984 using coarse-mesh data assimilation with the observed (dashed line) and forecast (solid line) tracks of the low centre superimposed.

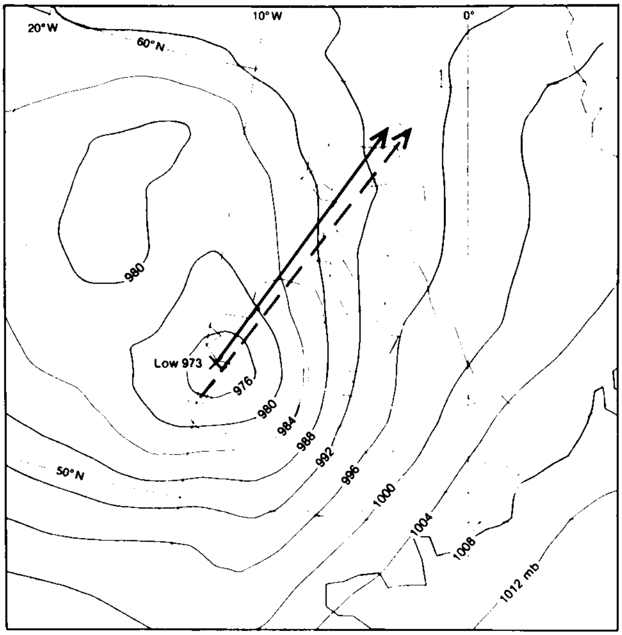


Figure 10. As Fig. 9 but using fine-mesh data assimilation.

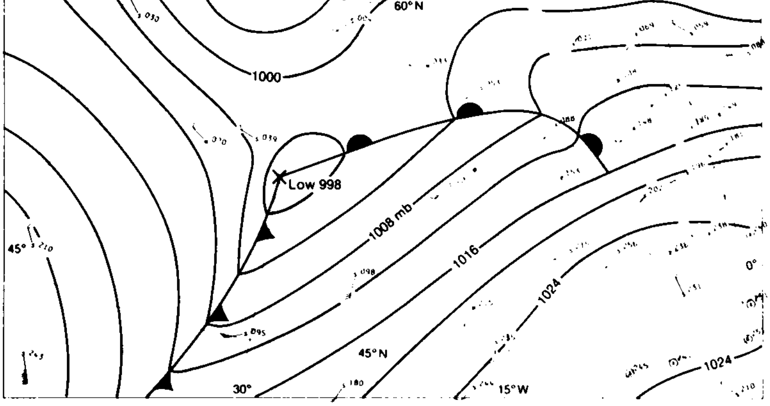


Figure 11. Subjective analysis of surface pressure at 00 GMT 10 October 1985.

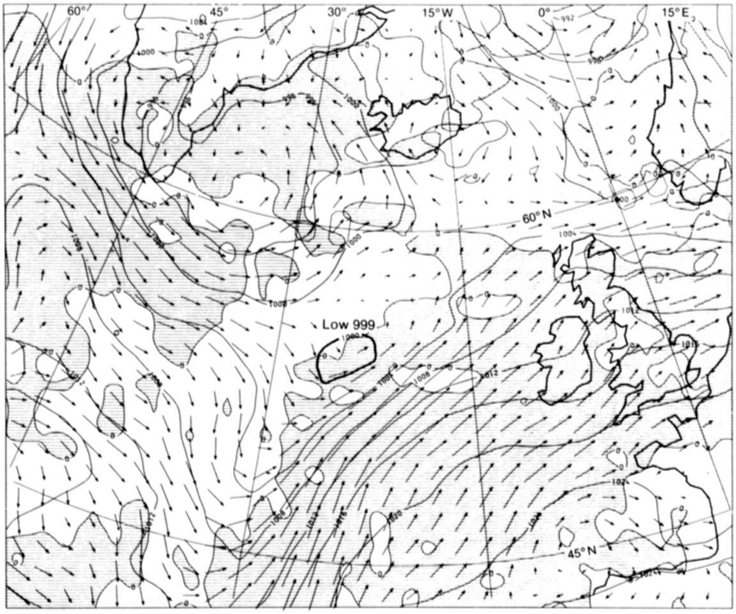


Figure 12. Objective analysis of data in Fig. 11 using coarse-mesh data assimilation. Shaded areas indicate upward motion and arrows show wind direction at 1000 mb level (the length of the arrow is proportional to the wind speed). Isobars are at 4 mb intervals.

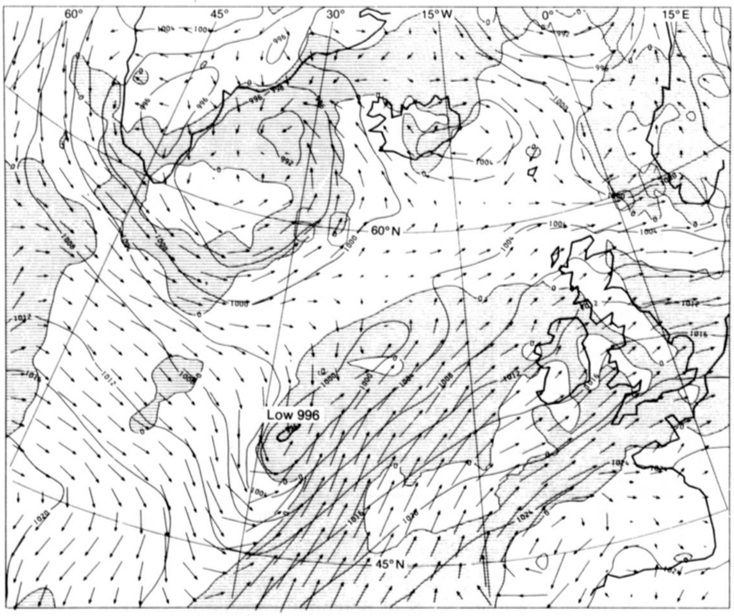


Figure 13. As Fig. 12 but using fine-mesh data assimilation.

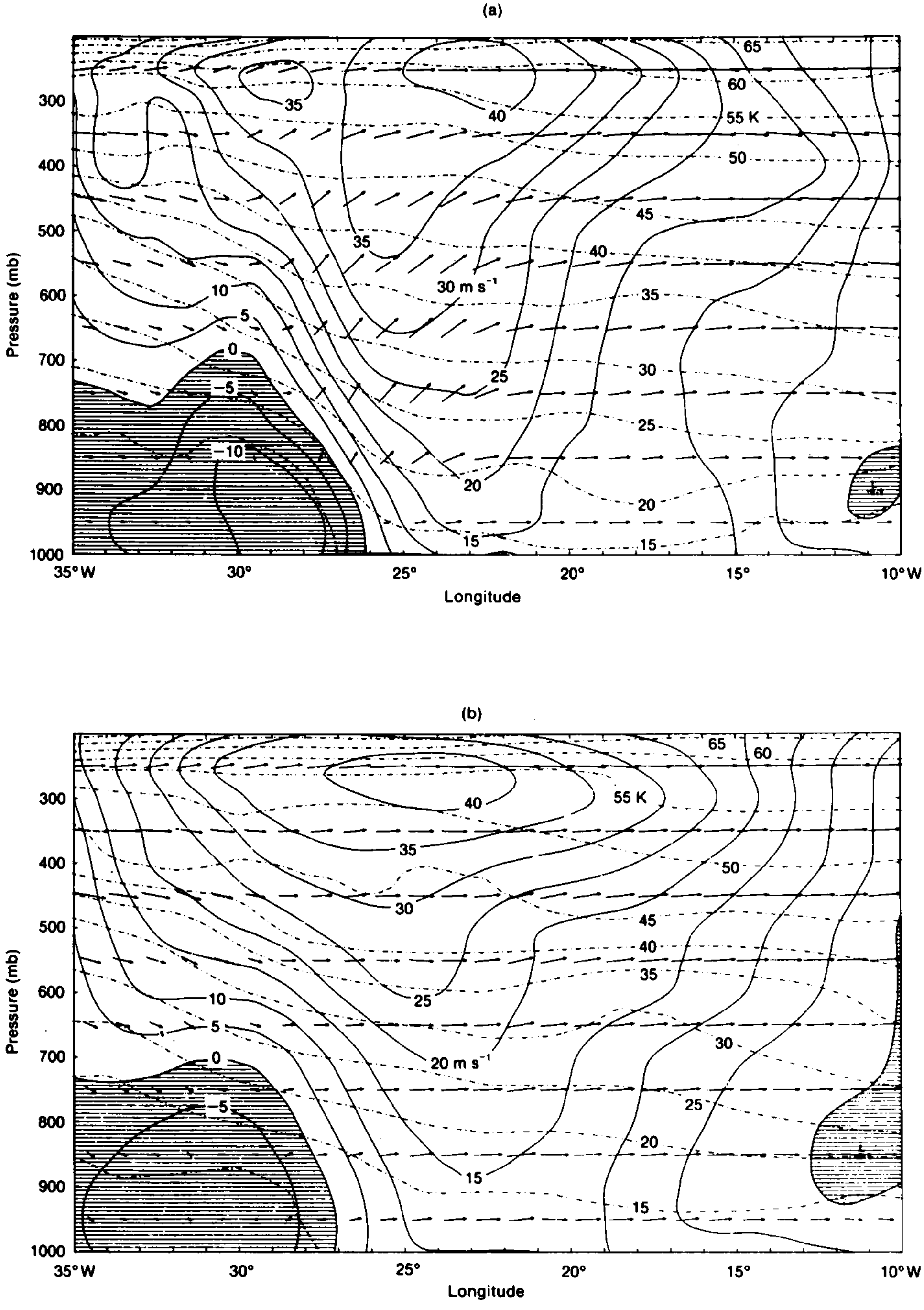


Figure 14. Vertical cross-sections through latitude 52° N of potential temperature (pecked line), southerly wind component (solid line with northerly winds shaded) and motion in the plane of the section (arrows with length proportional to wind speed) from (a) fine-mesh analysis and (b) coarse-mesh analysis for 00 GMT 10 October 1985.

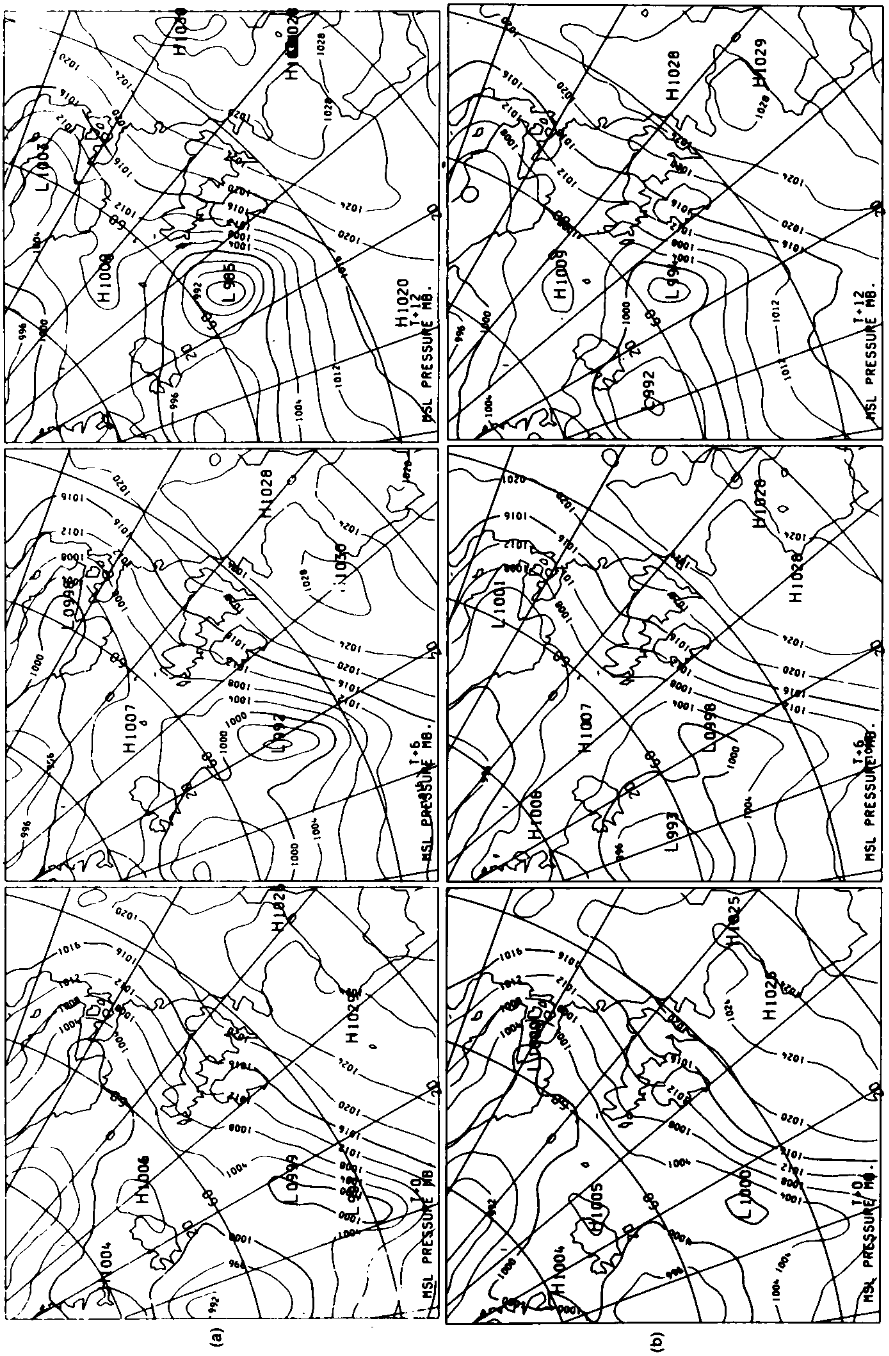
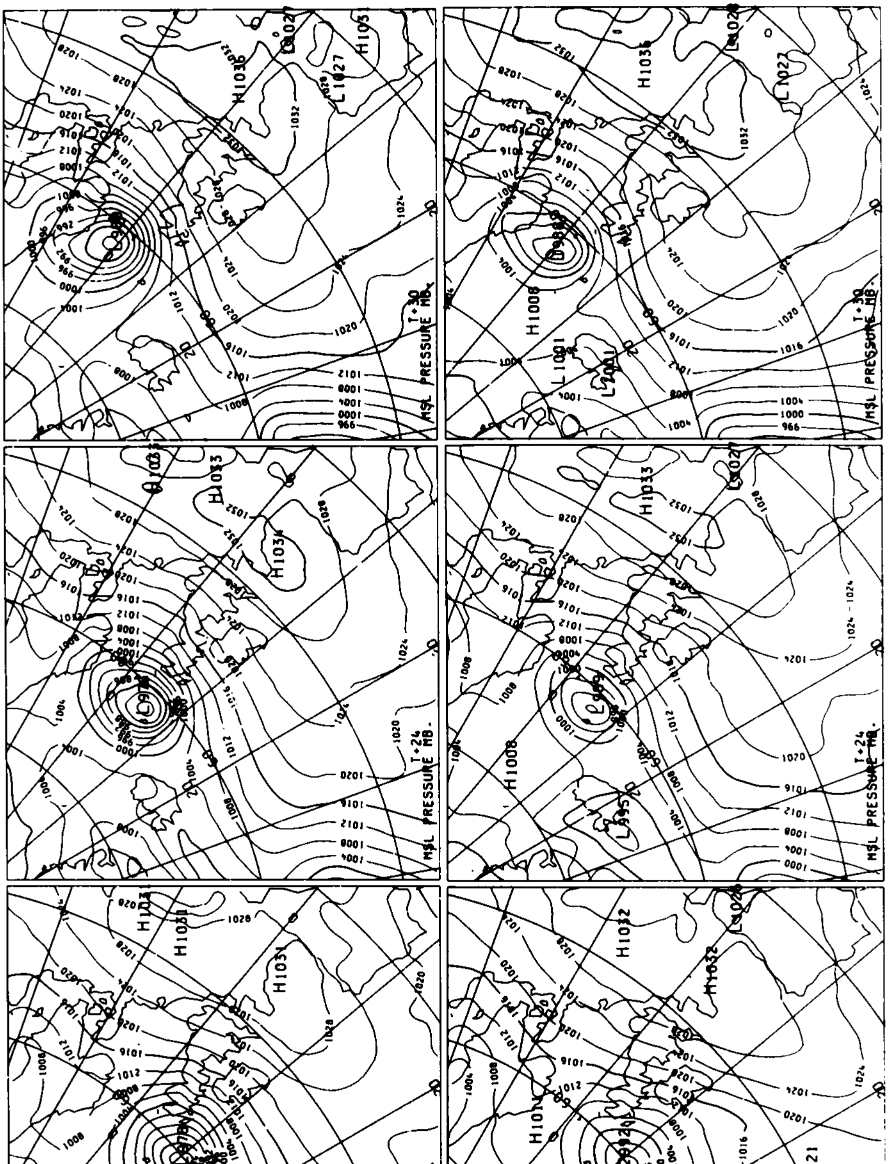


Figure 15. Surface pressure forecasts at T+0, T+6 and T+12 using fine-mesh forecast model starting from (a) fine-mesh analysis and (b) interpolated coarse-mesh analysis from data time 00 GMT 10 October 1985.



(a)

(b)

Figure 16. As for Fig. 15 but for forecast times T+18, T+24 and T+30.

coarse-mesh analysis. Table I shows the depth of the low at 6-hour intervals from three forecasts with the same data time and also from the verifying subjective analysis. Forecast (b) does not depart significantly from the coarse-mesh forecast based on the same analysis until T+12. This gives some indication of the time-scale needed for the model fields to adjust from the coarse-mesh solution to the fine-mesh solution. Had the major deepening of this feature taken place later in the forecast period, then the differences between forecasts (a) and (b) would have been much less. This case demonstrates that substantial improvements in the detail of a forecast are likely when using a fine-mesh data assimilation system, particularly if significant developments occur in the early stages of the forecast.

Table I. *Pressure of low centre at 6-hour intervals from subjective analysis and three computer forecasts.*

Date	Verifying time GMT	Coarse-mesh analysis, coarse-mesh forecast mb	Coarse-mesh analysis, fine-mesh forecast mb	Fine-mesh analysis, fine-mesh forecast mb	Subjective analysis mb
10 Oct.	00	1000	1000	998	997
	06	998	998	992	—
	12	996	994	985	985
	18	996	991	979	—
11 Oct.	00	995	998	976	974
	06	994	988	980	—
	12	996	990	986	984

4. Concluding remarks

It is hoped that the discussion in the preceding section has demonstrated the viability of a fine-mesh data assimilation scheme. Observations can be successfully assimilated into a fine-mesh limited-area numerical model so that an objective analysis appropriate to the scale of the model is produced, and useful improvements in the quality of subsequent forecasts can be achieved. As well as providing the initial conditions for operational fine-mesh forecasts, a tool suitable for investigating the potential of new high-resolution data sources such as that generated by the HERMES system is available.

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Comparison of wind speeds recorded simultaneously by a pressure-tube anemograph and a cup-generator anemograph

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Summary

Wind speeds recorded concurrently by a pressure-tube anemograph and an electrical cup-generator anemograph over a period of 1 year are compared. For 60-minute mean speeds, agreement between the two instruments is generally good. For maximum gust speeds in a 60-minute period it is found that the cup-generator anemograph records 6–7% lower than the pressure-tube instrument.

1. Introduction

The standard instrument for the measurement of wind speed and direction in the Irish Meteorological Service is the Dines pressure-tube anemograph. In recent years, rotating-cup anemometers, which are more adaptable for remote and digital displays, have come into use, mainly at airports, and the question of the comparability of the two types of instrument has become important.

Smith (1981) has compared wind speeds measured by pressure-tube and cup-generator anemographs at a number of stations in Britain but was hampered by the lack of a series of simultaneous observations by both instruments at the same site. A cup-generator anemograph is at present installed on the same mast as a Dines anemograph at Galway. In this paper, a comparison is made between values of both mean wind speed and maximum (gust) speed recorded by the two instruments. Following Smith, the cup-generator anemograph will hereafter be referred to as the CGA and the pressure-tube anemograph as the PTA.

2. Exposure of the instruments

Both anemometers are installed on a 9.1 m mast which has its base on the roof of a small hut about 2.5 m high. The head of the PTA is at the top of the mast. The speed and direction sensors of the CGA are mounted on opposite ends of a cross-arm which is fixed 1.0 m below the PTA head in the direction 035–215°. The cups are 0.3 m and the vane 0.4 m above the level of the cross-arm and each is 1.2 m distant from the mast with the cups on the south-western extremity. The PTA recorder is in the hut while the CGA recorder is in the nearby meteorological station building.

Galway synoptic weather station is situated about 3 km east of Galway city on the north shore of Galway Bay (53° 17′N, 9° 01′W). The ground around the anemometer hut is 18 m above mean sea level and slopes southwards towards the shoreline 0.9 km distant. The exposure is reasonably open despite the suburban location. The station building, 5.4 m high, is situated 59 m to the north-north-east of the anemometer mast. A housing estate to the south and south-east comes within 70 m of the mast at its nearest point but, because of the fall in ground level, the roofs of the houses are below that of the hut. There is a wooded area about 500 m to the east-north-east but, apart from this, there are few trees in the vicinity. Beyond 200 m in various directions there are a few scattered, mostly largish, buildings; beyond 500 m in the sector 240–030° are large housing estates interspersed with open spaces.

The effects of some of these topographical features may be traced in Fig. 1 which shows the variation of gust ratio with direction as given by the PTA. The ratios are high for a near-coastal location (L. Burke, personal communication) and reflect the suburban situation. The variation with direction is moderate compared to other stations. Fig. 1 refers to the period 1978–84. Because of the large variability of gust ratios, individual years do not provide sufficiently large samples to enable the variation of gust ratio with direction to be determined accurately. However, data for the year in which the wind comparison was done (1984) agree with Fig. 1 in a general way.

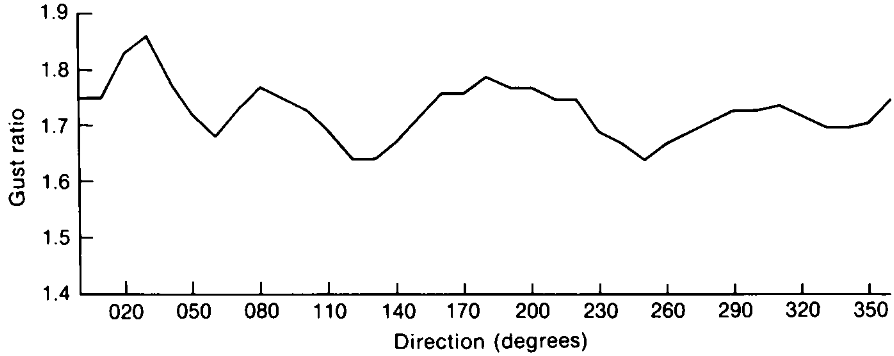

Figure 1. Median gust ratio in overlapping 30° sectors as given by the PTA, 1978–84 (gust ratio = maximum daily gust/10-minute mean centred on gust, mean speeds 7–37 kn only).

3. Characteristics of the Dines anemograph

The Dines PTA is described in the *Handbook of meteorological instruments, part I* (Meteorological Office 1956). The pressure difference between a 'pressure tube', whose opening is kept facing directly into the wind, and a 'suction tube', connected to a set of holes drilled in the vertical tube supporting the head of the instrument, is measured by means of a sensitive float manometer. This is connected to a chart recorder and the float is so designed that the wind-speed record is on a linear scale. The starting speed of the instrument is about 1.5 kn (Smith 1981).

The pressure difference Δp produced by the head of the PTA is related to the wind speed u by

$$\Delta p = \tfrac{1}{2} K \rho u^2 \quad \dots \dots \dots \dots \dots \dots \dots \dots \quad (1)$$

where ρ is the density of air. The instrument is calibrated on the assumption that the constant $K = 1.49$. However, it was discovered that turbulence associated with the bends in the pressure and suction tubes where they join the head caused variations in the value of K (Bilham 1927). This defect was finally corrected by enclosing the base of the head in a cylindrical shield with a conical top thus making K approximately equal to the theoretical value (Simmons and Johansen 1929). Wieringa (1980), citing work by Veryard (1925) and Giblett *et al.* (1932) as well as experiments carried out in 1952 in the Dutch National Aeronautics Laboratory, concluded that the correct value of K is 1.37 and that the PTA underestimates wind speeds by about 4%. However, this appears to be the result of a misunderstanding. The experiments described by Veryard were carried out on PTA heads without vanes or shields (Bilham 1927), and Giblett *et al.* (1932) applied corrections to data from instruments with an old type of hemispherically topped shield but not to data from a PTA with a modern-type shield. It is not clear whether the Dutch experiments were performed with or without vanes or what type of shield (if any) was used. For this reason, no correction was applied to the PTA wind speeds in the present study.

The lag in the response of the PTA to varying wind speeds is governed mainly by the movement of air through the pressure and suction tubes. According to Sanuki (1952), the indicated speed, v, is related to the actual speed, u, with respect to time, t, by the differential equations

$$\frac{dv}{dt} = C\sqrt{(u^2-v^2)} \text{ when } u^2 \geqslant v^2 \qquad \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

and

$$\frac{dv}{dt} = -C\sqrt{(v^2-u^2)} \text{ when } u^2 < v^2 \qquad \ldots \ldots \ldots \ldots \ldots \ldots (3).$$

The constant C is determined by the length, diameter and other characteristics of the tubes connecting the head of the instrument to the recorder. The *Handbook of meteorological instruments, part I*, (Meteorological Office 1956) gives data on the response to various applied air speeds of a PTA which had pressure and suction tubes of length 2 m and diameter 25 mm. These are in fair agreement with the theory and imply a value of C of around 0.7 s^{-1}. Sanuki's own experimental results for a PTA with 17 m tubes of diameter 17 mm give $C = 0.35\ s^{-1}$ (C decreases with increasing length and decreasing diameter). In the case of the Galway PTA the length of the tubes is 11 m and their diameter 25 mm so it is reasonable to assume that the appropriate value of C lies between the two values given above.

Because of its non-linear response, the PTA slightly overestimates mean speeds in fluctuating winds. Sanuki (1952) calculated the amount of this overestimation for a sinusoidally fluctuating air speed and found that, unlike the overspeeding of a cup anemometer, it is independent of the mean speed. He also found that the overestimation by the PTA was less than that by a standard cup instrument except possibly at high wind speeds. This conclusion should apply more strongly to the Galway PTA which has better piping conditions than Sanuki's instrument.

4. Characteristics of the cup-generator anemograph

The rotating-cup instrument is a Mk 2 electrical cup-generator anemometer and is the same type as the Mk 2 instrument referred to by Smith (1981). The rotating cups drive an a.c. generator the voltage output of which operates a Mk 4 chart recorder. Both anemometer and recorder are described in the second edition of the *Handbook of meteorological instruments, volume 4* (Meteorological Office 1981) and the recorder is described by Hartley (1955). The system has a high starting speed (about 5 kn) and the scale is highly compressed and non-linear below about 10 kn. These facts represent serious drawbacks in climatological use in view of the high frequency of winds of 10 kn or less.

The response time of a cup anemometer varies inversely with the wind speed so that the response distance (the product of speed and response time) is approximately constant. A graph in the *Handbook of meteorological instruments, volume 4* showing the variation of response time with speed for the Mk 4 CGA implies a response distance of 6–7 m. Smith (1981) states that the cups of the Mk 2 have a greater inertia than those of the Mk 4 but he is also of the opinion that observations from the two are compatible. The response time of the recorder used with the CGA is about 0.2 s (Pearce 1974) so that the recorder contributes very little to the lag of the overall system.

The overestimation of the mean speed of a turbulent airflow by cup anemometers is due to two factors sometimes referred to as 'u-error' and 'w-error' (MacCready 1966). The u-error is associated with turbulent fluctuations along the direction of the mean wind and is due to the variation of response time with speed, which implies a non-linear response. The magnitude of the error increases with the width of the speed trace and decreases, in percentage terms, with increasing mean speed. MacCready estimated the u-error to be about 1% for an anemometer of response distance 1 m at a height of 5 m and found that it was proportional to the response distance and inversely proportional to the height. This would imply that the u-error for a CGA with response distance 6 m at a height of 10 m would be about 3%. The w-error is associated with the vertical component of turbulence and increases with the variance of the vertical angle of the wind. In unstable conditions the error may be a few per cent.

5. Data

The comparison between the CGA and the PTA is based on wind speeds recorded during 1984. The data extracted from the CGA chart record consisted of the mean speed and direction and the highest gust speed in 60-minute periods ending at 12 and 24 GMT. Wind speeds were estimated to the nearest knot. The hours chosen are those at which time-marks were made on the chart and the timing uncertainty was thus minimized. Because of the high starting speed of the anemograph and compression of the lower part of the scale, only winds of Beaufort force 3 (7–10 kn) or greater were used.

Trouble was experienced with the CGA recorder on a few occasions, particularly in September and October, owing to the chart coming off its sprockets and to irregular movement of the chart. It was found necessary to reject the record from 9 September to 20 October. The zero error of the recorder was found to fluctuate slightly but averaged almost exactly zero over the portion of the record used. The average zero error did not exceed a few tenths of a knot in any month and it was not considered necessary to correct the tabulated speeds.

In addition to the above data, 60-minute means and gusts were extracted for 59 hours during periods of strong winds. This was done to increase the sample size for the higher wind-speed categories (force 5 and greater) and to spread the observations for these categories as evenly as possible over the 12 months. The winds for these 'selected' hours are less likely to be statistically independent than those for the fixed day and night hours. However, they were generally separated from each other by at least 3 hours.

The PTA is the official anemometer for the station and 60-minute means of wind speed and direction recorded by it are routinely tabulated for each hour. In addition, for the purposes of the present investigation, the highest gust in each hour for which data for the CGA had been extracted was obtained. Data for 6 hours had to be rejected because of partially defective traces. Because of the practice adopted of taking the highest gust in the hour regardless of its exact time of occurrence, the CGA and PTA gust speeds compared do not necessarily refer to the same gust.

The calibration of both anemometers was checked in October 1983 and the PTA was tested for possible leaks. The calibration of the PTA consisted of checking indicated speed against applied pressure differences using a sensitive manometer. In the case of the CGA, the voltage output of the generator was checked for known rates of rotation of the cup wheel and speeds indicated by the recorder were checked against known voltages. Facilities were not available to test the anemometer heads in a wind-tunnel. Apart from the faults in the CGA recorder previously mentioned, it is believed that both instruments were in excellent working order throughout 1984.

For the purpose of comparison, all winds with directions in the sector 335–095° were disregarded. This sector contains the directions for which the CGA vane and the tubes supporting the PTA head are upwind of the cups and also the directions for which the station building is upwind of the mast. Of a possible 732 observations (2 per day), 108 were rejected because of instrumental defects (mostly in the CGA in September/October), 198 because the wind was less than force 3, and 94 because the wind direction lay in the sector 335–095°, leaving 186 useful observations at 12 GMT and 146 at 24 GMT. To these must be added the 59 observations at the selected hours. For each of these hours, the ratio of the mean speed given by the CGA to that given by the PTA was calculated and also a similar ratio for the gust speeds. These ratios are hereafter denoted by R and R' respectively.

Because of the importance of extreme gust speeds, all daily maximum gusts in excess of 55 kn were read off the records of both instruments. There were seven such days, six in January and one in February.

6. Results

In order to investigate possible variations with wind direction, mean values of R and R' were calculated for each 30° sector from 095 to 335° for the 'day' (11–12 GMT) and 'night' (23–24 GMT) cases separately. No significant variation with direction was found for either ratio and data for all directions were therefore combined.

The observations were divided according to mean speed (as given by the PTA) into Beaufort forces 3 (7–10 kn), 4 (11–16 kn), 5 (17–21 kn), 6 (22–27 kn), and 7 or greater (28 kn or more). Average values of the ratios R and R' were then calculated for each month. Fig. 2 shows these ratios for the force 4 winds

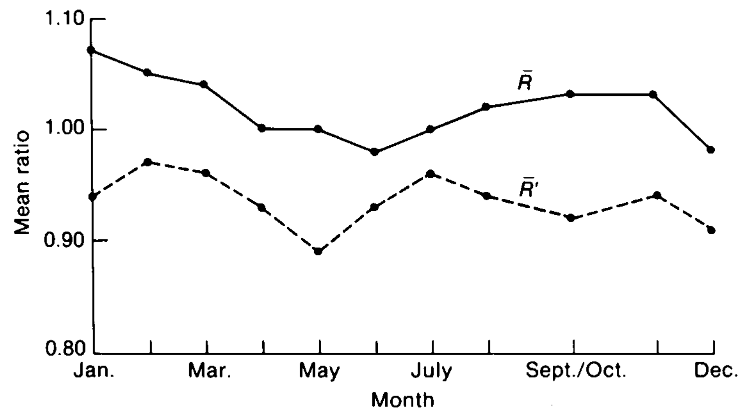

Figure 2. Monthly mean ratios (CGA/PTA) of mean wind speeds ($\bar{R}$) and maximum (gust) speeds ($\bar{R}'$) for 1984. Data are for force 4 winds only, day and night cases combined.

(the data for September and October have been combined because of the fact that the record for a large portion of these months had to be rejected). It may be seen that there is some variation in the ratios with time. The variation must be considered significant because, taking the extreme cases, the differences between the January and December values of $\bar{R}$ and the annual mean are statistically significant at the 1% level. Broadly similar variations were found in the case of the force 3 winds; there were insufficient observations of force 5 or more to enable reliable monthly averages to be calculated. Generally speaking, R and R' were above average in the period January–March and below average in April–June and in December. The variation does not appear to be related to seasonal meteorological factors and the small variation in the zero error of the CGA is insufficient to explain it. It may be due to drift in the calibration of the instruments or possibly to variation in the subjective error associated with manual tabulation. In any case, the data for the full year, when combined, cannot be considered to constitute independent, homogeneous samples.

Fig. 3 shows the average values of R and R' for the whole year for each wind force. The day and night observations are shown separately; 'all' indicates the combined day, night and selected cases. If we were to assume that the data were independent and homogeneous, the difference in $\bar{R}$ between day and night for force 3 winds would be significant at the 1% level and the difference in $\bar{R}'$ would be significant at the 5% level. This result is not likely to be very much affected by the month-to-month variation in the ratios since the frequency of occurrence by day and night of force 3 winds is rather evenly distributed over the months. Also, for force 3 winds, the night values of $\bar{R}$ and $\bar{R}'$ are less than the day values for each of the four quarters of the year. The day/night difference in the force 4 and 5 ratios are not significant at the 5% level and neither is the difference in $\bar{R}$ (day) between forces 3 and 4.

The mean CGA/PTA ratio for daily maximum gust speeds exceeding 55 kn was 0.947 with a standard error of the mean of 0.013. The speed of the gusts (as given by the PTA) ranged from 58 to 68 kn with a mean of 62 kn.

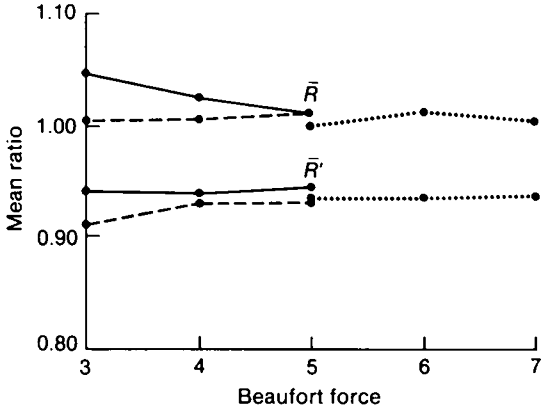

Figure 3. Mean ratios (CGA/PTA) of mean wind speeds ($\bar{R}$) and maximum (gust) speeds ($\bar{R}'$) for 1984. Solid line indicates day (11–12 GMT), pecked line night (23–24 GMT) and dotted line all (including selected) observations.

7. Discussion

Hartley (1955), from a comparison between a CGA Mk 1B and a remote-recording PTA mounted on the same tower, concluded that the instruments showed 'close agreement in both mean and maximum values'. On the other hand, Smith (1981) found that mean speeds derived from the CGA (Mk 2 and Mk 4) exceeded those from the PTA by 1–2 kn and that the greatest differences occurred at speeds below 8 kn and above 20 kn. This investigation was based on a study of records from five stations where there had been a change-over from a PTA to a CGA without change of site. The data were adjusted by reference to control stations with homogenous records spanning the times of change-over. Smith concluded that the differences at low speeds were due to observer error in reading the compressed, non-linear scale of the CGA and those for higher speeds were due to overspeeding of the cups.

Rijkoort (1955) compared a PTA with a cup anemometer and found that, for mean speeds below 5 m s^{-1} (10 kn), the PTA underestimated the mean wind compared to the cup instrument, but that for speeds exceeding that limit the opposite was the case. The difference between the two instruments was found to increase with the width of the trace and, for the higher speeds, overestimation by the PTA was as much as 10%. A feature of Rijkoort's experiment was that mean speeds from the PTA were estimated by eye from the charts whereas those from the cup anemometer were calculated from the number of contacts made in a given time. It is thus possible that the differences found were partially due to a systematic error in the estimation of the PTA winds and Rijkoort did in fact find some evidence of this. In the investigations of Hartley and Smith, as in the present study, both CGA and PTA mean speeds were estimated by eye.

For the higher wind-speed categories, Fig. 3 shows that agreement between the CGA and PTA on mean speeds is quite good despite the fact that the basic data were tabulated in whole knots. This disagrees with the findings of Smith on the one hand and Rijkoort on the other but agrees with Hartley's conclusions as regards mean wind speeds. The higher CGA/PTA ratios found for the day observations of force 3 and, to a lesser extent, force 4 may be due to overspeeding by the CGA which is expected to be most serious, relative to the PTA, at low mean speeds. Both Smith and Rijkoort also found overestimation by the CGA at low speeds. The difference between day and night may be due to the fact that overspeeding by the CGA is greatest in highly turbulent conditions which are most common in the daytime. However, caution is necessary in interpreting the force 3 results because of the large scatter in the ratios which are quotients of small whole numbers. While, as previously discussed, the difference between the day and night values of $\bar{R}$ for force 3 is probably significant, no great reliance should be placed on the amount of the difference. Also, the fact that a similar difference is found in the case of the force 3 gust ratios raises the possibility that some factor other than the response lag of the instruments may be involved.

It is clear from Fig. 3 that maximum gust speeds are significantly underestimated by the CGA relative to the PTA. This is to be expected at low mean speeds because of the large response time of the CGA but it is surprising to find it also at high mean speeds where the response time is much less.

To compare the actual results with theoretical expectations, use was made of Wieringa's (1973) model which gives the maximum (sinusoidal) gust in a given time interval as a function of gust period, mean speed, height above ground and roughness length. A roughness length of 0.5 m for Galway was assumed. The gust speed recorded by an anemometer is the product of the actual gust speed (which, according to the model, decreases with increasing gust period t) and the response factor of the anemometer (which increases with t) so that a maximum recorded speed is found at some value of t. For the PTA, the maximum recorded gust was obtained by integrating equations (2) and (3) numerically for sinusoidal inputs of various periods and of amplitudes given as a function of mean speed and period by Wieringa's model. A value of $C = 0.5\ s^{-1}$ was assumed. In the case of the CGA, the response factor was calculated assuming a response distance of 6.3 m for the anemometer and a response time of 0.2 s for the recorder (Pearce 1974). The results of the computations were that the CGA should record gusts about 7% lower than the PTA at a mean speed of 5 m s^{-1} (10 kn) but 3% higher at 20 m s^{-1} (39 kn).

Incidentally, the computations also show that, at high mean speeds, the value of t appropriate to the PTA maximum gust is 6–7 s. This is not inconsistent with the frequently quoted figure of 3 s for gust duration (positive departure from mean speed only). It confirms Wieringa's (1980) conclusion which was based on data from Giblett *et al.* (1932) and assumed a first-order, linear response for the PTA.

One possible explanation for the experimental result that the PTA records higher gusts than the CGA even at high mean speeds is that the PTA over-records the gusts owing to resonance phenomena. Borges (1968), in wind-tunnel experiments with a PTA, found a resonance peak at high mean speeds for a sinusoidal input of 0.2 to 0.3 Hz ($t = 3$ to 5 s) and concluded that the frequency response of floater-type anemographs is inadequate for the study of maximum gust speeds.

8. Conclusions

For winds of Beaufort force 3 to 7 inclusive (7–33 kn) the 60-minute mean wind speeds recorded by the cup-generator anemograph agree well, generally speaking, with those recorded by the pressure-tube anemograph. However, there is some evidence that, for force 3 and possibly force 4 winds, the CGA records a few per cent higher than the PTA during the daytime. The CGA Mk 2 underestimates maximum gust speeds compared to the PTA by 6–7% regardless of mean speed. This is contrary to the theoretical expectation that it should record higher than the PTA at high mean speeds.

Acknowledgements

This research was supported by the Irish Meteorological Service. I am grateful for the assistance of my colleagues in the Service particularly Messrs J. Kearney, L. Burke and U.N. Egan.

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Notes and news

Editor of the *Meteorological Magazine*

On 2 April 1986, R.P.W. Lewis, who had been Editor of the *Meteorological Magazine* for 12 years, retired from the Meteorological Office. During his period as Editor there were important changes in the appearance, style and content of the magazine with the aim of making it more attractive, readable and informative. The new Editor is R.W. Riddaway, with F.E. Underdown remaining as Assistant Editor. Nearly two years ago an Editorial Board was set up, and this will continue to advise the Editor on the content and presentation of articles. At present the Editorial Board consists of the following members:

R.W. Riddaway (Editor and Chairman)
D.A. Bennetts (Defence Services)
T. Davies (Forecasting Research)
W.R. Sparks (Observational Requirements and Practices)
P.G. Wickham (Meteorological Office College)

World Meteorological Day

In 1973, the world meteorological community celebrated a century of organized international collaboration in meteorology. One hundred years before that date, the First International Meteorological Congress met in Vienna and prepared the ground for the establishment of the International Meteorological Organization. This organization ceased to exist in 1951 and was replaced by an intergovernmental body known as the World Meteorological Organization (WMO). The Convention of WMO came into force on 23 March 1950 and this date has been celebrated annually since 1961 as World Meteorological Day.

To mark the occasion, the WMO Congress and Executive Committee (now Executive Council) recommended that all Members of the Organization should make a particular effort on this day to bring the importance of meteorology to the attention of everyone concerned. To facilitate this task, it was decided that a specific theme should be designated each year in order to ensure the co-ordination of activities and efforts. The theme for the year 1986 is 'Climate variations, drought and desertification'.

Although each Member of WMO celebrates the day independently, it is customary for the WMO Secretariat to prepare and distribute in advance information pertaining to the theme of the year. This year the material includes a booklet (WMO - No. 653) by F. Kenneth Hare, University of Toronto, entitled *Climate variations, drought and desertification* which aims to present a balanced perspective regarding the role of climate in the uses made of the arid zone by human society.

Mr W.A.L. Marshall, MBE

We regret to record the death, on 31 January 1986, of William Arthur Lewis Marshall, MBE at the age of 88. He retired from the Meteorological Office in 1959 after thirty-nine years of service. He was much respected both personally and professionally by the meteorological fraternity of his time.

'Curly Marshall' as he was called in his younger days joined the Office in 1920 as a Technical Assistant. In the mid-30s he was selected for sideways transfer to the Technical Officer grade. Until 1939 his duties were spent almost entirely within the Forecasting Division of M.O.2 in Kingsway. Following assignments away from London in the early part of World War II, one of these being on the initial trials of forecasting for smoke screens over factories, he returned in 1941 to take charge of the London Forecasting Office (later to become the London Weather Centre) where he remained for the next twelve years. With the upsurge of public interest in the weather and weather forecasting at the end of the war, following the wartime black-out of such information, he often appeared on radio and television and was interviewed frequently by the Press. It was during his time on the 'Victory House roof' that he prepared the first edition of *A century of London weather*. He wrote various articles that appeared in the *Meteorological Magazine* whilst his paper on the 'Comparison of wind recorded by anemograph with the geostrophic wind' still appears in meteorological bibliography to this day. He was appointed a Member of the Most Excellent Order of the British Empire in the New Year's Honours of 1952.

With the establishment of the new Scientific Civil Service at the end of World War II, Bill Marshall, as he was now more commonly known (the 'curls' long having disappeared) was regraded as a Senior Experimental Officer (SXO). However, with the introduction of the Chief Experimental Officer grade in 1953 he was one of the first SXOs so to be promoted and with this became Head of Communications, based at Dunstable.

His home on retirement remained at Totternhoe, a village just outside Dunstable. He is survived by his wife Lucy, and two sons the younger of whom, Tom, also entered the meteorological profession and retired as Deputy Director of Naval Oceanography and Meteorology at the Ministry of Defence in 1979. W.A.L. Marshall died on his 65th wedding anniversary. He was buried with deep snow on the ground. He would not have chosen this environment for the occasion but he would at least have taken satisfaction that the snow had been forecast.

Obituary

Dr A.E. Gill

We regret to record the death of Dr A.E. Gill, FRS, Senior Principal Scientific Officer in the Dynamical Climatology Branch who died, aged 49, after a very short illness on 19 April 1986.

Adrian Gill came to this country in 1960 as a research student at Trinity College, Cambridge where he worked with George Batchelor and became influenced by the famous Cambridge tradition in fluid dynamics set up by G.I. Taylor. Then followed a year at the Massachusetts Institute of Technology after which he returned to Cambridge. He was in Cambridge for the next 20 years pursuing research on various aspects of fluid dynamics particularly as applied to the atmosphere and the ocean. During the years in Cambridge Adrian built up a great research reputation and also built up, through students and many visitors, a strong and renowned research group.

Adrian was very much an international scientist. He travelled a great deal not just to conferences and the like but to work for substantial periods in other laboratories. Working summer vacations were spent at the Scripps Institute in La Jolla, in Vancouver, in Melbourne, in the Geophysical Fluid Dynamical Laboratory in Princeton (with which he had a particularly close relationship), in Boulder, Colorado, in Durban, South Africa, in Woods Hole, at the University of Washington, Seattle, in the Oceanographic Institute at Malaga in Spain and so on. He knew the whole world community in his subject extremely well — rather like an old-style travelling scholar. Through all these visits and interactions Adrian had an enormous influence on the subject and was of course himself influenced and sharpened so that he became a world leader if not the world leader in his field.

Adrian was of course a very able mathematician. But he was always keen to apply his mathematics to real problems. You might think that he could hardly have chosen more complex subjects to study than the ocean and the atmosphere. But unlike some mathematicians who seem to make easy things appear difficult, Adrian's genius was to break problems down to the simplest picture possible and then apply to that elementary model, simple and elegant mathematics. He always asked the simplest questions; with unusual insight he would isolate the bare essentials of a problem. Some of his papers are classics of their kind and will long be remembered. How does the dense water at the bottom of the ocean in the region of the Antarctic get there? What happens when a range of mountains rising from the ocean floor disturbs the flow? And no doubt most of all he will be remembered for his severe but effective simplification of the way in which the ocean and the atmosphere work together in the tropics. From this work was born the TOGA project — short for Tropical Ocean and Global Atmosphere — a very large international project concerned with the way atmosphere–ocean interaction influences climate. It turns out that there are strong connections between the state of the Pacific Ocean and the character of the climate elsewhere in the world, for instance, the occurrence of droughts in Africa or floods in South America. Adrian was most enthusiastic not only about this fascinating scientific problem but also about the way it related to important problems of the real world. He put a great deal of energy and time into his position as Chairman of the Scientific Steering Committee of the TOGA project.

In 1984 Adrian joined the Meteorological Office where he became an individual merit scientist. Together with his research group he moved from Cambridge to Oxford — not a very easy transition! In Oxford he set up a substantial group on ocean modelling and he helped to found the Robert Hooke Institute for Cooperative Atmospheric Research — a joint enterprise between the University, the Meteorological Office and the Natural Environment Research Council. There, with access to more people and greater resources, he was well on the way to leading the most effective scientific group in the world in coupled atmosphere–ocean models.

We can be thankful that Adrian has left us with a huge contribution to the science; in his way of working he has left an example of scientific dedication and a particularly effective way of pursuing the scientific enterprise. He has passed on his ideas and methodology to many students who he fostered so carefully and who are carrying on his work in various parts of the world. He has also left us with a superb textbook — *Atmosphere–ocean dynamics* — in which we can get the feel of Adrian's own inimitable style. Its concluding sentence is 'Nature is complex, there is much to be learnt'. We were all very much delighted, as he was, when he was elected a Fellow of the Royal Society just a month before his death.

In the last book of the Bible, the Revelation, we are told that in the heavenly city there will be no more sea. I do not think this is meant to imply that oceanographic skill will not be recognized in heaven — after all we are assured that life there will be more full than we can possibly imagine. But the writer of Revelation was imprisoned on an island — the sea was all around him, it meant barriers, separation. Adrian had a deep and thoughtful Christian faith and we can be glad for him that he has gone to that fuller life promised by no other than Jesus Himself. We can look forward — as I am sure even more do Helen, Jane, Simon and Adrian's family — to that time and place where the separation we feel so strongly today will no longer exist.

Mr J.L. Cadman

It is with regret that we record the death on 21 January 1986 of Mr J.L. Cadman, Professional and Technological Officer (PTO) I, of the Telecommunications Branch (Met O 5).

Jim Cadman joined Met O 5c in May 1978 as a PTO II from the Ministry of Defence Procurement Executive (MOD(PE)) and in January 1981 he was promoted to PTO I. From the start of his career in the Office he was deeply involved in the specification, procurement, and production of the major message-switching computer systems AUTOCOM Phase III and IV.

The Ferranti Phase III occupied his attention for his first three years in Met O 5 and the years since 1981 were mainly concerned with the detailed planning and implementation of Phase IV Tandem computers. For much of this time he wore 'two hats' having the additional responsibility of acting as the representative of the MOD(PE) Project Office.

Outside office hours Jim was a keen outdoor activity man, cycling to work most days, rambling at weekends and playing badminton indoors when he could. He was a musician of considerable talent and played the trombone with the Glenn Miller style band, the Millstones, at many social events.

Jim was a quiet man with a wry sense of humour and well liked within the Branch. He will be sadly missed.

Correction

Meteorological Magazine, April 1986, p.106, fourth line from bottom of section 3 should read 'E_{rg} represents the error of unadjusted radar rainfall values' not 'adjusted radar rainfall values'.

Meteorological Magazine

GUIDE TO AUTHORS

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Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

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 referred to 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.

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Meteorological Magazine

June 1986

Vol. 115
No. 1367

CONTENTS

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ISBN 0 11 727834 3 ISSN 0026–1149

Printed for HER MAJESTY'S STATIONERY OFFICE
by Delco Printing Co Ltd 6/86 Dd. 739131 C13

THE METEOROLOGICAL MAGAZINE

Fifty years of training in the Meteorological Office

HER MAJESTY'S STATIONERY OFFICE

July 1986

Met.O.971 No. 1368 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

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Fifty years of training in the Meteorological Office

This year is the 50th anniversary of the introduction of formal training courses in the Meteorological Office; and this issue is devoted to a modest celebration of this milestone.

It should not be imagined that there had been no meteorological training courses anywhere else in the country before 1936. One of the earliest pieces of instructional memorabilia which has recently been found has a civil aviation context. It is an exam paper in meteorology sat by candidates for the grade of First Class Navigator on 13 April 1926. Judging by this test of their skill in one subject, First Class Navigators of 60 years ago must have been very competent people. They were faced with questions on line squalls, the climatology of India and the theory of a Dines pressure-tube anemometer which even a student of meteorology might find quite taxing, and the following tailpiece to a question on upper winds would involve most of us in some lateral thinking today:

> Mention briefly four methods, other than pilot balloons, of measuring wind in the upper air including at least one method for obtaining the wind above clouds when the sky is overcast.

No prizes are offered for a solution to this, and anyone who finds it hard to conceive of the possibility of meteorological activity before the invention of radiosondes may be interested to refer to one of L.F. Richardson's (1924)* less well-known papers.

The final question in this exam paper takes us into an area which was to become the preserve of the professional weather forecaster:

> Give an account of the steps you would take at Cranwell to prepare a forecast at 8 p.m. in November of the local visibility between midnight and 4 a.m.

Those of us who have spent a whole professional career using forecasting techniques developed about 30 years ago, may wonder what was taught to trainees in earlier times to enable them to answer such a question. Though we have the textbooks that they used, there is now almost no knowledge of the practical craft that went along with the general synoptic principles and this is an unfortunate gap.

Where we are much more fortunate is in the continued presence with us of some of the principal architects of meteorological training in the modern era, and their memories are recorded in this issue. Although their contributions were submitted quite independently, they complement each other in a remarkably satisfying way both in their style and their content. R.J. Ogden unravels the details of the

* Richardson, L.F.; How to observe the wind by shooting spheres upward, *Prof Note, Meteorol Off,* 3, 1924. No. 34.

assistant training programme during a period when as many as a thousand recruits were trained in one year. C.J. Boyden writes about the training of forecasters, with which he was so intimately connected, while P.J. Meade recalls the first training course for scientists and demonstrates the link between training and research which persists to this day in the Meteorological Office structure where 'Training' still comes within the Research Directorate.

The last article describes developments in training since 1972 when the Training School moved from Stanmore to Shinfield Park, near Reading, and in the process was given the new title of Meteorological Office College. A television script-writer could hardly have contrived a more suspenseful point at which to terminate the latest episode of this particular serial. Without doubt we are about to enter a period of great technological change which will have a substantial impact on our knowledge of the atmosphere as well as on the working practices of applied meteorologists. How will the training of our staff alter to keep pace with these changes? Perhaps in ten years' time, another episode in the unfolding story will be chronicled in these pages.

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Meteorological Office training scheme: the first ten years

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Summary

Systematic training for forecasting began only three years before the outbreak of World War II, first with existing staff and in modest numbers. After the fall of France there was a great increase in recruitment, and the Training School — at Gloucester and later in London — was working at full capacity for much of the war.

It must be difficult for the meteorologist of today to believe that until 50 years ago there was no organized training at any level within the Meteorological Office. My own career began with two years at Edinburgh and a year at Lerwick, and, as there was no official post for me at either place, I had some time to read the few books on meteorology that were available. My introduction to forecasting came with a posting to M.O.6 in 1933, and there H.L. Wright and I spent some light-hearted hours learning the squiggles used in plotting a synoptic chart. Our training consisted of watching forecasters at work without getting in their way.

I was next posted to Calshot, where for a few months I masqueraded as an independent forecaster, fortunately without disaster, and then came a year or so on the forecasting bench at Headquarters, at what used to be Adastral House. I was fortunate in that this period included the six months when Professor Bjerknes worked there to further his ideas on frontal analysis and development. These were well known from his classic papers of 12 and 15 years earlier, but British forecasters varied greatly in their enthusiasm for applying them.

One evening in 1936 I found a note waiting for me as I came on night duty. It was from Mr R.G.K. Lempfert, deputy to the Director, asking me to see him in the morning. This I did, and I was astonished to be told I was to open a training school. I murmured something about the planning of the course and was told that Mr S.P. Peters had been giving some instruction in forecasting and would pass on a syllabus. As to when I should begin, Mr Lempfert thought Monday week would be suitable as he had already arranged for a room at Croydon Airport. The students were to be eight Assistants Grade II who, if successful on the course, would be promoted to Grade I.

The next few days were hectic. I realized that the best I could hope for was to prepare lectures for a week or two and trust I could keep ahead of the class for the six months the course was to last. Armed with a two-page syllabus from Peters I set about my task, basing my initial notes largely on the four volumes of Shaw's *Manual of meteorology* and the newly published *Physical and dynamical meteorology* by Brunt. These were supplemented later by *Some problems of modern meteorology*, consisting of important papers from the *Quarterly Journal* of the Royal Meteorological Society. Of the few other appropriate publications, I remember a short book on weather forecasting by J. Van Mieghem, published in 1936, which I found very stimulating and helpful in preparing lectures.

In relation to this initial class it is important to realize that in those days Meteorological Office staff were divided between Professional Assistants, who were recruited from the universities, and the ordinary assistants, most of whom joined straight from school. Officially, the graduates were the forecasters and the rest were not. Regardless of what actually happened at outstations, the distinction rankled in the minds of many non-graduates, who, with their years of experience, knew how important they were in the functioning of outstations.

In due course I confronted my class of eight veterans, all of them strangers to me (one had actually joined the Office before I was born). I began by referring to the 'gentlemen and players' atmosphere in the Office, of which we were all conscious, and I stressed that the success of the course depended on an open and friendly relationship between all of us. Their response from that day to the end of the course was magnificent. Naturally they were aware that their careers depended on their success on the course, but I remain convinced that an important feature of this course — and of many similar ones over the years — was that it largely destroyed the feeling of segregation.

Our stay at Croydon lasted only a few weeks. Someone had overlooked the fact that aircraft engines underwent tests for an hour or more almost every day in a nearby hangar, so lecturing and study were impossible.

Our next home consisted of two or three rooms above a Lyons tea-shop facing South Kensington station, and as far as I can recall we were there for something like two years. A.F. Crossley joined me in the spring of 1938, and thereafter we each had a class of graduate or non-graduate students.

One of the attractions of training forecasters was the complete independence it gave us. No one questioned a syllabus (or even asked to see one), and indeed Crossley and I organized our courses independently of each other.

How a course was organized was undoubtedly influenced by the threat of war, and the Munich crisis of 1938 (when we all dispersed to outstations for a week or two) brought an added sense of urgency to our work. We aimed to produce fairly competent forecasters in a reasonably short time, and to keep to a minimum any theoretical meteorology that was not essential. And, particularly with the non-graduate classes, the emphasis was on broad physical explanations rather than mathematically precise ones (if such existed!). Moreover, I was always at pains to distinguish between meteorological phenomena for which there were fairly satisfactory explanations and phenomena which were not understood. It does much for a forecaster's confidence if he knows that he is not alone in his ignorance.

I think it is true to say that almost every trainee forecaster enjoyed meteorology. This was partly because at an early stage on the course he could make use of what he had learnt. In the main I kept lectures to the morning period, with chart plotting and forecasting partly in the morning but mainly in the afternoon. Observing and pilot balloon work were fitted in between lectures, to give everyone a little fresh air as much as anything.

I have always considered it important that forecaster training — after the earliest stages of the course — should be on current weather, and this I have always achieved. (Normally, when the first lecture of the day ended at 9.15 a.m., a duplicated foolscap sheet of 0700 GMT observations would be available to each trainee.) In working a set series of past charts the trainee is aware that his instructor knows what happened next. With current charts they are on an equal footing, and it is good for the instructor to be wrong from time to time.

Success in the teaching of forecasting can be assessed by whether the student becomes excited and stimulated by his own efforts. For some years I had hanging on the wall a couplet from Shaw's Vol. IV, which ran something like this: 'The forecaster's heart knoweth its own bitterness, and the stranger intermeddleth not with its joy'. If a student really understood what Shaw meant he was well on the way to becoming a forecaster.

In 1939 there was a considerable expansion of training, for it was clear that war was imminent. A larger organization was set up in Central London, with Professor Brunt in charge, and I returned to operational forecasting.

With the fall of France the following year there was some difficulty in making good use of returning meteorologists. Nevertheless, it was decided that the Office should prepare for substantial expansion, and I was recalled to set up a training school at Gloucester in the autumn of 1940, and I was especially fortunate in being able to choose Mr J.P. Kay as my right-hand man.

Within a short time we were training large numbers of forecasters and assistants, most of them in uniform, including WAAF officers and airwomen. To the best of my recollection the forecaster courses lasted 12 weeks and the assistant courses 6, followed in each case by outstation training.

Gloucester was an ideal location for a training school and we had few reminders of the war apart from the arrival for training of various young men from the Continent who, often at great risk, had escaped to join their forces in England. I remember in particular two Norwegian youngsters who had managed to cross the North Sea in a rowing boat.

It was perhaps two or three years later that the School was transferred from Gloucester to London, to an empty convent in Kilburn. This was equally satisfactory for our purposes apart from the arrival of flying bombs. These did not interfere with training to any great extent but they were a novelty to many trainees and so were a strong counter-attraction during lectures.

The Kilburn convent was a long building which housed another Government department at the far end. One night an incendiary bomb set light to the end of the building remote from the night-watchman and, by the time he became aware of it, a large part of the building was destroyed.

I think it was after this fire that we moved to rooms over a furniture shop in Oxford Street. The accommodation was spacious in comparison with the upper floor above the tea-shop of ten years before, but could not be compared with the Training College of today. However, the intake of trainees declined as the war neared its end. As for myself, an overseas posting early in 1947 ended the ten most satisfactory years of my career.

Note on quotation from Napier Shaw

The words quoted are from Volume IV, page 285, and are adapted from Proverbs 14.10: 'The heart knoweth his own bitterness; and a stranger doth not intermeddle with his joy' (Authorized Version). More recent translations are easier to understand, e.g. 'The heart knows its own bitterness and a stranger has no part in its joy' (New English Bible).

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Transatlantic civil aviation — the initial phase: the first training course for scientists in the Meteorological Office

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Summary

In 1935 the Meteorological Office was notified of a requirement for a forecasting organization to take part in an experimental programme for the development of commercial air routes over the North Atlantic Ocean. Early in 1936 a number of graduates were recruited to train as forecasters and to assist in investigations of weather conditions over possible transatlantic air routes. The graduates received a formal course in synoptic and dynamical meteorology — the first such course ever given by the Office to its own staff and received practical training in the provision of forecasting services for civil aviation.

1. Introduction

The first training course for scientists in the Meteorological Office was arranged for a specific purpose, namely, the provision of a forecasting service for the development of commercial air routes over the North Atlantic. The course opened officially in February 1936 but did not get properly under way until a month or so later when an adequate complement of graduates, who were recruited steadily rather than simultaneously, had reported for duty. Before 1936, although the Office had been in existence for many years, formal training courses for new graduates would not have been a practical proposition because the rate of recruitment was slow and at times there was an interval of several years between one graduate and the next one entering the Office. Training had to be 'on the job' and, in my experience in working with senior colleagues, was thorough and effective.

When our own Government and that of the USA decided, through their official or semi-official airlines — Imperial Airways and Pan American Airways — that civil aviation had reached a stage that would justify an experimental programme to investigate the feasibility of scheduled commercial flights between North America and Britain, there was considerable scepticism, not least among a number of pilots, and widespread anxiety about the outcome of the projected trials. Pioneering flights like those of Alcock and Brown (1919) and Charles Lindbergh (1927) had stirred the imagination of the general public but there had also been many tragic failures. Each year in the 1920s and early 1930s there had been various attempts, usually sponsored by aircraft manufacturers and by oil companies, to fly the North Atlantic, eastbound or westbound, and in nearly all cases the aircraft and its crew had disappeared without trace. The weather took the blame for all these failures. In those days aircraft operated in the lowest few thousand feet of the atmosphere and in consequence had to cope with the worst conditions —in terms of strong winds and turbulence, rain and snow, squalls and ice formation — to be found on the route being flown. It appeared to be very well known that on most days one or more intense depressions with strong wind circulations usually moving in an easterly direction would be present over the North Atlantic. There was therefore a fairly widespread feeling that, with the aircraft available at the time, transatlantic aviation would be at best a hazardous undertaking.

As was only to be expected, the responsible authorities decided that civil aviation must advance and that lessons rather than extreme pessimism were to be drawn from past failures. It was therefore planned that a series of experimental crossings would start in the spring of 1937. Imperial Airways would use the new 'C Class' flying boats which had been designed primarily for the establishment of the Empire airmail routes from Britain to India and Australia, and from Britain to South Africa. These flying boats, described in the Press as 'giants', held up to 24 passengers on the relatively short steps on the so-called Empire routes but the two to be used for the early transatlantic flights, *Caledonia* and *Cambria*, were cleared of all passenger fittings so that additional fuel could be carried. For their part, Pan American Airways planned to use flying boats, with names like *Yankee Clipper*, already in service on air routes over the Pacific Ocean and possessing ample endurance for a crossing of the North Atlantic.

On the eastern side of the Atlantic the main flying boat base was to be at Hythe on Southampton Water, a base already in the course of development for the Empire airmail services; but the departure point for *Caledonia* and *Cambria*, as well as for the Pan American Airways clippers for westbound flights, was to be at Foynes near the mouth of the River Shannon on the west coast of Ireland. The responsibility for providing forecasting services at Hythe and Foynes was assigned to the Meteorological Office; in the case of Foynes mainly because the Irish Meteorological Service had only just begun to set up a forecasting service for civil aviation.

On the western side of the Atlantic, a new flying boat base at Botwood in Newfoundland was used. Clearly the designation of Foynes and Botwood was in order to keep the length of the route to a minimum and well within the range of the American and British flying boats. Responsibility for the forecasting service to be provided at Botwood was undertaken by the Canadian Meteorological Service. The person appointed to take charge of the forecasting centre at Botwood attended the first training course for scientists organized by the Meteorological Office. In common with the British trainees on the course, it was his first encounter with meteorology as a profession.

2. Training and investigations

When the requirement for providing a forecasting service for the experimental trials over the North Atlantic was notified to the Meteorological Office, the Director, Sir George Simpson, decided that the staff were already fully committed on current tasks and therefore there could be no question of redeploying forecasters to meet what was recognized as an exciting and very demanding new responsibility. He also appreciated that, in the time available before the inaugural flights were to take place, a considerable amount of research and investigation had to be carried out into the weather conditions for aviation over the North Atlantic. The Director therefore obtained approval for the recruitment of a number of graduates who would be trained in forecasting for transatlantic flights and would, under experienced supervision, investigate the frequency, intensity and direction of movement of Atlantic depressions and study other associated problems. The organizational and administrative base for these new arrangements took the form of an Atlantic Investigation and Training Section established with effect from 1 February 1936 in M.O.5, the Office's Overseas Branch. Mr S.P. Peters, a forecaster of wide experience and high reputation, was appointed to take charge of the section and he was assisted by two trained forecasters in the grade of Technical Assistant 1 (TA1), Messrs D.F. Bowering and E.S. Tunstall. Office accommodation was an enormous L-shaped room with 15 or more tables equipped with plotting slopes in the operational block at Croydon Airport which was then known as the airport of London, the forerunner of Heathrow. In the same building, but some distance away, was the important forecasting office serving civil air flights to the Continent and to destinations in the United Kingdom. The Observer grades in this office were to play a valuable part in the training of Mr Peters's class of graduates.

As recruiting proceeded we arrived on the course in ones and twos knowing little of meteorology and even less about the activities of a forecasting office. We each spent the first few days quietly with sheets of paper and a pamphlet giving instructions on the plotting of synoptic observations on weather charts, practised with station models until we were told our plotting was neat, clear and compact and then tried our hands at plotting weather maps and drawing isobars. Most of us at first tried to treat every pressure observation as absolutely accurate and, as a result, our isobars possessed innumerable squiggles which probably suggested to our mentors that we had been taught drawing by Picasso. All these exercises were necessary because as part of the training and investigation programmes we were to plot, analyse and draw charts for a whole year covering North America, the North Atlantic and Europe.

In these various tasks associated with weather maps Mr Peters watched over each individual's progress but the main practical assistance was provided by Bowering and Tunstall who gave every encouragement and also explained the observing procedures. However, in this latter area of the work we derived most benefit from the Observers in the forecasting office. We accompanied them on routine observing duties, carried out pilot balloon ascents and used balloons to estimate cloud height in marginal conditions. The Observers were particularly helpful and interesting in their description and discussion of clouds. One of their main duties was to watch the development and movement of cloud systems in all weather conditions and the picture that was presented to us was a dynamic one, in contrast to the static displays in the *International Cloud Atlas* — although these were also regarded as very valuable and interesting.

This preliminary training in the ancillary duties of a forecasting office lasted only a week or so although we continued with various aspects of the observational routine, notably pilot ballooning and cloud study. We were then each allotted a section of the period selected for the detailed plotting and study of Atlantic weather. We were presented with boxes filled with synoptic bulletins obtained partly from the US Weather Bureau and partly from the Forecasting Branch, M.O.2's archives. We also examined ships' logs, loaned to us by the Marine Branch, M.O.1, and were able to find valuable observations which were made on Atlantic voyages but not reported in time for inclusion in broadcasts of synoptic data.

Charts for a relatively short period were prepared primarily for a study of weather conditions since it was considered that these, rather than winds and other parameters, might present the greatest threat to the flying boats which would have an operational height of a few thousand feet. In short, it was assessed that very strong winds could be predicted and the flights postponed but that a great deal needed to be learned about the severity of weather conditions in the more intense depressions. There was also a secondary purpose which formed an important section of the whole investigation. The charts we prepared, supplemented by ten years of working charts (which did not go so far west as ours) borrowed from M.O.2, were used to estimate times of flight from Foynes to Botwood in great circle and rhumb-line routes. On certain occasions we considered alternative, better-weather routes, and measured route lengths and estimated flight times. Our main sources of information were, of course, the surface charts, and wind estimates were based on the sea-level isobars using the geostrophic scale. The report which Mr Peters prepared for submission to the Headquarters Branch, M.O.5, and for consideration by civil aviation authorities contained an assessment of Atlantic weather conditions month by month and also a statistical analysis and discussion of the flight times Foynes–Botwood over a period of about seven years.

A special feature of the investigation was carried out by one of the trainees, D.A. (now Sir Arthur) Davies, who made several Atlantic crossings in a cargo vessel, the *Manchester Port*, to study weather conditions at first hand and to make pilot balloon wind soundings whenever practicable. His results were incorporated in the report prepared by Mr Peters and referred to above.

At Croydon we were visited several times by the head of the Overseas Branch, Mr F. Entwistle, who was already a well known figure in international civil aviation and who was the architect of many of the meteorological procedures for the support of air navigation that are still in existence today. After the Second World War he became Head of the Navigation Directorate of the International Civil Aviation Organization, a directorate which included the Meteorological (MET) Division as well as several others. Mr Entwistle was always ready to talk to us individually or collectively. He clearly had great faith in the future of transatlantic civil aviation and emphasized that our responsibilities were to contribute to the safety of such flights and to try to avoid any death or glory exploits which had characterized so many earlier attempts to fly the Atlantic. We readily absorbed his enthusiasm and it may be said that, like the crew of stout Cortez, we looked at each other with a wild surmise. The analogy may be somewhat imaginative but Entwistle, who possessed that comfortable shape which in women who are not duchesses is described as stoutness, could be compared at least in one particular with stout Cortez.

It might be remarked that some of the foregoing paragraphs have tended to concentrate on the investigation leaving the important training aspect in the background. It will be understood, however, that the work of analysing and drawing synoptic charts formed an essential element in the training of forecasters. Moreover, the area of study, stretching from North America across the Atlantic into Europe, is probably the most testing as well as the most interesting for a forecster at the outset of his career. The other main components of training — lectures supplemented by wider reading and forecasting from current charts — were conducted by Mr Peters when he judged that our practical work on Atlantic charts had given us an adequate background on the behaviour of pressure systems and the weather associated with them.

It should be mentioned that, when the course took place in 1936, and indeed for some years afterwards, meteorological data for forecasting consisted of three-hourly surface observations with special intermediate reports from any station experiencing a sudden, adverse change, some pilot balloon wind observations from areas where the weather was fine or fair, and upper-air temperature and humidity observations up to about 25 000 feet made by RAF aircraft making vertical ascents from Duxford near Cambridge and Aldergrove in Northern Ireland.

The series of lectures, in so far as theory was concerned, were limited to presentation and discussion of forecasting techniques and procedures, including the application of empirical rules. Thus we learned about geostrophic winds and isallobaric analysis, about the tephigram and its use in forecasting maximum day temperatures (Gold squares), showers and thunderstorms, and about night minimum temperatures, frost and fog. In a more descriptive and practical, i.e. less theoretical, manner we studied and applied the Bjerknes hypotheses regarding the development of depressions on the polar front.

We were also encouraged to read not only the papers referred to in the lectures but also more advanced texts and to explore widely among the many mansions of meteorology. There was an excellent library with ample copies of such publications as Brunt's *Physical and dynamical meteorology*, Normand's papers on the tephigram, Bjerknes' description of the polar front and so on. Of particular interest was the major paper by V. Bjerknes which derived and discussed the equations of motion in three dimensions on a rotating earth and, incidentally, nearly did for dynamical meteorology what Horace Lamb in his massive treatise had done for hydrodynamics. We also derived much interest from reading some of the papers on turbulence referred to in Brunt's book. This wide theoretical reading provided a necessary corrective to some early discussions among ourselves when we wondered why, having graduated in mathematics and/or physics (there were some double firsts on the course), we should be employed in plotting charts and drawing isobars. Both the reading and the practical work provided reassurance that meteorology, whether in forecasting the weather or in some other branch of the science, contained a host of problems that could challenge the best brains and still escape complete solutions.

As regards current weather we took it in turn to plot and analyse the 07 GMT chart (at that time the main synoptic hours were 01, 07, 13 and 18 GMT) and by about midday the rest of the class were given a briefing on existing conditions and expected developments. In addition, a forecast for the Croydon area for the following 24 hours was issued. This daily exercise lacked the continuity that is provided by a complete series of charts but the effort was very satisfactory. Mr Peters played an advisory and helpful role and, when the forecast went badly astray, always claimed a share of the responsibility.

3. The purpose of the course is widened

The specific purpose of the course was to train new-entrant graduates to carry out investigations into North Atlantic weather conditions in preparation for scheduled flights by civil airlines and to provide the forecasting services for such flights. Almost immediately this purpose was slightly modified. The Colonial Office, then a Department of State but now absorbed into the Foreign and Commonwealth Office, had recruited two graduates, J. (now Sir John) Carmichael and W. Richards, for meteorological duties in the Sudan and in Singapore respectively. The Office was asked to train them in forecasting and our course under Mr Peters was the only one available. They both participated fully but were given ample time to read books and memoranda on weather in the tropics and subtropics. A month or so later a member of the Meteorological Service of Iraq, Mr Towfiq Fattah, joined the course for training and was absorbed into the various activities for the next five months.

Within a few months, by mid-1936, the purpose of the course was widened much further. The expansion of the armed forces against the possibility of war gathered momentum and the Office recruited a steady stream of graduates, mainly for service at new RAF stations although some were also required for duties with the Royal Artillery in connection with gunnery and sound ranging. At first these recruits came to our course for training as forecasters, with time allowed for any special studies that were required, and completed their training with us before leaving for duty with the Army or RAF. However, this arrangement could not continue since our course was destined to evolve into an Atlantic investigation and forecasting section discarding all responsibility for training. In the latter half of 1936, therefore, the Office set up an organization under Mr C.J. Boyden responsible for training staff at all levels and from that time on no more new entrants joined our course. This training organization has continued in existence, with many changes in location and in scientific and technical scope, throughout the intervening years up to the present day and is a permanent feature of the Office establishment.

The trainees who left our course for RAF stations had a particularly testing time. They had never issued a forecast for an actual flight; they had never served in an office of any description and presumably had no knowledge of the innumerable organizational and administrative details that are indispensable for efficient functioning. In many cases the RAF stations were new and still under construction so everything had to start from scratch. Fortunately, the RAF placed the highest value upon their forecasting service and goodwill was at hand in overcoming the various difficulties. Even so, such experiences exert considerable strain and all these trainees emerged with great credit and an unimpaired sense of humour.

From time to time we were joined on the course for short periods, 2–3 weeks, by members of the Office with some years' service. They needed either to refresh their knowledge of forecasting or to acquire some background as to the activities in a forecasting office. In this latter category was Dr F.J. Scrase who, after a long period of research into atmospheric turbulence followed by a few years at Kew Observatory, had received a posting to take charge of our office in Gibraltar.

4. Personalities and other items

The names of those who attended the course for a substantial period, i.e. omitting the 2–3 week attachments, reads as follows in alphabetical order: C.J.M. Aanensen, J.H. Brazell, J. Carmichael, D.A. Davies F.E. Dixon, Towfiq Fattah, R. Frith, J.L. Galloway, J. Harding, T.N.S. Harrower, G.W. Hurst, L. Jacobs, H.H. Lamb, F.E. Lumb, P. MacTaggart-Cowan, P.J. Meade, S. Proud, W. Richards and G. Thornton-Smith.

The majority of those named have had many years' service in the Office. Regarding some of the others, again taken in alphabetical order, the remarks which follow may be of interest: Davies became Director of the East African Meteorological Service soon after the 1939–45 World War and then held the position of Secretary-General of the World Meteorological Organization (WMO) for 24 years from 1956 to 1979. On his retirement he was appointed Secretary-General Emeritus by WMO and HM The Queen conferred a knighthood on him. Dixon transferred to the Irish Meteorological Service and Galloway to the Canadian Service. MacTaggart-Cowan in due course became Controller of the Canadian Service. Proud was lost at sea in 1941 while serving on a weather ship which was sunk by enemy action.

Visitors to the course included J. Bjerknes who was on a six-month attachment to M.O.2, from the Norwegian Service. He spoke to us about his work on polar front depressions and had an informal chat with each member of the course. Two senior members of the Office, Dr J.M. Stagg and Mr R.P. Batty, paid short visits and spoke about the responsibilities and work of the Office.

Members of the course enjoyed a fair amount of extramural activity. Some joined local orchestras and others represented clubs at rugby, tennis, squash and badminton. At the Air Ministry sports in June, the course fielded a tug-of-war team which reached the final, only to lose after a protracted struggle. The team was coached with dedication and fiery eloquence by one of the observers in the forecasting office.

5. Final days at Croydon

By the early days of 1937, numbers on the course had dwindled since for some time trained staff had been leaving for their outstations and new entrants to the Office had been joining the courses run by Mr Boyden. The size of the Atlantic unit remained in doubt. The Head of Branch, Mr Entwistle, envisaged that a forecasting section consisting of Mr Peters (in charge) and four forecasters would go to Foynes, whilst a small group of about six forecasters would remain at Croydon to carry out investigations into problems identified by the section at Foynes during their operational work and to provide a pool of trained forecasters for posting to any new transatlantic bases that might be opened. In the end this plan could not be realized because the demand for forecasters arising from the expansion of the RAF was too great.

At the end of January 1937, therefore, the residue of the course was reduced to the Foynes contingent, namely Peters, Davies, Harding, Meade and Proud. We were to disperse in the first week of February and reassemble a few days later at Foynes. Then a last-minute change was made. A telephone call from Headquarters told Mr Peters that Imperial Airways intended to begin operations at Hythe, Southampton immediately and that one of the forecasters in the Foynes section was to go to Hythe instead. Peters was told to decide. Obvious choices for Foynes were Davies, who did the *Manchester Port* crossings, and Harding who had already shown an extraordinary flair for forecasting. So Peters had to decide between Proud and me, knowing that we were both keen to go and, as he assured us, wanting both of us in the team. He did the sensible thing. He explained the position to us and suggested we might like to sort it out between us. If we could, well and good, if not he would decide. Proud and I agreed that this was a question of sufficient importance to be settled in the bar of the Airport Hotel and we went there straight away. When the beer had been bought a coin of the realm was extracted from the change and sent spinning into the air. Proud called correctly and went to Foynes and I went to Hythe. We returned to the office to report to Peters and a slight mishap occurred. Stanley Proud had a sparkling wit expressed in throwaway remarks delivered with a dead pan face. As we entered the office he uttered one such aside and when we reached Peters's desk I was wearing a broad smile and Proud remained dead pan. Peters jumped up and said, 'I can see how you have settled it. Never mind, Proud, the work at Hythe will be extremely important and you will find it most interesting.' When we explained the true position, Peters seemed convinced that we had played a practical joke on him and we thought it best to keep out of his way for the rest of the day.

After the experiences of my former colleagues who left the course in order to open forecasting offices on new RAF stations, I went to Hythe in a frame of mind that might be described as somewhat lacking in confidence. All was well, however. Until office accommodation became available at the flying boat base, I used the facilities of the forecasting office at the RAF station at Calshot at the mouth of Southampton Water about eight miles from Hythe. The officer-in-charge was Mr R.A. Watson, a man of wide culture and gentle humour with many years' forecasting experience both at home and abroad. He readily expanded the plotting and analysis routine so that the working charts would cover the Mediterranean and part of the Middle East as well as Europe and the eastern Atlantic. Mr Watson took a great interest in my work and helped in all possible ways. On operational days I would plot and analyse my own charts and, with his advice, compile the forecast and then go to Hythe to brief the pilots. My first forecasts were a link with the forthcoming Atlantic trials since the proving flights of *Caledonia* and *Cambria*, testing range, communications and other factors, took the form of non-stop flights from Hythe to Alexandria on the Egyptian coast.

6. Conclusion

The investigation and training section of the Office's Overseas Branch was established officially on 1 February 1936 and was in existence at Croydon for one year and a few days. The training element of the section was discontinued but the investigation and forecasting component proved remarkably fertile. The work carried out at Croydon led to the development, in collaboration with the Canadian Meteorological Service, of meteorological procedures for long-distance civil aviation routes which were implemented for the experimental flights between Foynes and Botwood. These procedures, which included the provision for exchanges of data, analyses, and advisory route and terminal forecasts, were largely adopted world-wide for operations by civil airlines.

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Meteorological Office training of assistant staff: 1939–51

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Summary

The purpose of this note is to place on record an account of the early, peripatetic years of formal assistant training in the Meteorological Office. The pattern of recruitment controls the logistics of the training organization and the academic background of the intake influences the manner of teaching. These two matters are thus highly relevant to any account of training and some remarks on them are given in an introductory section; this also includes comment on the available sources of information. The training story itself then unfolds in the main body of the note.

Introduction

Civilian assistant grades and qualifications

In 1939, assistant duties at outstations were shared by two quite distinct grades of staff, namely Observers and Assistants Grade III (AIII).

The Observer grade was devised during the early 1930s partly to provide an opportunity of civilian employment for selected airmen who had satisfactorily completed a long term of regular service in the RAF. Recruitment ceased in 1938 when about 70 Observers had been appointed; the grade then became obsolescent and the staff were later absorbed into the AIII grade. Observers had no specific academic qualifications and were given no formal training; despite this, by 1939, when most of them were aged 30 to 40, many had become very highly skilled at observing, coding, decoding and chart plotting.

The AIIIs were recruited from 1936 to 1939 at age 17 to 20, and were required to have Inter BSc or Higher School Certificate (roughly equivalent to GCE A-level) in three principal mathematical or scientific subjects; the annual salary at age 19 was £130 (which approximates to £2250 at present-day prices) but £10 was deducted for each year below age 19. By contrast with the Observers, therefore, AIIIs were not only much younger but much better qualified academically; indeed, although the work they did was that done in later years by Scientific Assistants (SAs), from the qualification point of view they were more than on a par with post-war Assistant Experimental Officers (AXOs).

From October 1939, assistant recruits were appointed to a new temporary grade of Meteorological Assistant (MA) on a fixed salary of £110 p.a. The entry age was set at 17, and the minimum academic qualification was lowered to Matriculation including passes in elementary mathematics and physics; but over-age candidates were also considered and indeed some university graduates who were not at that time accepted as direct-entrant forecasters first joined instead as MAs.

Civilian assistants were recruited into the MA grade until the end of 1946, but from 1947 onwards appointments were made into the new post-war grade of SA, initially on a temporary basis. The entry qualifications remained broadly the same as those for MAs but the age of entry was considerably widened to include those in their twenties and salaries were on an incremental scale.

The initial wartime expansion: September 1939–spring 1940

Putting the Office on a war footing involved a big increase in 24-hour working and consequently a large influx of assistant staff. Recruitment is all too often a very protracted affair, but the approach of war showed that if the need is really urgent, procedures can be speeded up considerably. When I answered my doorbell one day in late August 1939, the telegraph boy handed me not the familiar pale orange envelope in which telegrams were normally delivered but a vivid red one on which the word PRIORITY was outlined in dark blue down the left-hand side. In response to my application for appointment as an AIII, the text summoned me for interview the very next day in Adastral House, then on the corner of Kingsway and Aldwych. A provisional offer of appointment was made two days later and, after undergoing a full Civil Service medical examination and checks having been made with the character referees I had named, I was given just three days notice to report for training at Berkeley Square House on Friday 15 September 1939.

Small groups of AIIIs had been recruited in May, July and late August, bringing the total AIII complement on 1 September 1939 to 136. There was a large intake of AIIIs in September and early October and continuous recruitment for the new MA grade followed without pause. During the spring of 1940, when 260 AIIIs and MAs had joined since the outbreak of war, recruitment was suspended (Air Ministry (Air Historical Branch) 1954).

The recruitment of airmen for the newly formed Meteorological Branch of the Royal Air Force Volunteer Reserve (RAFVR) was first sanctioned during the early summer of 1939; airmen who had by then enrolled were mobilized at the outbreak of war and were absorbed into the assistant cadre of the Office. Small numbers of airmen continued to join through the autumn and winter, bringing the total intake by the spring of 1940 (when, as for MAs, recruitment was suspended) to 240 (Air Ministry (Air Historical Branch) 1954).

Taking into account the 70 or so Observers, the total assistant complement on 1 September 1939 was a little over 200; in less than nine months it had risen to over 700.

The next burst of recruitment: December 1940–April 1942

Recruitment of MAs resumed in December 1940, initially with intakes of 15–20 at fortnightly intervals. Early in 1941, with continuing expansion of the RAF both in the United Kingdom and overseas (assistants were sent even to West Africa and to the RAF flying training schools in Canada), a much more vigorous campaign was mounted. The traditional small notices in tiny print in newspapers were supplemented by more eye-catching material and trails for MA jobs were given on radio (for security reasons, weather forecasts were not broadcast during the war, and the 12.55 p.m. time-slot on the BBC Home Service was used instead for Government announcements). A recruitment board toured the country, visiting places such as Darlington, so that applicants did not have to travel long distances to London for interview. All this activity resulted in a marked increase in MA recruitment during the spring and summer of 1941 and, significantly from the training point of view, produced some sharp peaks in the intake; these caused logistic problems of a type that recurred in later years.

The influx of MAs eased off during the winter, and in the spring of 1942 virtually ceased for about 18 months, being replaced by the very large Women's Auxiliary Air Force (WAAF) intake. During the period of roughly 18 months from December 1940 to April 1942, over 500 MAs had joined the Office together with well over 100 airmen.

The major WAAF inflow: September 1941–June 1943

Early in 1941 it had been agreed that a new trade of Meteorologist would be introduced in the WAAF. Recruitment began during the late summer, initially at the rate of 15 per fortnight. It no doubt soon became evident that the WAAF could provide very competent outstation assistants; by February 1942 the intake had been stepped up to around 30 per week and it remained more or less at that level for nearly 18 months until June 1943. By this time, over 1800 Met Waafs had been enrolled and they had taken over almost the entire complement of outstation assistant posts in the United Kingdom.

Throughout the period of massive WAAF recruitment airmen had continued to join in small numbers, just over 50 coming in during the year from June 1942 to May 1943. There appears to have been no MA recruitment during this time except for a few people engaged specifically for work at Headquarters.

The surge in recruitment of airmen: June 1943–August 1945

By June 1943, the need for airmen overseas in support of RAF and Army units in North Africa, the Mediterranean and the Middle East was increasing and recruitment was stepped up; around 500 Met airmen joined the service in the 12 months to May 1944, together with about 30 MAs. Met airmen went into Europe shortly after D-Day and more were required in India in preparation for the Far East campaign; so the rate of intake again accelerated and over 1100 were enrolled between June 1944 and June 1945, and there was a further steady trickle of about 110 MAs during the same period.

A handful of Waafs enrolled during the late summer and early autumn of 1943, but the trade of Meteorologist was then closed; those still wanting to join were unable to do so and had to sign on, at least for a time, for other trades. However, by late 1944 it had become evident that with yet more RAF stations being opened in the United Kingdom there was once again a marked shortage of assistants. The trade of Meteorologist was therefore reopened and between November 1944 and June 1945 a further 180 Met Waafs were recruited. From the training point of view this caused major problems because the new intake of Waafs came at a time when airman recruitment was at peak level.

The academic requirements for both Waaf and airman recruits were similar to those for MAs, but to an increasing extent much greater emphasis was placed on strong motivation and some ability in mathematics together with a good general education to School Certificate level rather than on the possession of specific certificates. This practice (which no doubt stemmed from the large numbers required) certainly had implications for the training programme as it could not be assumed that all students were familiar with the concepts of elementary physics; but an absence of scientific knowledge could be, and was, overcome by teaching. Overall, the wartime intake of service personnel fitted in very well and maintained high standards of professional competence.

During the final year of the war, certain trades in both the RAF and the WAAF became over-full (e.g. Wireless Operator and Student Pilot but never Meteorologist); personnel in such trades were then declared redundant and were forced to remuster. For some, the opportunity this gave to join the Met service was very welcome, but others came much less willingly. As those remustered carried their rank with them, assistant training courses in late 1944 and in 1945 often included Corporals, Sergeants and even the occasional Warrant Officer; some of these were not at all pleased at finding themselves 'back at school' alongside new-entrant airmen and Waafs, and considerable tact was needed on the part of the instructors.

The last intake of Waafs appears to have been in June 1945, and that of airmen in August 1945 when the war in the Far East finally came to an end.

Post-war recruitment: 1946–51

It might be supposed that with the cessation of hostilities and the consequent contraction in the meteorological support needed by the armed forces, there would be little need for civilian recruitment during the immediate post-war years. Indeed, during the ten-month period from September 1945 to June 1946 inclusive, the total MA intake appears to have been two. But a time bomb was ticking away in the background because during the two years of 1946 and 1947 perhaps as many as 4000 Met airmen and Waafs were demobilized.

Recruitment of MAs restarted on a modest scale in July 1946, but clearly the Office became very worried about the assistant staff situation. During the autumn Waafs, and no doubt airmen, were asked to defer their release dates by six months and letters were also sent to those on demobilization leave inviting them to apply for temporary civilian posts in the Office. These measures had a limited success, but recruitment on a very large scale became essential in order to maintain the meteorological service.

During the autumn of 1946, assistant recruitment was at the rate of 10–20 every three weeks. This intake increased sharply the following spring and reached an astonishing peak of 50–60 in every week of September 1947; not surprisingly the training organization had many problems in dealing with a concentrated influx of this magnitude. By the end of the year, when the flood tide had receded, more than 1000 MAs had been added to the complement. In the subsequent years from 1948 to 1951 the annual intakes varied between 200 and just over 300.

Sources of information

Brief references to the Meteorological Office Training School in Berkeley Square from 1939 to 1940 are made both in the official account (Air Ministry (Air Historical Branch) 1954) of the Meteorological Office during the war and in an article about training by Meade (1952); articles concerning training published subsequently by Gordon (1959) and Johnson (1972) refer to the early years only by quotation from Meade's article. An account of training during the years from 1936 to 1946 has also recently been prepared by Boyden (1986); this primarily concerns forecaster training.

The earliest documentary evidence known to exist relates to courses at the Meteorological Office Training School at Gloucester between late 1940 and mid-1942. A file preserved at the Meteorological Office College, Shinfield Park, lists names of students who attended each course, together with the ending but not the starting dates of the courses; for some curious reason these were not identified by serial numbers in the usual way. The College also holds records of the courses at the WAAF School in London from 1941 to 1943 and at the combined Schools at Kilburn and Oxford Street from 1943 to 1946; these give lists of students on each serially numbered course, but unfortunately neither starting nor ending dates of the courses were recorded. From the beginning of 1947, full details of students and courses have been entered in an Assistant Student Register which is still in use at the College.

In order to unravel the tangled story of assistant training, it was necessary to reconstruct as precisely as possible the dates of over 500 courses. Meteorological Office seniority lists prepared for internal use during the early 1950s proved to be a fruitful source of information; for all established staff then serving, these lists tabulate dates of joining the Office and whether as AIII, MA, SA, airman or Waaf. In the large majority of cases, though by no means invariably, the date of joining during the period of this review was the starting date of an assistant course; this established a skeleton framework of dates and the rest of the timetable had to be inferred by interpolation and from other considerations.

The other major input to this note, especially concerning the war years, has been my own personal recollections together with those of over 25 friends and colleagues whom I have consulted. After 40 years and more, memories are inevitably patchy, less than precise and sometimes undeniably in error; but by cross-checking with each other and with the surviving fragments of record, a coherent pattern has emerged. Most importantly, the recollections have made it possible to turn what would otherwise have been a very bare record into a story of real people in real places.

The story of assistant training

Pre-war arrangements

Before May 1939, the normal training procedure for AIIIs was the time-honoured practice of 'sitting by Nellie' or rather her male counterpart. Except for those few people needed at Headquarters, recruits were posted on appointment to an outstation where they were expected to pick up what they needed to know by reading and from staff on duty. Not surprisingly, the effectiveness of this practice was distinctly uneven. It depended not only on initiative and the ability of an individual to educate himself, but also very much on the competence and enthusiasm of the local staff who had perforce to act as tutors in addition to carrying out their normal duties.

The first assistant course ever run by the Meteorological Office started on 1 May 1939, when 12 new-entrant AIIIs assembled at the Meteorological Office in Edinburgh, then in Drumsheugh Gardens. The instructors were O.B. O'Sullivan (AII) and T.R. Soden (Observer). The course lasted for eight weeks and included lectures on elementary meteorological theory; for some of the outdoor practical work, the students had to travel over two miles to the Observatory at Blackford Hill on the south side of the city.

A week after the end of this initial venture, a second course of 12 AIIIs run by the same instructors started at Manston on 3 July 1939. A third course also assembled there on 29 August 1939, but the outbreak of war barely a week later put an end to the proceedings; this course was abandoned early in September and the students were posted to outstations for further training.

The Training School in Berkeley Square: 1939–40

When the Meteorological Branch of the RAFVR was formed, it was envisaged that officers and airmen would be given appropriate instruction at evening classes. A panel of volunteers from the Meteorological Office was formed to provide the instruction, and syllabuses were devised. But by the end of August 1939 nothing further had been done because suitable accommodation in which to hold the classes could not be found in London (Air Ministry (Air Historical Branch) 1954). Thus when the airmen reservists were mobilized at the outbreak of war, they had to be dispersed to outstations for on-the-job training as had been the norm for AIII staff before May 1939.

Matters then moved at great speed. The idea of evening classes was abandoned; within a few days rooms for a new Meteorological Office Training School were found in Berkeley Square House and Professor David Brunt of Imperial College was appointed to take charge, his most immediate task being to train the RAFVR officers as forecasters (Air Ministry (Air Historical Branch) 1954). But the accommodation available was more than sufficient for forecaster training and it was decided to make use of the surplus to provide short courses for civilian assistants. Furniture, instruments, equipment, books and other training material were rapidly assembled and instructors were appointed to deal with a first intake of new-entrant AIIIs on Friday 15 September 1939.

The new assistant courses were of two weeks' duration. Elementary theory lectures on temperature, pressure and its relation to wind, cloud formation, fog, pressure systems and fronts were given by A.F. Crossley, a Technical Officer who had been an instructor at the pre-war Training School in South Kensington (Boyden 1986). But the all-important instruction in practical work was in the hands of instructors new to the job (C.H. Wood and S.C. Batchelor, both AIIIs) and was clearly being developed as the course progressed. I still have a vivid recollection of the way in which we were introduced to the synoptic code. An instructor wrote on the blackboard:

$$IIIC_LC_M \quad wwVhN_h \quad DDFWN \quad PPPTT \quad UC_Happ.$$

He didn't tell us what these letters stood for nor what purpose they served, but merely said, 'Learn that' and walked out of the room. Admittedly we had been provided with copies of *Wireless weather messages* and the instructional booklets on chart plotting and pilot balloons also, for theoretical background, with Pick's *Short course in elementary meteorology* and *The weather map*. Using these we were evidently expected to devil out a great deal for ourselves and no fewer than 16 of the 60 instructional periods during the fortnight were allocated to private study. For ex-sixth form students, this was not unreasonable, but the different educational background of the subsequent MA courses no doubt dictated a different approach.

We had, and needed, 16 periods for practical work on coding, decoding and chart plotting. Although we did not realize it at the time, the surface observation code of those days was far from satisfactory. The ranges of visibility and cloud height implied by the single code figures were far too coarse for aviation purposes, so we had to learn the extra groups that were then added to the synoptic message, prefixed by the letters FFF, JJJ, HHH and so on; interestingly, as the need for these stemmed from the demands of international civil aviation, fog visibilities and cloud heights were given in metres, a fact not appreciated by the RAF.

Only eight periods were devoted to the making and recording of surface observations; no doubt it was felt that this vital subject could be covered more effectively during our subsequent on-the-job training at outstations. But we did spend ten periods on pilot balloon work and this was a popular activity as it took us into the fresh air on the roof. We were given dire warnings as to what would happen to anyone who let go of an overfilled balloon with the balance weight still attached. Some of the brighter members of the class soon tumbled to the fact that underfilled balloons had negative buoyancy; several of these were released to descend slowly into Berkeley Square where they bounced up and down amidst the traffic.

Although when we left the course we certainly needed a long spell of further training at outstations, a great deal had been packed into two weeks. Perhaps most importantly, we enjoyed the course, and the friendly, relaxed and chatty approach of the instructors made us feel that the Meteorological Office would prove to be a pleasant organization for which to work.

The steady programme of assistant courses every fortnight in Berkeley Square appears to have been completed by the end of February 1940, although at least one further course was held during the spring. Having also completed the major commitment for forecaster training for the time being, the School was closed during the early summer (Air Ministry (Air Historical Branch) 1954).

The Training School at Gloucester: 1940–42

During the Berkeley Square interlude, the Meteorological Office Training School had been under university aegis, but when the School was re-established during the autumn of 1940 at Eastern Avenue, Barnwood, on the outskirts of Gloucester, direction reverted to the Meteorological Office where it has remained ever since. Mr C.J. Boyden, a Senior Technical Officer who had run the pre-war forecaster training in South Kensington (Boyden 1986), was appointed to take charge, with J.P. Kay as his deputy. The classrooms were in the temporary hut-type buildings associated with an RAF station, but it was a pleasant, semi-rural location with the Cotswold scarp as a backdrop. The civilian students were billeted with landladies in the city and surrounding villages.

The assistant courses at Gloucester were initially of four weeks' duration. The first one started on 17 December 1940, and from then on one and sometimes two classes began every fortnight until early June 1941, so that there were normally two to four classes in the School at the same time. Lectures in elementary theory appear to have been given by one or other of the instructors responsible primarily for the forecaster classes, but the all-important practical work was handled by Messrs Coutts, McLeod, Waite and later Davies who were all AIIIs. During a short early-summer hesitation in the inflow the course was reorganized to cover a five-week period; the need for this extension no doubt stemmed from the introduction of new codes and procedures and the need to give even greater emphasis to pilot balloons and ballistic wind computations.

Members of the staff of the Training School, 1941. Back row from left to right: F. Gorner, A.E. Parker, C.N. Mcleod, J.M. Coutts, J.P. Kay,? Front row: Ruth Hitchen, C.J. Boyden, Flying Officer M.W. Brown.

When asked for their dominant memories of assistant training, those who attended courses at Gloucester (and for that matter subsequent courses at Oxford Street and Kilburn) almost without exception spoke of many hours on pilot balloons and the associated computational work. This may strike present-day readers as surprising, but there were two good reasons why it was so. Upper-air forecasting was then in its infancy and a regular input of wind information was essential; indeed at many stations in the United Kingdom, pilot balloons had to be made regularly whenever cloud conditions permitted. At one Fighter Command Station where I was based in 1941 and 1942, weather permitting, we were required to make three ascents every night, using candle lanterns suspended on lengths of elastic beneath the balloons to make them visible. In the depths of winter this could be a finger-numbing experience, but in summer we had the compensation of hearing the nightingales that were plentiful in that area. But over and above the needs of aviation forecasting, pilot balloons also provided a key input for calculation of the ballistic winds needed by both field and anti-aircraft artillery. Preparation of the two types of coded METEOR messages involved quite lengthy manual computation, and thorough training was needed for this. In some Commands overseas, small groups of Met airmen were formed into independent Mobile Pilot Balloon Units that worked directly in support of the Army as well as contributing to the synoptic network.

The first of the new five-week courses started in July 1941 and, with regular double or triple class entries, the number of simultaneous classes in the School soon rose to three or four and even briefly in September to five. During the winter the intake eased off, and the virtual suspension of MA recruitment brought the need for assistant courses at Gloucester to an end in early June 1942 (the School remained there until August 1943 to deal with forecaster courses). During the 18 months of assistant training at Gloucester there had been 37 courses attended by a total of over 600 students; most of these were MAs (472 male and 27 female), but there were also 125 British airmen, a few airmen from both France and Norway and three small contingents of Canadian Army personnel who had participated primarily for instruction in pilot balloon work and ballistic wind computation.

The 1941 overflow operations in London and Edinburgh

The vigorous MA recruitment early in 1941 produced a surge of new entrants who could not all be accepted in the Gloucester School, presumably due to a shortage of classrooms. Additional training facilities had to be found elsewhere and it was evidently decided that London and Edinburgh were the places in which temporary single-class operations could most readily be mounted.

At interview boards in London around this time, candidates who did not live in the London area were asked if they had friends or relatives there with whom they could stay whilst undergoing training if their applications were successful. The Office then arranged for a series of three four-week assistant courses to be held in Princes House, Kingsway, with A.J. Scriven and I.G. Hughes as instructors. The first class started on 25 February, a second on 25 March and the third probably on 6 May 1941. Some of the observational work, in particular pilot balloons, had to be done on the roof of Victory House, the London Headquarters of the Meteorological Office, which was on the other side of Kingsway further up the road; the Senior Directorate whose offices were just beneath this roof were not too pleased at the inevitable noise this caused, with parties of teenagers walking up and down, hydrogen cylinders being rolled on the roof, etc.

No records of these courses have survived, but two small memories have. The first was the consternation of the instructors on receiving a very justified complaint from a policeman about being hit by a filled inkwell dropped on to him from the classroom window. The other concerned a class sent on to the roof to do an observation who reported visibility '6I' because they could see the appropriate visibility mark, namely a tower of the Crystal Palace which had survived the 1936 fire. After checking subsequently, the instructor told them that they were quite wrong and that the visibility was no more than '6H' as the tower was invisible; but he had to apologize next day when it was discovered that, between the roof visits of the class and himself, the tower had been demolished as an unnecessary landmark that might have helped enemy aircraft to pinpoint targets.

The London operation catered for the overflow from the southern half of the country. For candidates from Scotland and the north of England, two courses were run at the Meteorological Office in Drumsheugh Gardens, Edinburgh, where the very first assistant course had been held in May 1939. No records exist, but it is known that the instructor in charge was C. Doherty and that a four-week course with 12 students started on 25 March and another with rather more students on 22 April 1941. During the fortnight commencing 25 March there were thus six classes simultaneously under training — four at Gloucester, one in London and one in Edinburgh; this marked the peak of the MA recruitment during the spring of 1941.

The WAAF Training School in London: 1941–43

The introduction of the trade of Meteorologist in the WAAF clearly promised a new and potentially large source of recruits for the Office, and it was decided to set up a separate Training School for them in London. Accommodation in which to make a start was found in an annex to the London School of Economics (LSE), in Houghton Street, just off the Aldwych. In line with the courses for MAs and airmen at Gloucester during the summer of 1941, the initial training was to last for five weeks.

The new WAAF School opened in considerable haste and on a shoe-string. D.H. Clarke (then AII but shortly afterwards promoted to AI) was appointed to take charge and arrived to take up post on Tuesday 9 September 1941 to prepare, single-handed, for his first class of 11 students who booked in just three days later. I.G. Hughes (who had worked with the Princes House courses) arrived on Monday 15 September and a second class of 15 students came on the following day. New courses then started at roughly fortnightly intervals and by the end of the year there were five classes simultaneously in the School; by this time T.A. Quinn, G.A. Cowling, W.S. Stubley and J.R. Ramage had joined the staff.

It seems likely that, with an expanding programme, a move was inevitable in order to obtain more classroom accommodation and on New Year's Day 1942, less than four months after its foundation, the School made the first of what turned out to be a series of moves. Its second home was in the Land Registry, only a short distance away at the south-eastern corner of Lincoln's Inn Fields. By all accounts the accommodation there was by no means satisfactory. The building had been bomb damaged; many of the windows were boarded up making artificial light essential throughout the day and it was also very draughty. To add to the problems, the heating system broke down completely during the cold weather in January and the School had to be closed for several days; three classes in the School at the time had their courses extended by a week to compensate for this. By mid-February 1942 two classes were arriving every week, so that with five-week courses it was only a matter of time before there were ten classes in the School simultaneously. T.R. Soden, G.R. McKeon, F.G. Dolbear and R. Wrench joined the staff during this period, but there appears still to have been a total absence of administrative support staff; D.H. Clarke was reduced to making his course reports in manuscript.

In the middle of May 1942 the School moved again, this time about half a mile away to Russell Square House at the north-east corner of Russell Square in Bloomsbury. The accommodation there consisted of the top two floors of the building which also housed Ministry of Information staff and, at street level, a bank; it seems to have been a distinct improvement on the depressing environment in the Land Registry. But once again, after only four months, the School had to pack its bags, almost certainly to obtain more classroom space. The new premises were on the upper floors above Drages' furniture shop, 73–77 Oxford Street, backing on to Soho Square, and here, no doubt to the relief of the staff, the School remained for 11 months until the move to Kilburn in late August 1943. It was characteristic of the disturbed conditions during wartime that the various moves of the School had to be made at very short notice; indeed, some of the staff first heard of an impending upheaval from the office cleaners who were usually well informed on such matters.

With effect from the move to Oxford Street in mid-September 1942, the course was re-planned to cover a six-week period. New codes were still being introduced, but the primary gain of the extension was that the final week of the course could be entirely devoted to practical work in a fairly realistic simulation of the daily commitment at an outstation. This is a feature that has remained part of assistant courses ever since, except during the emergency situation that developed early in 1945.

Although the School in London had been established to provide training for members of the WAAF, the termination of assistant training at Gloucester in early June 1942 meant that other arrangements had to be made for the airmen who were continuing to sign on in small numbers. From this time, therefore, occasional airmen appeared in classes in both Russell Square and Oxford Street and, by the summer of 1943, the airmen intake dominated the School. This necessitated a change of emphasis in the curriculum; most of the airmen were destined to serve overseas and, as at Gloucester, pilot balloon work and ballistic wind computations became a major feature of the course rather than merely one aspect of it.

For the Waafs, who with very few exceptions served only in the United Kingdom, efficient operation of the meteorological telecommunications was a matter of considerable importance. During the early part of the war switchboards at collecting centres were very simple to operate, and the quarter-hour breaks in the teleprinter broadcast allowed plenty of time for collection of observations sent slowly by outstation staff. But by 1942, as I found to my embarrassment during an emergency detachment to HQ 11 Group, Uxbridge, switchboards had become more complicated and the increasing number of new stations had lengthened the collectives to the point where one-finger exercises at outstations could no longer be tolerated. Waafs who attended courses in 1941 and 1942 had been given no special training in teleprinter work and many of them were subsequently sent for specialist instruction, for example to the Post Office in Birmingham. In early 1943, therefore, it was decided that teleprinter training would have to be included in the assistant course and as a stop-gap measure from February 1943 onwards the

WAAF courses were extended to seven weeks; the girls were then able to spend a series of afternoons either at a large Post Office exchange near Euston (where the Weatherline messages now originate) or at the Police College near Hendon. This arrangement appears to have lasted for about five months, i.e. until the purely WAAF classes virtually ceased.

With a weekly double class entry and six-week courses, 12 classrooms were needed, and these were available at Oxford Street. But a minor surge in WAAF recruitment in January 1943, together with the extension of the course for teleprinter training, meant that during February and March 1943 there were up to 15 classes simultaneously in the School. This must have caused some administrative headaches, but the problem was evidently overcome, presumably by obtaining temporary extra classrooms in the building. When a similar crisis occurred nearly two years later at Kilburn, more drastic measures had to be taken.

Whilst attending the meteorological courses in Central London, the Waafs were billeted in what had been a well-appointed block of flats called Fountain Court in Buckingham Palace Road, near the coach station. A canteen on the premises provided breakfasts and evening meals, but the girls had to fend for themselves at lunch-time; they were given luncheon vouchers for 1*s.* (5p), although in 1943 this covered the cost of no more than a light snack in a Lyons tea-shop. However, the instructors would have been grateful for even that modest subsidy, because the London allowance to cover the extra costs of 'digs', travel and food was then just 8*s.*6*d.* (42½p) per week and this rarely permitted the indulgence of a snack at Lyons.

The numbers of students who completed training at the WAAF School during its independent existence before the move to Kilburn are shown in the Table below:

Location	Period	No. of courses	No. of Waafs	No. of airmen
LSE Annex	Sept. 1941–Dec. 1941	6	95	0
Land Registry	Jan. 1942–May 1942	24	329	0
Russell Square	May 1942–Sept. 1942	32	454	16
Oxford Street	Sept. 1942–Aug. 1943	78	943	119

The School at Kilburn: 1943–46

During the war Gloucester was a billeting area and domestic accommodation was in very short supply. By mid-1943, the shortage had become so acute that billets could no longer be found for the forecaster students and a move became inevitable. Alternative accommodation was allocated in the then vacant Orphanage of Mercy in Randolph Gardens, London NW6, and the move took place in August 1943. The space available there was much more than was needed for the forecasting courses, so it was decided to move the WAAF School also to Kilburn later the same month (Air Ministry (Air Historical Branch) 1954). All meteorological training was then once again under the same roof with Mr C.J. Boyden in overall charge of the combined Schools, but D.H. Clarke remained responsible him for assistant training.

The orphanage was a large building standing in its own grounds just off Maida Vale, the section of the A5 trunk road linking the Edgware Road to Kilburn High Road. This is a heavily built-up, unattractive part of London and, despite the mosaic flooring of the corridors, the building provided a gloomy and rather depressing environment for meteorological training, especially during 1944 when the V1 flying bombs droned across the sky. Another Air Ministry civilian department shared the accommodation so that the total number of people at the site was large enough to justify a lunch-time canteen which made use of the kitchens.

One slightly bizarre aspect of the Kilburn School was that students on observing practice outside worked against a background of grunts and the sort of odours more usually found in rural locations. During the war, backyard pigs could be kept under strict controls to augment the meat ration, and the local council had authorized the erection of pigsties in Paddington Recreation Ground just across the road. The orphanage was a rambling building and airmen exploring the unused first-floor dormitories were startled to discover a notice on the wall reading, 'If you need a mistress, press this bell', but soon found that the facility had been discontinued.

Just one WAAF course was held at Kilburn in October 1943 before the trade was closed so that, with no need for teleprinter training, the courses for airmen (and MAs) followed the normal six-week pattern. Until the spring of 1944 only one class started each week and for about nine months the School was running at half capacity; but the intake then doubled and by midsummer 1944 there was again a full complement of 12 classes at a time. The reopening of the WAAF trade led to weekly intakes of three classes; admittedly, the complication of teleprinter training did not recur because by then arrangements had been made for the girls to go on a fortnight's course given by RAF Signals personnel at Cranwell immediately following their meteorological training, but it was clearly only a matter of time before the School population built up to 18 simultaneous classes.

To postpone the inevitable crisis, the course was first redesigned to be completed in five instead of six weeks; classes in the School over Christmas 1944 were not given the traditional extra week to compensate for the holiday break and subsequent classes had five-week courses. But this still left a need for 15 classrooms and something had to be done to prevent the School from bursting at the seams. Fortunately, extra space was found, albeit some distance away, in Cornwall House on the South Bank, near Waterloo Station. D.H. Clarke took charge of this 'outstation' and from early February to mid-June 1945, two or three classes were accommodated there. The arrangement made was for certain classes to book in and spend an initial week at Kilburn during which they were given all their introductory and elementary theory lectures; no doubt reeling from this onslaught they then moved across London for the remaining four weeks of practical work in Cornwall House. The outstation also provided an emergency home for classes that had to be evacuated from Kilburn as a result of bomb damage not long before the end of the war; fortunately, this occurred during the night when neither staff nor students were there.

Whilst attending courses at Kilburn (and Cornwall House), the Waafs were billeted in various blocks of flats (Bentinck Close and Albany Mansions among them) on the north and west sides of Regent's Park. Some of the airmen lived in a hostel in Hallam Street, just off Portland Place, others were in Viceroy Court near Bentinck Close, but some had the prestigious address of the St Regis Hotel in Cork Street, Mayfair.

The intake eased off fairly steadily from late spring 1945 and from June onwards there was no need for the Cornwall House outstation; the course probably reverted to its normal six-week length during August. By then the inflow had almost ceased and, apart from a few late-entrant airmen, the only new students were 40 who from their names appear to have been Dutch airmen and airwomen; these added yet further to the ethnic diversity of students that had passed through Kilburn which had already included over 50 Canadian Army personnel, some Canadian airmen and airwomen, a contingent from the West Indies (who were highly amused at finding pigs in Central London) and some Belgians. The backbone of the UK students in 170 classes at Kilburn comprised 1574 airmen, 196 Waafs, and 86 male and 58 female MAs. One well-remembered component of the UK Met Service during the later stages of the war that did not pass through Kilburn was provided by Polish airmen and airwomen; the reason for this is that the Polish Air Force set up their own Met Training School at Hucknall.

After the autumn of 1945 there was just one, unnumbered, course consisting of two female MAs but no others. Thus in March 1946 there were only forecaster students in the School when a serious fire occurred one Friday night in the convent kitchen. The building had to be evacuated, and the School moved once more to the Oxford Street accommodation in which it had been from September 1942 to August 1943.

The second period in Oxford Street: 1946–47

The first post-war assistant course in Oxford Street did not start until July 1946, so there was plenty of time to revise the syllabus for peacetime work. Although pilot balloons were still taught, there was no longer the need to give marked emphasis to them and ballistic wind computations were hardly mentioned. There was still a welter of codes of all kinds, but it was possible to include a more comprehensive background of elementary meteorological theory.

When I arrived in September 1946 as an instructor, there were four classes in the School, but this number dropped to two right through the winter. However, there was a particularly successful recruitment campaign in Northern Ireland during the autumn and it was decided that it would be simpler and cheaper for courses to be run there than to bring 45 new entrants to London for training. So D.H. Clarke, W.S. Stubley and J.H. Albion went over to Sydenham Airfield, Belfast, taking with them or sending all the necessary training equipment. From mid-November to Christmas they ran three simultaneous courses and this cleared the intake.

The classrooms in Oxford Street were on the fifth and sixth floors of Drages' building and those at the back overlooked Soho Square; when taking a class one day I recall stopping in mid-sentence with astonishment at seeing a kestrel hovering about 20 feet away, level with the windows. As in so many London buildings at that time, the window frames had been badly warped by the effects of bombing and let in plenty of draughts. Life became particularly unpleasant during the prolonged cold spell that lasted from mid-January to mid-March 1947. To make matters worse there was a very serious fuel shortage and the Government appealed for volunteers to work at weekends in railway goods yards, trying with pickaxes to free coal that had been frozen solid in the trucks by snow and ice. The lifts were not used and there was no heat in the radiators; we all wore overcoats in class and I found out how difficult it is to hold a piece of chalk when wearing cycling gauntlets. Plotting practice could only be in short bursts, interspersed with breaks during which numbed fingers could be warmed. The gas ring produced no more than tiny beads of flame; the first member of staff to arrive in the morning put on a kettle and each time it boiled (three or four times during the day) tea was made for staff and students alike. In addition to the cold, we had long periods of monotonously dull weather; members of one class saw only stratocumulus and a few glimpses of altostratus during the entire six weeks of their course.

Early in 1947, Mr C.J. Boyden who had been in charge of the School continuously since 1940 was posted overseas and was replaced by Mr R.E. Farms. In late April 1947, after a little over a year in Oxford Street on this occasion, the School moved yet again, to Alexandra House in Kingsway. On the morning of the move, the students all reported to Drages to collect charts, sheets of synoptics and their filled red and black inkwells. They were given coppers for the bus journey along New Oxford Street and Holborn and set off with their books and all this clutter; on arrival at Alexandra House they were able to get straight to work, leaving the instuctors to look after the move and installation of all the instruments and equipment.

The School in Kingsway: 1947–51

Within a period of seven months during 1947, the School experienced what proved to be the most dramatic surge of activity in its 50-year history. At the time of the move from Oxford Street there were four assistant courses in progress. A steady build-up started in mid-May and at the end of September there were over 300 students in the School, divided into no less than 20 separate classes. By the beginning of December the tide had receded and once again only four classes were in residence.

Not surprisingly this explosion in the student population caused not a little chaos. The Air Ministry accommodation officers must have been at their wits' ends. Since the time of the move the School had occupied rooms not only in Alexandra House but also in Princes House next door, to which there was internal access on some but not all floors (this was the building where the 1941 courses had been held). More rooms were allocated in these buildings but, as the number of classes continued to grow, by July there was no more space available and three outposts had to be established in other buildings —Adastral House on the other side of Kingsway, Bush House in the Aldwych (best known perhaps as the headquarters of the BBC Overseas Service) and Pen Corner where some rooms above Waterman's Pen Shop on the corner of Kemble Street further up Kingsway were taken over. New instructors arrived thick and fast to cope with the influx of students and had little or no time for preparation before finding themselves responsible at least for the practical work with a class. Stocks of basic equipment like humidity and pilot balloon slide-rules were nowhere near enough for each class to have its own supply, and the instructors had to waste a lot of time touring the neighbourhood trying to locate what was needed for work with a class. The students in the outposts also had to walk up and down Kingsway, for example to visit the School cinema to see instructional films, for which very carefully prepared timetables were needed.

Another totally unexpected consequence of the recruitment surge was that so many students completed their courses within a short period that outstations simply could not absorb them all for the essential spell of on-the-job training. There was no possibility of keeping them in an already grossly overcrowded School, so the solution adopted was to set up two dummy outstations. Rooms were found at Blackbushe and Manston airfields; W.S. Stubley and G.F. Clapp were detached to the former and two other instructors to the latter. At each place, full 24-hour working was maintained so that the students had their first taste of roster duties including nights; they were given full work programmes including the answering of telephone enquiries, some of these originated by the local meteorological offices at the airfields who could easily monitor and, when necessary, correct the information provided. It is believed that two classes both spent two or three weeks at each station; with a declining output of students, the operation was then brought to a close before winter started.

One of the key features of assistant training over the years was the continual development of hand-out leaflets of all kinds, from step-by-step instructions for using humidity and pilot balloon slide-rules or filling in the Observation Register, to notes about cloud types and succinct summaries of essential basic physics. These speeded up the instruction and saved the need for a great deal of note taking. New ideas in the light of experience led to many revisions and amendments, and there was a constant need for preparation of material for coding, decoding and plotting practice. The amount of typing and duplicating involved was very considerable indeed and one of the key members of staff was Miss Ruth Hitchen who had started with Mr Boyden in the very early days at Gloucester; she had come with him to Kilburn and Oxford Street and went on to Stanmore where she finally retired in 1967. Her expertise with wax stencils and rotary duplicators was legendary. Now that photocopiers are so widely available, it requires an effort of memory to recall life without them; yet most outstations during the war had to manage using hectographic ink or carbon paper and the ubiquitous trays of jelly, and even at large establishments like the Training School there was nothing better than the extremely messy rotary duplicators like the Gestetner. When a duplication task was complete, most typists would drop the inky stencil with distaste into the waste bin; but Ruth kept everything not purely ephemeral swathed in sheets of blotting paper and serially numbered, so that one could ask for another 100 copies of something and get them in a very short time. Moreover, she was prepared to put carefully masked used stencils back into her typewriter and make amendments to them, and even to splice pieces of new stencil into old ones.

These activities not only obviated the need for a great deal of retyping but saved a tremendous amount of time and provided the instructors with a really first-class service.

During the autumn and early winter of 1948, the School undertook a very onerous additional task. The World Meteorological Organization had decided to introduce a completely new set of synoptic codes on 1 January 1949, and these had to be taught well before the operative date. Complete sets of data had to be prepared by translating then current data into the new codes, and completely new training leaflets on coding and plotting matters had to be prepared. Operational staff at outstations were faced with similar problems so, to help with the familiarization process throughout the Office, the leaflets and sheets of practice data were circulated to all outstations. There is no doubt that all this careful preparation paid handsome dividends and helped to minimize the trauma of the change,

Throughout 1948, 1949, 1950 and 1951 the School population varied between two and five classes at a time with no surges in the intake. Mr P.J. Meade, who by then was Head of the School, instituted a review of assistant training. It had long been thought that too much was being crammed into the six weeks of the assistant course and early in 1949 an extension to eight weeks was agreed. Under the new arrangements the instruction was completed in the first six weeks allowing the final two weeks to be entirely devoted to outstation simulation work; this no doubt reduced the period of on-the-job training needed subsequently at outstations. It had taken almost ten years to get back to the eight-week course that had had to be abandoned because of wartime pressures. In early 1950 another improvement was introduced whereby older assistants were brought back to the School for three-week refresher courses. Seven of these were run during 1950 and one in early 1951; in particular these courses aimed at brushing up the background of elementary theory needed for success at Civil Service Establishment Boards, as well as broadening the practical experience of those who had become specialized in their work.

On 22 August 1951, the School moved to Stanmore where it was to stay for about 20 years, ending the 12-year period of upheaval and movement described in this note during which more than 500 assistant courses had been run at no less than 17 different locations to provide for over 7000 students.

Acknowledgements

My thanks are due to Mrs Aries who obtained some old staff records for me, to Miss Mackay and Miss Tait for information about the 1941 courses in Edinburgh, also to P.G. Wickham who disinterred the old files at the Meteorological Office College and to Dr C.J. Readings for permission to extract and use data from them. I am most grateful to G.A. Cowling, I.G. Hughes and W.S. Stubley, who were all instructors at the WAAF School and elsewhere, for reading and making useful comments on drafts of this paper. I am also very much in debt to those whose memories have helped to bring this story to life: Mrs I. Borrett, P.D. Borrett, K. Bryant, P.G. Deeks, W. Dewhurst, J. Findlater, J.O. Friend, D.B. Green, D.W. Greenhalgh, R.C. Hackwell, E.C. Harris, Mrs S.D. Ogden, Miss P. Parker, Mrs D. Pennell, Mrs J. Robinson, J. Scott, A.B. Shaw, Mrs C. Siemssen, S.B. Siemssen, Miss B.J. Spear, Mrs C. Thomas, Mrs C. Todd, and K.E. Woodley.

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Training in the Meteorological Office: some notes on the period from March 1948 to February 1952

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Summary

After World War II a reconstruction of the Meteorological Office took place. The new establishment came into effect on 1 March 1948 and, compared with the pre-war size of the Office, showed a considerable expansion. Since most of the wartime entrants had left to follow their chosen careers, there were serious shortages in various grades and so the recruitment and training of staff were to be of major importance for some years ahead. The most urgent need was to fill the forecaster vacancies and special measures were taken to try to overcome the problem. This article covers the first four years' activities of the Training Branch, M.O.14.

1. Introduction

Previously I wrote an article for this magazine (Meade 1952)* describing the organization for training, the various courses that were provided for home and overseas students and the arrangements for external training. This article is readily accessible in the libraries of Meteorological Services and in what follows I propose to avoid excessive repetition and confine myself to some of the highlights of the four-year period when I had responsibility for training.

Since formal training in the Office began in 1936 the number of staff carrying the title Head of Training, or its equivalent, must be quite substantial. I would hazard a guess that few had sought the job but that all had very quickly found it to be one of the most satisfying and inspiring assignments in the Office's many mansions. I was shocked and somewhat disappointed when the Director, Sir Nelson Johnson, told me that I was to be responsible for training. However, by the time he had finished explaining what he wanted done and discussing ways and means with me, my only doubt was whether I would be equal to a task of such wide scope and potential importance.

The principal reason for my appointment, which came into effect on 1 March 1948, was probably that I had spent the preceding 14 months, from 1 January 1947 to 29 February 1948, as personal staff officer to the Director, assisting him in planning the post-war organization of the Office, described at the time as the reconstruction, and in his Presidency of the International Meteorological Organization (IMO).

During World War II the IMO had lain dormant. Founded in 1873, it was an association of directors of Meteorological Services and had done valuable and essential work in promoting international co-operation but it had no official status. However, wartime requirements for meteorological information had demonstrated the importance to each country of its meteorological organization. It had become clear that the existing arrangement of IMO was too informal and that it should be transformed into an official inter-governmental body. This was achieved in 1951 with the creation of the World Meteorological Organization (WMO) which gained further official recognition as a specialized agency of the United Nations.

Sir Nelson Johnson was thus the transition President with the dual function of reviving the activities of IMO and preparing the way for the creation of WMO with its official standing and enhanced responsibilities. In those days the secretariat of IMO was very small compared to the large, more or less autonomous organization that functions in Geneva today. Almost everything that came to the

* Meade, P.J.; Training in the Meteorological Office, *Meteorol Mag*, **81**, 1952, 129–137.

secretariat, whether from Meteorological Services or from the presidents of the reactivated technical commissions and regional associations, was referred to Sir Nelson for instructions. It fell to me to investigate the background, in consultation with appropriate colleagues, and draft letters for the President's approval and onward despatch.

The reconstruction of the Office for its post-war responsibilities was a lengthy business involving many government departments and protracted and often frustrating arguments. In the final stages there was an intervention, which proved decisive, by the staff association, the Institute of Professional Civil Servants. One day the full story should be told. The evolution of the Office may be readily understood by examining the changes in its upper structure. Before the outbreak of war in 1939 the Director was supported by three Assistant Directors and there were seven Branches. By the end of the war the Director had the help of a Deputy Director, five Assistant Directors and 14 Branches. The post-war establishment introduced on 1 March 1948 gave the Director a Principal Deputy Director, three Deputy Directors (for Forecasting, Services and Research), nine Assistant Directors and 22 Branches. In one Branch, M.O.2 the Central Forecasting Office, three Senior Principal Scientific Officers (SPSOs) were established so that, with nine SPSO Assistant Directors, there were 12 SPSO posts altogether. Clearly the reconstruction provided much-improved career prospects and this progress has continued over the years in various reorganizations, notably that which resulted from the report of the Brabazon Committee and gave the Office in 1957 its first Director-General. It should be mentioned that any comparisons between the establishments of 1948 and of the present time need considerable care because apart from the expansions that have occurred there have also been changes in nomenclature. For example, the Branches of 1948 headed by Principal Scientific Officers (PSOs) are now, if they still exist, parts of much larger Branches headed by SPSOs.

In the restructured Office a separate Branch, M.O.14, was formed for training. In briefing me about my appointment as Head of Training, Sir Nelson Johnson said that my experience of working with him had given me full information about the Office's plans and objectives and also about developments in the international field. Such knowledge would provide a valuable background and he asked me to set high scientific and technical standards and to take personal responsibility not only for training but also for the recruitment of Scientific Officer (SO) and Experimental Officer (XO) staff through the Civil Service commissions. This latter task I carried out with the help of my deputy, Mr K.H. Smith, who was a tower of strength in all ways and succeeded me as Head of Training in March 1952.

2. Problems of staff shortages

Recruitment of staff was one of the most intractable problems facing the Office in the post-war period. During the war there had been an enormous expansion with members from other professions, mostly teachers, and school-leavers crowding into the Office on mobilization into the Royal Air Force Volunteer Reserve. These people did excellent work for the armed services at home and in overseas theatres of war and it was hoped that a substantial number would remain with the Office after the war, making meteorology their chosen profession. A fair proportion did stay but the majority decided to return to their former employment or, in the case of those who joined us on leaving school, to seek other jobs or continue with their education. For the Office to revert to its pre-war strength would have led to very serious difficulties because current commitments in 1948 were much greater and more widespread and, in addition, gave many indications of further expansion. Recruitment was therefore given high priority and this was obviously of particular concern to the Training Branch which was preparing instruction courses for new staff at SO, XO and assistant grades.

It was a difficult time for recruitment because reconstruction was going on everywhere and in the labour market as a whole there were more vacancies than qualified applicants. Science graduates were able to pick and choose and move around almost at will. The position was similar with regard to those leaving school with A-levels or equivalent qualifications and there was also the added attraction of expanding university places. In the case of assistants entering with O-levels or equivalent, recruitment was relatively easy but there was a large turnover since those who were acceptable to the Office were in great demand, often at higher salaries, in other sectors of employment.

We realized therefore that SO courses would probably be small as far as our own intake was concerned but there was the possibility of a few extra students from the various colonial Meteorological Services and from foreign services. For the first three years the annual SO courses contained four or five trainees; in the fourth year, 1951/52, we had ten trainees on the course.

With regard to assistants the only practical attitude was to accept that large numbers would be taken on and that a fair degree of wastage would occur, mainly within a year or two of an assistant leaving the Training School. In each of my four years in charge of training we ran courses for about 250–300 assistants. Naturally we made efforts to persuade these young people to look upon the Office as their chosen career. We described the variety of work that was available and encouraged the more promising to take advantage of facilities for further study in mathematics and physics with the object of becoming qualified for class-to-class promotion.

The worst problem of all was the shortage of staff in the XO class. At that time the Office was predominantly a forecasting organization and many outstations had to carry out their work in spite of acute shortages at Assistant Experimental Officer (AXO) and XO levels. One remedy that was resorted to provided the Training School with a most interesting challenge and proved quite successful.

3. Strengthening the XO class

The advantage of having recruitment interviews centralized in one person, the Head of Training, was that it was possible to set and maintain standards at each level of entry. The Director would not have permitted any lowering of standards which might have assisted in obtaining a short-term solution at a cost of unwelcome problems over the more distant future. The serious shortage of forecasters in the XO class was considered to be of limited duration, up to about ten years perhaps. For one thing assistants taking advantage of concessions for external studies might provide a steady and most welcome source of supply to the forecasting grades.

After wide consultation and discussion it was decided to carry out a trawl among assistants of some years' experience to find out if there were any who could be considered fairly close to AXO standard and who might with a little help cross the line dividing the assistant from the XO class. Officers-in-charge were invited to nominate likely candidates. At the same time we in the Training Branch examined the personal cards of all assistants in order to pick out those who had obtained credits or, preferably, distinctions in mathematics and physics in the School Certificates (equivalent to O-levels). In effect we were looking for assistants who, but for the war, would probably have continued their education in science and possibly proceeded to a university.

The result of the trawl was very encouraging and the next step was to test the quality of the potential candidates at an internal board chaired by the Assistant Director for Personnel (AD Met O(P)) Mr M.T. Spence, the Head of the Establishment Branch and myself. The majority were accepted as promising AXO material and were brought to the Training School for further development. The first few weeks were spent on an intensive course in mathematics, mainly calculus, and physics with heat and thermodynamics as the main topics. The objectives were to make sure that the trainees would be capable of understanding the tephigram, geostrophic and thermal winds and the construction of upper-air charts. Very few had to be returned to their stations and the remainder were told to enter the AXO Civil Service competition and, at some risk, embarked on the initial forecasting course. Most of these specially selected assistants satisfied the Civil Service Commission at the first attempt, the others a year later.

The experiment, because that is what it was, was considered to be well worthwhile and steps were maintained to monitor the progress of assistants who were showing promise as well as a keenness to make their way in the Office. In my first two years 97 AXOs were trained in forecasting of whom only 27 were direct entrants, the other 70 being promoted from the assistant grade. The experiment and its results became well known throughout the Office and helped to serve as a spur to assistants to undertake external studies, for which generous concessions were available, and thus improve their prospects of class-to-class promotion. Thereafter our initial forecasting courses invariably contained a substantial proportion of assistants who had been raised to AXO. Many of the assistants selected in the trawl had successful careers in the Office. An outstanding example was W.R. Brady who for many years was a valued member at senior forecaster level of the Central Forecasting Office.

4. Employment of German meteorologists

Around 1948/49 staff shortages among our units serving the Army and RAF in the British zone of Germany were particularly worrying because of the intensive flying and associated operations taking place. The Chief Meteorological Officer, Mr R. Cranna, noted that the German Meteorological Service was at a low ebb and in consequence a number of experienced German meteorologists were unemployed. He therefore suggested to the Air Staff that deficiencies might be overcome by recruiting German forecasters and assistants to work under British supervision at RAF airfields in the British zone. The proposal was approved subject to satisfactory assurances on such questions as security on the one hand and competence in English language, forecasting and briefing on the other.

It was then decided that the assistants would go directly to stations where only a minimum of training and familiarization would be required. For the forecasters I was called upon to provide a detachment from the Training School for duty in Germany for about six months. The arrangements were quickly made and offices and a classroom were provided in the Deutsche Seewart building in Hamburg. We soon found that the English language presented few problems to the German forecasters and that all they required was a short refresher course in forecasting together with instruction in briefing RAF aircrews. The forecasters had already acquired, under the leadership of Schregardus, much experience with up-to-date techniques of upper-air analysis and altogether the courses we provided were very rewarding as well as going far to solve urgent staffing problems. It was a pleasure to see the enthusiasm of the German forecasters.

5. Refresher courses

An annual training conference, chaired by AD Met O(P) and attended by Heads of Branches, provided useful information and discussion regarding any shortcomings in the standards of training and gaps in the various courses. Visits to outstations were also very productive. In the case of AXOs it was possible to gauge their progress directly because a few years after their initial course they would return to the Training School for an advanced forecasting course. This course was an essential step on the way to promotion to XO.

Promotion boards were another source of information about training requirements. In the organization as it existed up to about 1950, staff would not be expected to return to the Training School after their advanced forecasting course. That is, XOs and above would have no further contact with training. However, promotion boards from XO to Senior Experimental Officer (SXO) and from SXO to Chief Experimental Officer (CXO) revealed tendencies for staff in busy forecasting centres to become somewhat rusty in their technical background and to experience difficulty in keeping abreast of new scientific methods in forecasting. The need for refresher courses was therefore quite clear and, in deciding to arrange them, it was also felt that, ignoring the aspect of rustiness, staff would benefit from a quiet few weeks, away from personal contacts and telephones, spent in reading and practical work and also in discussions with instructing staff.

6. Some non-routine items

(a) *The 1949 synoptic codes – trade unions lend a hand*

The appointed date for the introduction world-wide of new synoptic codes covering surface observations from land stations and ships, and also upper-air observations of wind, humidity and temperature was 1 January 1949. Compared with the existing codes, the changes were comprehensive and detailed. The whole reporting system had fallen into some disarray because during the war various countries or groups of countries, to suit their own purposes, had made amendments and additions to the international codes which had come into operation in 1935 and were totally inadequate for post-war requirements.

In the second half of 1948 the Training School was giving instruction in both the current codes and those to be introduced in the new year. Of course, trainees who would still be attending the School at the year's end were taught only the new codes.

During October 1948 I received a telephone call from the Principal Deputy Director, Meteorological Office, Dr J.M. Stagg. He started as follows: 'I want to tell you about a serious and urgent problem that has arisen. I am not asking you to do anything about it — indeed I have no authority to ask you to take any action in this case.' He then went on to explain that booklets had been printed giving instructions about the new codes and had been despatched by the Stationery Office to our Branch at Harrow. The booklets, numbering several thousand in about a dozen packages, were overdue and had been traced to the parcels depot at Euston station where they were held up because of a strike. Dr Stagg mentioned that the instructions had to be distributed to our own stations at home and overseas and also to colonial Meteorological Services, the Voluntary Observing Fleet and many other people and organizations. The strike had been on for some time, had had a lot of press coverage and there was no indication as to when it would be settled. He ended by saying that the problem was desperately urgent and telling me to be very careful.

It was obvious what had to be done so I collected five trainee assistants from one of the courses and explained the problem. I told them I was going to ask the trade unions involved to allow me to search for the parcels and remove them. The assistants' sole task would be to help in the search if approval was given and, if not, we would just have to return to the School. (News quickly went round the School as to what was afoot and it seemed that everyone, instructors and trainees, wanted to be involved.) The six of us took a bus from the School in Kingsway to Euston station and, telling my companions to stay in the background, I approached the pickets and said I had an urgent need for some of the parcels that were held up and added that I would like to see their leaders. The pickets were in a good humour and several of them accompanied me to the union leaders. I explained the problem and stressed that the country would look pretty foolish and inefficient all over the world if we failed to introduce the new procedures at the end of the year.

Without any further discussion the main union leader said (expletives removed): 'Go ahead, help yourself and the best of luck. If you find what you're looking for, it'll be a miracle.' I called the assistants over and we deployed among the stack of parcels which was about 100 metres by 6 metres and about 3 metres high. We were looking for parcels with official labels on and addressed to the Meteorological Office, Harrow and within about ten minutes we had found the lot. They were well separated but were prominent and waiting to be found. A van was summoned from the Air Ministry and very soon the parcels were on their way to Harrow for distribution to be set in motion. I reported to Dr Stagg that I had found as much good nature among union leaders and pickets as I was accustomed to find in many other activities.

(b) *Recruitment by the Crown Agents*

When British colonial Meteorological Services required new graduate staff they would ask the Crown Agents to recruit them. This was done with our help in interviewing the applicants and the successful candidates came to us for training before proceeding overseas. The first such graduate who reported to the Training School was destined for one of the colonial services in West Africa and was clearly going to be an excellent acquisition.

After a while we learned that his conditions of service laid down that he was on half basic pay while training in this country and would not be on full pay until he went abroad to take up his duties. Our trainee was finding his financial position becoming increasingly desperate as it was bound to do, since at the time living in London on full pay would have been hard enough. I made repeated attempts by letter and telephone to improve the position but it seemed the regulations were there and had to be observed. The problem was solved when another member of the course suggested we should refer not to the Crown Agents but to the half-Crown Agents. I relayed this suggestion to the Crown Agents and soon the graduate in question was on full pay back-dated to the day he reported to the Training School.

(c) *Publicity*

The Training School received a lot of publicity, too much in many ways, but at a time of staff shortages publicity was regarded as a valuable aid to recruitment. The source of publicity was the Air Ministry information circulars which were regularly issued to the Press and the British Broadcasting Corporation. The Air Ministry was the Office's parent department and the Public Relations Branch kept in touch for news about any special activities. In the training field, interest was always aroused when overseas meteorologists were attending our courses and this aspect accounted for one notable occasion.

In 1951, after the School had moved to Stanmore, we happened to have under training as forecasters meteorologists from West Africa, Ceylon (now Sri Lanka), Iraq and Burma, all at the same time. The Air Ministry informed the Press, there was an immediate response and arrangements were made for journalists and photographers to visit the School one afternoon. The overseas trainees were informed and seemed pleased. At the appointed time some 30 people with equipment appeared and I wondered how we would cope. I gave them a brief talk and led them along the corridor towards the forecast classroooms. However, as we were passing one assistant classroom the door opened and one or more of the journalists noted that the class was a mixed one and enquired, 'Do you train women as meteorologists?' On being told that we did, the Press lost all interest in the overseas trainees and wanted to visit the classes that had women students. It would be more realistic to describe them as girls or young ladies since they were all recent school-leavers. The sequel was an enormous amount of publicity in the national and provincial Press, and also in women's magazines showing the girls sending up balloons to measure the upper winds, peering into the screen to read the thermometers or plotting charts. Our overseas trainees were very disappointed but a few weeks later, through the good offices of the Public Relations Branch, a smaller and more manageable press party arrived, the doors with the mixed classes were kept shut and our overseas members were able to send home cuttings and photographs from the newspapers.

7. Conclusion

The Training School described in my 1952 article and recalled in this one may be quite different in various ways from the training organization that functions in the Office at the present time. In those days the efforts of the Director to build up a substantial research effort had still to bear fruit and so training was mainly concerned with synoptic and dynamic meteorology with a fairly small element of climatology. Within this relatively limited spectrum training was great fun. The instructors were dedicated and possessed a good sense of humour. The trainees, almost without exception, were conscientious and enthusiastic and, as is customary with young people, had a cheerful and confident outlook.

551.5(09):06:37

The Meteorological Office College, 1972–86

By C.J. Readings
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Summary

The development of training at the Meteorological Office College at Shinfield Park, near Reading, is described. Traditional courses for scientific staff, in atmospheric sciences, weather forecasting and observing are now complemented by courses in computer programming for which special accommodation has been provided. Technical training, both electronic and non-electronic, is another area which has undergone significant development recently.

Introduction

This article concentrates on the 15 years since the Meteorological Office's main training facility was moved from Stanmore to Shinfield Park (lying on the southern outskirts of Reading) and its title changed from the Meteorological Office Training School to the Meteorological Office College; a move described in some detail by Johnson (1972). In that time the College has matured and expanded so that it now meets the bulk of the Meteorological Office's training requirements as well as providing a service to many national Meteorological Services abroad. This process of evolution has accelerated recently, reflecting the advent of new technology, so the moment is opportune to take stock and review the changes which have taken place since 1972. Other articles (Boyden 1986, Meade 1986a, 1986b, Ogden 1986) cover various aspects of the pre-Shinfield era and the reader is also referred to articles by Meade (1952) and Gordon (1959) as well as the one by Johnson (1972) for further details of this period.

Although this article concentrates on the post-Stanmore era it is useful to start by listing the Heads of Meteorological Office Training as this helps to set the current position into context:

Training courses		Meteorological Office Training School		Meteorological Office College	
1935	S.P. Peters	1939	Prof. (Sir David) Brunt	1971	D.H. Johnson
1936	C.J. Boyden	1940	C.J. Boyden	1974	D.E. Jones
		1947	R.E. Farms	1976	S.G. Cornford
		1948	P.J. Meade	1984	C.J. Readings
		1952	K.H. Smith		
		1954	A.H. Gordon		
		1962	W.R. Galloway		
		1965	R.J. Ogden		
		1969	D.H. Johnson		

All these helped to lay the foundations for what is now a very effective training establishment and it should be recognized at the outset that without their endeavours, and those of their colleagues, the current levels of excellence would never have been achieved.

Effective training is fundamental to the well-being of the Meteorological Office and so it is not surprising that it is overseen by a Board (i.e. the Training Board) which includes (among others) the Director-General, the Director of Services and the Director of Research. The Principal of the College acts as its Secretary. This high level of representation ensures that training is reviewed at the highest possible level. Day-to-day control of training has recently been strengthened through the Principal of the College being given overall responsibility for monitoring all training funded by the Meteorological Office, internal and external. The various facets of the training programmes will now be considered in turn.

Recent developments in the training of scientific staff

(a) *Assistants*

This year the training of new-entrant Assistant Scientific Officers (ASOs) posted to outstations will undergo a fundamental change with the existing Initial Assistants (IA) and Advanced Assistants (AA) courses, each of four weeks, being abolished and being replaced by a new Outstations Assistant (OA) course which will last seven weeks. All new-entrant outstation ASOs will attend this course within a few weeks of joining the Meteorological Office so instead of learning skills on one course (the IA) and theory on another (the AA) a few years later, they will receive all their fundamental training on entry. This reflects recent changes both in the Meteorological Office's requirements and the career structure of scientists. Accompanying this will be slight changes to the syllabus as the advent of new technology means there is a need for ASOs to be familiar with the operation of computers (shortly to be introduced at outstations) and with electronic instrumentation. There will be less need for plotting but a clear grasp of the fundamentals of meteorology will, if anything, be more important.

In parallel with this, the training of new-entrant ASOs posted to Bracknell will be extended by one week to include instruction in the use of the computer facility at Bracknell (i.e. COSMOS) as most Headquarter Branches want ASOs to have some level of competence in this area. This course will be known as the Bracknell Assistants (BA) course. There are clearly defined segments within these and other courses which are intended to facilitate the transfer of ASOs from Bracknell to outstations and vice versa.

The Extension Assistants (EA) course for the experienced members of the grade will increasingly occupy an even more important position than it does at present with the advent of new technology and the ensuing need to train all assistants in the operation of this new equipment while at the same time ensuring that they retain a clear appreciation of the fundamentals of meteorology. In common with all other refresher courses, the interval between any individual's attendance at successive courses has been set at five years by the Training Board.

(b) *Station supervisors*

Five years ago a two-course scheme was introduced to cater for the needs of station supervisors, namely the Initial Supervisors (IS) course attended on promotion, and the Further Supervisors (FS) course to be attended every five years subsequently. The IS course concentrates specifically on the duties associated with the grade. There are many visiting speakers to this course who cover subjects as diverse as welfare and administration. The first FS courses have recently been held and they have a strong meteorological content as well as cultivating team project work. In the near future the content of both these courses will be affected by the advent of new technology which will inevitably alter working practices.

(c) *Forecasters*

The basic pattern for training forecasters is well established. Depending on their background, new entrants to the field take either the Applied Meteorology Course (AMC)* or the Initial Forecasting Course (IFC), followed by the Advanced Forecasting Course (AFC) once they have attained a certain level of competence and experience. After that they attend the Extension Course (EC) followed by Further Extension Courses (FECs) every five years which revise and update their skills.

The changes over the past decade have been more of content than of form though they have been quite radical, reflecting the increased dependence on numerical products. Local forecasting techniques are still important as is the prediction of mesoscale weather systems, but as broad-scale developments are quite effectively predicted by numerical models there is now much less emphasis on Sutcliffe's techniques (and other allied approaches) than was once the case. Forecasters still receive some instruction in these areas but the aim is restricted to providing them with the background needed to assess numerical products.

The traditional emphasis on aviation forecasting has been modified to cater for the increased effort in public service forecasting. Briefings using the current weather are still an important feature of forecaster training but nowadays television and radio presentations are also covered. Closed-circuit television is used not only to instruct on television presentation but also to improve briefing techniques generally — a visual record of performance being far more effective than verbal criticism alone.

Other changes have followed upon the drastic decrease in overseas forecasting commitments to the RAF. This has led to the demise of the Tropical and Mediterranean Meteorology courses though a general introduction to these areas is still included in all initial courses. A new development is the South Atlantic Meteorology (SAM) course reflecting the increased commitment in that area.

(d) *Support scientists*

Support scientists, who have essentially the same academic qualifications as forecasters, work mainly at Bracknell in Headquarters Branches supporting a wide variety of research and other activities of a non-forecasting nature. To cater for the increasing numbers of these staff the AMC was introduced in 1973. It was developed from the IFC by separating out the practical forecasting techniques and leaving a ten-week meteorology theory module common to all applied meteorologists. After a one-week project period, support scientists proceed to their Branches at Bracknell. Subsequently they attend the same

* With a forecasting techniques segment (i.e. AMC (F/C)).

refresher courses as the forecasters. Furthermore, as most of them have to use the COSMOS computer system, they also attend computer/programming courses at an early stage of their careers.

(e) *Research scientists*

The corner-stone of the training given to research scientists is the Scientific Officers (SO) course, the first part of which they attend shortly after joining the Office. This lasts some five months and includes instruction in forecasting techniques (including detachment to an outstation) as well as meteorological theory. Recent changes have led to a slight shortening of the course with the dropping of the traditional research project but with an increased emphasis on a review project, in which the trainee scientist surveys the present state of knowledge in a chosen area of meteorology. The second part of the course, consisting of Advanced Lectures, now takes place in the autumn some eight months after the end of the initial SO course. In these lectures the topics are covered at a level which is at the forefront of present knowledge. They span the whole range of the Office's research interests and run on a three-year cycle.

Training in computer skills

When the Office first started using computers, programmers were trained by computer manufacturers but, as numbers increased, *ad hoc* training courses were run at Bracknell by experienced Office staff. Then in 1970 the IBM 360 arrived and for four years programmers were trained under contract by IBM. When the 'free' training ran out recourse was made to self-teaching methods but these did not prove very satisfactory and in 1976 the first programmer training course was held at Shinfield (13 miles from the computer!). Regular courses followed, with the 'Initial Programming Course (IPC) then on-the-job training then Second Programming Course (SPC)' pattern being developed. The College's first computer (a Digital PDP 11/34) arrived in the summer of 1980, solving some problems but creating others due to the mismatch between the PDP and the IBM. In summer 1985 the PDP 11/34 was replaced by a number of IBM Personal Computers (PCs) which in addition to being totally compatible with COSMOS can also be operated independently as small computers in their own right. This equipment is now housed in purpose-built accommodation (Fig. 1) and has proved very effective.

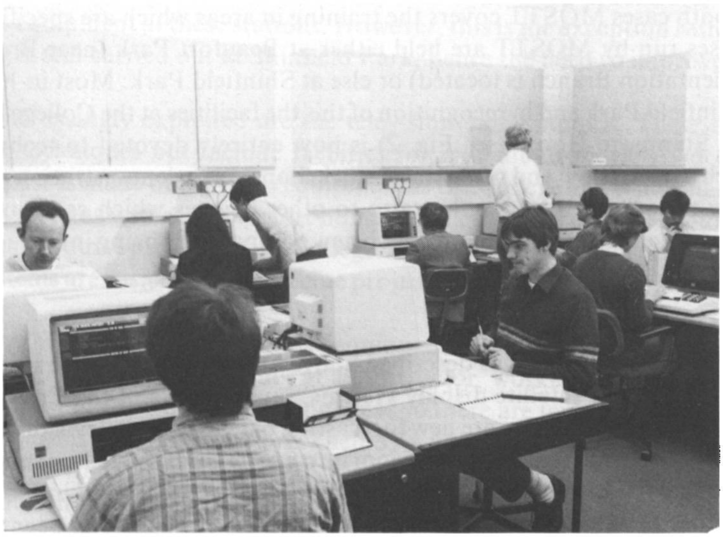

Figure 1. A class operating the IBM Personal Computers at the College.

The training of programmers continues to follow the pattern as originally conceived but with the COSMOS Programmers Course (CPC) replacing the SPC, so that the current pattern is 'IPC then on-the-job training then CPC' supplemented by a series of specialized seminars. In addition there is now a COSMOS Users Course (CUC) intended to provide non-programmers with a basic introduction to the use of COSMOS. This course will shortly form an integral module of the new BA course. In fact, the need for computer literacy is increasing so fast that most members of the Office will shortly need some level of competence in this area. In response to this trend members of many courses are already being taught how to extract synoptic data from the main data banks on COSMOS, how to use the terminals to manipulate statistical data, how to extract forecast model data, etc. This general requirement will grow, though the main use of the College computer facility will remain the training of programmers.

Although not strictly relevant to this section it is convenient to mention here the use of the computing facilities to support a limited number of 'self-teach' packages. Currently such activities are mainly confined to the Meteorological Statistics Course and parts of the mainstream computing courses. However, this is an expanding field and the use of the equipment in the computer section for this purpose will undoubtedly grow over the next few years.

Technical training

Almost all of the Office's technical staff are recruited from the ASO grade. This has been the case for many years though the form their training has taken has changed from time to time. Currently it is carried out in partnership with the Reading College of Technology which provides the basic training, leaving the Meteorological Office School of Technical Training (MOSTT) to cover the areas particular to the Office. This includes instruction in the maintenance of meteorological equipment and training in good industrial practices. The training is likely to be shortened in the near future but at the moment it lasts 15 months. On successfully completing the course a technician gains a Technical Education Council certificate as well as being regraded to Radio (Met) Technician (R(M)T). In addition to the course for R(M)Ts, MOSTT also runs short courses on specific pieces of equipment. These courses typically run for a week and are open to all technical staff, not just R(M)Ts. Specialized courses are also organized for overseas technicians, namely the Basic Electronics Course (run in collaboration with Reading College of Technology) and the Instrument Maintenance Course (with Farnborough College of Technology). In both cases MOSTT covers the training in areas which are specific to meteorology.

The training courses run by MOSTT are held either at Beaufort Park (near Bracknell, where the Operational Instrumentation Branch is located) or else at Shinfield Park. Most in-house training is in fact carried out at Shinfield Park and in recognition of this the facilities at the College have recently been refurbished. Part of Stanmore House (see Fig. 2) is now entirely devoted to technical training and includes facilities such as electronic and mechanical workshops and a demonstration room (Fig. 3). This is of benefit not only to technical training but also to other courses which can now easily be shown equipment. This is important given the pace at which new equipment is being introduced at outstations.

New buildings and facilities

In order to cater for the many changes described above and the advent of new equipment, such as word processors and radar and satellite display systems, several parts of the College have had to be refurbished. Notable among the changes are new forecasting bays and two television/radio studios. The former were formed by subdividing a large classroom into a series of booths the configuration of which can be changed according to need (see Fig. 4). All are linked by electrical trunking so that there are few restrictions on the siting of equipment. As new outstation display systems appear they can easily be incorporated into the forecasting bays making it possible to simulate most types of outstation.

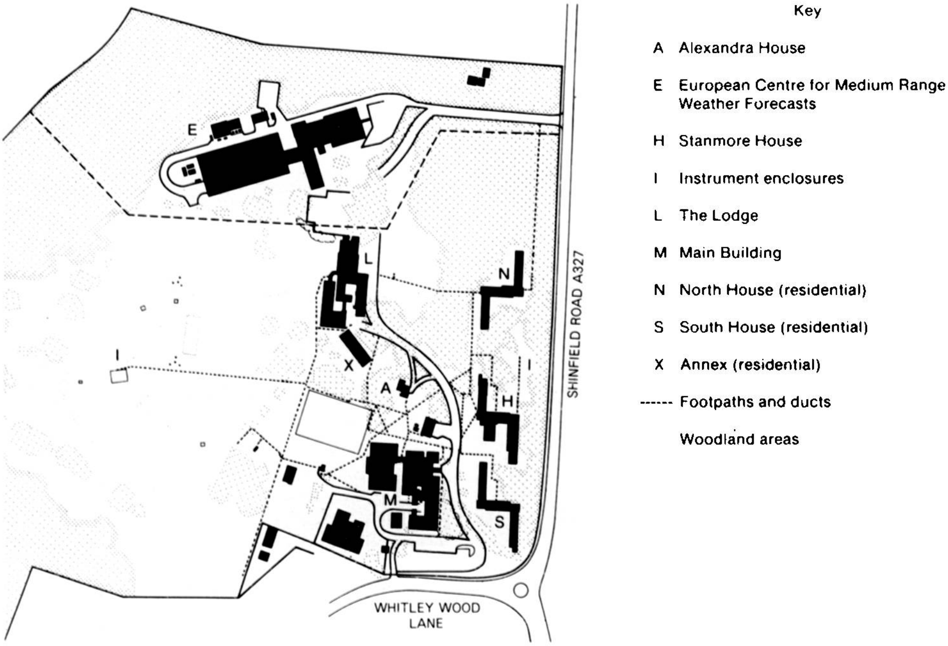

Figure 2. Site plan of the Meteorological Office College, Shinfield Park.

Many changes have taken place in the last two years and reflect the evolving nature of the Office's training requirement. Staff now not only have to acquire traditional knowledge and skills but also have to learn how to exploit new equipment. In some instances, in fact, it has proved necessary to run courses at the outstations themselves. Recent examples of these include training given at Glasgow and Manchester Weather Centres to instruct staff in the use of the word processors, coinciding with the introduction of this equipment at these stations. However, this is the exception rather than the rule and the bulk of training is still carried out at Shinfield Park, hence the need to improve the facilities at the College.

Other facilities increasingly exploited are the television/radio studios. These are mainly used for training in briefing techniques but include facilities for individuals to view video films or listen to cassettes. Extensive use is made of the video equipment at the College and it now has a growing stock of useful commercial videos as well as some short home-made examples on meteorological subjects made by staff and students as course projects at the College. Plans to acquire video projection systems are well advanced. Such systems are easier to use than cine projectors, and video is rapidly replacing cine film as a training medium.

The new computer rooms are currently fully equipped with IBM PCs and include slave terminals which enable students to follow the teaching of an instructor working from a master terminal. Cable trunking now links most of the College teaching areas so there are few restrictions on the siting of this equipment. The College is also linked to Bracknell by a 64 000-bit-per-second line which permits the rapid reception of large volumes of data.

Other accommodation has also been improved in recent years. There is now a conference room and several seminar rooms. The old Industrial Civil Servants' rest room, now renamed Alexandra House, has been equipped so that new-entrant assistants can experience the rigours of observing in quite

Figure 3. Technical training: (a) installing and calibrating a digital temperature indicator, (b) using de-soldering equipment, (c) making engineering tools, (d) an introduction to electronic test equipment.

realistic surroundings, isolated from other buildings and relying on telephone links. On the social side there have been improvements in many areas, the most notable of which have been the installation of an all-weather cricket pitch and the refurbishment of the squash court.

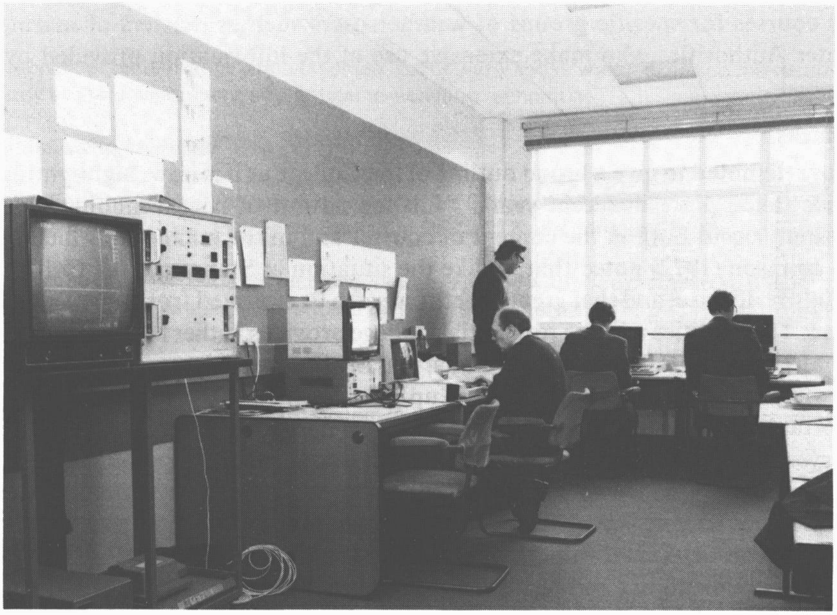

Figure 4. New equipment in a simulated forecast office. On the right, two forecasters receiving instruction in the use of word processors. On the left, a Jasmin display showing areas of rainfall observed by the national radar network. In the centre, an instructor studying a satellite image being received via an aerial system located on the roof of the building.

Other users and uses

The facilities of the College are not solely devoted to the mainstream courses outlined above. They are increasingly being used by Branches such as Observational Requirements and Practices, Advisory Services, and Personnel Management for seminars and conferences. The Meteorological Committee and its Research subcommittee both meet regularly at Shinfield and several World Meteorological Organization Working Group meetings have been held there. The Outstation Colloquia and the Chief and Principal Meteorological Officers' Conferences are regular features of the College calendar. Last year a Summer School was held for the first time. The subject of this School was 'Mesoscale meteorology' and it was attended by over 70 people including academics as well as scientists and forecasters from the Office. It was judged to be a very successful innovation and it is probable that Summer Schools will be repeated at two-yearly intervals.

Many of the courses run at the College are open to non-members of the Meteorological Office, a point that is often not generally realized but which plays a significant part in helping to broaden the perspective of the training provided at the College. All the forecasting and observing courses are open to non-Meteorological Office personnel and over the years hundreds of overseas students from over 80 different countries have attended courses at Shinfield Park. These courses are supplemented by others, such as the Basic Electronics Course and the Instrument Maintenance Course mentioned above, which are specifically designed to meet the needs of developing countries.

Another activity of continuing importance is the training of non-Meteorological Office observers. Three courses are specifically run for this purpose, namely the Co-operating Observers (CO) course, the Auxiliary Observers (AO) course and the Air Traffic Control Observers (AT) course. The latter is unique in that those who successfully complete both it and a subsequent week of on-the-job training under the supervision of an experienced observer, receive a Certificate of Competence. The College has also run special courses for specific groups of weather users such as masters of marine vessels and members of Water Authorities who make extensive use of the information provided by the weather radar network.

Concluding remarks

This article has attempted to give a broad outline of the College as it is now, highlighting many of the changes that have taken place in recent years. With the advent of new technology further marked changes will certainly occur both in the content of courses and in the manner in which they are run.

In his article, Johnson (1972) noted that, unlike the situation at Stanmore, the College at Shinfield Park would be fully residential and that great benefits were to be expected from this. These benefits have been fully realized. The facilities which a residential College provides, either for undisturbed study in the evenings or for after-dinner talks and discussions, are invaluable. So too are the opportunities for informally renewing old friendships and striking up new ones. In the past 15 years the College has become an important focus for maintaining the internal corporate spirit of the Meteorological Office, just as it also serves quite significantly to generate external links with international meteorology.

As well as being widely regarded as a training establishment of the highest quality, the College is a place where people live. Its permanent staff devote considerable amounts of their own time towards providing facilities and a social environment which makes it a pleasant place at which to stay. This is the context in which the opportunities and challenges of the next few years will be met.

Acknowledgements

An article of this form would not be complete without acknowledging the support and help of all the instructors at the College, colleagues throughout the Meteorological Office and co-operating educational establishments, all of whom play a part in running the courses. Special mention should be made of the Reading College of Technology and the Farnborough College of Technology. The authors would also like to acknowledge the help provided by their neighbours at the European Centre for Medium Range Weather Forecasts and at the Department of Meteorology at the University of Reading. All, in their various ways, help the College meet the needs of the Meteorological Office in particular and meteorology in general.

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Correction

Meteorological Magazine, June 1986, p.187. We regret that the following sentence was omitted after the first paragraph of the Obituary of Dr A.E. Gill: 'The following is the address given at the funeral service by Dr J.T. Houghton, Director-General, Meteorological Office'.

Meteorological Magazine

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Meteorological Magazine

July 1986

Vol. 115
No. 1368

CONTENTS

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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.

ISBN 0 11 727835 1 ISSN 0026–1149

Printed for HER MAJESTY'S STATIONERY OFFICE
by Delco Printing Co Ltd 7/86 Dd 739131 C14

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

August 1986

Met.O.971 No. 1369 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1369, August 1986, Vol. 115

551.501.45:551.521.11:551.524.36

A comparison of the principal component and near neighbour methods for the areal quality control of minimum temperature and sunshine duration

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Summary

The principal component approach currently used for the areal quality control of temperature and sunshine is investigated with a view to optimizing the implementation of the technique. A near neighbour scheme was used as a benchmark against which the performance of principal components might be assessed. It was found that each approach provided a similar standard of quality control and that the implementation of the principal component technique was close to being optimal. The potential of the principal component method to obtain improved results was impaired by its tendency to fit errors and its inability to cope with skewed distributions. Nevertheless it gained over near neighbours as the data became less well correlated, and hence was able to produce better estimates at the more isolated stations. The adverse effects of a non-normal distribution also degraded the near neighbour scheme by reducing the efficiency of its flagging routines. The latter approach, however, was found to perform better for new stations for which pre-calculated components were not available.

1. Introduction

The climatological data banks held by the Meteorological Office on both paper and computer media form the only sources of information available to answer thousands of enquiries per year. The integrity of these data is therefore of prime concern to all and depends mainly on the standards of quality control maintained by a suite of programs based on consistency checks in time, space, and between elements. This paper is mainly concerned with the methods used to operate spatial consistency checks, especially those relating to daily observations of minimum temperature and sunshine. For wind and rain sophisticated near neighbour techniques are well established whereas for temperature and sunshine a simple near neighbour approach (Bryant 1979) was replaced by a principal component method (Spackman and Singleton 1982). In making this innovation a number of arbitrary decisions were made and a major aim of this work is to explore the scope for optimization of this new approach. A sophisticated near neighbour scheme was used as a benchmark against which the performance of the principal component technique might be assessed. The discussion is restricted to the use of the conventional station network although it is recognized that remote sensing may have a future role to play. A fuller account of the work described in this paper is provided by Tabony (1985).

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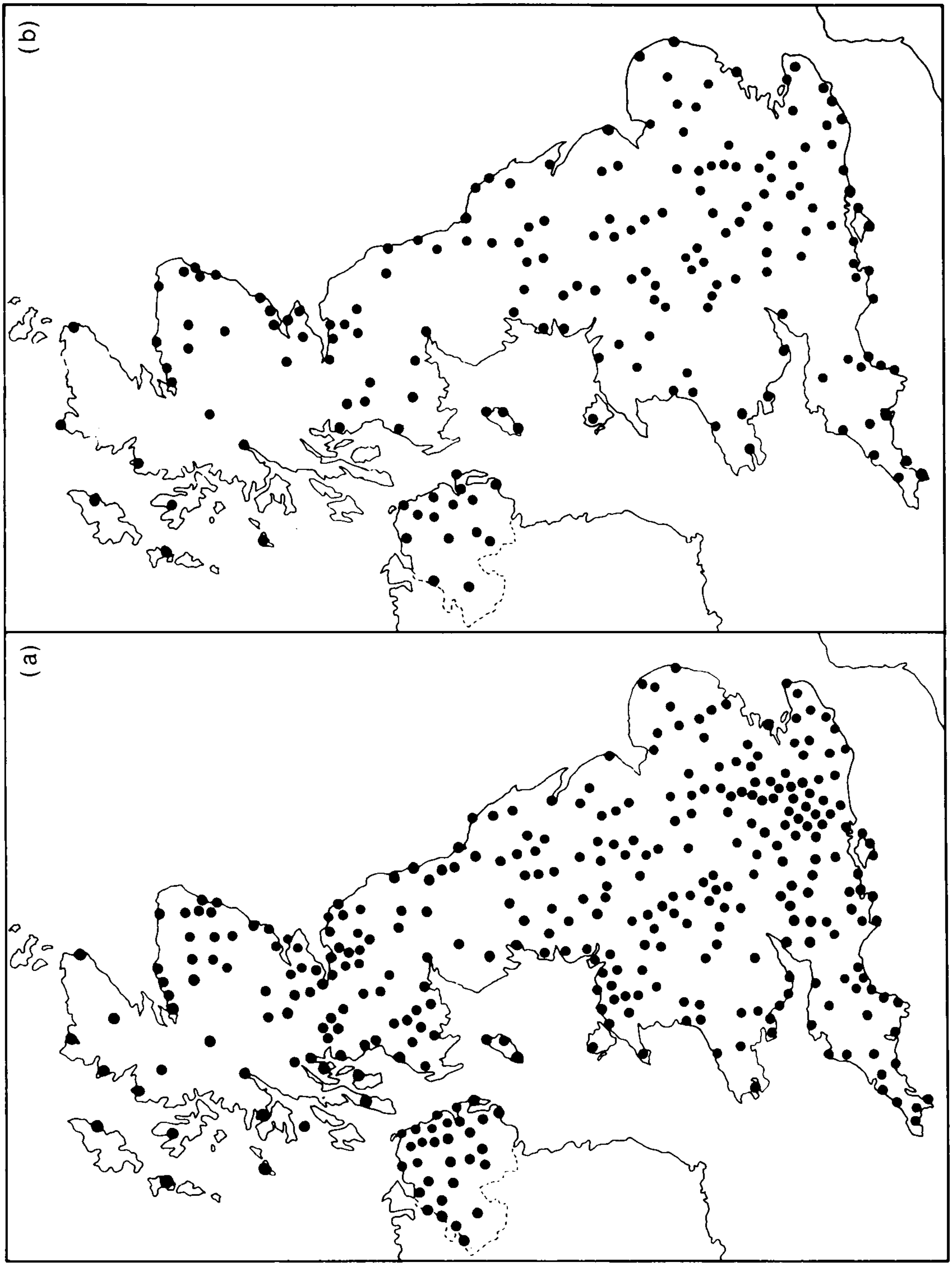

Figure 1. Distribution of stations for (a) minimum temperature and (b) sunshine.

2. The data used and some of their characteristics

Data were extracted from every day during the period 1979–83 for sunshine and every third day for the period 1973–82 for minimum temperature. The persistence of temperature made it unnecessary to use data from every day in order to obtain near maximum information from the data set. The stations used were limited to those with 90% of data available in the periods considered, with the remaining values estimated as having the same temperature anomaly or percentage of average sunshine as that obtained from the mean of half a dozen or so neighbouring stations. This reduced the number of stations considered to 373 for temperature and 197 for sunshine, about one half to two thirds of the full network, and their distributions are shown in Fig. 1.

One of the most important criteria for the success of spatial quality control is the degree of correlation amongst the station network. In the present application the highest inter-station correlations average 0.92 for both elements considered, but the correlation decay is more rapid for sunshine than temperature (Hopkins 1977). This is reflected in the fact that for eighth-ranked neighbours, the correlation has fallen only to 0.87 for minimum temperature but to 0.80 for sunshine.

Another distinction between temperature and sunshine is that while the distribution of temperature is reasonably normal, that for sunshine is markedly non-normal, displaying U-shaped characteristics. This is likely to pose problems for all techniques based on the assumption of linearity.

3. The distribution of errors

In order to assess the performance of a quality-control system it is necessary to test it on data which have been contaminated with a realistic distribution of errors. A guide to these was obtained by examining the amendments made by the quality-control staff to the climatological returns for 50 to 100 stations in England and Wales during 1982–83. Errors of less than 2 °C or 2 hours of sun were ignored and only amendments ascribed by the writer to areal quality control were considered. This procedure led to error frequencies of 1 in 100 for minimum temperature and 1 in 190 for sunshine. The magnitude of sunshine errors varied seasonally in proportion to the maximum possible amount of sun, while those for temperature showed little seasonal variation. The annual distributions of temperature and sunshine errors are illustrated in Fig. 2, along with a fitted gamma distribution for temperature and a truncated normal distribution for sunshine which were used to represent the errors. The temperature and sunshine data under analysis were then contaminated with the appropriate distribution of errors.

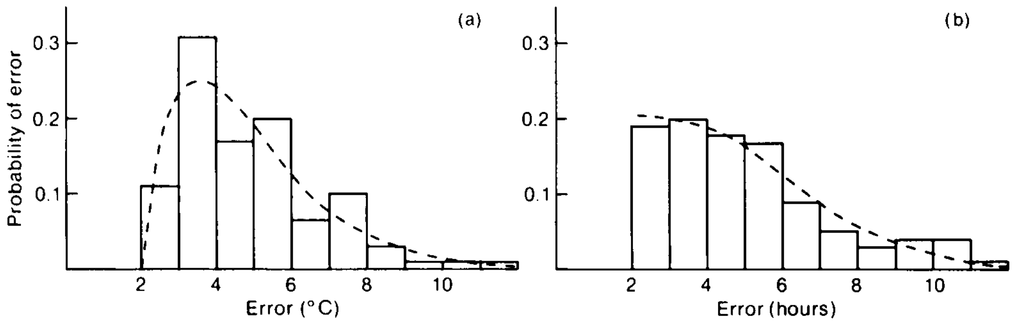

Figure 2. Histograms of errors identified by spatial consistency checks together with fitted distributions (dashed line) for (a) minimum temperature and (b) daily sunshine.

4. Comparison of principal component and near neighbour techniques

Principal component analysis enables fields of correlated data to be adequately represented by a small number of orthogonal patterns (components) in which each component explains the greatest fraction of the remaining variance. Its mathematical aspects are described in standard statistical texts (e.g. Kendall 1980) while a more discursive account is provided by Johnston (1980). Principal component analysis is now a very popular tool in meteorology and has two main uses — data reduction and data exploration, in which the rotation of the components to aid interpretation has been widely practised and discussed (e.g. Richman 1986). Quality-control applications are essentially concerned with data reduction, however, and so rotation of the components is unnecessary.

The principal component and near neighbour techniques both use relationships apparent during a past period of data to estimate observations at a station from neighbouring observations. In the near neighbour technique, only a single regression equation is available for making estimates on each and every day. In the principal component approach, each component can be regarded as a series of regression relations between stations whose weighting will vary from one day to another. The observations on a given day can then be reproduced by a linear combination of the regressions represented by the components.

If the data are very highly correlated then the near neighbour scheme should work reasonably well. Minimum temperatures at neighbouring stations with similar site characteristics, for instance, might be satisfactorily estimated by assuming a constant difference between the two. It is evident, however, that the principal component technique gains over near neighbours as the data becomes less well correlated. If the comparison were between minimum temperatures at a frost hollow and a standard site, for instance, then the differences between the two would be much smaller on cloudy than on clear nights. A 'constant difference' assumption would then be unsatisfactory whereas the principal component technique would be able to invoke different sets of regressions on clear and cloudy nights.

The advantage afforded to the principal component technique by its multi-regression approach is lessened if the input data are skewed. In these circumstances the physically based relations between stations will be non-linear whereas the regressions represented by the principal components are constrained to be linear. This disadvantage could be overcome by normalizing the data beforehand but this is not always easy. For sunshine, for instance, the skewness can act in opposite senses on different days, while for rainfall nothing can be done about that part of the skewness which is due to the large number of dry days.

The advantages which principal components may possess over near neighbours when operating on 'clean' data are also lessened when the test data contain errors, as will be the case for quality-control applications. The reason for this is that the principal component technique tends to fit errors, whereas the near neighbour approach does not. In the principal component method, the pattern of observations on a given day is matched against the patterns represented by the components. The presence of errors may cause some mismatching, but this is unlikely to be serious for the leading components. Thus mistakes in only 1% of observations are unlikely to upset estimates of north–south or east–west gradients across the country. The probability of a mismatch is much greater for the higher-order components, for which the number of stations contributing substantially to the pattern is much smaller. If a component was determined largely by the behaviour of only ten stations, for example, then an error in an observation at one of the stations would seriously upset the weighting to be attached to that component.

5. Estimation by principal components

The accuracy of the estimates is assessed by calculating the root-mean-square (r.m.s.) value of the residuals between the estimates and the true observations. The tendency of the principal component technique to fit errors means that the residuals on occasions of erroneous observations will be larger than those associated with correct observations, and a distinction must be drawn between the two. The residuals of correct observations decrease as the number of components increases. When all the components are used, the input data will be reproduced exactly, even though they are independent of those used to construct the components. The situation is analogous to the fitting of a series of N data points with an N-dimensional polynomial. The use of all components will not result in good error detection, however, since the errors will be fitted as well as the correct observations. The residuals of erroneous observations will decrease with an increasing number of components at first, then increase as the higher-order components fit the errors.

A thorough testing of the principal component technique involves a consideration of the following points:

(i) The assignment of variables to stations (S-mode analysis) or days (T-mode analysis).

(ii) The form of input data supplied, e.g. whether to use 'station anomalies', representing departures from the long-period station mean, or 'daily anomalies', representing departures from a mean for the day. There is also the choice of basing the analysis on a correlation or covariance matrix.

(iii) The domain covered, i.e. whether the United Kingdom is considered as a whole or divided into smaller regions.

(iv) Whether it is better to separate the seasons or perform a single 'mixed season' analysis.

(v) The number of years' data that need be used.

It was found that none of these factors affected the performance of the technique by very much. The current quality-control system uses a covariance-based T-mode analysis of daily anomalies for the whole of the United Kingdom using data taken from all seasons in the period 1972–79. Since the residuals based on 1 year of data are only a few per cent larger than those based on 8 years, little is lost by computing components from only 1 year of data. Typical residuals obtained from such annual analyses are presented in Table I.

Table I. *Residuals associated with the principal component technique*

	Minimum temperature r.m.s. residuals (°C) from:			Sunshine r.m.s. residuals (hours) from:		
No. of components	Original data	Independent data	Erroneous observations	Original data	Independent data	Erroneous observations
0	2.19	2.16	2.22	2.52	2.52	2.50
1	1.69	1.71	1.75	2.10	2.11	2.10
2	1.43	1.45	1.46	1.92	1.95	1.96
3	1.33	.1.36	1.39	1.76	1.79	1.79
6	1.13	1.20	1.23	1.49	1.54	1.54
9	1.02	1.13	1.18	1.33	1.41	1.40
12	0.94	1.09	1.15	1.23	1.32	1.33
15	0.88	1.05	1.11	1.15	1.25	1.29
18	0.83	1.03	1.10	1.07	1.19	1.28
21	0.79	1.01	1.10	1.02	1.15	1.29
24	0.75	1.00	1.10	0.97	1.11	1.31

Usually the most difficult problem in any application of principal components is to decide how many components to use. For present purposes this number can be defined as that which produces the minimum r.m.s. residual of erroneous observations. The complexity of the patterns being matched depends mainly on the number of stations used and it was found that the best number of components could be expressed as a fraction of the number of stations used. The linear relationship will hold only so long as the best number of components is much less than the number of (independent) days, since, if less than the number of stations, this places an upper limit on the number of components required to account for all the variance.

The more highly correlated the data, the fewer the number of components that need be used. Thus for minimum temperature it was found that the best number of components to use was 6% of the number of stations while for the less correlated sunshine data the figure rose to 9%. As the complete network of 350 sunshine stations will provide more correlated data than that used here (197 stations), it may be speculated that the best number of components will be 8% of the full number of sunshine stations. The best number of components to use may therefore be estimated as

$$600 \times 6\% = 36 \text{ for minimum temperature}$$

and $$350 \times 8\% = 28 \text{ for sunshine.}$$

The minimum in the relationship between the magnitude of the residual and the number of components is very flat, as can be seen from Table I. The current quality control uses only 15 components, and the residuals of erroneous observations could be decreased by 10% by increasing this number to about 30.

Seasonal variations in the r.m.s. residuals of erroneous observations reflect variations in the input data. For minimum temperature they are slightly larger in winter than in summer, while for sunshine they range from 0.8 hours in winter to 1.7 hours in summer. Geographical variations in the r.m.s. residuals of minimum temperature are illustrated in Fig. 3 and range from 1.5 °C in the data-sparse Scottish Highlands to 0.7 °C in, for example, parts of Northern Ireland and southern England. Residuals of summer sunshine reveal a similar dependence on the station network with r.m.s. values ranging from less than 1.5 hours over much of England to over 2 hours in other districts. In winter, however, geographical variations are much smaller. This is because there are a large number of sunless days for which in data-sparse areas the estimates are easy to make.

6. Estimation by near neighbours

Four main steps were used in the development of a near neighbour scheme:

(i) The eight most highly correlated stations were chosen to act as 'neighbours'.

(ii) The neighbouring observations were 'reduced' to those appropriate to the site characteristics of the test station by using the conventional conversion factors of percentage of monthly average for sunshine and difference in monthly average for temperature. The monthly ratios or differences were not used directly but were meaned over all months.

(iii) A simple scanning procedure was used to eliminate erroneous observations at neighbouring stations which degrade the accuracy of the estimates derived from them.

(iv) The acceptable estimates were combined using a weighting scheme based on an inverse square law in correlation space.

Since the quality of the estimates is unaffected by whether or not there is an error at the test station no distinction need be drawn between correct and erroneous observations — their r.m.s. residuals will be the same. Table II shows that these values lie around 1.0 °C for minimum temperature and 1.1 hours for daily sunshine, very similar to the figures obtained from principal components. The similar standard of estimates obtained for sunshine is due to the competing effects of poorly correlated and non-normally distributed data, the former favouring principal components and the latter near neighbours. The gain of principal components over near neighbours as the data become less well correlated is demonstrated by the more pronounced geographical variations for near neighbours (Fig. 4) than for principal

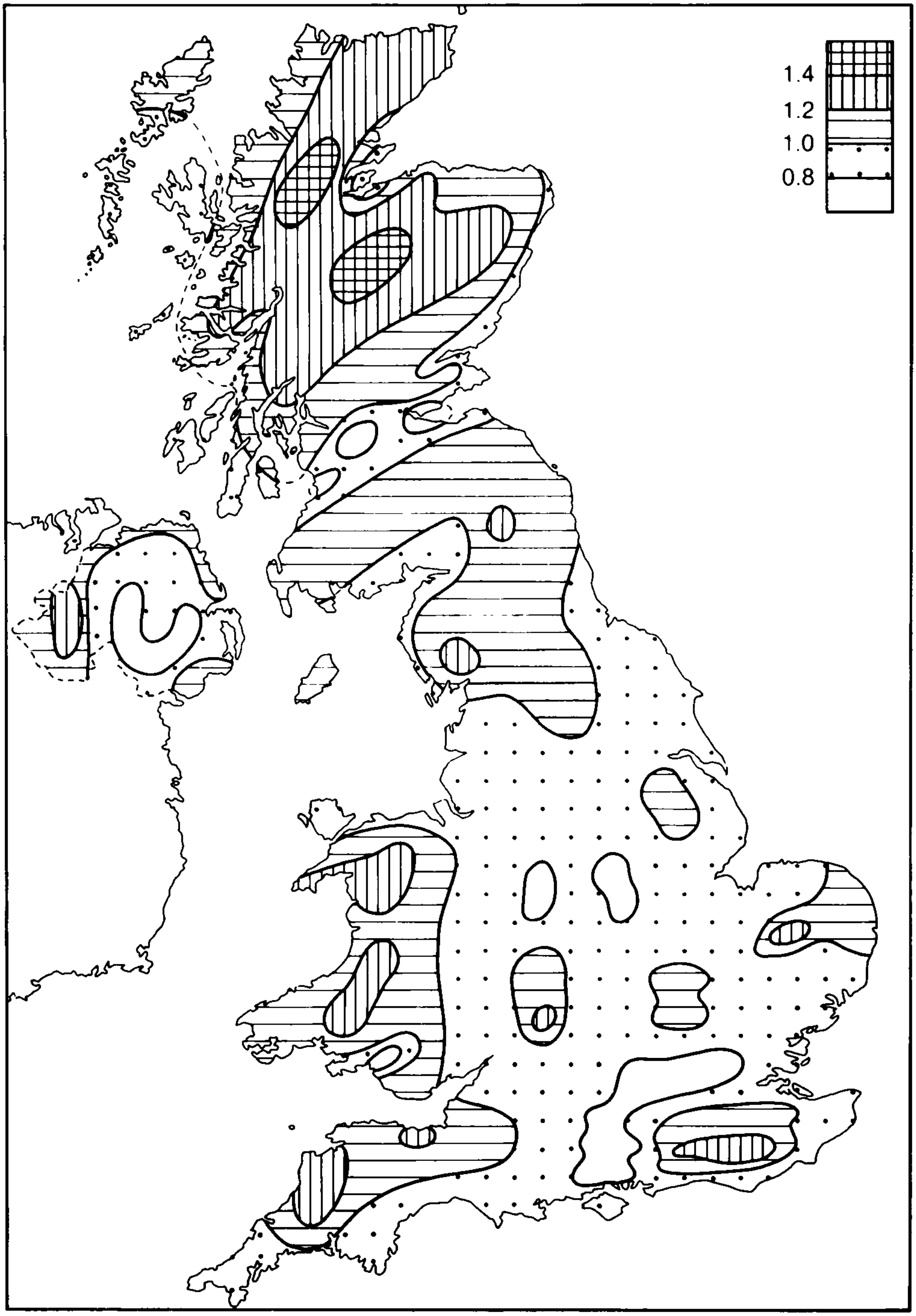

Figure 3. Geographical variations in root-mean-square residuals of minimum temperature (°C) obtained from principal component analysis (15 components, 1973 tested on 1978).

Table II. *Residuals associated with the near neighbour technique*

Regression technique	Data used	r.m.s. residuals Min. temp. (°C)	r.m.s. residuals Sunshine (hours)
Constant difference/Ratio	30-year averages	1.00	1.10
Constant difference/Ratio	1-year calibration period	1.02	1.10
Constant difference/Ratio	4-year calibration period	0.95	1.08
None (station = neighbour)	Current month	1.16	1.11

components (Fig. 3). For the highly correlated dense networks near neighbours holds a small advantage, whereas for the less well correlated data-spare areas principal components is clearly superior.

7. Estimation from the current month

One requirement of an operational quality-control system which has to be recognized is the need to cope with new stations. For these stations past data are unavailable for the calculation of principal components or near neighbour regressions, and substitute information has to be derived from data for the 'current' month, i.e. the month being quality controlled. This has the advantage that the data to be estimated are not independent of those being used to form the components or regressions, and so the estimates of correct observations will be better than those based on past data. The disadvantage is that the erroneous observations either contaminate the components or have to be excluded from the regressions, and so their estimates are worse than those obtained from past data.

For the near neighbour technique the data can be scanned and likely errors removed before the regressions are developed. It was found that the r.m.s. residual of 1.10 hours for sun decreased to 1.00 hours for correct observations but increased to 1.19 hours for erroneous observations. For minimum temperature the constant difference approximation was replaced by a conventional linear regression made suitable by the fact that it was being tested only on dependent data. This led to the r.m.s. residual of 1.00 °C decreasing to 0.71 °C for correct observations but increasing to 1.17 °C for erroneous observations. From these figures it can be deduced that the current month technique is providing a similar standard of quality control to that obtained from past data.

For principal components the current month approach is less satisfactory for two reasons:

(i) The missing components for the new stations have to be estimated from data for the current month. Although the components are biased towards the sample of data on which they were tested, some of the directness of the near neighbour technique in using exactly those data which are to be estimated is lost.

(ii) The technique does not lend itself to the scanning and removal of likely errors before the components are calculated.

Thus it was found that for minimum temperature, r.m.s. residuals based on 15 components fell from 1.05 to 0.93 °C for correct observations but rose from 1.11 to 1.78 °C for erroneous observations.

8. Flagging routines

The overall performance of any quality-control procedure depends on:

(i) the accuracy with which true values can be estimated on occasions of erroneous observations,

(ii) the number of errors which are not queried (type I error), and

(iii) the number of invalid queries raised (type II error).

So far attention has been concentrated on item (i) and the residuals of erroneous observations. The accuracy with which correct observations are estimated is also relevant, however, since this affects the number of invalid queries raised.

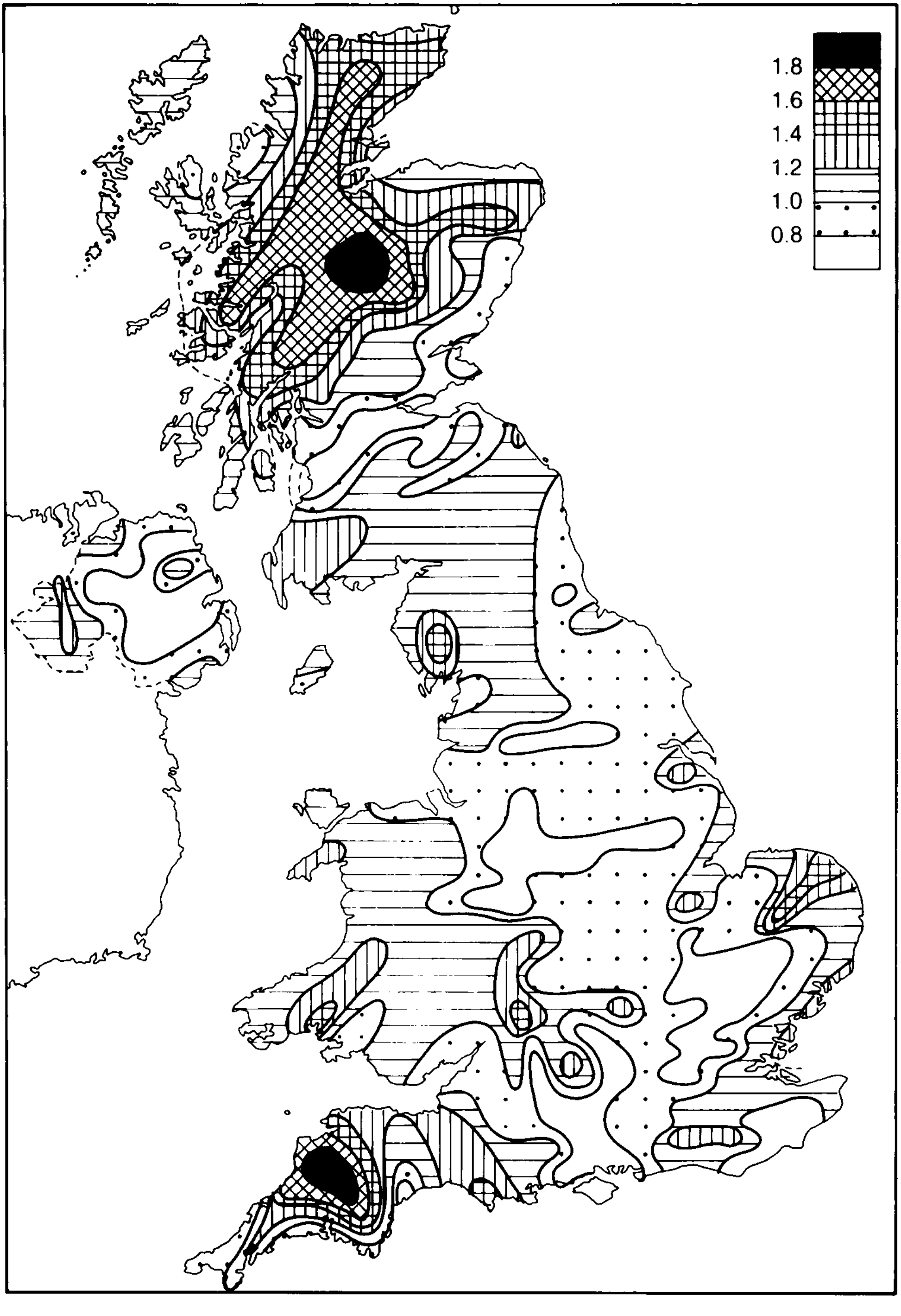

Figure 4. Geographical variations in root-mean-square residuals of minimum temperature (° C) using near neighbour technique (1973 tested on 1978).

A reasonable measure of the effectiveness of a quality-control system is the proportion of error variance detected. No absolute measure of merit is possible, however, since subjective judgement is required to decide whether to aim for quality and minimize the proportion of error variance detected, or to go for economy and minimize the number of invalid queries raised.

The best way of raising queries is to flag observations for which the residual exceeds a specified number (S) of standard deviations of the residuals. It is also advantageous to supply an absolute threshold (D) to prevent small differences from being queried. The current quality control uses only S, but it is set at such a high value (3.25) that small values of D will have little impact.

There are a number of points of interest concerning the calculation of the mean and standard deviation (SD) of the residuals:

(i) All stations in the United Kingdom could be used, but high and low variances of residuals in differing regions could have adverse effects on the efficiency of the flagging in each district. Alternatively, therefore, the mean and SD could be calculated from stations in districts about one-tenth the size of the United Kingdom (say) or in smaller groups of counties.

(ii) The systematic error in the residuals over a region could be removed.

(iii) The residuals could be trimmed before the mean and SD are calculated.

All these options were tested on principal components, for which the current scheme uses residuals analysed by district, untrimmed, but with the systematic error removed. For near neighbours only the conventional procedure of using the residuals from the nominated neighbours was tried, but there is no reason why the other options could not be used. It should be noted that the 'flagging routines' can affect the overall accuracy of a technique. The r.m.s. residuals presented so far were calculated about a mean of zero; if systematic errors over a district can be removed, then this increases the accuracy of the technique.

For minimum temperature, the smallest residuals of erroneous observations have been seen to be associated with 22 components (6% of the 373 stations used). When the performance was assessed in terms of the numbers of type I and type II errors, the continued decrease of the residuals of correct observations with an increasing number of components led to the 'best' number of components being increased to 30. Removing the systematic error in the residuals, however, produced a marked improvement in the results for a small number of components, leading to a stable performance between about 5 and 50 components.

The tuning of the quality control of minimum temperature by variation of D and S is illustrated in Fig. 5 for both near neighbours (past data and current month approaches) and principal components (with the options used by the current operational system). It can be seen that near neighbours, and in particular the current month approach, has slight advantages over principal components. In general, however, about 80% of errors can be detected by raising twice as many queries as there are errors. A point of interest is the extent to which the flagging threshold of $S = 3.25$ used in the current system is geared to economy. The number of invalid queries raised is very small, but this is only achieved at the expense of 40% of the errors remaining undetected.

The tuning of the quality control of sunshine is illustrated in Fig. 6 and reveals three main points of interest:

(i) Errors become more difficult to detect as their frequency decreases below 50%, a phenomenon discussed in the next section. In order to make comparisons with minimum temperature, therefore, the frequency of errors has been increased from 1 in 190 to 1 in 100. Fig. 6 shows that this almost halves the number of invalid queries when expressed as a proportion of the number of errors.

(ii) Analysing residuals by a small group of counties (as in a typical near neighbour scheme) is less effective than analysing them by district. This is attributed to the non-normal distribution of sunshine, which increases the sampling variability of the residuals. This renders the mean and SD calculated from a small number of stations a poor guide to the identification of errors.

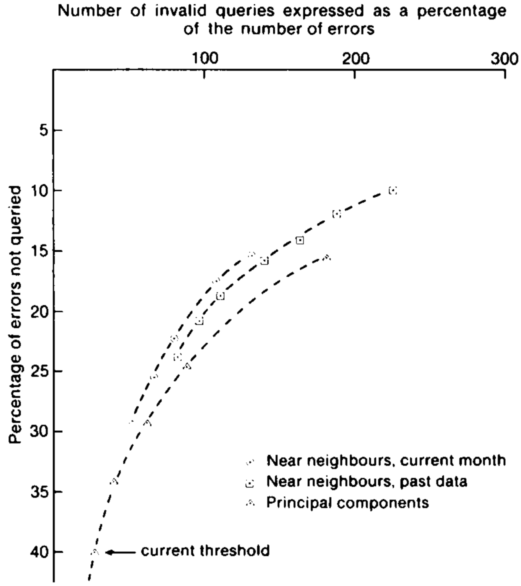

Figure 5. Effect on the number of errors not queried and the number of invalid queries of tuning the quality control of minimum temperature (1973 tested on 1978) by variations of S and D.

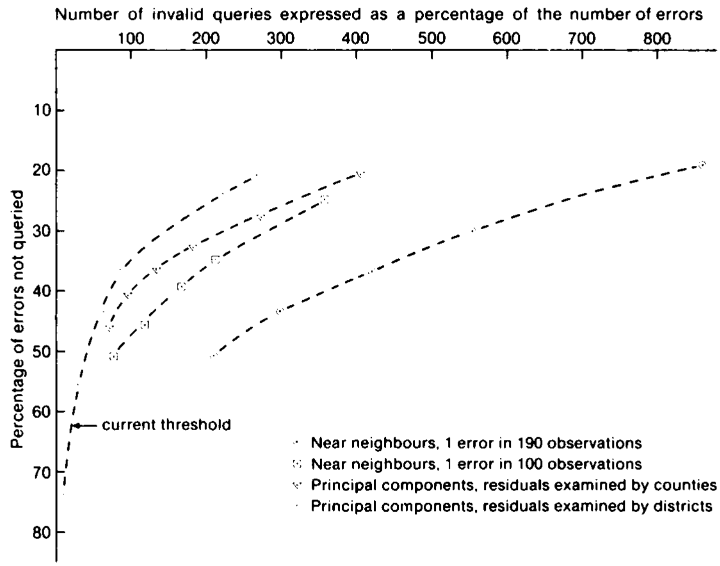

Figure 6. Effect on the number of errors not queried and the number of invalid queries of tuning the quality control of daily sunshine (1979 tested on 1983) by variations of S and D.

(iii) Near neighbours performs worse than principal components even when the residuals from the latter are analysed by counties. This is because although the residuals from both techniques have a similar mean, those for principal components have less scatter, the residuals being smaller for the more isolated stations. It is these isolated stations which generate the most queries and so an improvement in the estimates for these stations helps to reduce the number of invalid queries raised. These arguments apply to temperature as well as sunshine, but the different rates of correlation decay cause the effect to be much greater for sunshine than temperature.

9. Effect of the frequency of errors on their detection

A decrease in the frequency of errors is associated with an improvement in the accuracy with which estimates of erroneous observations can be made, but the improvement is only slight. Of more importance is the fact that as the error frequency decreases the detection of those errors becomes progressively more difficult, and the reasons for this are discussed below.

Consider a situation in which a set of observations contains some errors of $\pm 4\,^\circ$C and that the accuracy (r.m.s. residual) with which true values can be estimated is $1\,^\circ$C for both correct and erroneous observations. If as many as 50% of the observations are in error then the distribution of residuals is as illustrated in Fig. 7(a). There is good discrimination between the correct and erroneous observations with very little overlap between the two distributions. Suppose next that the frequency of errors was decreased to 1 in 10, a situation illustrated in Fig. 7(b). The relative increase in the number of correct observations has increased the overlap between the residuals of the correct and erroneous observations. If the frequency of errors is decreased to 1 in 100 (Fig. 7(c)), the overlap between the two sets of residuals is increased still further and encompasses almost 40% of the errors.

It should be borne in mind that a decreasing frequency of errors is associated with a *decrease* in the *total* number of queries raised; it is only when expressed as a fraction of the number of errors that a drastic increase in the number of invalid queries occurs. Nevertheless, Fig. 7 does demonstrate that, all other things being equal, it becomes progressively more difficult to discriminate between correct and erroneous observations as the proportion of errors decreases below 50%.

The situation illustrated in Fig. 7 approximates to that pertaining to the quality control of minimum temperature, although in the latter case the errors are not fixed at $4\,^\circ$C and so the spread of the residuals of erroneous observations will be greater than that indicated. Nevertheless, it can be seen how the current threshold of $S = 3.25$ is close to the point at which an observation is just as likely to be in error as it is to be correct. If S is decreased below this value the proportion of errors detected increases but the number of invalid queries rises rapidly.

The threshold to be chosen for raising flags depends on a management decision as to whether to aim for economy or quality. For England and Wales, areal quality control occupies one-sixth of the time of four persons involved in all aspects of the quality control of temperature and sunshine, and most of this is involved in the oral or written checking of observations. There is therefore little extra staff effort involved in aiming for quality rather than economy. For temperature it seems reasonable to generate twice as many queries as errors, corresponding to the setting of $D = 2.5$ and $S = 2.0$ (as opposed to

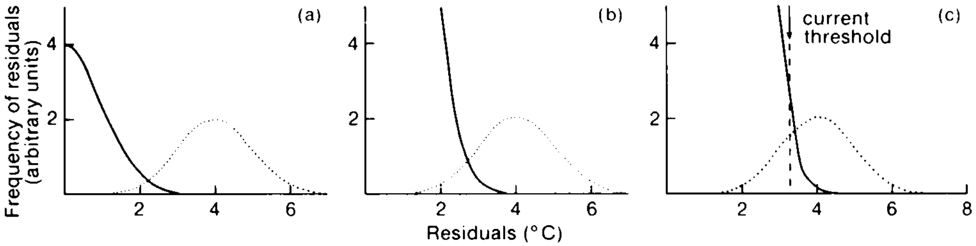

Figure 7. Effect of proportion of errors on their ease of detection, where the proportion of errors is (a) 50%, (b) 10% and (c) 1%. Solid lines indicate residuals of correct observations, dotted lines residuals of erroneous observations.

$S = 3.25$). Most of the extra errors detected will be small, however, mainly between 2.5 and 3.25 °C. So far it has been tacitly assumed that, once a query has been raised, the human scrutineer is able to make the correct decision as to whether an observation is in error or not. With the small errors under discussion the success rate may be small but will depend on the experience of the scrutineer.

10. Conclusions

The principal component and near neighbour techniques provide similar standards of quality control, with r.m.s. errors of estimates of about 1 °C for minimum temperature and 1.2 hours for daily sunshine. Principal components gains over near neighbours as the data become less well correlated and hence has the advantage of performing better at the more isolated stations. The near neighbour technique, however, produces the better estimates for new stations for which past data are unavailable. The effect of non-normally distributed data is to degrade both the estimates obtained from principal components and the effectiveness of flagging routines based on only a small number of stations, as in a typical near neighbour scheme.

The current quality-control system is close to being optimal but the following points are worthy of note:

(i) The residuals of erroneous observations can be reduced by about 10% by doubling the number of components used from 15 to 30. However, the removal of systematic errors on the one hand, and the effect of the residuals of correct observations on the other, combine to produce a standard of quality control which changes little over a wide number of components.

(ii) The system of calculating principal components from every third day over an 8-year period could be replaced by one based on using every day's observations from only 1 year of data. The decrease in accuracy for established stations (about 5%) would be offset by a simpler updatable system in which the number of new stations would be kept to a minimum (3%).

(iii) The current level of tuning of $S = 3.25$ is geared to economy by raising queries at a threshold at which observations are just as likely to be in error as they are to be correct. By generating twice as many queries as errors, the threshold could be reduced to about 2.5 °C, but the potential benefits would probably be lost through the inability of the human scrutineer to correctly identify these small errors.

The overall standard of quality control attained by the use of the conventional station network may be considered as adequate for temperature but unsatisfactory for sunshine. This is a consequence of the reduced network of stations and greater correlation decay for sunshine compared with temperature. The position with regard to sunshine is likely to change dramatically in the future as an increasing emphasis towards radiation is accompanied by the availability of satellite-derived observations. These should make it possible to estimate and quality control sunshine and radiation from a relatively sparse network of ground stations.

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551.515.41:551.576.11

Cumulonimbus clouds: an introductory review

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Summary

This article, on cumulonimbus clouds, is one of a series of teaching papers on mesoscale meteorology developed at the Meteorological Office College. It describes the important physical and dynamical aspects of cumulonimbus development, highlighting the roles of convectively available potential energy and wind shear. The aim is to provide simple conceptual models to help in the interpretation of observations; it is not a comprehensive review.

1. Introduction

All atmospheric motion is ultimately caused by solar energy but there are many ways in which this becomes available. One of the more direct is caused by the ground heating up and this in turn warming the air in contact with it. Differential heating, caused for example by variations in the nature of the ground, leads to local increases in the air temperature and in these regions the air can become buoyant and rise as a thermal, the strongest eventually developing into convective or cumulus clouds. Such clouds are often small and herald fine, sunny weather, but sometimes they develop vigorously until they extend over the depth of the atmosphere and produce torrential rain and hail, frequently accompanied by thunder and lightning. This article discusses the structure and evolution of these very large convective clouds which are often colloquially referred to as thunderstorms, although of course the presence of thunder is not essential to their formation and evolution. The aim of the article is to provide simple conceptual models to help in the interpretation of observations; it is not a comprehensive review. For more information about thunderstorms see Atkinson (1981) and Ludlam (1980) both of which provide comprehensive reference sections.

2. Quantitative description of the growth of a thunderstorm

Thunderstorms can be initiated by many atmospheric processes but to illustrate some of the important features of a developing cloud it is helpful to consider the relatively simple mechanism outlined above. As a thermal rises from the ground it cools adiabatically until eventually condensation takes place. At first the cloud droplets are small, typically 1 or 2 μm in diameter, but they grow rapidly, initially by condensation and later through collisions. If the temperature of the thermal decreases sufficiently then a few of the droplets will freeze at about $-15\,^{\circ}$C, and by about $-35\,^{\circ}$C (typically at a height of 7 km) the cloud is almost completely glaciated. The drops of water and ice particles (if present) eventually become sufficiently heavy that they fall through the buoyant updraught, growing even larger by 'sweeping up' smaller droplets, and emerge from the base of the cloud as rain, hail or snow. Below cloud base the air is unsaturated and often at a temperature above $0\,^{\circ}$C; in consequence any hail and snow begin to melt and the raindrops partially evaporate, both processes leading to a cooling and moistening of the air as the latent heats of melting and evaporation are extracted. The cold air sinks and forms a downdraught which spreads out on encountering the ground to produce a gust front at its boundary with the ambient air and creates the localized, strong, cold winds, squall lines and large wind direction changes that are frequently associated with thunderstorms.

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Thunder and lightning, although spectacular, are in fact of minor importance to the storm evolution, and severe storms can occur without their presence. The severity of a storm is essentially determined by the strength and duration of its updraught and downdraught for which the model described above gives a qualitative explanation. However, invariably we wish to quantify the effects, for unless the amount of rain and the strength of the winds can be related to the initial environmental conditions, it will not be possible to give advance warning of the characteristics of such storms.

3. Parcel theory

The simplest model of convection is called parcel theory which is based on the assumption that a positively buoyant parcel of air moves upwards without disturbing the environment. This is demonstrated on the tephigram shown in Fig. 1. Consider a parcel of air within a thermal rising from the ground. Initially it is unsaturated and as it rises it cools adiabatically, i.e. the parcel conserves both its potential temperature and humidity mixing ratio. In Fig. 1 this behaviour occurs in the region below point A. When the parcel reaches point A the air becomes saturated, cloud forms and further ascent follows the saturated adiabat, i.e. the parcel conserves wet-bulb potential temperature (θ_w). This behaviour occurs between points A and B, and throughout this part of the ascent the latent heat release is sufficient to keep the parcel buoyant, and therefore it accelerates until it reaches point B where it attains its maximum vertical velocity. All the thermodynamic energy released between A and B (shaded area — on a tephigram such areas are proportional to the energy available for convective processes) is translated into kinetic energy. Above B the parcel is colder than its environment and the energy transfer is reversed, kinetic energy is converted to thermodynamic energy, the process continuing until the hatched area above B is equal to the shaded area below B.

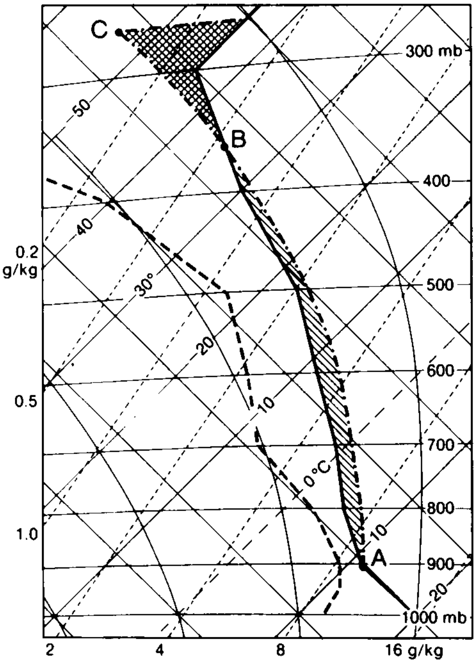

Figure 1. Tephigram illustrating the parcel theory. For details see text.

However, as the cloud develops, the assumption that it moves without disturbing the environment no longer holds. Observations readily show that at the cloud boundary the cloudy air mixes with the dry environmental air. Dryer air, with a much lower θ_w than the cloudy air, is 'entrained' into the cloud and the development is slowed down, so that in practice the cloud top rarely overshoots point B. Unfortunately it is impossible to quantify mixing in this simple model as this depends crucially on the ambient winds — a feature not included. It is therefore necessary to develop more sophisticated models of convection.

Two parameters govern the severity of convective storms; the convectively available potential energy (CAPE) and the vertical structure of the wind. The CAPE is the available potential energy that can be released through convection and is represented by the shaded area between A and B in Fig. 1. Broadly speaking, the larger the CAPE the more active the storm. However, the CAPE expresses only that energy that can be released by a parcel during ascent; it does not impart any organization to the release. In any given volume of atmosphere the CAPE can be released through many small clouds, or through one severe storm. The choice between these two extremes is governed by the ambient wind.

4. Single-cell clouds

When there is no wind a buoyant parcel of air rises vertically. As it rises, cloud droplets and then rain, hail and/or snow form. Eventually the precipitation particles achieve sufficient size for their fall speeds to exceed the updraught speed and they fall towards the ground. Initially their descent is within cloudy air and the particles continue to grow through accretion of cloud water. As they fall, they exert a slight drag on the air which gradually reduces the speed of the updraught. In addition any hail may melt, thereby cooling the air, further reducing the updraught. Eventually the precipitation falls clear of cloud and starts to evaporate. All these processes assist in the production of a downdraught which, because there is in this case no wind, is situated directly beneath the updraught. This downdraught therefore cuts the inflow to the cloud and the cloud rapidly decays. The active lifetime of these clouds is typically ½ hour; but some cloud at high level may persist for much longer.

Conditions of no wind are rare within the atmosphere. However, the wind is often uni-directional, as for example in the cold air well behind a cold or occluded front; Fig. 2 shows an example of a model of a cloud growing in uni-directional wind shear. Fig. 2(a) shows an early stage of cloud development, before rain has formed, and the updraught, leaning slightly to the right as a consequence of the ambient shear, is clearly visible. A much later stage of development is depicted in Fig. 2(b). Of particular note is the fact that updraught and downdraught coexist. The presence of vertical shear has permitted the precipitation to fall clear of the updraught and the cloud lasts longer than when there was no wind, a typical lifetime now being ¾–1 hour. Below 700 mb the downdraught is the dominant feature. When it reaches the ground it spreads out as a gust front, undercutting the warmer, environmental air and ultimately cutting off the low-level inflow to the cloud. The gust front is discussed in more detail later.

(a) *Steering level*

In Fig. 2, for illustrative purposes, the wind speed at the ground was chosen to be zero, and the wind increased with height. In consequence the cloud tended to move towards the right at some speed greater than zero, but slower than the winds at high level. The level at which the wind speed equals the cloud speed is referred to as the 'steering level' and in this example is at about 700 mb. As a general rule the height of the steering level can be determined from the height of the cloud base (h_{base}) and the height of the cloud top (h_{top}), and will lie at approximately

$$h_{base} + \frac{1}{3}(h_{top} - h_{base})$$

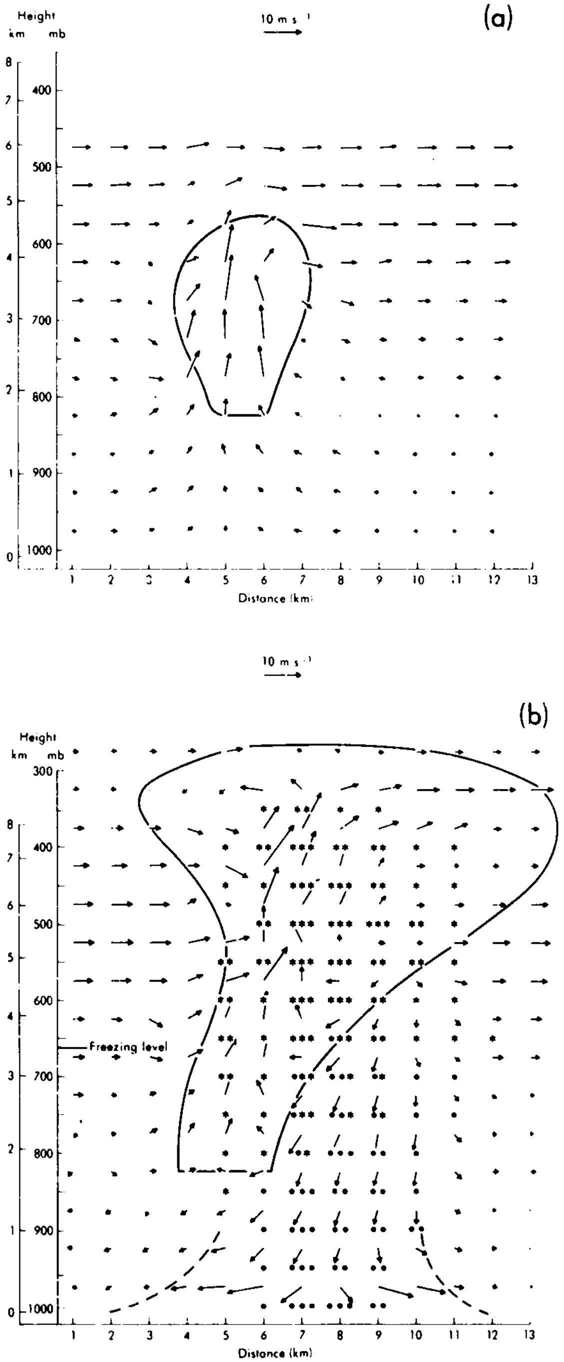

Figure 2. Model of isolated cumulonimbus cloud growing in uni-directional wind shear depicting (a) an early stage of development and (b) a more mature stage. * and • indicate snow and rain, intensity proportional to the number of symbols (from Bennetts 1983).

for all single-cell cumulonimbus clouds, and the clouds will slope 'down shear' as shown in Fig. 2 (note that the steering level changes as the cloud grows). It is useful to look at the structure of the wind relative to this steering level, as in Fig. 3. Using the cloud structure shown in Fig. 2, the low-level inflow comes in from the right (wind speed at 700 mb greater than wind speed at 900 mb) and the upper-level outflow moves away in the opposite direction (wind speed at 500 mb greater than wind speed at 700 mb). Since the cloud also leans towards the right the downdraught cuts the inflow. So, although a cloud growing in uni-directional shear has a longer lifetime than one growing in no shear, it still remains essentially a short-lived storm. To achieve a long-lived storm it is generally necessary to have 'directional shear' so that the downdraught falls to one side of the inflow. This aspect will be discussed in detail in the section on multicelled storms.

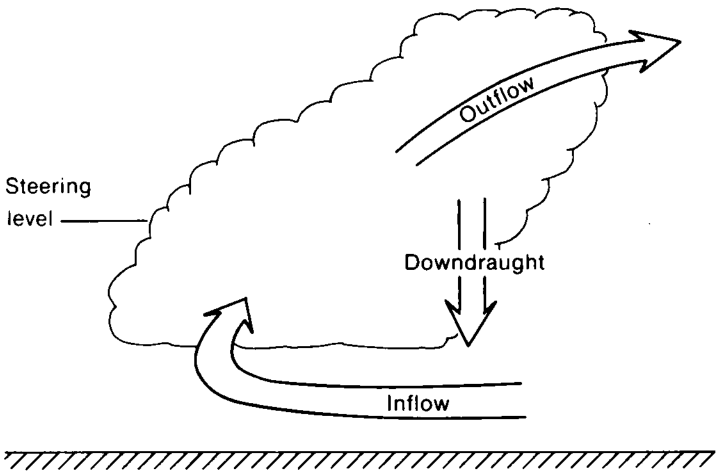

Figure 3. Schematic diagram of internal motion relative to the cloud.

(b) *The gust front*

The gust front is typically 500–1000 m deep and spreads out at 5–10 m s^{-1} relative to the cloud, but, because the depth and speed are so dependent on both the strength of the storm and the structure of the low-level winds, observed values vary widely. The boundary between the cold density current and warm environmental air is characterized by large changes in both wind speed and direction. The boundary-layer air is forced over the nose of the cold air, inducing ascent and creating a narrow region of marked convergence. Both the convergence and induced ascent are strongest where the outflowing cold air opposes the (undisturbed) low-level wind.

5. Multicelled storms

In the previous section it was noted that in conditions of no wind, cells were short-lived because the downdraught developed directly beneath the updraught cutting off the supply of moist low-level air. Uni-directional shear lengthened the lifetime of the cloud by permitting updraught and downdraught to coexist for a short time, but, even in these conditions, the inflow was eventually disrupted by the downdraught.

However, if the downdraught is displaced to one side of the inflow, much longer-lived clouds can develop. This can occur if the wind changes direction with height; for example, consider the hodograph shown in Fig. 4(a). There is no longer a level at which the cell motion matches both the wind speed and direction. However, the cell speed remains similar to the 700 mb wind and always lies within the

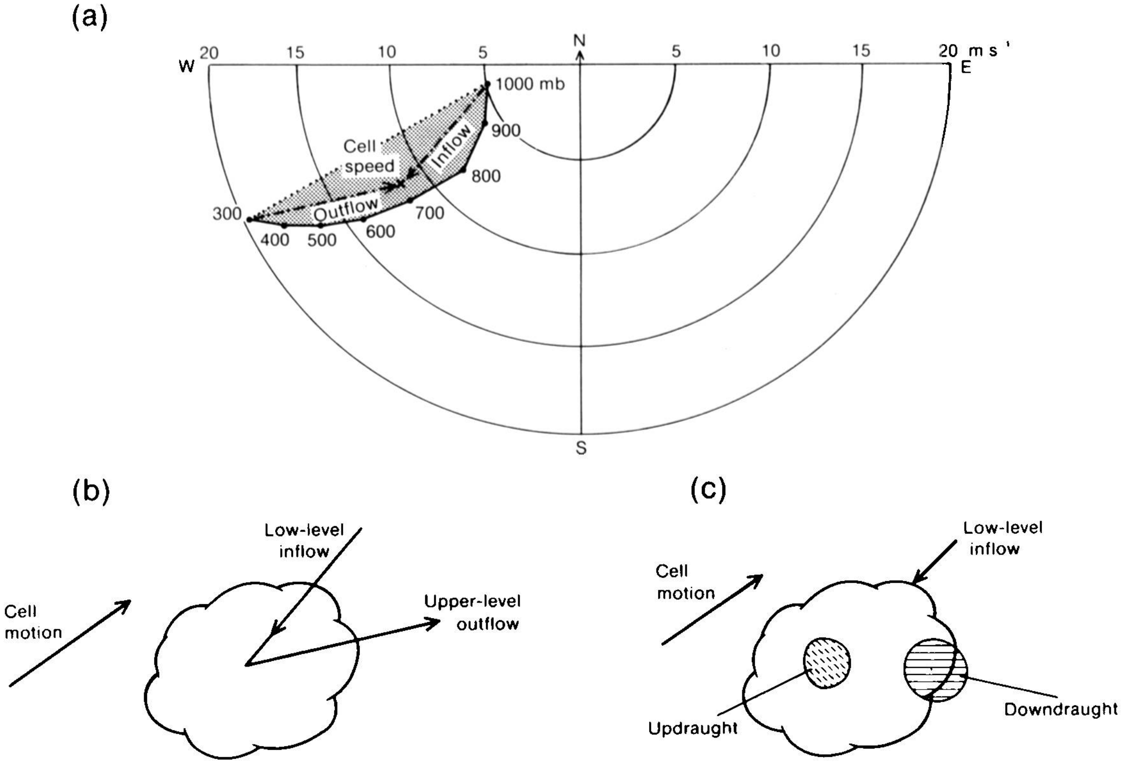

Figure 4. (a) Hodograph showing change in wind with height. The stippled area indicates the 'envelope' of the hodograph. (b) Directions of cloud-relative inflow and outflow. (c) Positions of updraught and downdraught.

'envelope' of the hodograph. Relative to the cell the low-level wind enters the cloud from the north-east and leaves towards the east-north-east (Fig. 4(b)). In consequence the downdraught is situated on the eastern flank, clear of the inflowing air, as shown in Fig. 4(c). Obviously as the downdraught spreads out it will eventually cut the inflow, but the more the downdraught is separated from the inflow the longer the elapsed time before it is cut, and hence the longer the life of the cell.

Typical lifetimes of cells growing in different conditions are as follows:

Vertical shear	Lifetime of cloud
No wind	½ h
Uni-directional shear	¾–1 h
Directional shear	1 h

6. Daughter cells

Since the downdraught forms after the formation of precipitation, i.e. late in the evolution of a cell, any increase in cell lifetime produces a disproportionate increase in the lifetime of the downdraught. In consequence the downdraught, and hence the strength and duration of the gust front, is much increased in clouds growing in directional shear. In such cases the convergence at the gust front may be strong enough to lift boundary-layer air above its condensation level. This is evident in the frequent observations of small cumulus round the base of mature cumulonimbus clouds. If the gust front is moving fast the clouds are generally small and rapidly decay. However, if the gust front becomes quasi-stationary (i.e. slow moving relative to the 'parent' cell) a large quantity of moist boundary-layer air is lifted at one point, sometimes in sufficient quantity to trigger a new cumulonimbus cloud. Such conditions are most likely to occur where the outflow opposes the low-level inflow.

The new cloud is called a daughter cell and may, in time, generate another daughter cell. The collection of individual cells is referred to as the storm. Because the cells always form to one flank of the storm, the storm will appear to move to the left or right of the cells. Since the cells move with the speed of the wind at the steering level, the storm will appear to propagate relative to the winds at all levels.

An example of such behaviour occurred on 5 June 1983 (Hill 1984). During the afternoon a series of six multicellular hail storms moved along the south coast of England Fig. 5(a). The detailed structure of one of the storms (E) is shown in Fig. 5(b). It can be seen that although the storm as a whole, shown by contours of rainfall intensity every 30 minutes, moved along the south coast, individual cells, marked with a cross at 15-minute intervals, had a more northerly track, appearing to form on the south-eastern, and decay on the north-western flank. Detailed calculations show that:

$$\text{Cell speed} = 12.0 \text{ m s}^{-1} \text{ from } 230°$$
$$\text{Storm speed} = 12.5 \text{ m s}^{-1} \text{ from } 260°.$$

Fig. 5(c) shows a hodograph of the midday ascent from Crawley. Low-level winds were from the north-east and high-level winds were generally from the west. Cell speed is marked with a cross, close to the 700 mb wind as expected, and the cell-relative inflow and outflow is illustrated in Fig. 5(d). The downdraught formed on the eastern flank and a daughter cell was generated where the gust front opposed the low-level inflow, i.e. to the east of the parent cell. The evolution of the storm is shown diagramatically in Fig. 5(e).

There is one area of slight disagreement in that the conceptual model predicts new cells forming on the east flank whereas observations showed that they formed to the south-east. This, however, is only an

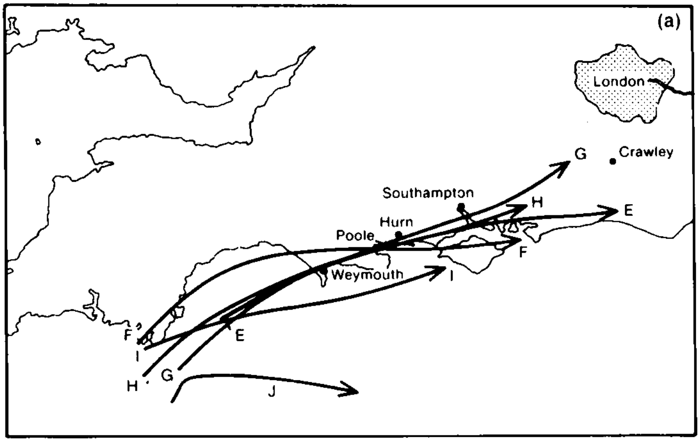

Figure 5. Various aspects of the storms of 5 June 1983. (a) The tracks of the six storms labelled E–J (from Hill 1984). (b) Detailed structure of storm E showing contours of radar reflectivity at half-hourly intervals for the storm, with cell positions (x) marked every 15 minutes. Rainfall rates (mm h^{-1}) as shown in key. (c) Hodograph for Crawley at 1200 GMT. (d) Schematic diagram showing the structure of the parent cell and position of formation of the daughter cell. (e) Schematic plan of storm development showing cell and storm motion.

apparent disagreement for the model predicts the position of formation, whereas the new cells are not seen by radar until some 20–30 minutes later, when the cells have begun to produce precipitation.

Another interesting example of how cell and storm motion can differ occurred on 14 August 1975, the day of the 'Hampstead storm' (Miller 1978). The hodograph for this storm is shown in Fig. 6(a). There was a very marked directional change in the low-level winds, but above 800 mb the wind was almost

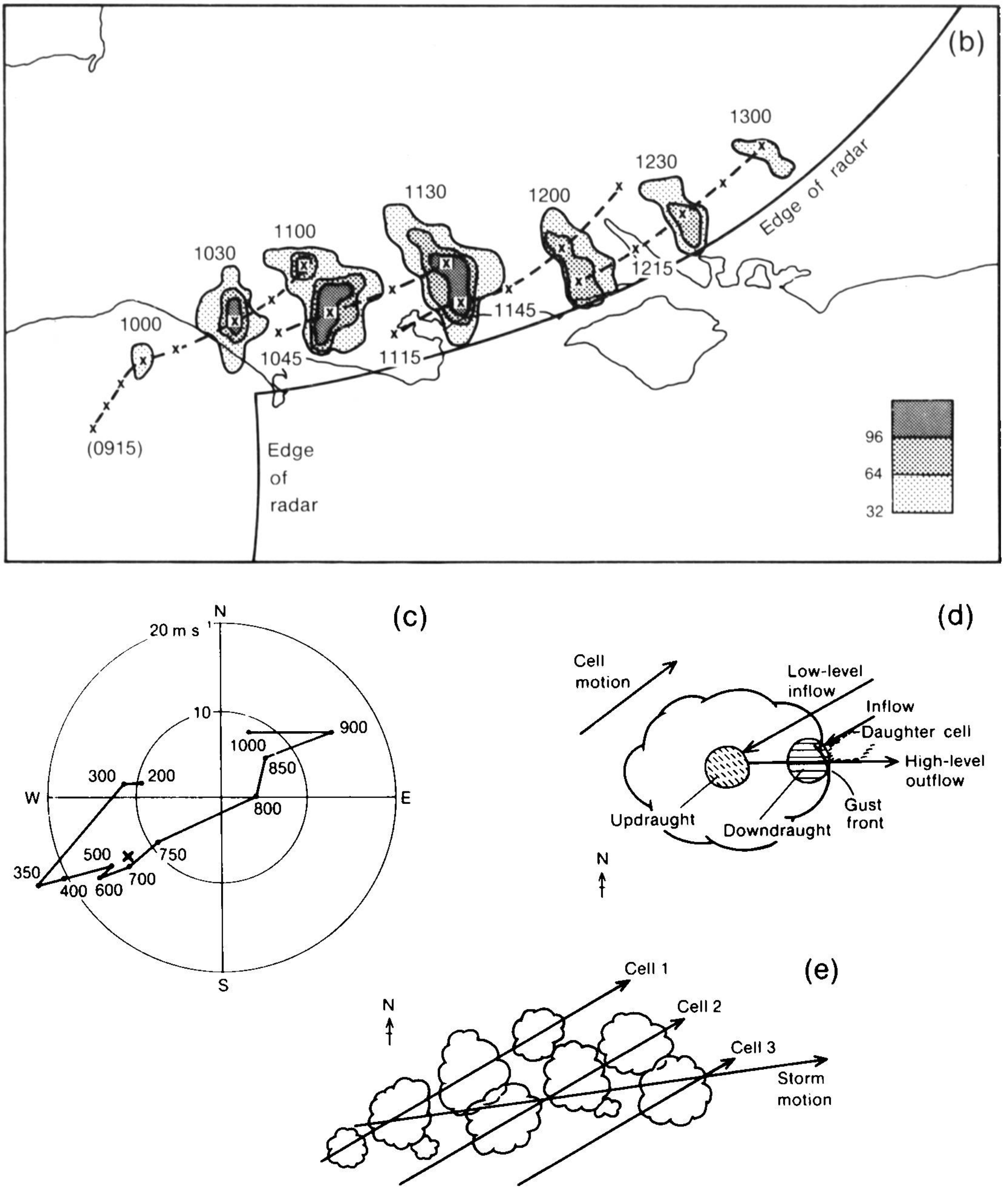

Figure 5 continued.

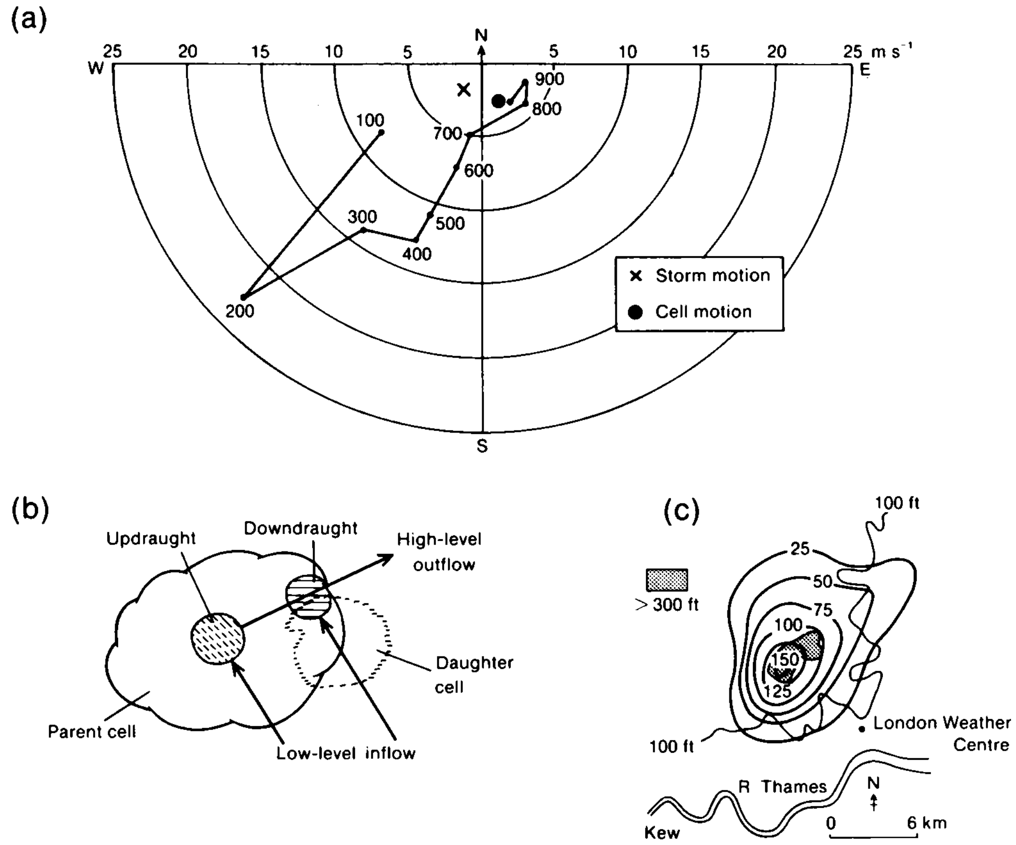

Figure 6. Various aspects of the Hampstead storm, 14 August 1975. (a) Hodograph (from Miller 1978). (b) Cell-relative positions. (c) Isopleths of rainfall (mm) for the period 0900 GMT on 14 August to 0900 GMT on 15 August over north London (from Miller 1978).

uni-directional and increased in strength with height. The mean motion of the cells was towards the north-west. As shown in Fig. 6(b) the downdraught formed on the eastern flank and a daughter cell developed on the south-east flank. Relative to the cell the storm propagated south-eastwards; relative to an observer on the ground the storm appeared stationary (Fig. 6(a)). To the residents of Hampstead cells were seen to form to the south-east, deposit their rain overhead and decay as they moved towards the north-west. This pattern was repeated five or six times and the accumulated rainfall is shown in Fig. 6(c). Fortunately such stationary storms are rare.

A useful rule describing the movement of storms is as follows:

Wind veers with height — storm moves to right (of cell).
Wind backs with height — storm moves to left (of cell).

7. Supercells

One further type of storm remains — the supercell. It is rare in the United Kingdom but common in continental regions where it is responsible for considerable damage mainly through the production of giant hailstones, sometimes up to the size of golf balls. It is much larger than normal storms, often up to

50 km in diameter, and is associated with very strong wind shears over significant depths of the atmosphere. These storms tend to occur when the CAPE is large; typically five to ten times larger than the values generally found in the United Kingdom, e.g. parcel to environment excess temperatures of around 10 °C.

The main characteristic of a supercell is that it is in quasi-steady state with updraught and downdraught coexisting for typically 1–3 hours, but on occasion for up to 12 hours. In some ways a supercell may be seen as the ultimate multicelled storm where the downdraught is so positioned that the daughter cell is co-located with the updraught of the parent cell.

An example of a hodograph associated with a supercell is shown in Fig. 7(a). Consider first the structure of a multicell storm growing in this environment (Fig. 7(b)). Each cell would have a steering level (see section 3(a)) close to that of the mid-level winds, the downdraught would form on the eastern flank, spread out, ultimately cut the inflow and possibly generate a new cell to the east.

However, supercells are always observed to have a motion outside the envelope of the hodograph (see Fig. 7(a)) — precisely why is not yet fully understood. In consequence storm-relative winds are rather different, Fig. 7(c). In particular, mid-level winds are stronger and tend to have an influence on the position of the downdraught which, in supercells, forms on the opposite side of the updraught to the inflow. Maximum convergence occurs directly underneath the original updraught.

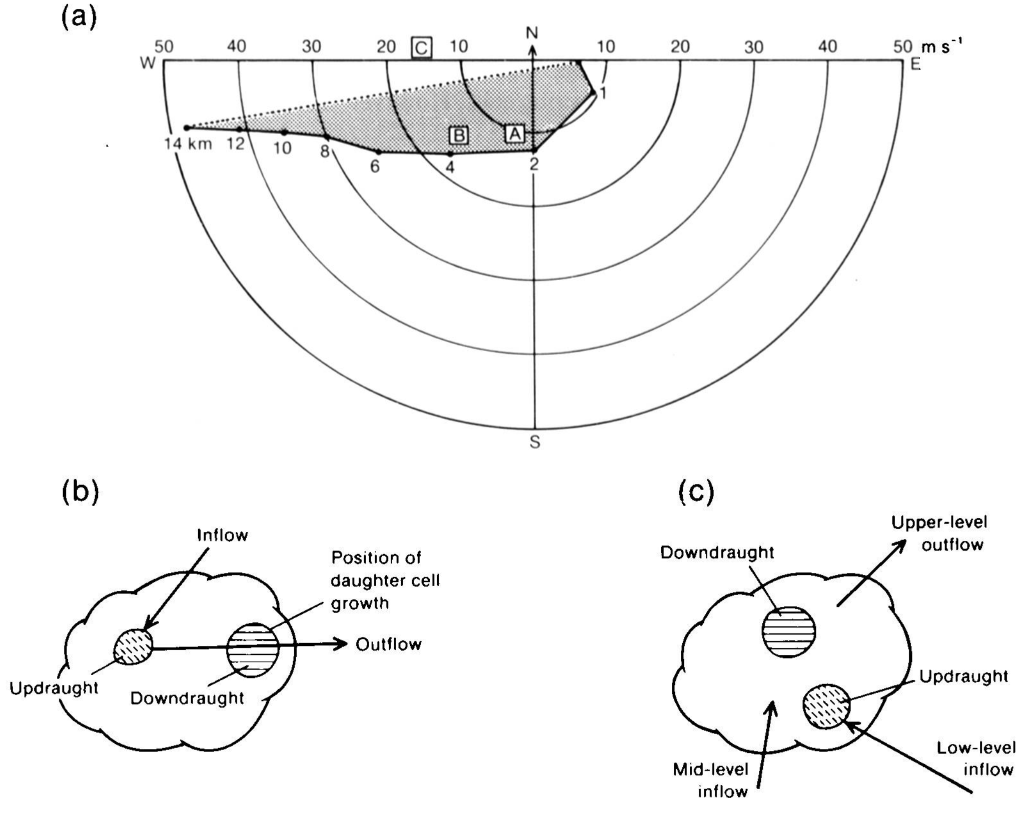

Figure 7. (a) Hodograph associated with a supercell showing individual cell speed at A, multicell storm speed at B and supercell storm speed at C. (b) Schematic diagram of growing multicell storm. (c) Schematic diagram of supercell.

8. Merging storms

Another way in which large cumulonimbus storms can develop is through merging although, to be precise, merging should be viewed as just one aspect of cloud–cloud interactions. Merging can occur in many ways. For example, within a region of forced ascent in a trough line, clouds are frequently forced together and merge. Although each individual event may not be predictable, in general, within the trough line, enhanced convection is expected. However, this is not the only way in which clouds can merge. Consider a uniform, unstable air mass having uni-directional vertical wind shear, such as occurs, for example, well behind a cold front over the sea. Further, assume that within this air mass there develops a population of single-celled clouds. At any given time clouds will exist at all stages of development (i.e. there will be a range of cloud-top heights, the younger the cloud the lower the cloud top). Since the steering level varies during the evolution of the storm the propagation speed of different clouds will vary. Therefore occasionally, by chance, some clouds will move close together and interact. Generally this interaction will reduce the size and strength of both clouds as, due to their close proximity, their inflow regions will overlap and they will compete for the unstable boundary-layer air. However, sometimes the interaction is beneficial and 'merging' results. One way in which this can occur is when the upstream cloud is larger than the downstream (i.e. possibly slightly older). The development in such cases is shown in Fig. 8, and a comparison of the rainfall rate of a single-cell and merger cloud growing in the same environment is shown in Fig. 9. Merging can enhance the rainfall significantly and lower the cloud base.

In consequence, even when the air mass is uniform and conditions are unsuitable for multicellular development, a few large cells can still develop. The occurrence of these is random, depending on the relative position and development of neighbouring cells. However, it is essential to remember that they can, and do, occur.

9. Precipitation

So far, the storms have been discussed in terms of their dynamics. However, it is equally important to know how much precipitation falls to the ground. We have already seen that, in terms of understanding the cloud, the most useful frames of reference are axes moving with either cell or storm velocity. In consequence, for rainfall studies, it is useful to consider the two aspects:

(a) rainfall from a given storm, and
(b) rainfall at the ground,

allowing storms to be studied independent of their translation speed. Before the advent of radar this was difficult, but today storms may be readily studied in their natural frame of reference. It is interesting to reconsider the stationary Hampstead storm for which the mean rainfall total was 100 mm. If that storm had instead had a storm velocity of say 5 m s^{-1}, the rainfall at Hampstead would have been reduced by a factor of about 4, to ~ 25 mm, and the Hampstead storm would have caused little comment, being an average summer thunderstorm.

Indeed, many other severe storms go unnoticed simply because they move quickly and give little rain at any given ground station. It is therefore important to predict those few occasions when the storm velocity is close to zero.

In tackling this problem it is useful to introduce the concept of the 'efficiency' over the lifetime of a storm which may be defined as

$$\text{efficiency} = \frac{\text{total rainfall at ground (cell-relative)}}{\text{total cloud water condensed}} .$$

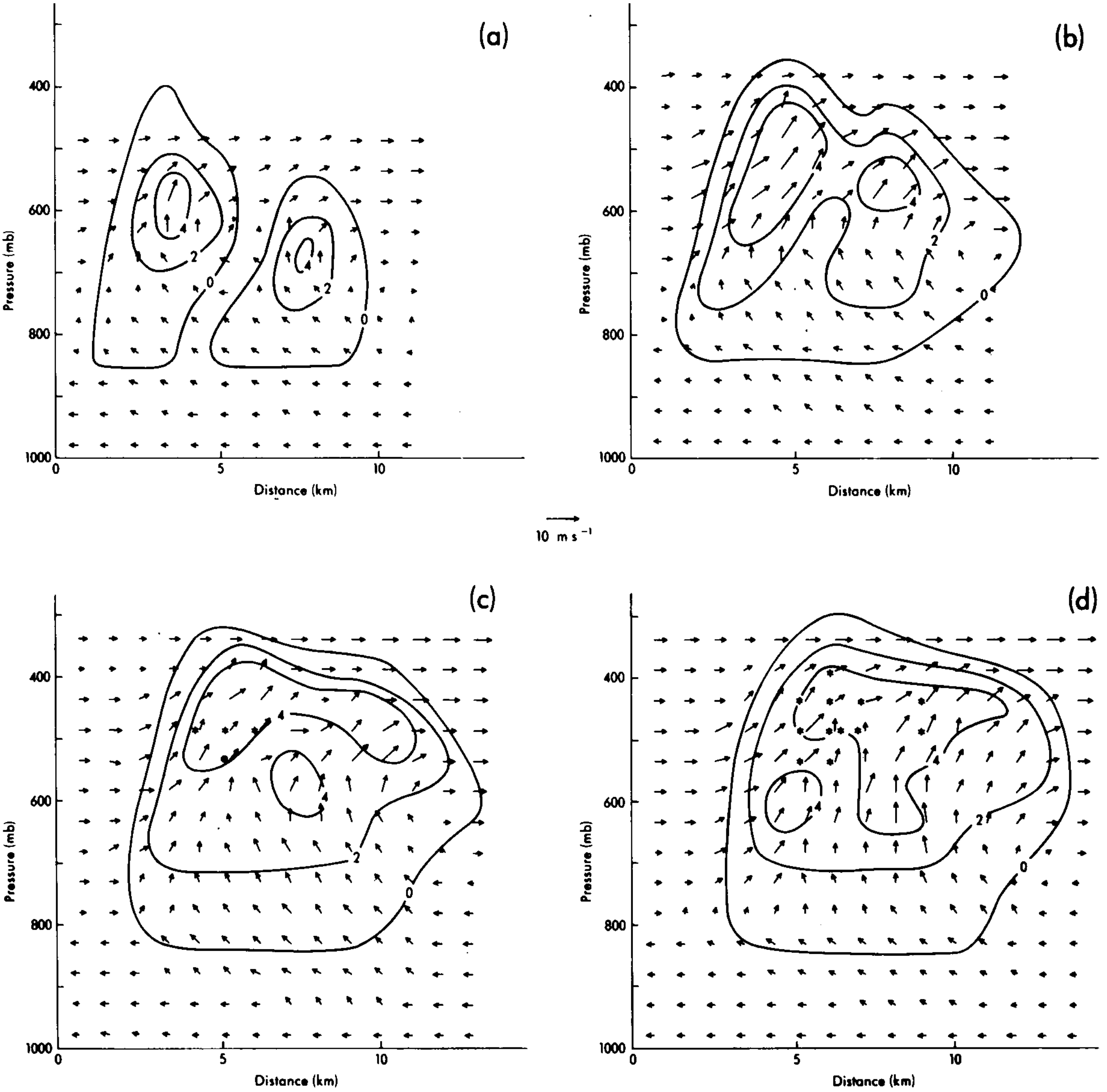

Figure 8. Distribution of cloud water and ice (g kg^{-1}) and wind vectors within clouds at simulated times of (a) 12 minutes, (b) 16 minutes, (c) 20 minutes and (d) 24 minutes. * and • indicate snow and rain (from Bennetts *et al.* 1982).

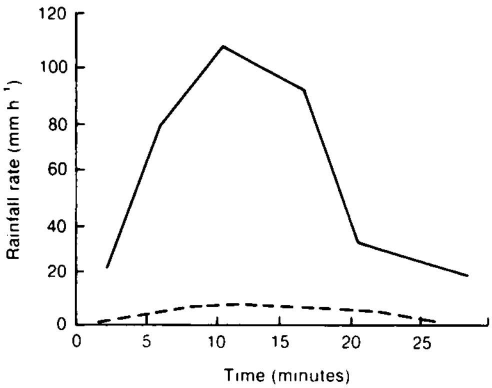

Figure 9. Observed rainfall rates from merged (solid line) and single-cell (dashed line) clouds. On a given day, when the wind direction changed little with height, a population of maritime single-cell clouds was observed by radar. The dashed line shows the maximum instantaneous rainfall rate anywhere within the cloud, plotted as a function of time from initial observation, for a typical cloud. The solid line is representative of the largest (in rainfall rate) cloud observed. (From Bennetts *et al.* 1982.)

This equation may be rewritten as

$$\text{efficiency} = \frac{\text{production of rain}}{\text{CW}} + \frac{\text{accretion}}{\text{CW}} - \frac{\text{evaporation}}{\text{CW}}$$

where CW = cloud water condensed, and the relative magnitude of these terms depends on the trajectory of rain as it falls to the ground. This is illustrated in Fig. 10.

Fig. 10(a) shows the evolution of rain within a single cell growing in no shear. Precipitation is generated fairly high in the cloud, falls through cloud accreting cloud water and growing rapidly until it reaches cloud base, and then evaporates between cloud base and the ground. Compare this to the evolution within a single cell growing in uni-directional shear, Fig. 10(b) (paths are relative to the cloud). In the shear case the ratio

$$\frac{\text{accretive path length}}{\text{evaporative path length}}$$

is very much reduced and therefore the higher the shear the lower the amount of precipitation reaching the ground, in spite of the fact that the lifetime of the cell slightly increases as the shear increases.

Each cell of a multicellular storm has a similar behaviour but because there are several cells the total rainfall can be quite large.

In both single cells and multicells efficiency remains low (~ 30%) as each cell has a large remnant cloud which slowly dissipates after the rain has ceased. In contrast, supercells achieve a steady state. At the end of their life, there is only the remnant from one cell and in consequence they have a much higher efficiency, sometimes up to 80%.

Merging clouds produce high rainfall for a different reason. Here, the presence of the smaller cloud alters the path length ratio, see Fig. 10(c), with precipitation from the upstream cloud falling through the smaller cloud.

10. Conclusions

Parcel theory tells us whether or not convection can occur; the vertical structure of the wind tells us how that convection will be organized. It is therefore important to consider both aspects when forecasting the behaviour of convection.

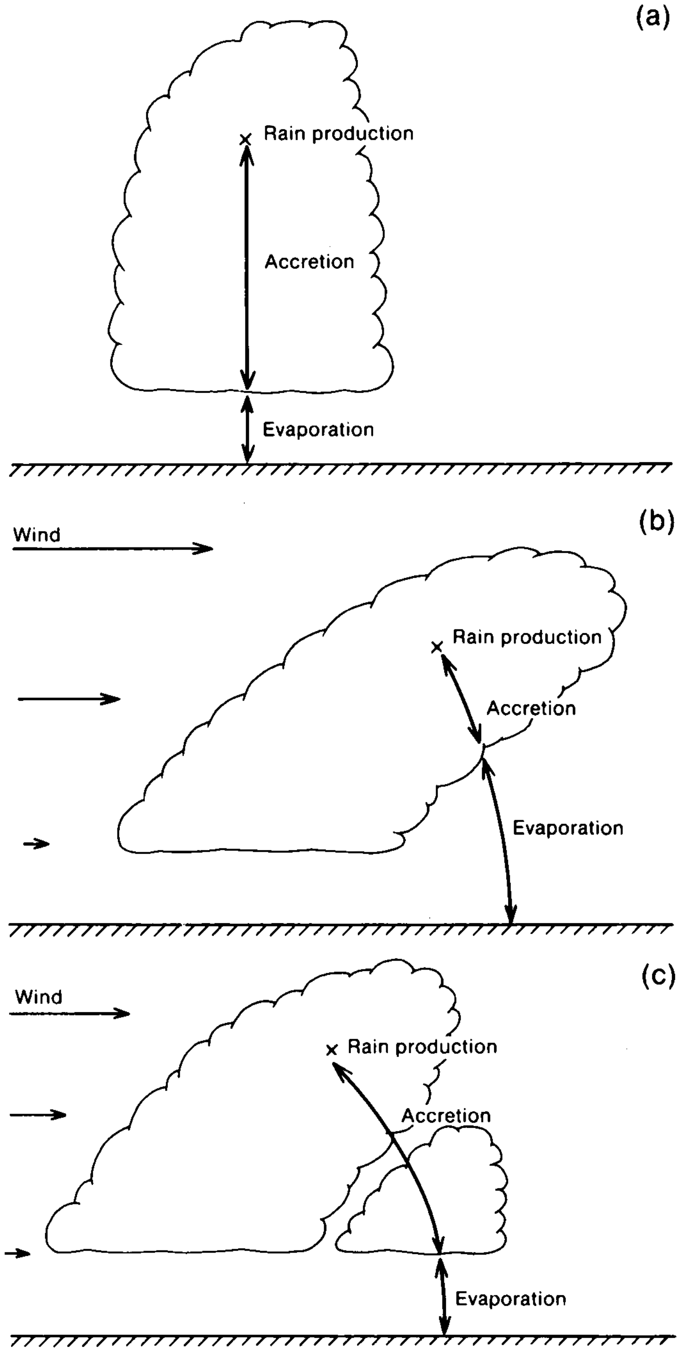

Figure 10. Comparison of accretive and evaporative path lengths for (a) single-cell cloud growing in no shear, (b) single-cell cloud growing in uni-directional shear and (c) merger growing in uni-directional shear.

Although it is difficult to forecast the precise behaviour of cumulonimbus clouds on any given day, the following general rules give some guidance by providing simple conceptual models to assist with the interpretation of such observations as may be available, e.g. radar network data.

After an examination of the tephigram, the vertical wind profile should be studied and classified according as to whether the wind direction is fairly constant throughout cloud depth, or varies markedly with height. The typical behaviour of these two categories follows:

Uni-directional shear

When the wind direction is fairly constant at all levels up to cloud top, convective clouds are generally single celled, short-lived (about ½–¾ hour) and tend to form and disperse under the influence of local effects. Rainfall may be quite heavy, but will rarely last long as the precipitation-induced downdraught tends to cut the cloud's supply of low-level boundary-layer air, leading to rapid decay.

Directional shear

It is not until there is a directional change in the vertical wind profile that long-lived storms become possible. A directional change, with height, permits the downdraught to form to one side of the inflowing air allowing updraughts and downdraughts to coexist for a significant time. This may lead to the formation of daughter cells on one flank of the parent cell and, over a period of 15–30 minutes, the centre of activity transfers from the decaying parent cell to the rapidly growing daughter cell. Such a process can continue for a succession of cells, each cell propagating with the steering level wind, but with the storm appearing to propagate relative to the winds at all levels. In such cases a useful rule is: wind veers with height — storm moves to the right; wind backs with height — storm moves to the left.

The final type of cloud is the supercell. These are very rare in the United Kingdom, but precursors to their formation are large values of the CAPE, typically ten times larger than the values commonly found in the United Kingdom, and very large wind shears.

It is also important to remember that clouds may, on occasions, merge. This is to be expected within, for example, trough lines, but can also occur in relatively uniform air masses. In the latter case the process is random and can occur whenever there is a vertical wind shear such that clouds at different stages of development have different steering levels, and hence slightly different translation velocities. This induces relative motion and they may, on occasions, merge, producing a significant increase in rainfall.

Acknowledgements

We would like to thank all the staff and students at the College who have helped in the development of this paper, especially Miss W.L. Adams who analysed the radar data and produced Fig. 5(b).

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The Mobile Meteorological Unit in the South Atlantic 1982–86

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Summary

On 2 April 1982 Argentina invaded the Falkland Islands and South Georgia. Within six days the first deployment of the Mobile Meteorological Unit (MMU) had taken place to Ascension Island and on 5 July 1982 the first MMU officer arrived in the Falkland Islands, where the Unit was destined to remain for nearly four years. This article gives an account of the MMU in the South Atlantic from April 1982 to April 1986.

1. Introduction

The Mobile Meteorological Unit (MMU) was formed in the early 1960s as part of the Royal Air Force Tactical Communications Wing. With a ceiling of 20 officer volunteers drawn from Headquarters Branches and outstations of the Meteorological Office and holding active Class CC (Civil Component) Commissions in the Royal Air Force Reserve of Officers, the role of the Unit was to be able to deploy at very short notice, in an emergency, within the NATO area. The Unit was, accordingly, equipped with its own air-portable accommodation, meteorological instrumentation and communication equipment and officers were provided with suitable clothing for operations in warm or cold climates. The Unit's role was exercised from time to time but, by the late 1970s, with the increasing use of host nation meteorological support, the future of the MMU had become uncertain and the morale of its members was not high. The events of April 1982 changed that.

2. Ascension Island

Three days after the invasion of the Falkland Islands (see Fig. 1) found the MMU on standby with four members of the Unit ready to move at 24 hours' notice. The following day, 6 April, instructions were received to deploy to Ascension Island. A (fortuitous) delay enabled the Unit to gather together further charts and equipment suitable for operations in the South Atlantic and departing from RAF Lyneham on 8 April the Unit detachment, comprising two forecasters and two communicator/observers under Squadron Leader W.R. McQueen, arrived with its equipment in the small hours of 9 April at Wideawake airfield, Ascension Island.

On the instructions of the Senior British Officer (SBO), Ascension Island, the MMU was deployed to English Bay at the extreme north of the island, some seven miles from Wideawake airfield. Interference to meteorological radio communications from a nearby transmitter complex, however, combined with the remoteness of the Unit from its aircrew customers quickly confirmed the unsuitability of locating the Unit at English Bay. Further consultations with the SBO resulted in the establishment of the MMU at Wideawake airfield where the equipment was reassembled. The Unit became fully operational on 12 April and provided meteorological support for all air operations out of Ascension Island over the North and South Atlantic. The MMU's contribution to Operation Corporate, the code name for the recovery of the Falklands and South Georgia, had begun.

The MMU 'office' at Wideawake airfield was under canvas (Fig. 2), and domestic accommodation remained hutted at English Bay. Neither were air-conditioned. The shifts worked were long — 24 hours on, 24 hours off — the work-load heavy, and enthusiasm for composition rations quickly waned. The seven-mile transfer before and after each 24-hour shift was described as 'being over roads which required

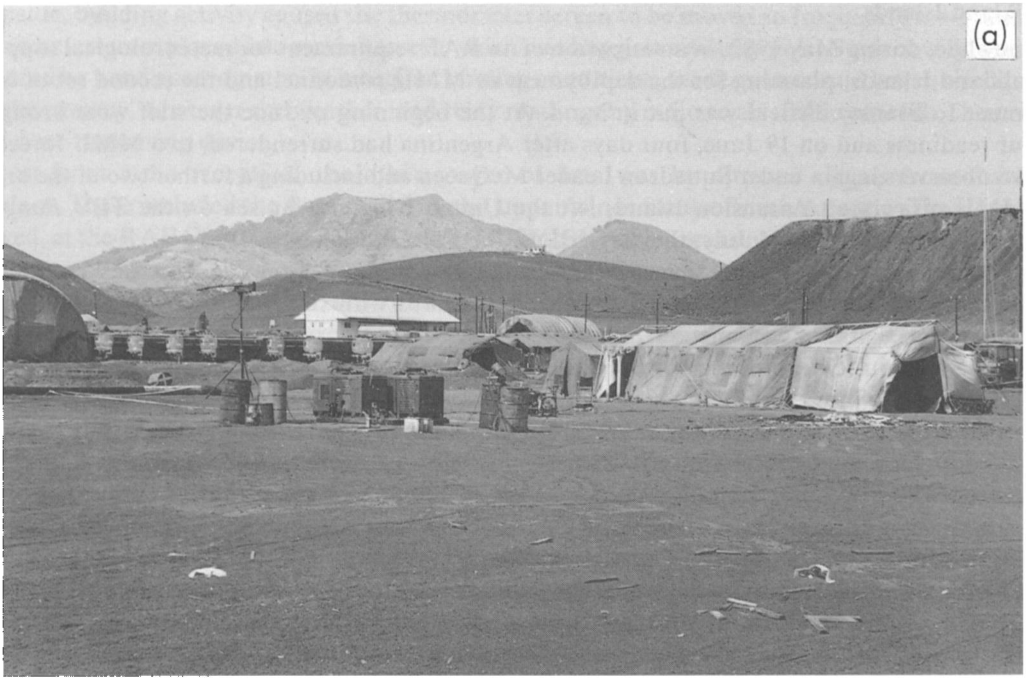
Figure 1. Map showing the position of the Falkland Islands and other places mentioned in the text.

some attention'. On 14 April two additional MMU officers were flown to Ascension Island but, owing to the severe shortage of accommodation on the Island at this time, one of these officers plus one of the original four was instructed to return immediately to the United Kingdom. The Unit strength thus remained at four and, although *roulements* (the rotation of military personnel/equipment) took place approximately every six weeks, it was to be August — nearly two months after Argentina had surrendered — before the strength of the detachment could be increased to five.

Nonetheless, with invaluable weather satellite imagery, improved reception of international meteorological radio telegraph and facsimile broadcasts and, from 17 April, forecasts of winds and temperatures at several upper levels from the Meteorological Office 15-level computer model (the southern hemisphere aspect of which had been subject to extensive programming work at very short notice), the MMU was able to meet the exacting demands placed upon it by RAF activity — particularly for air-to-air refuelling — in the North and South Atlantic as the Task Force moved southwards.

Following the recovery of the Falkland Islands, conditions at Ascension Island gradually improved. In June essential servicing of communication equipment was undertaken by staff from Bracknell. In July domestic accommodation was transferred to a bungalow in Georgetown and, although rooms were still shared, this was a great improvement. As mentioned earlier, in August the detachment strength was increased. Towards the end of the year additional furniture was received for the office and, finally, in March 1983 the MMU moved from its tented accommodation to an air-conditioned cabin. Throughout this period the routine had settled down mainly to forecasting for northbound flights to Dakar and the United Kingdom, and near-daily C130 flights and their supporting tanker aircraft to RAF Stanley.

During 1983 plans were made to transfer the RAF Ascension meteorological commitment from the MMU to normal civilian manning and, as mess accommodation became available at the new RAF complex at Travellers Hill, the change was gradually made between December 1983 and March 1984 — the last Ascension-based MMU officer arriving back in the United Kingdom on 28 March 1984.



Photographs by courtesy of Flight Lieutenant P. Wyatt (MMU)

Figure 2. The MMU tented office at Wideawake airfield, Ascension Island, (a) outside and (b) inside views.

3. Falkland Islands

Meanwhile, during May 1982, in anticipation of an RAF requirement for meteorological support in the Falkland Islands, planning for the deployment of MMU personnel and the second set of MMU equipment to Stanley airfield was put in hand. At the beginning of June the staff were brought to 48-hour readiness and on 19 June, four days after Argentina had surrendered, two MMU forecasters and two observers, again under Squadron Leader McQueen and including a further two of the original four MMU officers on Ascension Island, left the United Kingdom by sea on the TEV *Rangatira*. Twenty-two days later, on 11 July, they arrived off the Falkland Islands.

On 13 July, naturally believing themselves to be the first MMU personnel on the Falkland Islands, they set out to 'set up shop' on Stanley airfield. It was thus with some amazement (and not a little disappointment) that they were met on the airfield by a fellow MMU officer who, at very short notice to meet an urgent requirement for meteorological observations to support RAF operations at the airfield, had flown to RAF Stanley arriving on the 5th.

The appalling conditions obtaining at and around Stanley airfield were comprehensively covered by the media at the time. Suffice to say that with minefields everywhere, and unusually severe South Atlantic midwinter weather, any difficulties which had been encountered on Ascension Island soon paled into insignificance. Even with the MMU's well-known reputation for improvization and innovation, improvements were to be very slow.

The MMU was allocated a small room at the front on the ground floor of the airfield control tower (Fig. 3). Conditions were primitive. Apart from one table, furniture consisted of crates and boxes. Lighting was by one 60-watt bulb. All radio equipment was in the room, as was the weather satellite reception equipment. Administrative matters were also dealt with here. In such conditions the MMU officers grappled with southern hemisphere weather forecasting.

Photograph by courtesy of Mr E. Hibbett

Figure 3. Control tower, RAF Stanley, Falkland Islands. The weather satellite dish aerial can be seen on the ground (left) and the laser cloud-base recorder on the roof (right).

Outside, building activity caused the thermometer screen to be moved so frequently that, finally, the thermometers were placed in a marine screen which was hung on a nearby pole. Surface wind speed was measured by hand anemometer. In marginal landing conditions, an observer could be required to stand near the runway, whatever the weather, and relay readings by radio to air traffic control. There was no cloud-base measuring device.

Apart from radio reception, the other source of data was by directed signals from the United Kingdom. These included the Bracknell forecast upper winds for the South Atlantic. The signals were received, at the RAF Communications Centre (COMCEN) which was several hundred yards away, and had to be collected; additionally, all outgoing traffic — e.g. routine observations, airfield landing forecasts and aircraft debrief data — had to be taken to the COMCEN. When transport was not available this was a tiresome chore; at night, if contact with the patrolling guard dog handlers could not be made, the 'signals run' was even more unpopular.

Domestically, conditions were little better. Accommodation, two to four per cabin, remained on the TEV *Rangatira* which was moored in Stanley harbour. Travel to work comprised transfer from the ship by landing craft followed by a five-mile journey over pot-holed roads by truck to the airfield. Because both components of the journey were so unreliable, 24-hour duties were worked. The return journey for tired staff seemed even more unpleasant, especially as it was often 27 hours before staff were back on board the *Rangatira*. Even then, despite their extreme tiredness, frequent messages over the ship's tannoy system, military exercises, and the difficulties shift workers always experience when sharing accommodation, would often combine to make sleep difficult.

Apart from the air freighting to Stanley of an anemometer mast and its installation with its associated equipment, overall conditions for the MMU in the Falkland Islands during the ensuing months improved only marginally. The small size of the MMU and its concurrent commitment on Ascension Island dictated that Stanley *roulements* had to be by air from the United Kingdom — i.e. the Unit could not tolerate the time penalty of travel by sea between Ascension Island and the Falkland Islands. At the same time, pressure on air-bridge seats between Ascension Island and RAF Stanley resulted in detachments being set at three months. It is little wonder that the above regime, with some weeks in which more than 100 hours were worked, often led to officers returning to the United Kingdom visibly tired and drawn.

In May 1983, however, the situation began to improve with the servicing and upgrading of communications and other equipment by staff from Bracknell. (Meteorological Office technicians were subsequently to visit the South Atlantic offices at regular intervals.) During June and July domestic accommodation was transferred, at last, to one of the nearer floating accommodation units known as Coastels and towards the end of the year extra office accommodation became available in the control tower thus relieving the cramped conditions. A laser cloud-base recorder was received and was immediately made operational. Although a 'nodding beam' cloud-base recorder had been on the islands for many months, it had proved impossible to obtain the necessary priority for its installation. This was symptomatic of the frustrations experienced at the time.

There were setbacks, though. Despite strenuous efforts locally and in the United Kingdom, attempts to obtain a dedicated vehicle for the MMU were unsuccessful and the untold inconvenience and inefficiency this caused continued — as did reliance for transport on the enormous goodwill of air traffic control and operations staff. In June an officer on his second tour of duty at RAF Stanley broke his wrist while observing in gale force winds from the ice-covered aircraft dispersal area and was casualty evacuated.

In addition to its basic role of providing continuous observations, forecasts for local military operations, and route forecasts, the MMU undertook other tasks. These included the installation of meteorological instruments, and the training in weather observing of Service personnel at remote exposed sites and of Army personnel *en route* to South Georgia. By now, the decision had been taken to construct a major airfield at Mount Pleasant. The MMU helped the Property Services Agency (PSA) to set up a rudimentary observations programme there and, later, the MMU became increasingly involved 'on the spot' as the planned Main Meteorological Office (MMO) at Mount Pleasant took shape.

Further changes and improvements occurred during 1984 and 1985. In July 1984 the MMU at last received its own vehicle. That November a satellite telegraph link from Bracknell into the Stanley office became operational and eliminated the requirement for directed signals and the routine reception of radio telegraph broadcasts. Meteorological bulletins originating in the United Kingdom or taken from the Global Telecommunication System were automatically routed on to the link. In February 1985 a facility to send messages to Bracknell for automatic handling also became operational. In April responsibility for forecasting for the Falkland Islands Protection Zone was transferred to the MMU from the Royal Navy and on 1 May 1985, when RAF Mount Pleasant became partially operational, the MMU became responsible for its landing forecasts, weather warnings and route forecasts. Indeed, when the first wide-bodied aircraft landed at Mount Pleasant on that day, the captain congratulated the MMU on an excellent landing forecast — the weather improving, as forecast, shortly before the aircraft landed. *Roulements* were now by British Airways 747s or RAF Tristars in and out of RAF Mount Pleasant; this was a considerable improvement on the air-bridge flights.

A civilian Meteorological Office observer had been posted to RAF Mount Pleasant for the initial operations and worked from temporary accommodation. During the rest of 1985 the observing programme and staff there gradually increased. At the end of 1985 the MMO building was formally accepted by PSA from the contractors, and between February and April 1986 the MMO built up to its full complement. At the end of April, as the RAF transferred its operations from RAF Stanley to RAF Mount Pleasant, the MMO, under a Principal Meteorological Officer, accepted full responsibility for all the MMU's functions at RAF Stanley and the MMU was simultaneously withdrawn.

Thus ended almost exactly four years of MMU operations in the South Atlantic.

4. Commentary

The greatest strain upon the MMU was from July 1982 to the end of 1983 when, within its original complement, the Unit was operational at both South Atlantic locations. During this period officers could expect less than a month in the United Kingdom between detachments. In November 1983 the MMU ceiling was increased to 25. Although this ceiling was never to be quite reached, further volunteers into the MMU, combined with the civilianization of Ascension Island by March 1984, sharply reduced the burden. Nevertheless, 5 officers each completed no less than 9 tours of duty in the South Atlantic and a further 12 officers each completed 6 or more tours.

By 1982 the long-term future of the MMU had been uncertain for some years and for this reason it had not been possible for resources to be allocated for updating equipment. When the call came in 1982 the MMU radio communications and weather satellite reception equipment were antiquated — the radio equipment had valves! The continuous operation of such equipment in poor conditions resulted in considerable maintenance problems. That these difficulties were largely overcome, frequently by the exchange of numerous signal messages, reflects the considerable efforts and expertise of the Meteorological Office Telecommunications Branch at Bracknell and the MMU personnel and RAF technicians on the spot.

In addition to the essential support received from the Telecommunications Branch, the MMU also acknowledges the support it received from the Directorate of Naval Oceanography and Meteorology, from the Principal Forecasting Office, Headquarters Strike Command, and from a number of Headquarters Branches at Bracknell. These include, in particular, the Special Investigations Branch (which not only put together within days in April 1982 a South Atlantic climate brief but subsequently actioned, at short notice, many requests for statistical data in the South Atlantic region), the Central Forecasting Branch, and the equipment section of the Finance and Supply Branch.

5. Awards and appreciations

Following Operation Corporate, Squadron Leader McQueen was awarded the MBE and ten members of the MMU were awarded the South Atlantic Medal. The invaluable service provided by the MMU, both during Operation Corporate and afterwards, has been recognized in many quarters, and messages of appreciation have been received from the Air Staff, the senior Directorate of the Meteorological Office and the Director of Naval Oceanography and Meteorology. Most recently, Air Vice-Marshal K.F. Sanderson, CB, RAF, Air Officer Commanding Directly Administered Units, Headquarters RAF Strike Command, paid tribute to the MMU, complimenting the officers on their enormous contribution to RAF operations in the South Atlantic, their dedication to duty during frequent tours often in poor living and working conditions, and noting that, for many, this had meant a great deal of separation from their families. The Unit itself is listed on the Falkland Islands War Monument together with the other branches of the RAF which took part in the Falklands Campaign (Fig. 4).

Figure 4. Falkland Islands War Monument, Port Stanley. *Photograph by courtesy of Mr E. Hibbett*

6. Acknowledgement

The writer gratefully acknowledges receipt of a lengthy note on the MMU prepared in August 1985 by the late Wing Commander Max Lloyd, OCMMU.

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Irish Meteorological Service jubilee

By F.E. Dixon*

Summary

Nineteen eighty-six is the jubilee of the Irish Meteorological Service. This is therefore an appropriate time to describe the establishment of the Service and the way it has developed during the last 50 years.

When the Meteorological Office was established in 1867, and for long afterwards, until the development of radio, Ireland was of exceptional importance. The telegraphic reporting station at Valentia Observatory (at one time called the Western Observatory) gave the first indications of each successive new weather system approaching Europe from the Atlantic. R.H. Scott, the first Director of the Meteorological Office, had a particular interest in Ireland, being a native of Dublin, and for many years he personally carried out the annual inspections of the Irish stations.

The establishment of the Irish Free State in 1922 had little effect on meteorological matters, newspaper forecasts still being supplied from London and the observing stations of all kinds being controlled by the Meteorological Office. It was transatlantic flying which brought about a change: an Irish Trans-Atlantic Corporation originated as early as 1931 and it was formally incorporated in Ireland in the following year, and registered in London in 1935. At an Ottawa conference in November 1935 to work out detailed arrangements the Irish Free State committed itself, *inter alia*, to establish a Meteorological Service and the UK Government undertook to contribute £6000 a year for it and the other facilities.

There was no delay in the inauguration of the new Service with the appointment of Austin H. Nagle as first Director, in 1936, with a good Irish name and several years' experience in the Meteorological Office. At first he had only clerical staff, but another Irishman was found, S.G.G. Kelliher, recently retired from the Colonial Service, who was at first put in charge of Valentia Observatory. He later proved to be the ideal man to visit voluntary climatological stations and persuade the observers to transfer their allegiance to the Free State. No other professional staff were appointed until 1939, and for the flights in 1937 and 1938 forecasters were seconded from the Meteorological Office, with S.P. Peters in charge at the new flying-boat base in Foynes. The men appointed in 1939 included seven potential forecasters (four Irish, two English, one Welsh) and Mr Nagle organized a thorough training course for them at the Imperial College, London, under Professor D. Brunt. World War II brought this to a premature close, and the training was finished in Foynes under Professor L.W. Pollak, a Czech refugee. It was fascinating to discover that in World War I he had served on the Austrian front opposite S.P. Peters and had been able to break the code and make use of Peters's pilot balloon reports! Little has been revealed about the co-operation of the neutral Irish Free State and the belligerent United Kingdom but J.M. Stagg disclosed in his account of the D-day forecasts that a report from Blacksod was crucial in deciding which team of forecasters had the right analysis.

When R.H. Scott died in 1916 his executors put most of his library at the disposal of the Meteorological Office, and they placed it in the Valentia Observatory. When the Irish Meteorological Service came into being the Meteorological Office generously allowed this Scott library to remain intact, and also sent surplus and duplicate volumes to assist in establishing a library in the new headquarters in Dublin. The Royal Meteorological Society also gave valuable additions.

* Formerly of the Irish Meteorological Service.

The headquarters had been moved twice in the 50 years, from 14/15 St Andrew Street, Dublin, to 44 Upper O'Connell Street, and now to a modern specially designed building at Glasnevin, a northern suburb. Aviation forecasting is now only a small part of the output of the Service, and every application of meteorology is dealt with — agriculture, shipping, industry, etc.

The Irish Meteorological Service is an offspring of the Meteorological Office, and both parent and child can be proud of the developments of the last 50 years.

Conference report

The Sixth Conference on Atmospheric Radiation of the American Meteorological Society, Williamsburg, Virginia, 13–16 May, 1986

The conference was held concurrently with the Second Conference on Satellite Meteorology/Remote Sensing and Applications and consisted of eight sessions plus two joint sessions. The first session, on Aerosols and Radiation, started with an invigorating paper from C.F.Bohren (Pennsylvania State University) emphasizing the need for more advanced treatment of the extinction of light by non-spherical particles than the widely used approximation of Mie theory using equivalent spheres. This session also included discussion of the 'nuclear winter' with some attention being paid to the properties of combustion-produced aerosols. A paper describing the results of a flight made by the Hercules aircraft of the Meteorological Research Flight during a straw-burning episode was of interest in this regard.

The second session, Clouds and Radiation, contained papers aimed at the two phases of FIRE (First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment) in 1987 and 1988 looking at the properties of cirrus and stratocumulus. This was followed by a poster session dealing with radiation instrumentation, including ground, airborne and satellite instruments, illustrating well the increased interest and effort in this area.

Two sessions were then held jointly with the satellite conference. The first reported the objectives, performance and initial results of ERBE — the Earth Radiation Budget Experiment now flying on the ERBS and NOAA-9 satellites. The systems are working well and a high-quality global data set of great potential value to many atmospheric scientists is emerging. A subsidiary measurement from a solar monitor implied that the solar constant has been close to 1365 W m^{-2} for the last six months. The second joint session reported results from SAGE II (the Stratospheric Aerosol and Gas Experiment), flying on board ERBS, launched in 1984. Profiles of aerosol, ozone, nitrogen dioxide and water vapour have been collated for over a year now, and all objectives appear to have been achieved.

The fourth and fifth sessions of the radiation conference covered the remote sensing of clouds, aerosols and temperature, with a variety of sensors — airborne lidar and radiometers AVHRR/2 and HIRS2/MSU. Contributions included observations of the El Chichon stratospheric aerosol and satellite observations of the smoke from a large Canadian forest fire.

The next session, Spectroscopy and Band Models, contained two invited papers on the infra-red absorption spectrum of water vapour. In particular, these showed that the cause of the continuum absorption in the atmospheric window at 8–13 μm had not yet been resolved, although evidence now favoured accumulated absorption by the far wings of water vapour lines, rather than absorption by aggregates of two or more molecules of water vapour, neither cause could be ruled out. Band models have been developed to such a degree that they can now be compared with line-by-line models, but it was reiterated that atmospheric measurements, both broad band and high resolution, are required in order to verify the line-by-line models.

In the seventh session, Radiative Transfer, several theoretical studies of 'realistic' atmospheres were presented, including one based on the application of the principle of fractal dimensions (after Mandelbrot) to a study of the effect on radiative transfer of microscale inhomogeneities of liquid water content in layer and broken cloud. The conference closed with a session entitled Earth Radiation Budget and Climate Applications, containing work on the Nimbus-7 Earth Radiation Budget climate data set as well as other aspects of the global radiative balance.

The general view emerging from the conference was that modelling had to some extent outrun the observational data, and that there was a pressing need for further airborne and satellite measurements of radiative transfer. Further details about the papers presented can be found in the proceedings which were published before the conference began.

C.G. Kilsby

Review

Reviews of United Kingdom statistical sources, Volume XVII: Weather, by B.W. Atkinson, *and Water,* by E.C. Penning-Rowsell and D.J. Parker, 170 mm × 250 mm, pp. 226, *illus.* Pergamon Press, Oxford. Price £27.00, US $35.00.

This book forms part of a series under the general title *Reviews of United Kingdom statistical sources* that covers topics as diverse as 'Crime' and 'Civil aviation'. The primary aims of the series are to enable the user to find out what sources of statistical data are available, where the data may be obtained and what limitations there are to their use. The authors of the two reviews in this volume achieve this aim. Available data refer only to those which are likely to be released to a bona fide enquirer in any format.

Extremely useful features of the reviews are the references. Each review contains a quick reference list (QRL) of data publications ordered by content, a QRL of the same publications by author or organization and a general bibliography of works discussing wider aspects. The reader is constantly referred to these in each text but unfortunately there are a number of errors that often direct one to the wrong reference. There is also a subject index on textual references in which entries are permuted.

The text of each topic is designed, in so far as the varying subject matter will allow, to follow a standard format so that users can expect a similar pattern throughout the series. This is certainly the case for *Weather* but less so for *Water* though familiarity with the one helps facilitate the use of the other. Both reviews start with a brief summary of the topic covering such aspects as its organization, the measurements (stating when and how they are made), the units used, the reporting channels and where the data are processed. Each then goes on to discuss the various types of data in detail.

Weather starts with a potted history of observing and instruments, and goes on to describe the various types of observations and networks. The distinctions between synoptic and climatological networks and observations are not made perfectly clear, but the text does contain all the relevant information. The chapter closes with a paragraph on the nature and form of the data.

The second chapter gives the sources of surface data. The variables covered are climate, weather, sunshine, radiation, temperature, evaporation and evapotranspiration, visibility, pressure, and cloud. A standard form is followed with paragraphs on how the measurements are made — data in research literature, published data, and unpublished data both non-machinable and machinable. The definition of radiation reads as though the pre-existence of electric and magnetic fields is necessary for the propogation of radiation, but this apart it is all relatively straightforward and the author refers to all the major sources of data.

Chapter three covers upper-air data. Radiosonde data are in the same form as described above but radar and satellite data are more descriptive and give only general works as data sources. The final chapter is entitled 'Improvements and future developments' and some of the developments discussed have already taken place (the review was written in 1982). Hence, the introduction of the new common code has seen the end of some returns and a greater usage of the computer as an archive which, as the author points out, is not always the boon it may seem for the potential user. Of the criticisms levelled at the Meteorological Office the major one is the fact that one single comprehensive volume of data sources did not exist before this review was written. It is restricted to national data and anyone seeking more detailed local information will need to contact the National Meteorological Library.

Prof. B.W. Atkinson is at least fortunate in the respect that the bulk of weather data are located under one roof and that standards and formats are generally consistent. Dr E.C. Penning-Rowsell and Dr D.J. Parker, the authors of *Weather*, are faced with a water industry that has gone through a number of reorganizations in the last 35 years, and with each change there has been a like change in the nature and extent of published data. Consequently much of the data described are of recent origin and of an uneven and varied nature both spatially and temporally. Nevertheless, the authors manage to present a lucid account of a patchwork quilt of data.

After the brief introduction, data sources and institutional arrangements are discussed giving information on the structure of the Water Authorities in England and Wales and the Scottish River Purification Boards, followed by a section on financial aspects and manning and performance ratios. Subsequent chapters give information on supply, pollution and related statistics, recreation and amenity statistics, and flood alleviation. The varied nature of the data sources precludes a consistent form.

The final chapter is entitled 'Evaluation' and it is worth quoting the closing paragraph more or less verbatim '... nevertheless it will be apparent ... that taken as a whole the data series on the water services in the UK are both chaotic and inaccessible. They pose innumerable problems for the researcher attempting more than a superficial analysis of spatial and temporal trends. In addition it should be stressed that the accuracy and appropriateness of the data may well be less than it appears, not least owing to irregular and inconsistent sampling, and that a most careful evaluation is necessary of any data used'. *Water* was written in 1983 and since then the Government has announced its intention to privatize the water industry and who knows what changes this will effect.

This volume will provide any user with a quick and easy reference to the major national sources of data for both topics but no more than this. At £27.00 it is not destined to become a best seller but should prove a useful addition to any reference library.

R.D. Whyman

Books received

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

Fields, currents and aerosols in the lower troposphere, by R. Reiter (Rotterdam, A.A. Balkema, 1986. £29.75) is the result of a spontaneous attempt to compile the results of ten years of intensive research concerned almost exclusively with atmospheric electricity and radioactivity. The idea was to bring forth the mutual relationships between all separate findings of research in diverse fields. All these results still hold good and have been repeatedly confirmed. In this revised and enlarged edition the recent literature in the individual fields of research has been added at the end of certain chapters and some important new findings reported.

Structure and variability of the Antarctic Circumpolar Current, by E'. I. Sarukhanyan (Rotterdam, A.A. Balkema, 1986. £19.00) describes the salient features of the spatial structure of the Antarctic Circumpolar Current (ACC) based on the analysis of long-term observations on the current. These observations were made during 1975–79 in different regions of the Southern Ocean, in the course of the large-scale field experiments under the 'POLEX-South' and 'International Research Studies on Southern Ocean' programs. The geostrophic transport of waters in the ACC system has been evaluated. Basic scales of the tidal, inertial and synoptic oscillations of the current velocities have been established.

The Bunker climate atlas of the North Atlantic Ocean, Volume 1: Observations, by H.-J. Isemer and L. Hasse (Berlin, Heidelberg, New York, Tokyo, Springer-Verlag, 1986. DM 275) is based on data originally evaluated by Andrew F. Bunker of Woods Hole Oceanographic Institute. It deals with the surface climate of the North Atlantic Ocean from the equator to 65° N, in the period from 1941 to 1972. By the use of monthly and annual mean charts and other diagrams the annual cycles of various oceanic and atmospheric surface parameters are presented. Volume 1 contains the observed meteorological quantities. For the most part they represent the basic information required to understand Volume 2, which presents derived parameters such as energy budget terms and ocean transports.

Honour

We would like to congratulate Mr J. Findlater on his award of the Imperial Service Order in the Queen's Birthday Honours List. Mr Findlater recently retired from the Meteorological Office, Bracknell as a Principal Scientific Officer in the Special Investigations Branch. During his distinguished career in synoptic meteorology he gained international recognition for his discovery in the mid-1960s of the East African jet (sometimes referred to as the Findlater jet) when he was forecasting at RAF Nairobi. During a further tour in East Africa in the 1970s he took a leading role in planning investigations of the jet during the Monsoon 77 and MONEX experiments, and in aircraft studies of its structure.

Award

The President and the Council of the Royal Society have announced that the Royal Society ESSO Energy Award for 1986 will be made to Dr P.W. White, Dr M.J.P. Cullen, Dr A.J. Gadd, Mr C.R. Flood, Mr T.N. Palmer, Mr K. Pollard and Dr G. Shutts of the Meteorological Office, Bracknell for work on the development and introduction of a global weather forecasting system that provides accurate forecasts of wind and temperature for the civil aviation industry, by which aircraft routes are selected to make maximum use of the prevailing winds resulting in considerable fuel savings.

The Award, which was instituted in 1974 and is provided by a gift to the Royal Society from the Board of Directors of the Esso Petroleum Company (now ESSO U.K. plc), consists of a gold medal and a prize of £2000. It is made annually to a person or team who, in the opinion of the Council of the Royal Society, has made an outstanding contribution to the advancement of science or technology leading to the more efficient mobilization, use or conservation of energy resources.

The Award will be presented at a special meeting of the Royal Society on the evening of Monday 13 October 1986 at which Dr White will give a lecture about the work.

Meteorological Magazine

GUIDE TO AUTHORS

Content

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

Preparation and submission of articles

Articles for publication and all other communications for the Editor should be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For *Meteorological Magazine*'.

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*.

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 referred to 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.

Tables should be numbered using roman numerals and provided with headings. We consider vertical and horizontal rules to be unnecessary in a well-designed table; spaces should be used instead.

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 difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

Illustrations

Diagrams must be supplied either drawn to professional standards or drawn clearly, preferably in ink. They should be about 1½ to 3 times the final printed size and should not contain any unnecessary or irrelevant details. Any symbols and lettering must be large enough to remain legible after reduction. 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.

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Meteorological Magazine

August 1986

Vol. 115
No. 1369

CONTENTS

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ISBN 0 11 727836 X

ISSN 0026–1149

Printed for HER MAJESTY'S STATIONERY OFFICE
by Delco Printing Co Ltd 8/86 Dd. 739131 C13

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S
STATIONERY
OFFICE

September 1986

Met.O.971 No. 1370 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1370, September 1986, Vol. 115

551.551.5:551.509.5:629.7

Automated clear air turbulence forecasting

By D.A. Forrester
(Meteorological Office, Bracknell)

Summary

A trial with three major civil airlines was held during 1984–5. Computer-produced forecast charts of clear air turbulence probability were issued to pilots of selected flights with a request for annotation of route and turbulence experienced on the flight. Over 700 charts were returned; a statistical analysis of these has demonstrated a significant degree of skill in the probability forecasts.

Introduction

Clear air turbulence (CAT) is responsible for discomfort and injury to airline passengers and crew, increased flying costs and, occasionally, stress damage to aircraft. Since there is, as yet, no on-board method of detecting CAT in advance of an encounter, any improvements in the forecasting of CAT of moderate or severe intensity must be welcomed by the civil airline operators and the military.

Computer forecasts of moderate or severe CAT for 18 and 24 hours ahead have been produced on a regular basis by the Meteorological Office since 1980. The algorithm in use was derived by Dutton (1980) using multiple regression techniques to correlate civil airline pilot reports obtained during the 1976 North Atlantic Turbulence Survey with forecast parameters from the operational numerical weather prediction (NWP) model. Details of the algorithm itself are given in Appendix 1.

Recognized deficiencies in the forecasts produced by the old 10-level NWP model, namely inaccuracies in the positions and strengths of jet streams, reduced the accuracy of the automated CAT forecasts, and their dissemination to customers was, therefore, not warranted. However, with the introduction of the new global 15-level model (which has a grid length of about 150 km in mid-latitudes) in September 1982, the forecasting of jet streams has improved sufficiently to consider operational use of these automated CAT forecasts.

A limited verification exercise was undertaken in the winter of 1982/83 and this demonstrated that the skill of the objective CAT forecast was significantly higher than that of the subjective forecast (which was used as input to the routine significant weather chart). This led to the arrangement of a trial with British Airways (BA) whereby the meteorological office at London/Heathrow provided a computer-generated chart of the forecast CAT probability for selected North Atlantic and European flights, with a request to the pilot to annotate the chart with the route, the turbulence experienced on the flight, any other relevant comments, and the return of the chart.

The trial, which began in July 1984 and lasted until the end of July 1985, served three main functions. Firstly, it introduced pilots to a new type of forecast, namely one in which the parameter being forecast was expressed in terms of a probability of occurrence. This is more difficult to comprehend and use than a conventional yes/no type of forecast. Secondly, it provided sufficient material to conduct a detailed verification exercise and thirdly, it provided the data to carry out statistical regressions in the future, if required, to improve the forecasts further.

Details of the trial

During the first 5 months of the trial, charts were issued to five BA flights daily — three North Atlantic (New York or Washington) and two European (Athens or Tel Aviv). As the number of charts returned was rather low (less than 10%), BA agreed to extend the trial to cover all long-haul flights departing from Heathrow, and also to invite Pan American World Airways (PA) and Air Canada (AC) to join in the trial. From December, charts were issued to about 100 BA flights per week. An additional chart covering Europe and much of Asia and Africa was produced and disseminated to BA flights to the Middle East, India and East Africa. From February, charts were also issued to three PA flights daily (two to New York, one to San Francisco), and from April to three AC flights daily (one to Toronto, the others to Edmonton, Calgary or Vancouver). The number of charts returned from PA was about 33%, and from AC about 40%. The return rate from BA increased only slightly to about 10%. In all 821 charts were returned over the 13-month trial period. However, some of these charts had no indication of the route flown and had to be discarded. Also charts from 2–9 February were not included because during this period the Meteorological Office Cyber computer was withdrawn from service (to allow enhancement work to be carried out), and Washington data was used to produce the CAT charts. Finally 584 North Atlantic (NAT), and 157 European (EUR) and Middle Eastern (MID) charts were usable. In the following analysis it will be assumed that the usable charts constitute an unbiased sample of all flights.

The CAT forecast probabilities were computed from vertical and horizontal wind shear, the vertical being the dominant contributor (see Appendix 1). At the cruising altitude band (29 000–43 000 ft) the 15-level model has a vertical resolution of about 5000 ft. Computation of vertical shears entails a considerable degree of smoothing, thus making the vertical resolution of the CAT index rather poor. The horizontal resolution is, however, good, since the index is based on 15-level model winds which are held on a 1½° latitude by 1⅞° longitude grid. CAT probability values are produced at each grid point on standard pressure levels (200, 250, 300 mb). However, owing to the poor vertical resolution, only a single level was used in the trial. Initially this was the 250 mb level, but from 12 December a new chart showing the average of the 200, 250 and 300 mb probabilities was produced for the remainder of the trial.

To simplify the chart as much as possible, the only contours marked were those representing probabilities significantly higher than the background value, which is about 2%. Initially these were the 3% and 6% contours but with the introduction of the new program in December the general appearance of the chart was improved and the overall probability levels were raised slightly making it more useful to contour the 4% and 6% values.

Fig. 1 shows the 24-hour CAT probability forecast chart valid at 0000 GMT on 3 January, which was carried on a flight departing from London/Heathrow at 1830 GMT bound for New York. The route and the pilot's remarks are shown. At any particular point the probability is that of encountering moderate or severe CAT per 100 km of flight path. To obtain the probability (P) for a longer section of flight path, the individual probabilities (p_i) are combined as follows:

$$1 - P = (1 - p_1)(1 - p_2) \ldots (1 - p_n).$$

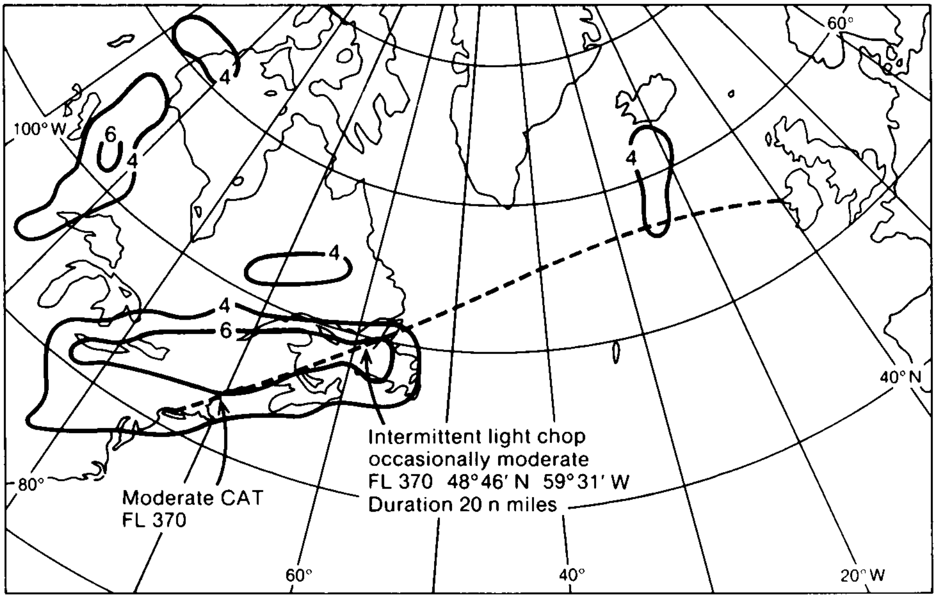

Figure 1. 24-hour CAT probability (%) forecast chart for 0000 GMT on 3 January 1985 with route of flight and pilot's remarks shown.

For example, 4% per 100 km becomes 18% over 500 km and 34% over 1000 km; 6% per 100 km becomes 27% over 500 km and 46% over 1000 km.

A criticism that may be raised against the present study is that the North Atlantic results are based entirely on westbound flights. It can be argued that eastbound flights experience more turbulence because, on average, their routes keep closer to the favourable jet core. However, since the jets coincide, on average, with the areas of highest CAT probability, it is felt that this is not too serious a criticism. In the 1976 survey, both eastbound and westbound flights were included.

Analysis of the charts

The flights were divided into the following groups:

(i)	BA—NAT	July–12 December 1984	88 flights
(ii)	BA—NAT	13 December 1984–2 February 1985	95 flights
(iii)	BA—NAT	13 February–July 1985	142 flights
(iv)	PA—NAT	February–July 1985	154 flights
(v)	AC—NAT	April–July 1985	105 flights
(vi)	BA—EUR	July–December 1984	67 flights
(vii)	BA—MID	December 1984–July 1985	90 flights

To analyse the charts, each route was divided into 100 km segments, and each segment was classified according to forecast CAT probability (low, medium or high) and turbulence experienced (nil, light, moderate or severe). This information, originally in the form of 3 × 4 contingency tables, is summarized as a set of 2 × 2 tables for each of the above groups (Tables I–VII) and for all NAT flights (Table VIII). From these a skill score (R) can be computed (see Appendix 2). If R is large then the chance of encountering moderate or severe CAT within high forecast probability areas is much greater than that of encountering it within low forecast probability areas. Also a chi-square (χ^2) test can be carried out to test

Table I. *Frequency of occurrence of CAT for British Airways flights on North Atlantic routes July–December 1984. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–3%	>3%	All
Nil or light	3969	825	4794
Moderate or severe	135	94	229
All	4104	919	5023

$P_L = 3.3\%$ $P_H = 10.2\%$ $P_B = 4.6\%$ $R_L = 0.7$ $R_H = 2.2$ $R = 3.1$ $\chi^2 = 83$

Table II. *Frequency of occurrence of CAT for British Airways flights on North Atlantic routes December 1984–February 1985. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–4%	>4%	All
Nil or light	5082	478	5560
Moderate or severe	91	77	168
All	5173	555	5728

$P_L = 1.8\%$ $P_H = 13.9\%$ $P_B = 2.9\%$ $R_L = 0.6$ $R_H = 4.7$ $R = 7.9$ $\chi^2 = 258$

Table III. *Frequency of occurrence of CAT for British Airways flights on North Atlantic routes February–July 1985. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–4%	>4%	All
Nil or light	8455	705	9160
Moderate or severe	112	37	149
All	8567	742	9309

$P_L = 1.3\%$ $P_H = 5.0\%$ $P_B = 1.6\%$ $R_L = 0.8$ $R_H = 3.1$ $R = 3.8$ $\chi^2 = 59$

Table IV. *Frequency of occurrence of CAT for Pan American flights on North Atlantic routes February–July 1985. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–4%	>4%	All
Nil or light	8980	769	9749
Moderate or severe	108	32	140
All	9088	801	9889

$P_L = 1.2\%$ $P_H = 4.0\%$ $P_B = 1.4\%$ $R_L = 0.8$ $R_H = 2.8$ $R = 3.3$ $\chi^2 = 42$

Table V. *Frequency of occurrence of CAT for Air Canada flights on North Atlantic routes April–July 1985. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–4%	>4%	All
Nil or light	6964	311	7275
Moderate or severe	27	4	31
All	6991	315	7306

$P_L = 0.4\%$ $P_H = 1.3\%$ $P_B = 0.4\%$ $R_L = 0.9$ $R_H = 3.0$ $R = 3.2$ $\chi^2 = 5.5$

Table VI. *Frequency of occurrence of CAT for British Airways flights on European routes July–December 1984. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–3%	>3%	All
Nil or light	1450	249	1699
Moderate or severe	24	30	54
All	1474	279	1753

$P_L = 1.6\%$ $P_H = 10.7\%$ $P_B = 3.1\%$ $R_L = 0.5$ $R_H = 3.5$ $R = 6.6$ $\chi^2 = 65$

Table VII. *Frequency of occurrence of CAT for British Airways flights on Middle Eastern routes December 1984–July 1985. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–4%	>4%	All
Nil or light	4002	203	4205
Moderate or severe	109	10	119
All	4111	213	4324

$P_L = 2.6\%$ $P_H = 4.7\%$ $P_B = 2.7\%$ $R_L = 1.0$ $R_H = 1.7$ $R = 1.7$ $\chi^2 = 3.2$

if there is any relationship between forecast and experience. It must be stressed that the analysis is completely objective, and no account is taken of 'near misses'.

A difficulty in the interpretation of the turbulence reports was encountered for some of the flights. A few pilots chose to use a symbol to indicate turbulence, and it became clear that different pilots were using the same symbol with different meanings*. In all, 24 reports were found to be ambiguous.

Several comments on the effectiveness of the charts were received. These were mainly complimentary, except one that exhibited concern from a legalistic viewpoint at the introduction of probability turbulence forecasting. Further comments were made on the presentation of the charts, and these pointed out some weaknesses which have since been remedied.

* The official World Meteorological Organization/International Civil Aviation Organization symbols are  for moderate and  for severe, but before about 1960 the symbols were  for light,  for moderate and  for severe.

Table VIII. *Frequency of occurrence of CAT for all flights on North Atlantic routes July 1984–July 1985 (the 3% probability level was used up to 12 December 1984, but was replaced by the 4% level after that date). Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–3% 0–4%	>3% >4%	All
Nil or light	33 450	3 088	36 538
Moderate or severe	473	244	717
All	33 923	3 332	37 255

$P_L = 1.4\%$ $P_H = 7.3\%$ $P_B = 1.9\%$ $R_L = 0.7$ $R_H = 3.8$ $R = 5.4$ $\chi^2 = 565$

Results

Tables I–V and Table VIII show that over the North Atlantic and North America R was very high (7.9) in winter and ranged from 3.1 to 3.8 throughout the rest of the year, averaging 5.4 over the whole year. This high degree of skill is borne out by the results of χ^2 tests on the 2×2 contingency tables. All show significance at the 5% level and all except Table V show significance at the 0.1% level. Table V covers the summer period when there were rather few reports of moderate turbulence (and none of severe). Although less successful in the sense that only 4 out of the 31 turbulent route segments fell in areas of medium to high probability (> 4%), the amount of the area forecast to be above 4% was substantially smaller than that during the other periods.

Table VI shows that over Europe the skill is also high ($R = 6.6$ and $\chi^2 = 65$). Table VII, however, shows that over the Middle East the skill is rather poor ($R = 1.7$ and $\chi^2 = 3.2$). Much of the turbulence experienced on these flights would appear to be topographically related.

Examination of the 3×3 contingency tables obtained from the original 3×4 tables by combining moderate and severe CAT into a single category shows, using χ^2 tests, significant skill in forecasting light turbulence (as well as moderate to severe). It also demonstrates that the skill in forecasting moderate to severe turbulence exists in both medium probabilities (4–6%) and high probabilities (> 6%).

To demonstrate that the ambiguity in the interpretation of the turbulence symbol had not significantly biased the results, another set of 2×2 contingency tables was constructed by grouping together all turbulence (light, moderate and severe). The R values corresponding to Tables I–VIII are, respectively, 2.4, 4.6, 3.4, 3.4, 4.5, 4.1, 2.2 and 3.8 and the corresponding χ^2 values 97, 307, 134, 164, 95, 84, 17 and 927. While not quite so prominent as before, the winter period still stands out strikingly. Significant skill in forecasting light turbulence is also shown in the summer period. (It should be noted that the χ^2 values for the individual tables cannot be directly compared since the marginals and totals in the tables are not identical.)

As mentioned in the Introduction, a limited comparison of objective and subjective CAT forecast charts was carried out in 1983. For each of five selected days (30 and 31 December 1982 and 4, 9 and 16 January 1983) all aircraft reports from flight levels in the band 29 000–43 000 ft within a specified area of the North Atlantic (30–70° N, 0–60° W) for the period 09–15 GMT were scrutinized. Reports of moderate or severe turbulence during the 6-hour periods were correlated with both the objective 24-hour forecast CAT chart valid at 1200 GMT, and the subjectively prepared CAT chart for the same time. The 2×2 contingency tables obtained are given in Table IX. Although the 'success' in forecasting moderate or severe CAT appears marginally worse in the objective method (10 out of 22) when compared with the

Table IX. *Comparison of objective and subjective CAT forecasts made in 1983 using selected aircraft reports over the North Atlantic. Probability, usefulness and skill score of forecasts are listed below the tables (see Appendix 2 for explanation of notation)*

Reported turbulence	Objective CAT probability forecast 0–3%	>3%	All
Nil or light	528	91	619
Moderate or severe	12	10	22
All	540	101	641

$P_L = 2.2\%$ $P_H = 9.9\%$ $P_B = 3.4\%$ $R_L = 0.6$ $R_H = 2.9$ $R = 4.4$ $\chi^2 = 15$

Reported turbulence	Subjective CAT forecast No	Yes	All
Nil or light	369	250	619
Moderate or severe	11	11	22
All	380	261	641

$P_L = 2.9\%$ $P_H = 4.2\%$ $P_B = 3.4\%$ $R_L = 0.8$ $R_H = 1.2$ $R = 1.5$ $\chi^2 = 0.8$

subjective method (11 out of 22), it is to be noted that the number of all reports which occur in areas of high forecast CAT probability in the objective method is only 16% (101/641), substantially smaller than the number of all reports in areas of forecast CAT ('yes' areas) in the subjective method, which is 41% (261/641). Therein lies a significant improvement in skill. For the objective forecasts R is 4.4, but for the subjective forecasts only 1.5; χ^2 values are 15 and 0.8 respectively. These results for the subjective forecasts agree closely with those obtained for the North Atlantic using data from the 1976 survey (Dutton 1979). No comparison with the subjective forecast has been attempted in the current study, since the forecaster is now making more use of the objective forecast charts in the preparation of his forecast.

Conclusions

The results of this study demonstrate an encouraging degree of skill in the current Meteorological Office automated 18- and 24-hour CAT forecasting program and are in general agreement with the results of a previous study based on the 1976 survey, thus demonstrating that the regression equation devised for the old 100 km limited-area 10-level model can be used with confidence for the new 150 km global 15-level model.

Acknowledgements

The author wishes to express his thanks to the many pilots who took the trouble to complete and return the charts, to John Rankin of British Airways for organizing the trial, and to the staff at the meteorological office at London/Heathrow for distributing the charts.

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1980 Probability forecasts of clear-air turbulence based on numerical model output. *Meteorol Mag*, **109**, 293–310.

Appendix 1 — *CAT index*

Based on the pilots' reports from the 1976 North Atlantic Turbulence Survey together with forecasts from the operational limited-area 100 km mesh 10-level model, and using statistical multiple regression techniques, Dutton (1980) developed a predictive equation for the probability of moderate or severe CAT in terms of vertical and horizontal wind shear. The CAT index E is given by:

$$E = 1.25\, S_H + 0.25 S_V^2 + 10.5$$

where S_H is the horizontal wind shear in m s^{-1}/100 km and S_V is the vertical wind shear in m s^{-1}/km.

The index E is converted to the probability p of encountering moderate or severe CAT per 100 km of flight path using the values given in Table AI. If $E \leq 5$ then p is set to 0.0% and if $E \geq 30$ then p is set to 7.5%. The average, or background, value of p is about 2.0%. Thus only areas where the probability is forecast to be significantly higher (or lower) than this background value are actually useful. The table also lists values of the model wind shears which can produce various values of E and p.

Table AI. *Values of E and corresponding p values which can be produced by given model wind shear values*

E	p(%)	S_V (if $S_H = 0$) m s^{-1}/km	S_V (if $S_H = 0$) kn/1000 ft	S_H (if $S_V = 0$) m s^{-1}/100 km	S_H (if $S_V = 0$) kn/100 n mile
5	0.0	—	—	−4.4	−15.8
7.5	0.95	—	—	−2.4	−8.6
10	1.55	—	—	−0.4	−1.4
15	2.2	4.2	2.5	3.6	13.0
20	2.8	6.2	3.7	7.6	27.4
25	4.2	7.6	4.5	11.6	41.8
30	7.5	8.8	5.2	15.6	56.2

Appendix 2 — *Contingency tables and use of χ^2 test*

The general 2 × 2 contingency table can be written in the form:

Reported turbulence	CAT probability forecast 0–4%	CAT probability forecast >4%	All
Nil or light	a	b	r_1
Moderate or severe	c	d	r_2
All	s_1	s_2	N

where a, b, c and d are cell frequencies, the marginal frequencies r_1 and r_2 are row totals, s_1 and s_2 are column totals, and N is the sum of all cell frequencies.

From these tables, it is straightforward to compute the percentage probabilities of encountering moderate or severe CAT in regions of low forecast probability ($P_L = c/s_1$) and high forecast probability ($P_H = d/s_2$). The background probability ($P_B = r_2/N$) is defined as the overall frequency of reports of moderate or severe CAT. The ratios of the conditional probabilities (P_L and P_H) to the background probability (P_B) can be used as a measure of the usefulness of the forecast (R_L and R_H), and the ratio of these can be regarded as a skill score (R), i.e. $R_L = P_L/P_B$, $R_H = P_H/P_B$ and $R = R_H/R_L$.

A χ^2 test, based on the null hypothesis that there is no relationship between forecast and experience, was carried out on each of the contingency tables. If there is no skill in the forecast, then the expected cell frequencies, given fixed marginals r_i and s_j, would be

$$E_{ij} = r_i s_j / N.$$

These can be compared with the observed frequencies O_{ij} by computing

$$\chi^2 = \sum_{ij} (O_{ij} - E_{ij})^2 / E_{ij}.$$

For a 2×2 table, which has one degree of freedom, a value of χ^2 greater than 3.8 indicates significance at the 5% level, and a value greater than 10.8 indicates significance at the 0.1% level.

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Errors in height estimation of convective cloud base

By M.P. Garrod*

(Wokingham, Berkshire)

Summary

Glider pilots have reported that the base of cumulus clouds over England is frequently found to be much higher than that reported by nearby ground observers. It has been found that condensation levels calculated from screen dry-bulb and dew-point data are generally closer to the true cloud base. It is suggested that estimations of cumulus bases would be improved if observers first calculated the condensation level.

Introduction

In spite of major developments in weather-sensing systems, the meteorological observer remains an important source of data for analytical work and forecasting. Almost all of the synoptic report is based on the use of measuring instruments but one section of it is largely dependent on the observer's judgement. This is the height of the cloud base, which is especially difficult to estimate during the daytime when a cloud searchlight cannot be used.

Cloud-base recorders, such as the Meteorological Office Mk 3A, are not installed at all observing stations. Although these instruments are excellent for measuring the height of continuous cloud cover, especially below 2000 ft, they suffer from progressively larger errors with height. At the top of the scale (4000 ft) the instrumental error, according to Douglas and Offiler (1978), is about minus 1332 ft. As it is necesssary for the cloud to pass directly over the vertical beam, this system is ill-adapted for recording well-broken cumulus above 3000 ft. In this instance the observer is obliged to make an estimate by eye.

Measurement of cloud base by glider pilots shows that an observer's estimate is often well below the true value. It has been noted, however, that the dry- and wet-bulb temperatures in the thermometer screen are an indication of the height of the convective cloud base. George (1970) published a diagram to calculate dew-point, relative humidity and convective cloud base from these measurements, but lacked supporting evidence of measurements from aircraft.

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A quick estimate of the cloud base is obtainable from the simple formula $(T - T_d) \times 400$ t, where T is the air temperature and T_d the dew-point at screen level. It has been found, over very many years of flying by the author, that this formula is capable of producing remarkably accurate results. It was therefore decided to carry out an investigation to determine the accuracy of observers' estimates, and to compare these with calculated values based on dry- and wet-bulb temperature readings.

Collection and comparison of data

The data used were recorded during glider flights over southern England between 1982 and 1985. Whenever the convective cloud base was reached, the height and position of the aircraft were noted, and also the time. A total of 37 observations was made. After each flight the relevant southern England surface synoptic charts were examined, and data extracted from the nearest ground observing station(s). For example, an airborne observation was made at 1230 GMT on 18 August 1983 near Market Harborough, and the 1300 GMT observational data of cumulus base, temperature and dew-point were noted for Birmingham and Bedford. If the airborne observation was made within five miles of a reporting station, that station alone was used for comparison purposes. In all other cases mean values of reported cloud height, temperature and dew-point were worked out, this being the nearest approximation to that which an observer below the glider would have reported. All values of cloud height, both observed and calculated, were converted to heights above mean sea level.

Fig. 1 illustrates the comparison between ground observers' estimates of the height of the cumulus base with that observed in the air. With the exception of four observations, all estimates of cumulus height above ground level lie beneath the correct estimate line. Extreme values are plus 16% and minus 55%, and the calculated mean deviation is minus 700 ft. This clearly indicates that a substantial proportion of observers underestimate the true height by at least 12% for cumulus which is above 3000 ft.

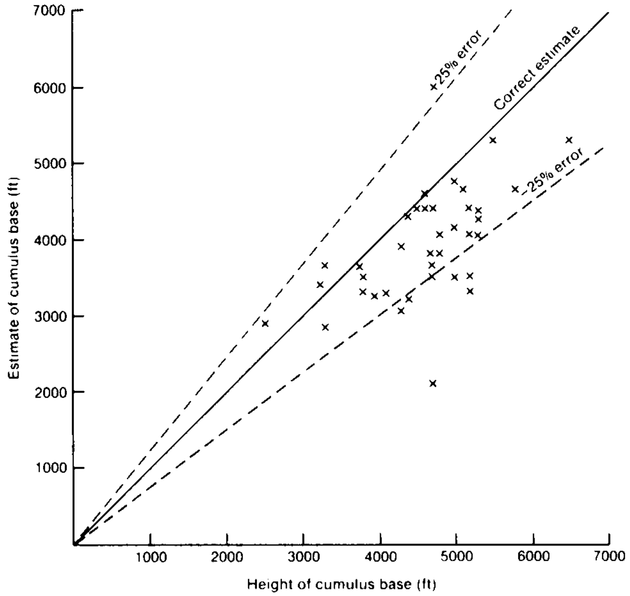

Figure 1. Plot of ground observers' estimates of cloud base height against height measured during glider flights. All heights above mean sea level.

Fig. 2 shows a plot of calculated convective cloud bases, using the formula $(T - T_d) \times 400 + H$ (where H is the height of the station above mean sea level), against those observed in the air. The scatter of plots is evenly distributed about the correct estimate line, the extreme values being plus 20% and minus 20%, and the calculated mean deviation minus 13 ft. Only four plots out of the total of 37 show an error exceeding 500 ft.

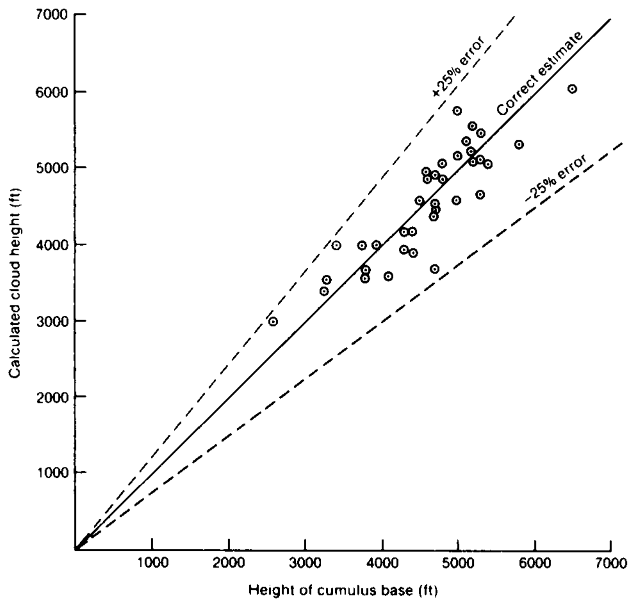

Figure 2. Plot of calculated cloud height against cloud base height measured during glider flights. All heights above mean sea level.

Possible data errors

The errors encountered in this investigation can conveniently be split into three types:

(i) *Instrumental and observing errors.* In the glider the height of the cumulus base was read from a standard aircraft altimeter which is checked annually; the maximum calibration error permitted is 50 ft in 5000. It is often found that the cloud base is rather diffuse so that a pilot may not be able to determine the exact height to better than ± 50 ft. It is therefore reasonable to assume that the height is within ± 100 ft of the true value, and that the errors of measurement are not significant over the range of heights encountered.

(ii) *Pressure setting errors.* The surface pressure fields were examined on each occasion to determine what changes took place over the area covered during the period of the flight. Any errors due to changes of mean-sea-level pressure were within ± 100 ft.

(iii) *Errors due to time and distance from ground observers.* Since airborne and ground-based observations were not usually synchronous, and there was no guarantee that an airborne observation would be taken directly above a ground station, comparisons of the observations may produce a biased result. In extreme cases daytime heating may raise the cloud base by as much as 1500 ft in an hour. However, it was judged that in most cases individual errors were unlikely to exceed ± 300 ft, and therefore the mean error was not significantly biased. It is perhaps worth noting that the worst plot (Fig. 1) came from an observation made within three miles of the nearest ground observing station, and within ten minutes of the normal observation time.

Discussion

The main conclusion to be drawn from this research is that, in the 37 cases examined, observers would have done rather better to use the temperatures from the thermometer screen as a guide to cumulus cloud height. It is worth considering why observers frequently underestimate the true height.

Perhaps the largest single factor is lack of regular feedback. Although meteorological observing stations on airfields occasionally receive reports of cloud height from aircraft, most of these occur when conditions inhibit flight operations. Cumulus, except in unusual circumstances, does not constitute a problem to aircraft operating in an airfield circuit or approach pattern. Without these reports, or any other source of height check, it is inevitable that errors occur. The fact that the ground-based observers usually underestimate the cloud base is probably due to a feeling that it is better to err on the low side on somewhat questionable safety grounds.

Rapid increases in cumulus base may outpace the observer's successive hourly reports. Rises of 2.5 °C per hour are not that uncommon in summer, resulting in a change of 1000 ft in the cloud base (provided the dew-point remains the same). The observer may not recognize by eye alone the magnitude of this change.

When the cumulus base occurs in the range 6000 to 8000 ft it is not surprising that observers fail to report with any consistent accuracy. Indeed, it would be very difficult for any observer to be able to differentiate between one cloud at 6000 ft and another at 8000 ft as the appearance would be almost identical. The magnitude of observational error for cloud at 6000 ft and above is illustrated in Table I. A random selection of 369 reports was taken from surface UK charts for 1500 GMT for the period May to August 1976, each report exhibiting at least 15 °C difference between air temperature and dew-point in conjunction with cumulus or altocumulus cloud. On the basis that the calculated value gives a correct height within 500 ft, then the bulk of reported heights are between 1000 and 2000 ft too low. Some 10% of reports in the sample show errors of as much as half the true height.

Table I. *Comparison of reported cloud base height with calculated height using a random sample of observations extracted from months May to August 1976 when air temperature and dew-point difference equalled or exceeded 15 °C in conjunction with cumulus or altocumulus cloud (total sample 369)*

Reported temperature difference and calculated height °C	ft	Reported cumulus or altocumulus height (ft) at 1500 GMT < 4000	4000–4400	4500–4900	5000	6000	7000	8000	9000	10 000
26	10 400	0	0	0	0	1	0	0	0	0*
25	10 000	0	0	0	0	1	0	0	0	0*
24	9 600	1	0	1	1	0	0	0	0	0*
23	9 200	1	1	0	1	3	1	0	0*	0
22	8 800	0	1	0	5	6	3	1	0*	0
21	8 400	1	4	3	9	7	1	0*	0	0
20	8 000	1	1	2	8	12	2	0*	0	0
19	7 600	3	7	5	9	10	4	0*	0	0
18	7 200	3	4	5	22	14	1*	0	0	0
17	6 800	6	8	10	6	9	0*	0	0	0
16	6 400	5	10	11	28	16*	1	0	0	0
15	6 000	13	20	17	33	10*	0	0	0	0

* indicates correlation between reported cloud height and calculated cloud height (within 500 ft)

The *Observer's handbook* (Meteorological Office 1982) quotes 1000–6500 ft as the 'wider range of height of base sometimes observed'. However, there have been a number of reports by glider pilots which confirms the existence of cumulus above 8000 ft*. Although these are few and far between, the surface temperature and dew-point differences in Table I (up to 26 °C) make 10 000 ft quite feasible provided the vertical temperature profile is favourable. Indeed, unconfirmed reports suggest that convective cloud formed at 11 000 ft on one day during the summer of 1976.

Advice to meteorological observers

It is quite clear that the human eye has severe drawbacks when applied to estimating height of cloud above ground level. It relies on relative shape, size, outline structure and speed of movement, and no two observers are likely to agree. Although cloud below 3000 ft can be estimated fairly accurately in absolute terms, guidance is clearly required for higher levels. The screen temperatures will provide that help with respect to cumulus cloud.

There are however some provisos. The screen temperatures may not be representative of the air reaching the condensation level over the whole sky, especially near coasts or in mountainous regions. For example, a sea-breeze front can exhibit as much as a 2000 ft change in convective cloud base in a matter of a few hundred yards. The onset of showers will result in marked fluctuations in both air temperature and dew-point values and, until the effects have passed and the ground has largely dried out, the calculation of cumulus height is likely to give a false value. It is recommended that the calculation method is confined to periods of the day when the temperature is rising. There is some evidence to suggest that once the temperature has passed its peak and begun to fall, it no longer gives as accurate a guide.

One final word of warning. Although it is possible to use the screen temperatures as a guide to the height of stratiform type clouds, there will be many occasions when the two are not correlated. It is not recommended as a general practice.

Acknowledgement

The author is indebted to Mr T.A.M. Bradbury for his advice in the preparation of this article.

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* On 8 August 1975 the author found the cumulus base to be 8300 ft above mean sea level near Brize Norton (surface air temperature 33 °C, dew-point 12 °C).

551.515.427:551.558.1

Daytime peninsula convection — 13 May 1986

By the Satellite and Radar Studies Group
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Satellite and radar pictures taken when there is an unstable polar airstream over the British Isles indicate that the distribution of convective cloud and showers is rarely randomly scattered. Whether the air mass is unstable to sea temperatures, land temperatures or both, distinct lines or bands of convection lying parallel to low-level winds are usually clearly evident. For example, a persistent feature during north-westerly winds in the winter season, when the air is unstable to sea temperatures, is a line of showers emanating from the North Channel between Scotland and Northern Ireland (Browning *et al.* 1985)*. Significant lines of cloud and precipitation are also observed over land during spring and summer following daytime heating.

South-westerly airstreams of polar maritime origin occurred frequently over southern and central Britain during the spring of 1986. Convective clouds and showers sometimes occurred over the sea, mostly as comma-shaped clusters, but most convection took place over land during the day. May 13 was typical of such days, the mid-afternoon distribution of cloud and rain being shown in Figs 1 to 3. Early in the day, convection occurred over western areas of the British Isles, particularly near high ground such as over Wales, but by early afternoon much of mid-Wales had become cloud free with the convection

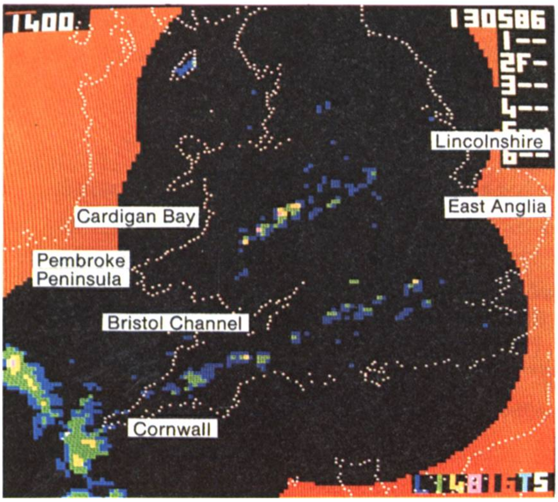


Figure 1. Radar network picture at 1400 GMT 13 May 1986. Rainfall intensities are indicated by colours as follows: dark blue = ¼–1 mm h⁻¹, green = 1–4 mm h⁻¹, yellow = 4–8 mm h⁻¹ and magenta = 8–16 mm h⁻¹. (Precipitation was not observed over south-east England owing to blocking of the radar beam by high ground.)

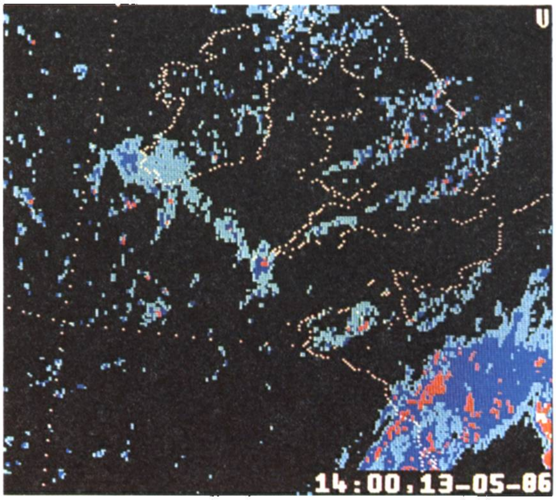
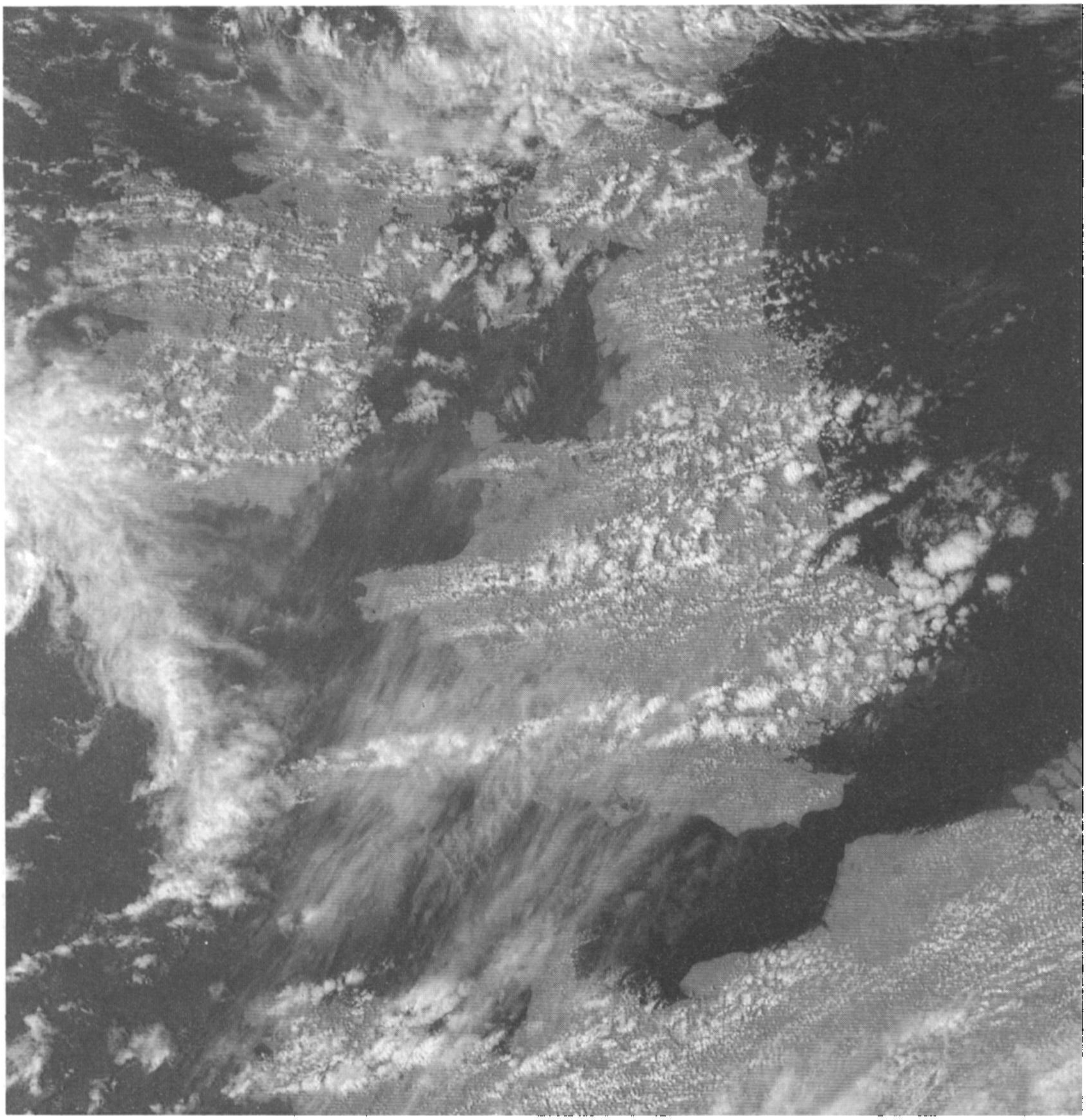


Figure 2. Digitized Meteosat image at 1400 GMT 13 May 1986. Colours indicate cloud thickness; pale blue represents thinner cloud, red represents thickest cloud. The data have been re-projected on to the same grid as the radar picture (Fig. 1) allowing direct comparison of cloud and rain data.

* Browning, K.A., Eccleston, A.J. and Monk, G.A.; The use of satellite and radar imagery to identify persistent shower bands downwind of the North Channel. *Meteorol Mag*, **114**, 1985, 325–331.



Photograph by courtesy of University of Dundee

Figure 3. NOAA-9 visible image at 1406 GMT 13 May 1986.

being aligned in bands along the wind direction. Additionally, two other areas of convection were present; one over East Anglia and one west of Cornwall. The broad area of convection over East Anglia, seemingly related to the band downwind of the south-west peninsula, actually developed separately over south-east England near the remains of a weak surface trough that had been tracked by radar from west to east across Britain during the previous 12–18 hours. The band of convective precipitation which lay over the sea immediately west of Cornwall was associated with another minor trough.

With the exception of that over East Anglia, the convection over land was clearly organized into bands extending downwind from major peninsulas. The radar network picture at 1400 GMT (Fig. 1) indicates that all precipitation over land was confined within two well-defined bands originating over the Cornish and Pembroke peninsulas. The NOAA-9 image at 1406 GMT (Fig. 3) clearly indicates the overall pattern of convection, but also shows distinct cloud-free wedges. The major cloud-free areas are immediately downwind of the Bristol Channel and Cardigan Bay. Close examination of this image, however, also shows smaller-scale cloud lines and clear slots.

The Meteosat digitized visible image at 1400 GMT (Fig. 2) gives an indication of the thickest (brightest) cloud. In this image, all sea, land and thin cloud has been set to black, with the remaining thick cloud colour-coded. Comparison of the image and the corresponding radar picture (Fig. 1) shows that the brightest clouds are well correlated with showers. The first indication of the formation of distinct cloud and shower lines was observed at about 1300 GMT, with a maximum intensity of precipitation at or soon after 1500 GMT. The organization decayed rapidly soon after 1700 GMT.

During May 1986, the line of cloud from the south-west peninsula was a frequent occurrence, having been observed on seven out of the eight afternoons on which relatively cloud-free polar air masses reached Cornwall from the south-west. On the one day that the cloud line failed to appear, a slow-moving weak cold front was close by. The Pembroke cloud line was less persistent, having been clearly observed on only four out of the eight occasions. The orientation of the cloud lines varies slightly depending on the wind direction. In a west-south-westerly airstream, such as occurred on 13 May, the south-west peninsula line may well reach London, whilst in a south-south-westerly airstream it has been observed to extend across central England towards Lincolnshire. Occasionally cloud has extended as far as the North Sea before dissipating. Generally the Pembroke line has not been observed to extend as far downwind, although it does seem to have the same range of orientations as the south-west peninsula line. The cloud lines need not necessarily be associated with precipitation —in dry air masses they may be composed of shallow convective cloud. On the other hand, the convective clouds may be associated with a well-marked line of showers. In the example illustrated, inland locations within the convective bands had frequent heavy showers throughout the afternoon while other places, a few tens of kilometres north and south, had a dry sunny afternoon.

The origin of the cloud lines appears to be closely correlated with sea-breeze circulations, with the afternoon maximum of the onshore wind component leading to convergence over peninsulas and the possible formation of cloud and showers. Conversely, significant bays will tend to be regions of divergence, the resulting descent suppressing convection, thereby leading to the formation of cloud-free slots.

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A case study of the detection of fog at night using channels 3 and 4 on the Advanced Very High Resolution Radiometer (AVHRR)

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Summary

An image created from Advanced Very High Resolution Radiometer satellite imagery using a bi-spectral technique is able to provide detail of fog cover not possible by conventional means. Comparison with surface observations is examined in detail on an occasion of patchy fog over England and Wales.

1. Introduction

Eyre *et al.* (1984) described a new technique for the detection of fog at night using two of the infra-red channels on the Advanced Very High Resolution Radiometer (AVHRR), flown on the TIROS-N series of polar-orbiting satellites. This bi-spectral technique identified the areas covered by fog by using the fact that water clouds, including fog, have a lower apparent temperature in one of the infra-red channels than in the other. Land and sea surfaces have similar apparent temperatures in both channels.

In general, objects emit electromagnetic radiation that is characteristic of their temperatures. By measuring that radiation, it is possible to determine their temperatures.

An object at a certain temperature can emit up to a maximum amount of radiation, this limit being given by Planck's law (Houghton 1977). The hypothetical objects that emit this maximum amount are known as 'black bodies'. It is found that real objects radiate less efficiently than would be predicted by Planck's law. This efficiency is known as the 'emissivity'. The 'brightness temperature' of an object is the temperature of a black body that emits the same amount of radiation as the real object; the physical temperatures of real objects are higher than their brightness temperatures. In an accurate computation of the temperature of an object from its emitted radiation, an allowance would have to be made for this efficiency.

The AVHRR radiance measurements from channels 3 (3.7 μm) and 4 (11 μm) can be calibrated using data from the views of deep space and the on-board calibration targets to obtain brightness temperatures in the two infra-red channels. These can then be compared for each pixel (picture element). Theoretical considerations suggest that the magnitude of the difference would give some indication of the vertical thickness of the fog.

Eyre *et al.* (1984) included an example from August 1981 in which a composite image had been created to show the temperature of areas covered by fog or low stratus in shades of grey, with the surface temperatures in clear areas in various colours. In the present study, it was decided to investigate in more detail the relationship between the magnitude of the temperature difference between the two AVHRR channels and conventional observations of the distribution of and horizontal visibility in the fog. It was hoped that this procedure would yield a threshold temperature difference for use in future operational products for forecasters.

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2. The case study — 23 October 1983

A case study was selected by examining the operational charts held at the Meteorological Office Archives. The aim was to find a case in which there was patchy fog across the country rather than widespread coverage since it was felt that one of the main advantages of the detection of fog using satellite techniques was that much more detail could be provided on the spatial coverage than was possible using conventional data. It was found that 23 October 1983 fulfilled these requirements.

The raw AVHRR data were obtained from the University of Dundee and processed on the HERMES (High-resolution Evaluation of Radiances from MEteorological Satellites) system in the Satellite Meteorology Branch of the Meteorological Office (Turner *et al.* 1985). All of the relevant conventional data were obtained for the period of the study.

At 0600 GMT on the 23 October 1983, a large anticyclone with mean-sea-level pressures up to 1039 mb was centred over south-east Europe with a ridge extending west-north-westwards into central and southern England. A frontal trough lay across Northern Ireland and north-east Scotland and this moved eastwards to cross most of the United Kingdom during the day.

The UK chart for 0500 GMT (Fig. 1) shows virtually no cloud over England, Wales and northern France. Strong to gale force south-westerly winds persisted in the north of Scotland but over central and southern England the winds were mainly south to south-easterly, with speeds of 5 kn or less.

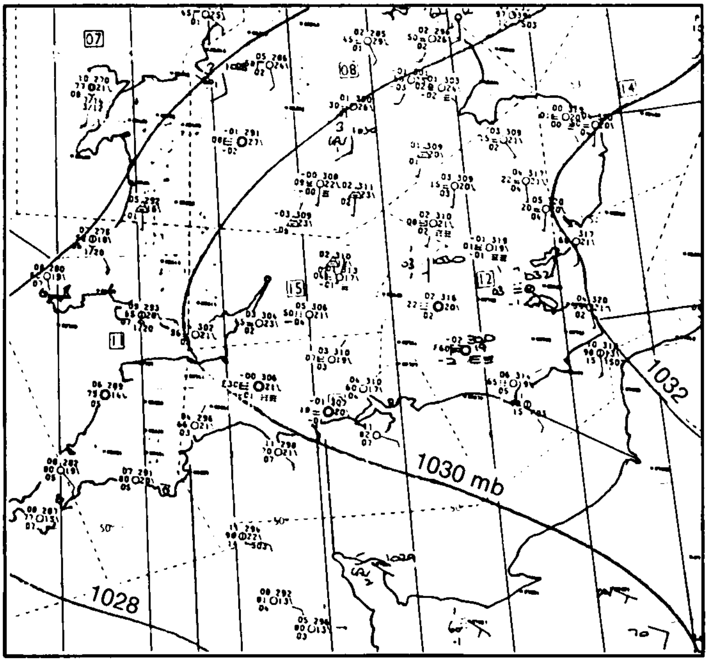

Figure 1. Surface analysis and observations at 0500 GMT 23 October 1983.

3. Analysis of fog cover

(a) *From surface observations*

At midnight, fog was reported only from Coltishall and Gatwick, both with the sky visible, although there was mist reported in northern England, Dorset and in a belt across East Anglia and central

England. There was very little increase in the size of the areas covered by fog until after 0200 GMT. By 0500 GMT, fog was reported at most inland stations in the south-east.

Since variations in visibility can occur on a scale much smaller than that of the synoptic network, it is extremely difficult to produce an accurate analysis of fog coverage from the surface reporting stations alone. The observations at 0500 GMT (Fig. 1) show, apparently, three main areas of fog: the Somerset/Dorset area, the north-east coast of East Anglia and in an arc through Northamptonshire, London and Surrey. The south, east and western coasts generally had good visibility at this time, but in central areas of England, the visibilities reported were very variable.

(b) *From the satellite imagery*

On 23 October 1983, a NOAA-7 satellite passed over the United Kingdom on a south-bound orbit at about 0433 GMT. The digital measurements of radiance from the AVHRR were calibrated over a range of 25.5 K and quantized to eight bits. The smallest detectable change in the scene temperature is about 0.1 K, approximately the level of the radiometric noise of the long-wave detectors of the instrument.

An image can be formed from the difference in the brightness temperatures viewed by the two channels for each pixel (Fig. 2) providing that certain corrections are made (Allam 1986). The contrast in this image has been selected to display a range of temperature differences from about −4.0 K to +4.5 K in steps of 0.03 K. Light areas in Fig. 2 occur where the channel 3 brightness temperatures are lower than those for channel 4 and, from both theoretical considerations and the previous study (Eyre *et al.* 1984), are indicative of fog-covered areas. The dark spots in the image occur where the channel 3 brightness temperatures are higher than those for channel 4. This situation occurs when a relatively hot object occupies a small proportion of a single pixel. Blast furnaces, gas flares and stubble fires are common causes.

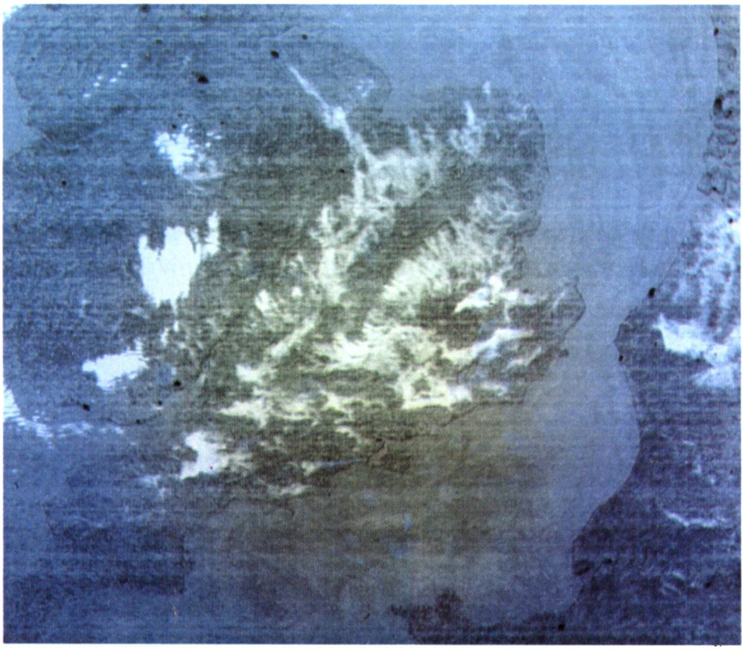

Figure 2. Satellite image for 0433 GMT 23 October 1983 formed from the brightness temperature difference between the two AVHRR channels (channel 4 − channel 3) after applying corrections. Light areas correspond to regions in which fog would be expected to occur. Dark spots indicate relatively hot areas (for example, blast furnaces).

4. Comparison of conventional data with imagery

In order to compare the details of the satellite image with conventional observations and local topography, a method was adopted of locating each pixel in the satellite image which contained an observation site. Using information on the orbit of the satellite and the geometry of the scanning pattern of the instrument, an attempt was made to compute the coordinates within the image of certain geographical locations.

Owing to errors in the knowledge of the orbit, this attempt was not completely successful. An empirical correction was obtained by comparing the computer positions of twelve prominent coastal features with their actual positions in the image. It was estimated that following this procedure a point with a specified latitude and longitude within the area of interest could be located to an accuracy of two pixels, or approximately 3 km.

The observations of weather and horizontal visibility for each station reporting at 0500 GMT were compared with the difference in brightness temperature between the two AVHRR channels. Since there were uncertainties of about two pixels in the location of the observing station within the image, it was decided to use an average temperature difference over the nine pixels closest to that predicted to contain the station. Detailed visual inspection of the images showed scattered anomalous values, attributable to noise in the raw data. The mean of the nine pixels could easily give a distorted average in an area with a few anomalous values so the median was used.

Another difficulty is that the conventional data and the satellite image are asynchronous. This could be crucial when the visibility is changing rapidly. For variables that vary smoothly in time, a method of interpolation could be used to estimate a value at any time between two observations. Since the horizontal visibility does not vary smoothly at the onset of fog, this approach could not be used. Accordingly, observations at the nearest time to the satellite pass have been used.

Fig. 3 shows the median brightness temperature difference for the nine pixels closest to the predicted point of observation plotted against the horizontal visibility for 0500 GMT. A curve that fits the points is also shown. A general increase in the value of the temperature difference is noted as the visibility decreases. At high visibilities, the mean value of the difference is about 0.4 K, suggesting that the

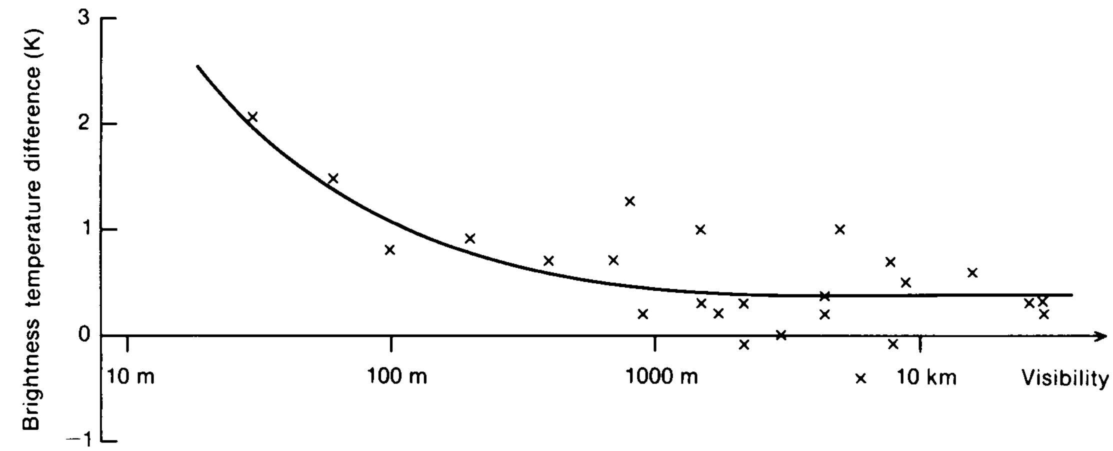

Figure 3. Graph of brightness temperature difference between the two AVHRR channels (channel 4 − channel 3) against logarithm of reported visibility at 0500 GMT 23 October 1983.

emissivity of the land is slightly different at the two wavelengths. If there was no difference in the emissivity, the mean temperature difference should be slightly negative, since a pixel containing objects with different brightness temperatures would appear warmer at 3.7 μm than at 11 μm (Saunders 1986).

It is difficult to determine a clear threshold in the difference between the brightness temperatures of the two channels that can be applied to distinguish visibilities below 1000 m from those above it. However, a difference of 1 K could be used to discriminate between visibilities above and below about 150 m, assuming that the two isolated points with visibilities greater than 150 m and differences greater than 1 K are due to noise in the validation technique.

5. Discussion of results

It should be emphasized that the bi-spectral method of detecting fog is based upon the characteristics of the liquid water in the field of view, and especially upon the drop-size distribution and total amount. While it is clear that both of these factors will affect the horizontal visibility, it is not clear that changes in them will affect equally both the radiation in the two infra-red regions used in the technique and that in the visible region used to estimate the visibility.

It should also be noted that the directions of the two types of measurement are different; the satellite observations are dependent upon the vertical, or near-vertical, distributions of liquid water and temperature, whereas visibility measured by observers on the ground is determined by the horizontal distribution of water.

Areas of shallow fog may occur that are sufficiently thick to produce a significantly different spectral signal from surrounding areas, yet may not be deep enough to cause a significant deterioration of visibility measured at the eye-level of an observer. It is also possible, particularly at night, that significant areas of fog may remain undetected by the observer. Thus the observation of visibility may not be characteristic of the region around the station.

Furthermore, the positions of most of the stations reporting fog at 0500 GMT were situated away from the coherent areas of light pixels shown in Fig. 2. The fog observed was of limited vertical extent since, in all cases, the sky was not obscured.

The satellite data are effectively averages over space. Even the pixels produced by the AVHRR, which at best are approximately 1 km square, could be expected to contain areas both with and without fog. It is unlikely that the detail of the spectral signal that is characteristic of such regions will be unravelled using the conventional observing network, but it might be possible using some sort of mathematical simulation.

6. Circumstantial evidence for fog from the image

Referring again to the image shown in Fig. 2, a number of areas of interest can be related to the local topography and conventional observations.

In the extreme south of England where the winds were very light, the bright areas are associated with valleys, shallow depressions and gaps in ridges.

The conurbation of London itself is virtually clear of bright areas, even though they are present in the estuary of the Thames. As an urban area, its higher surface roughness can increase the depth through which turbulent mixing occurs, preventing or delaying the onset of fog formation. Also, the temperatures in urban areas tend to be higher than in the country, with the same effect.

To the north of London, there is a perceptible flow of air from the south. Bright areas are shown within the small valleys that dissect the Chilterns and their continuation into East Anglia, producing the dendritic pattern in the image. The bright areas cease northward of the ridge in a strip about 50 km wide.

It is plausible to suggest that a combination of a katabatic drainage flow down the sides of individual valleys, coupled with the light general flow from the south, would cause cold air to ascend each valley to the top of the ridge, cooling as it did so. On reaching saturation, fog could form. North of the ridge, the air would descend and warm adiabatically, preventing further condensation. Since some liquid water would be deposited on the upslope, the warming of the air could be enhanced by a *föhn* effect.

The distribution of the bright areas in the north of East Anglia is more problematical, since the lack of significant topography would seem to preclude not only any lifting of moist air, but also any concentration of cold air through katabatic drainage flows. It is possible that local variations in relative humidity are important in such cases.

The Somerset Levels are another area of interest. This region, bounded by hills, is very flat and low-lying with numerous dykes for drainage. It is an area prone to fog and shows up well in Fig. 2.

Other topographical details can be picked out by comparison with a detailed topography map; valleys in the south appear bright, whereas a square-shaped hill in Surrey is dark, surrounded by light areas. In all these examples, the light areas correspond to regions in which fog would be expected to occur.

Clearly shown in Fig. 2 are the dense white areas over South Wales and parts of the Midlands. From their brightness and the presence of billows, it is possible that they are areas of cloud that have formed by the forced ascent of moist air over the hills to the south. Unfortunately, there are no observations to confirm this.

7. Conclusion

It is proposed that there is evidence, both direct and indirect, to support the proposition that the areas of the image in which the brightness temperatures seen in AVHRR channel 4 exceed those in channel 3 by more than one degree are probably the sites of significant banks of water droplets, some of which could be thick enough to reduce the horizontal visibility to less than a few hundred metres.

In the light of the scatter of points in Fig. 3, particularly towards high visibilities, the quantitative aspects of this study should not be emphasized. The case shows some of the complications to be expected in an operational environment. In particular, the fog was thin and patchy, both of which increase the problems of interpretation. However, the qualitative aspects of the image suggest that the technique is potentially of great use to forecasters, since it provides a unique view of the spatial distribution of fog.

Further case studies are being examined in which the fog is thicker and more uniform. It is hoped that these will increase our understanding of the quantitative aspects of the technique. The availability of such images to operational forecasters will provide them with the geographical location of fog at a fixed time but they will still need to use their forecasting skills to predict its development in space and time. The regular use of these images should also increase the understanding of the behaviour of fog, both on synoptic and local scales.

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551.509.331:551.526.6:551.582(4):551.465.5

Gulf Stream variability and European climate

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Summary

The influence of mid-latitude oceanic variability on the atmospheric general circulation is not well understood. Nevertheless, some modelling and observational evidence is presented to suggest that, in winter-time, persistent sea surface temperature anomalies near Newfoundland could influence climate downstream over Europe. The discussion is a summary of a more extensive paper which recently appeared in the *Quarterly Journal of the Royal Meteorological Society*.

Introduction

Almost a century and half ago, Sabine (1846) suggested that variations in the strength of the Gulf Stream were 'the cause of remarkably mild winters which occasionally occur in England'. We now know, however, that there is no single cause for such climate variability; indeed, complex models of the atmosphere show considerable inter-annual variability in the absence of any oceanic variability. Despite the enormous advances in our understanding of the atmospheric general circulation since Sabine's time, the role of variations in the position and strength of the Gulf Stream on European climate are not well understood.

One of the regions of the North Atlantic where such variations can be quite marked is to the south-east of Newfoundland, near the interface of the warm Gulf Stream waters and the cold Labrador Current waters. Variation in monthly mean sea surface temperature (SST) in this region can be particularly large (up to 3 K in winter with larger values at other times of the year). Moreover,this is one of the most active regions of the extratropical atmosphere. In winter, with large air–sea temperature differences (associated with cold air streaming off the American continent) and strong meridional SST gradients, cyclogenesis is intense.

Not surprisingly therefore, this region has been the focus of attention of a number of studies investigating the possible influence of mid-latitude oceanic variability on atmospheric climate. Namias (1964), for example, found that blocking activity over northern Europe during the late 1950s was associated with abnormally cold water near the coast of Newfoundland. More generally, Ratcliffe and Murray (1970) found significant lagged correlations between SST in this area (hereafter called the RM area) and surface pressure over Europe, suggesting that a knowledge of SSTs in the RM area may be of importance for long-range forecasting over Europe.

Two important developments have occurred since the work of Namias, and Ratcliffe and Murray, suggesting that further study of the problem is now opportune. Firstly, in the last decade and a half, an enormous amount of effort has been put into the construction of high-quality historical SST data sets suitable for climate studies. The Meteorological Office Historical SST data set (MOHSST) (Minhinick and Folland 1984) is second to none in this respect, careful attention being given, for example, to the correction of biases caused by different methods of measurement. Secondly, there has been substantial development of numerical models of the atmosphere since 1970, and it is now possible to test, in an atmospheric general circulation model (GCM), whether the SST anomalies observed by Ratcliffe and Murray have a consistent influence on the general circulation.

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For these reasons, it was decided to undertake a combined modelling and observational study of the influence of SST in the north-west Atlantic on the general circulation of the atmosphere, using the MOHSST and the Meteorological Office 5-level GCM. This article is an informal synopsis of some of the results of the study which have been published in full by Palmer and Sun (1985).

Model results

The results from eight 50-day winter-time integrations of the 5-level model from four different initial conditions are described first. For each set of initial conditions, two integrations were run: one had the positive SST anomaly, illustrated in Fig. 1(a), added to climatological SSTs, the other had this anomaly subtracted from climatological values. The magnitude of this anomaly is about as large as would ever be observed in the RM area, so the model experiment can be thought of as testing the response to extremes of variation in the north-west Atlantic. Figs 1(b) and 1(c) show the effect of adding or subtracting this anomaly to climatological values. For example, with warm SSTs, the Gulf Stream separates further north from the coast of America and the Labrador Current does not extend as far south.

Fig. 2 shows the 500 mb geopotential height difference field (positive anomaly run minus negative anomaly run) averaged over the four pairs of integrations. For this and other fields, the mean of days

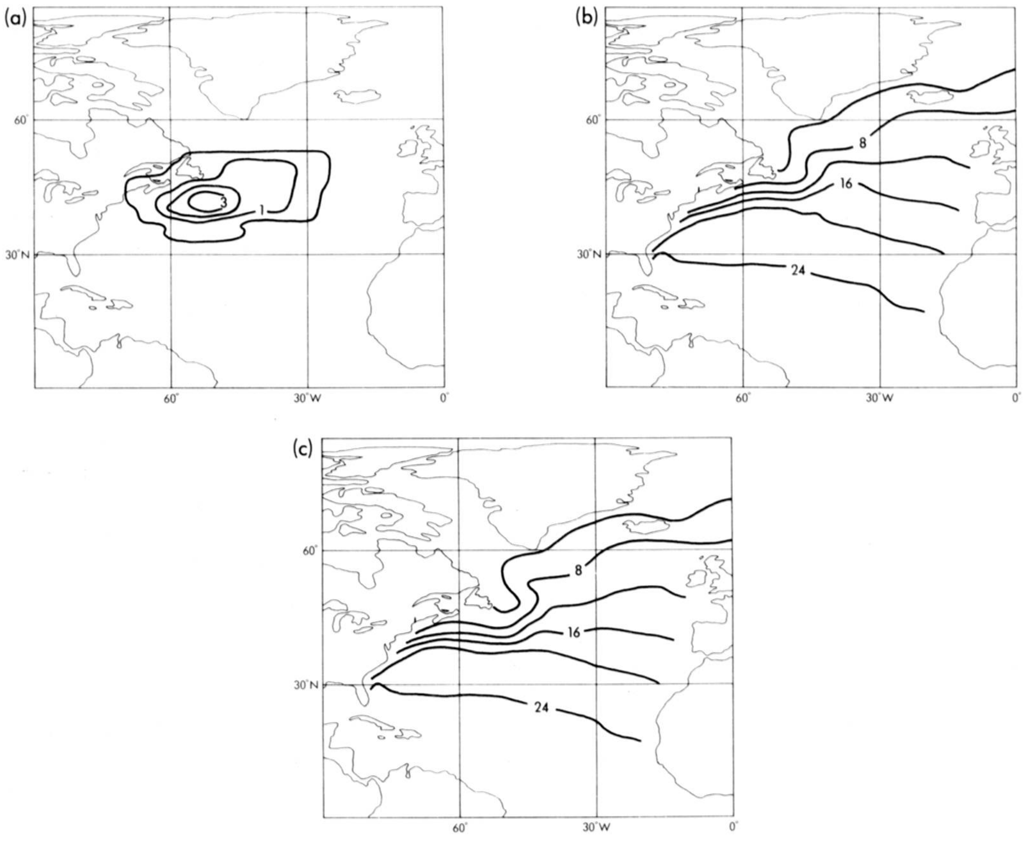

Figure 1. Sea surface temperature (SST) anomalies over the North Atlantic: (a) full anomaly (K) used for model integrations, (b) SST with this anomaly added to climatological values (°C) and, (c) SST with this anomaly subtracted from climatological values (°C).

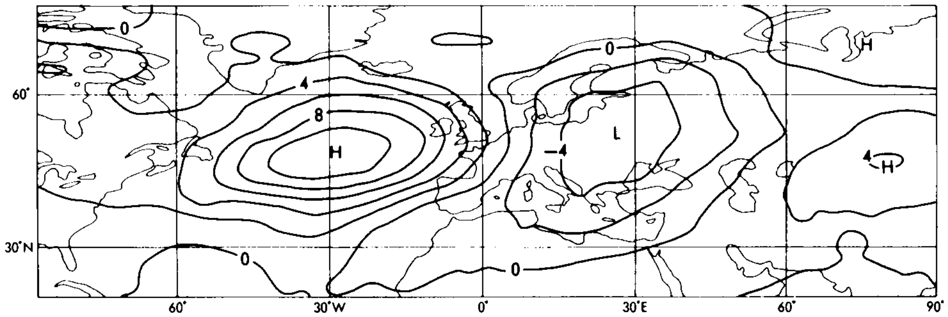

Figure 2. 500 mb geopotential height difference field (dam) averaged over the four pairs of integrations. Each pair consists of one 50-day run with the SST anomaly shown in Fig. 1, and one run with the negative of this anomaly. The mean of days 21–50 is shown.

21–50 of each integration was used. The two main features of this figure are the positive values over the North Atlantic, and the negative values over Europe. Fig. 3 shows this difference for each individual pair of integrations. The main point here is that there are counterparts to the positive and negative values in each of the individual difference fields. Palmer and Sun (1985) showed that the positive and negative values were statistically significant, by performing Student's *t*-tests on the four pairs of integrations. Elsewhere around the hemisphere, the 500 mb height difference field differed substantially from one pair of integrations to the next; from this it must be deduced that there is no consistent response, in such regions, to SST anomalies in the north-west Atlantic.

In order to test whether there is still a discernible signal over Europe and the North Atlantic when the SST anomalies are less extreme, four further pairs of integrations were run with plus and minus half the anomaly shown in Fig. 1(a). The 500 mb geopotential height difference field, averaged over these four pairs of integrations, also showed positive values over the North Atlantic, about half as large as those in Fig. 2, and weak negative values over eastern Europe. However, for this second set of integrations, the difference field varied a lot from one pair of integrations to the next, and results were only of marginal statistical significance.

In trying to understand the dynamical mechanisms at play in these integrations, it was found that the interaction between the mid-latitude cyclones and the time-mean flow was particularly important. It is well known in the theory of the atmospheric general circulation that baroclinic waves play an important part in maintaining the mid-latitude westerlies against frictional dissipation. With warm SST anomalies it was found that the storm tracks over the North Atlantic were displaced north of their normal position; conversely, with cold SST anomalies they were displaced south of their normal position.

A possible explanation for the results in Fig. 2 is that addition of the warm SST anomaly to the climatological value moves the zone of maximum baroclinic instability northward. This in turn moves storm-track activity northward, and thereby intensifies the North Atlantic westerlies. It can be seen from Fig. 2 that north of about 50° N the 500 mb westerlies are enhanced over the Atlantic. These ideas can be made more precise by using the so-called *E*-vector diagnostic (Palmer and Sun 1985).

Observational results

Having obtained the model results, attention was then focussed on the observations by using the MOHSST data as far back as the turn of the century, together with northern hemisphere archived 500 mb geopotential height and surface pressure data. It was also decided to analyse separately the

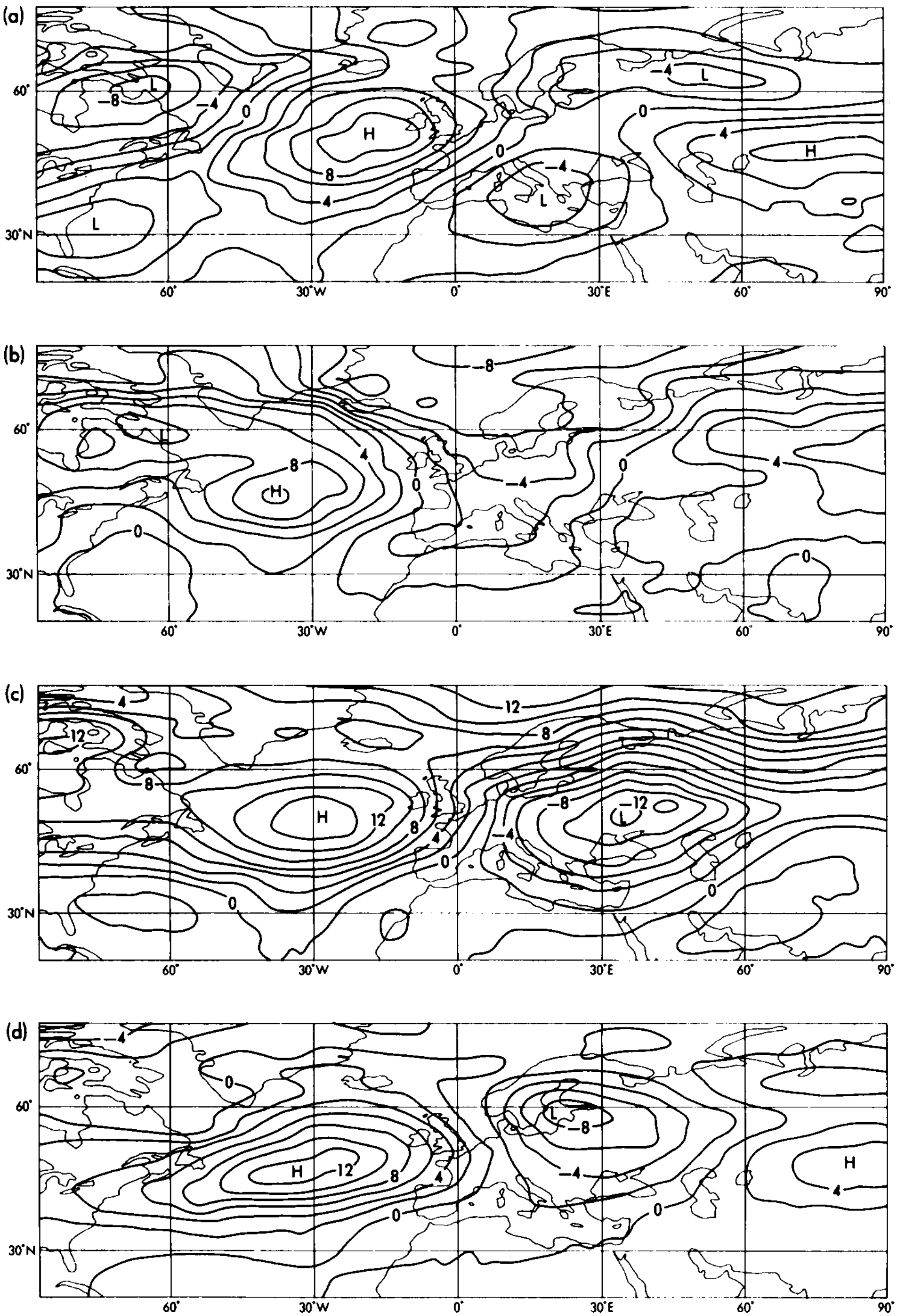

Figure 3. 500 mb geopotential height difference field (dam) for each individual pair of integrations.

periods 1901–30 and 1951–80 to avoid, as much as possible, decadal time-scale trends in the data (Folland *et al.* 1984).

First of all, the RM area was defined to be that within longitudes 60° and 40° W, and latitudes 40° and 50° N. For each month from November to February inclusive, SST anomalies were calculated for 10° × 10° areas over the globe. Cases when monthly mean SST anomalies averaged over the RM area were greater than 0.8 K were grouped together to form a composite warm SST anomaly. Similarly, anomalies in the same area colder than −0.8 K were grouped together to form a composite cold anomaly. The difference between the warm and cold composite SST anomalies is illustrated in Fig. 4 for the 1951–80 data. This clearly illustrates the effect of the compositing, with the difference field having a maximum of 2.4 K in the RM area. Also noticeable is the absence of a significant anomaly in any other area, the tropics in particular.

For each month designated either 'warm' or 'cold', the 500 mb geopotential height and surface pressure anomalies were calculated. These were composited to create mean synchronous atmospheric anomalies associated with the warm and cold composite SST anomalies. The 500 mb geopotential height difference between the composited warm and cold months for the 1951–80 period is illustrated in Fig. 5. Stippling on the figure indicates regions where the difference field is statistically significant (at the 5% level) using Student's *t*-test. A similar composite difference field was calculated using the 1901–30 data which produced very similar results over Europe and the North Atlantic.

Conclusions

The similarities between Figs 2 and 5 are quite striking. Both model and observations show significant positive values over the North Atlantic and negative values over Europe. This similarity suggests that the north-west Atlantic SSTs can indeed have some influence on downstream European climate. There are some differences in detail; for example, the positive centre in Fig. 2 is positioned about ten degrees east of the corresponding observational position. Perhaps the most important 'discrepancy' is the similarity in the magnitude of the model and observational results, given that the model SST anomalies in Fig. 1(a) are about twice as large as the composite SST anomalies in Fig. 4. However, this may not be serious. As diagnosed by Palmer and Sun (1985), the interaction between baroclinic wave activity and the time-mean flow is an important dynamical mechanism in this problem. It would therefore seem reasonable to suppose that a model which is unable to resolve adequately air–sea interaction processes in amplifying cyclones, would underestimate the response to a given SST anomaly in the north-west Atlantic. It is quite possible that the 5-level model, with a horizontal resolution of about 330 km, fits such a description.

The results of this study are in general agreement with the earlier results of Namias (1964) and Ratcliffe and Murray (1970). From Figs 2 and 5, cold SST anomalies in the RM area will tend to be associated with positive geopotential height anomalies over Europe, and hence enhanced ridging and possible blocking. Conversely, warm SST anomalies will tend to be associated with a more progressive westerly type of weather over the British Isles. It has been found that there is significantly more rainfall, particularly over the northern British Isles, when the SST is anomalously warm in the RM area. Of course, these correlations are far from perfect; variability in the north-west Atlantic SST explains only a fraction of monthly-mean climate variance over Europe. Nevertheless, C.K. Folland, of the Synoptic Climatology Branch at the Meteorological Office, has recently found that SST in the RM area is an important winter-time predictor in the multivariate statistical model used for long-range forecasting for the United Kingdom.

One question yet to be asked is what causes the Gulf Stream variability near Newfoundland. The answer is undoubtedly the influence of the atmosphere on the ocean. Palmer and Sun (1985) showed that

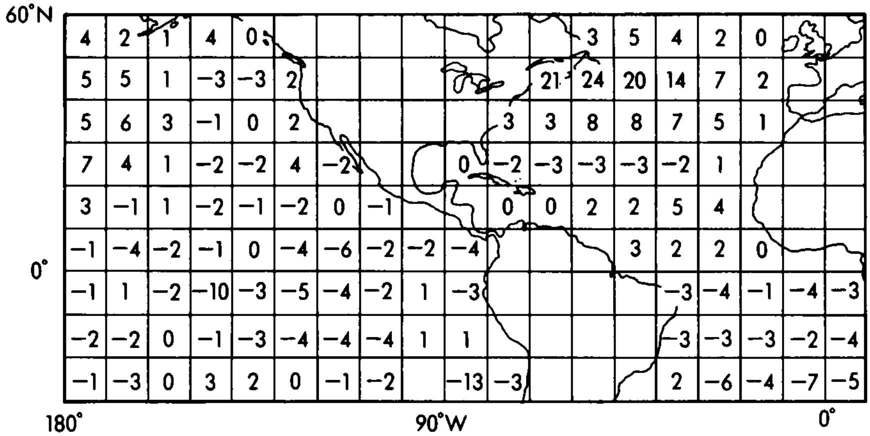

Figure 4. Observed composite sea surface temperature (SST) differences ('warm' — 'cold') in units of 0.1 K using monthly mean SST data averaged over 10° × 10° areas from 1951–80. Blank sea squares indicate missing data.

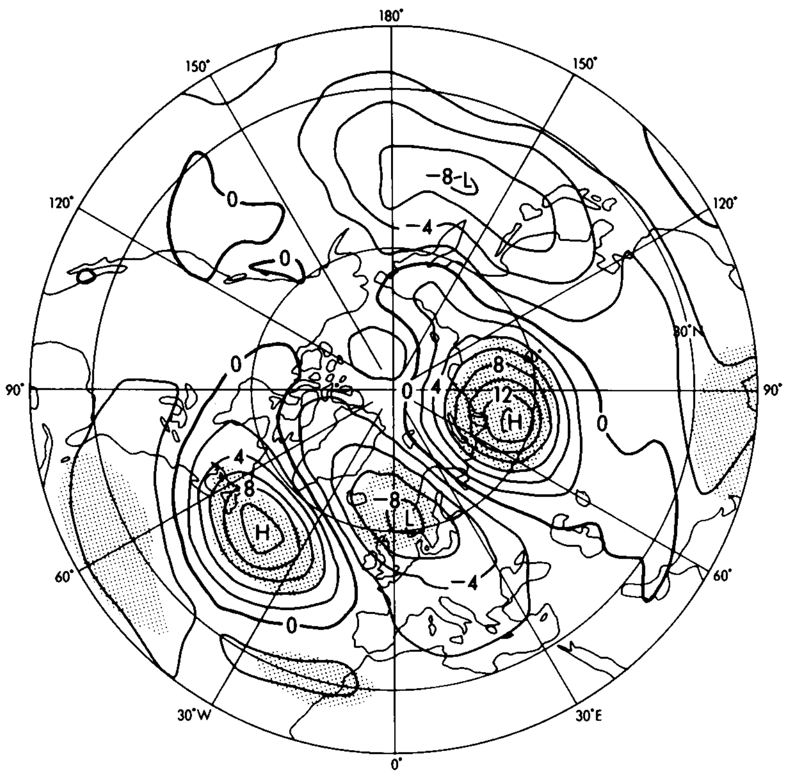

Figure 5. Observed composite 500 mb geopotential height difference field (dam), synchronous with 'warm' and 'cold' months in the RM area (see text), using monthly mean data from 1951–80. Stippling indicates areas that are signficant at the 5% level.

the atmospheric difference field in Fig. 5 had an equivalent barotropic structure (i.e. the patterns have a similar shape at all levels, although different amplitudes), so that the surface wind difference field over the RM area had a marked easterly component. If an anomalous easterly wind stress over the RM area was applied to an ocean model, the surface waters would warm through two effects: a reduction in sensible and latent heat loss from the surface, and the advection of warm waters in the mixed layer by the anomalous Ekman drift current. Such an experiment has been described by Daly (1978).

In summary, therefore, the whole process appears to involve co-operative ocean–atmosphere coupling. Which comes first in setting up the SST anomalies, the ocean or the atmosphere, is really a chicken-and-egg question. We shall never understand the process fully until coupled ocean–atmosphere general circulation models have been developed. Nevertheless, Sabine's conjecture, that Gulf Stream variability can have some effect on British winter-time climate, may have more than a grain of truth in it.

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Conference report

The State of the Art in Numerical Analysis, University of Birmingham, 14–18 April 1986

This conference, organized by the Institute of Mathematics and its Applications and the Society for Industrial and Applied Mathematics, was the third in a series that has been held every ten years to review progress made in the field of numerical analysis. The meeting consisted of 24 review lectures covering all aspects of the subject. Several of the speakers had given similar talks to the previous conference in 1976, and were well placed to review new achievments in the last decade.

The first session was on linear algebra. The problem here is how to handle large matrices such as those arising in statistical regression analysis. It was admitted by at least one of the speakers that in most realistic situations the errors in the data being analysed were much greater than those in the numerical analysis itself, certainly a common situation in meteorology. Also the 32-bit word used on IBM computers is inadequate for many calculations, requiring double precision to be used. A common difficulty in very large (real) problems is the storage of the matrices. Techniques available for data compression using hardware instructions available on such computers as the Cyber 205 were described.

In the second session approximation and data fitting were discussed. These were directly relevant to the analysis problem in numerical forecasting where scattered observations have to be merged with the forecast first-guess field. The theory of data fitting is most developed in one dimension where it is known how to impose monotonicity or convexity on the curve fitting the data points. Multi-dimensional problems are best treated as a product of one-dimensional problems. The best methods also give statistics about the fit achieved for the data. This is very important in the meteorological analysis problem.

The third session was on optimization and non-linear equations. There has been a very large amount of work in this area because of obvious industrial applications. The difficulty here is that a function of a large number of variables has to be minimized, possibly subject to constraints. This involves knowing the derivative of the function with respect to all the variables. These are not usually known analytically and have to be estimated. Evaluations of the function in real problems may be very expensive and it is desirable to do as few of them as possible.

Special problems where the behaviour of the solution can change discontinuously were also described. These represent situations where a mechanical system, for instance, can have more than one equilibrium state but where some of these equilibria become unstable as the control parameters change. It is important to be able to predict such behaviour.

Before the next session there was a talk on 'the sign of zero'. It might be thought that it is irrelevant whether zero is positive or negative, though perhaps not by meteorological observers. There are, in fact, computer calculations where it is important that zero can have a sign because of the limited precision available.

The next session was on ordinary differential equations. In integrating these forward in time it is essential to be able to distinguish correct solutions which grow with time from unstable computational solutions. A great deal of work is being done on finding precise ways to make the distinction, and to determine for which values of the time-step particular integration formulae are stable.

This was followed by a session on integral equations. This is an area where a good deal of progress has been made in the last ten years; partly because of the number of important problems where solutions within a domain have to be deduced from boundary information. The size of such problems can be greatly reduced if they can be formulated in terms of integrals along the boundary rather than over the whole domain. The session was followed by a talk on vector and parallel processors. The Meteorological Office has had a vector processor for some time and a great deal of work went into redesigning the operational analysis and forecast to take advantage of it. Future computers will have several processors which can work in parallel, and algorithms will again need to be redesigned. It is advantageous if the algorithms are insensitive to the order in which the computations are performed, reducing the need for synchronizing the processors.

The final session was on partial differential equations. A great deal of work is going into problems with moving boundaries, such as the oil/water interface in a reservoir. Meteorologists have not yet attempted to apply similar techniques to air masses. New efficient methods have been developed for iterative solution of the finite difference equations arising from steady state problems. Methods for tracking sharp fronts as they cross the domain have been greatly improved, but it is necessary to preserve the sharpness without allowing spurious overshoots. In the Meteorological Office fine-mesh model such overshoots result in spurious rain bands.

Most of the speakers made their material understandable to non-specialists in their particular area. My personal experience is in partial differential equations, so I found the review of work in data analysis very revealing and interesting. This area is as important to the Meteorological Office as are the improved methods for numerical weather and climate prediction. My only complaint was the familiar one of speakers trying to fit their whole talk onto one overhead projector transparency.

The proceeding of the Conference will be published by the Institute of Mathematics and its Applications in due course.

M.J.P. Cullen

Reviews

Handbook of applied meteorology, by David D. Houghton. 160 mm × 230 mm, pp. xv + 1461, *illus.* John Wiley and Sons Ltd, New York, Chichester, Brisbane, Toronto, Singapore. Price £98.25.

The main aim of this book is to provide a comprehensive reference of applied meteorology for professionals and technicians outside the meteorological profession. However, professional meteorologists will find a wealth of material in this massive book, particularly in the areas of applications and measurements. There are 46 chapters by over 50 contributors all, bar one, from the USA, and not surprisingly the subject matter is drawn largely from sources within that country.

The first four chapters in Part I provide a background for the rest of the book by dealing with atmospheric circulation systems, climatology, severe weather and weather forecasting. I suspect the majority of the intended readership will find some of the material difficult to follow, particularly the chapter on weather forecasting which is full of jargon. This chapter contains some interesting outlines of case studies originally published in journals,

Part II has nine chapters on measurements, ranging from ground-based observing systems to satellite-based systems. It gives a comprehensive list of instruments currently in use together with their applications and is a very useful reference work. The largest chapter on satellites is a summary of the history and techniques of satellite meteorology. Unfortunately, the authors miss the opportunity to emphasize the global coverage of satellite-based systems. Meteosat, GMS and INSAT do not rate a mention in this chapter but they are referred to later in the book under the heading of 'data'.

Part III, applications, is the largest section consisting of 25 chapters. The list of applications appears exhaustive and includes water management, agriculture, forestry, air pollution and dispersion measurements, health, architecture, energy, transport, wave propagation and weather modification. As in previous sections the chapter lengths and formats adopted by the authors vary considerably. Acid precipitation merits only 5 pages whereas weather modification fills 75. Forestry (60 pages) deals in some depth with the meteorological influences on forest management. Agriculture (20 pages) has only 2 pages devoted to the use of weather information and forecasts, and would have benefited from the fuller treatment adopted in the forestry chapter and by the inclusion of more information on weather influences on pests. Aviation (32 pages) gives a description of the way weather affects all aspects of flight, but there are no details of forecasting rules. Marine transport and weather-sensitive operations (19 pages) provides information on wave forecasting (including a short program listing) and is aimed chiefly at the offshore industry. Much more could have been written on weather-sensitive marine activities and on the impact of improved weather forecasts, particularly with regard to ship routeing and recreational activities. Energy use is covered by three chapters, one on factors affecting demand (44 pages) and one each on solar energy (25 pages) and wind energy (30 pages). The chapter on weather modification gives a balanced view on the controversial subject of cloud seeding for rainfall enhancement and hail suppression, and also discusses fog clearing and frost protection.

Part IV is a shorter section on societal impacts. The vogue for litigation in the USA has no doubt stimulated the chapter on property rights (although this is inconclusive) and there are chapters on environmental and economic impacts. The latter is only a short chapter and deals only with the impact of variations in climatic elements. There is no attempt to assess the economic benefit of improved forecasts.

The final section of the book, resources, provides an extensive (but not exhaustive) list of data, books and journals (*Meteorological Magazine* is included but not *Tellus* or *Beiträge zur Geophysik*). Research centres, libraries and education centres are also listed. The appendix includes a glossary and a selection of climatic data from around the world.

The professional meteorologist will find this a useful reference book. Most of the chapters on applications are worth reading and may stimulate ideas into finding a wider market for meteorological products. The book is well produced with few errors but the index is poor with many omissions. The page cost compares well with other technical books but at around £100 it is almost a luxury.

T. Davies

Books received

Weather at sea, by D. Houghton (Steyning, Fernhurst Books, 1986. £5.50) is designed as a yachtman's guide to the weather. It clearly explains the basic principles that govern the weather, describes how to use the various weather bulletins and how to draw a weather map from them, shows how to deduce modifications to the wind by the coast or the sea breeze, and how to work out the forecast for a route. It also explains how to keep an eye on developments by watching the clouds, wind, waves and barometer and finishes by discussing hazards such as gales, squalls, thunderstorms and fog.

Floodshock: the drowning of planet earth, by A. Milne (Gloucester, Alan Sutton Publishing Ltd, 1986. £12.95) details the history of the world's great floods from Noah until the present day. The emphasis is put on oceanic and ice-cap factors, including climatic change and catastrophe theory, in explaining the more serious and long-term threat to the world. It is a sequel to Milne's earlier book, *London's drowning*, which suggested that the main threat to London was the growing high surge tide and the sinking of the land. What is happening to London is a salutary warning to the rest of the world.

Air: composition and chemistry, by P. Brimblecombe (Cambridge University Press, 1986. £25.00 (hardback), £8.95 (paperback)) is about the atmosphere and man's influence on it. In the early chapters the author discusses the geochemical, biological and maritime sources of the trace gases; these are followed by chapters on the chemistry of atmospheric gases, suspended particles and rainfall. After dealing with the natural atmosphere the book examines the sources of air pollution and its effects: decline in health, damage to plants and animals, damage to constructional materials, pollution of interiors, acidification of rain, and changes in global carbon dioxide and methane. The final chapters are concerned with the chemistry and pollution of the upper atmosphere and the composition and evolution of the atmospheres of the planets of the solar system.

Meteorological Magazine

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Meteorological Magazine

September 1986

Vol. 115
No. 1370

CONTENTS

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ISBN 0 11 727837 8 ISSN 0026–1149

Printed for HER MAJESTY'S STATIONERY OFFICE
by Delco Printing Co Ltd 9/86 Dd. 739131 C14

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S
STATIONERY
OFFICE

October 1986

Met.O.971 No. 1371 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1371, October 1986, Vol. 115

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Experimental monthly long-range forecasts for the United Kingdom

Part I. Description of the forecasting system

By C.K. Folland and A. Woodcock
(Meteorological Office, Bracknell)

Summary

Although a public service of long-range forecasts for the month ahead for the United Kingdom ceased at the end of 1980, regular long-range forecasts have continued to be made, together with a restricted commercial consultancy scheme. A summary is given of the major changes in procedure and technique that have occurred since the public service ceased, together with an indication of the scientific ideas that currently guide long-range forecasting research. Companion papers by Murphy and Palmer (1986) and Folland *et al.* (1986) provide a detailed description of dynamical techniques applied to long-range forecasting and an assessment of the skill of the long-range forecasts issued since 1964.

1. Introduction

A public service of twice-monthly long-range forecasts for one month ahead began with a forecast for December 1963 and ceased after 17 years with the forecast for mid-December 1980 to mid-January 1981. A service of experimental seasonal (3 months ahead) forecasts for selected industrial concerns also ceased with the forecast for the winter of 1980/81. However, forecasts have continued to be made every half month for the 30 days ahead on an experimental basis, without a break. The forecasts are still sent to a limited number of commercial and corporate users if it is thought they may be able to gain cumulative benefits from a low average level of forecast skill over an extended period. Shortage of staff currently demands that the total number of users is kept small.

Analogue (chart-matching) techniques no longer form part of the process for forecasting atmospheric circulation; indeed two relatively new techniques, a regression technique and a more important technique using advanced multivariate statistics, now provide almost the only statistical input to these forecasts. The contribution of medium-range dynamical numerical weather forecasts has increased as they have become more reliable and available for longer periods ahead. An important activity of the forecaster is, therefore, the imaginative combining of dynamical and statistical techniques, although the impact of truly long-range dynamical forecasts has so far been fairly small. One result of the work is an increasing need to distinguish between the contributions from medium- and long-range techniques to the skill over the month as a whole.

2. Predictability — what should be predicted?

Variations of atmospheric circulation occur on all time-scales; in mid-latitudes, regional circulation patterns (space scale 4000–10 000 km) tend to group into persistent 'spells' or regimes containing one basic pattern that typically lasts for 10 days to 1 month with only short breaks. Sometimes, however, extended 'chaotic' periods occur when a coherent circulation regime is less apparent. Blocking is an example of a type of coherent spell whose dynamics are now starting to be revealed, see for example Shutts (1983). The majority of spells near the United Kingdom tend to be associated with other recognizable circulation regimes. Examples are: persistently westerly types with large day-to-day variability; persistently cyclonic types often associated, in the longitude sector of the United Kingdom, with weak tropospheric flow and mid-tropospheric jets to the north and south; and anticyclonic westerly types associated with a broad and persistent medium amplitude mid-tropospheric ridge (such as occurred frequently in the 'drought' year of 1975/76).

Fig. 1 illustrates two extreme examples of spells lasting about 3 months (Legg, personal communication). Figs 1(a) and (b) show the location of the average position of the maximum speed of the jet stream at 500 mb in each 5-day period (pentad) between June and August for 1983 and 1985 respectively. Averaging the 500 mb height data removes variations due to the passage of individual depressions. Lines have been drawn where the mean maximum speed of the jet exceeded about 50 knots. In general the centres of depressions will pass a few hundred kilometres to the north of, but approximately parallel to, the lines drawn in Fig. 1. Clearly the jet stream paths near the United Kingdom were systematically different in the two summers, most pentads showing a more southerly jet position in 1985 than any in 1983. So the contrasting characters of the two summers (especially over Scotland) were not the net, almost chance, result of a minority of exceptionally different pentads. Such clear inter-annual contrasts at specific times of the year are quite common, especially for periods of a few weeks. This characteristic of the atmosphere strongly hints at the sometimes (but not invariably) dominant role of mechanisms that control weather near the United Kingdom on much larger time-scales than those of individual baroclinic disturbances. Understanding and then forecasting the behaviour of these low-frequency weather processes can be seen as a central task of the researcher into long-range forecasting.

In numerical forecasting, it is widely accepted that there is, in principle, a limit to the time ahead that the skilful forecasting of *instantaneous* states of the weather observed at any point is possible. This 'limit of deterministic predictability' is thought to lie 2–3 weeks ahead in middle latitudes. The long-range forecaster must therefore have a basically different practical objective — to try to predict time and space averages of weather events and if possible forecast the statistical character of weather variability over a region and over a time interval. A further difference from medium-range forecasts, at least up to the present, is that the long-range forecaster concentrates on forecasting anomalies (deviations) from the climatological mean state for a particular time of year and region. The climatological mean can be calculated in advance and made available to the users; the task of forecasting the deviations from this mean is in principle simpler than forecasting the absolute values. This is especially true of patterns of surface weather, where the anomaly patterns tend to have a much larger spatial scale than those of their absolute values. Examples are patterns of monthly-mean temperature and rainfall over the United Kingdom. This approach reduces the number of degrees of freedom required to be forecast and is especially helpful in statistical forecasting.

There is, of course, no guarantee that these larger scales in space and time are really predictable beyond the deterministic limit. However, they tend to be more influenced by the 'slower' internal atmospheric features such as the upper tropospheric long waves, by persistent anomalous large-scale patterns of sea surface temperatures (Mansfield 1986, Palmer and Mansfield 1984, Palmer and Sun 1985), soil moisture (Rowntree and Bolton 1983) and snow or ice cover, and perhaps by slowly moving

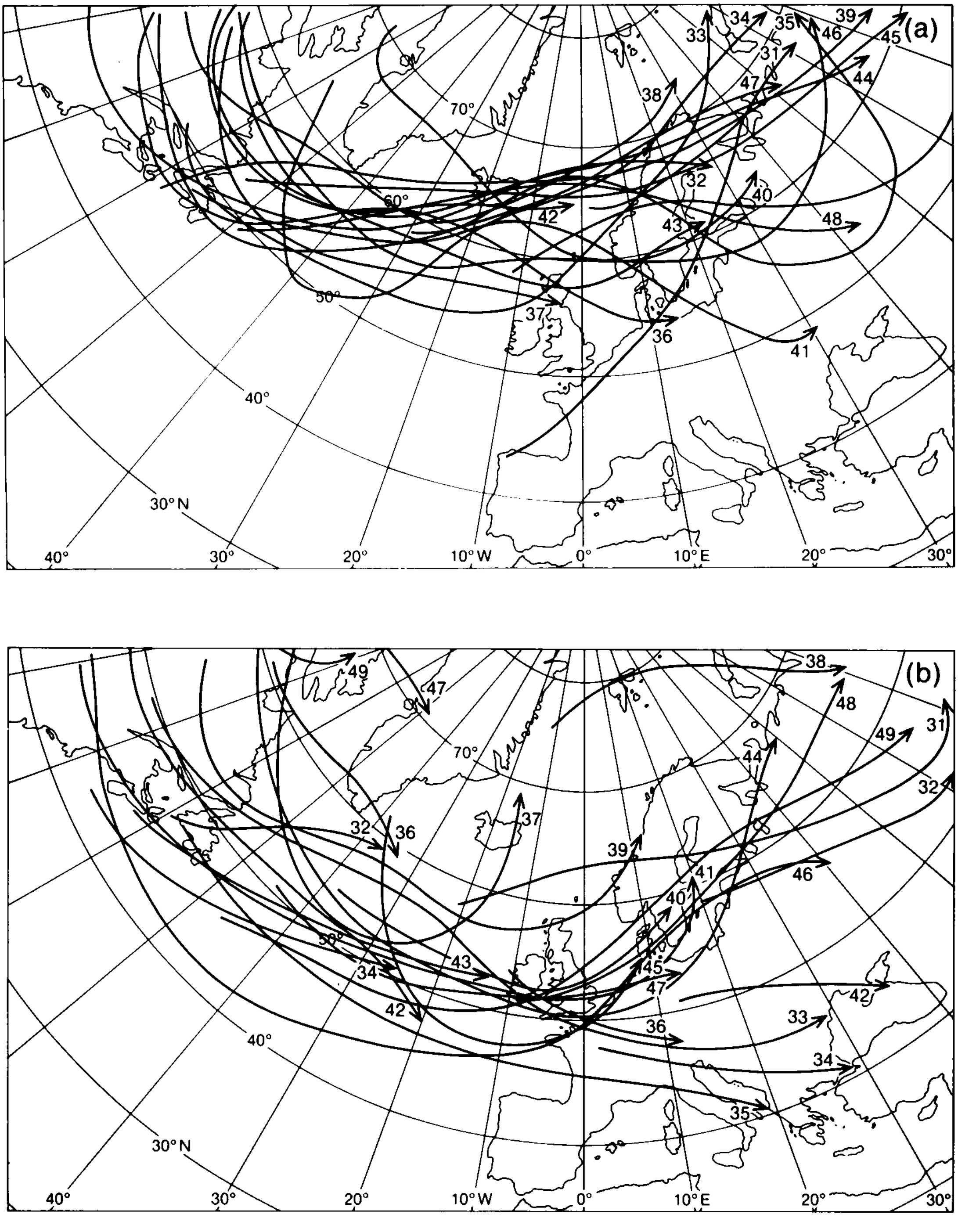


Figure 1. Position of 5-day (pentad) mean maximum jet stream speeds (> 50 kn) at 500 mb during June, July and August for (a) 1983 and (b) 1985. The arrows indicate the direction of the mean flow and the figures give the pentad number (e.g. 41 refers to the 41st five-day period into the year).

or varying patterns of deep tropical atmospheric convection (Weickmann *et al.* 1985). A real hope for useful predictability comes from the many studies of the variability of large-scale time-averaged (e.g. monthly-mean) atmospheric circulation patterns. A large proportion of the total non-seasonal variance seems to be caused by a surprisingly small number of patterns (Craddock and Flood 1969, Blackmon *et al.* 1984, Barnston and Livezey 1985), even if different analysts do not always agree on the same patterns. The patterns so far identified may not reflect coherent dynamical processes (though some theories exist, e.g. Simmons *et al.* (1983)), but the studies do hint that the number of degrees of freedom that need to be forecast with skill before long-range forecasts become truly useful may be much less than is sometimes suggested, as for example by Tapp (1984). Another quite hopeful sign is that moderately useful regional monthly temperature forecasts, especially for certain seasons, have been issued in recent years (see for instance Folland *et al.* (1986) and Kalnay and Livezey (1985) who discuss forecasts issued by the National Weather Service of the USA).

3. Potential value of long-range forecasts

The user of long-range forecasts is often interested in how long a spell of weather that has already started will last, what the following spell will be like and approximately when it will start. Substantial fluctuations of temperature (from the climatological average) are often involved in the change from one weather spell to the next. Thus large variations of temperature (about the climatological average) occur on time-scales of weeks or more. The relative strengths of these variations are illustrated using a power spectrum analysis of daily Central England Temperature (Fig. 2) for 1936–85 from which the long-term average for each day has been removed. The variance of any range of frequency is given by the corresponding area under the spectral curve. The spectrum is in fact an average of ten individual spectra calculated for the non-overlapping 5-year periods between 1936 and 1985, and uses a recently

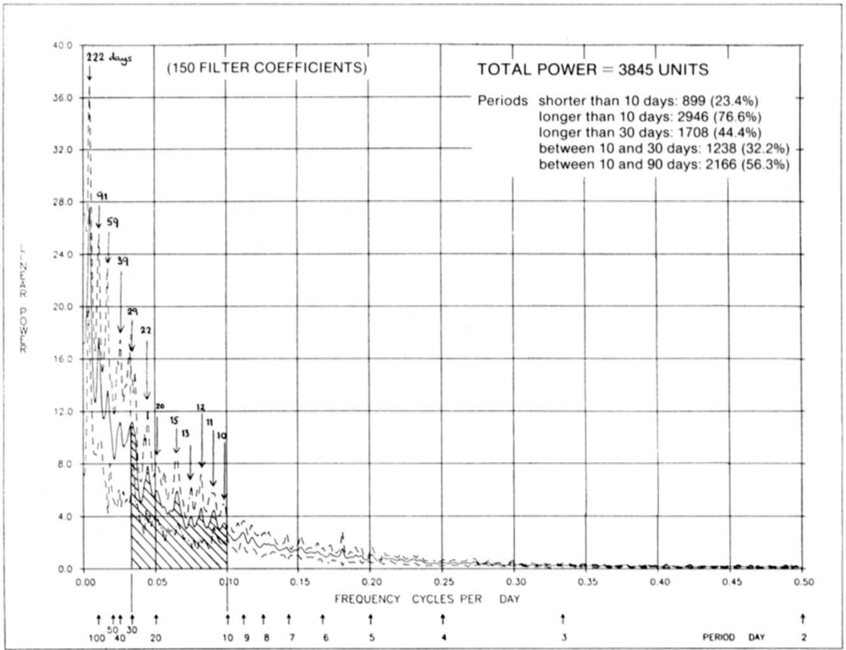


Figure 2. Mean maximum entropy method power spectrum of daily Central England Temperature anomalies 1936–85 with ±1 standard deviation marked as dashed lines.

homogenized daily Central England Temperature data set (Storey *et al.* 1985). The variance on short- and medium-range time-scales (2–10 days) is rather less (897 units) than that on time-scales of 10–30 days (1238 units) and only about 40% of that on the long-range, if periods up to, say, 90 days are included. Hence there is appreciably more variability of Central England Temperature anomalies to predict on long-range than on shorter-range time-scales. Gilchrist (1986) discusses this further.

4. Structure of the monthly forecasts

Fig. 3 shows the 10 districts covering the United Kingdom for which forecasts of surface weather anomalies are issued, and also the location of 149 climatological stations, having mostly long good-quality records, which are now used to help assess the skill of surface weather anomaly forecasts. A discussion of the scientific basis for the choice of these climatological stations is given in Folland and Shackleton (1984) and Folland (1983). The districts range in area from about 13 000 km^2 to about 40 000 km^2. Forecasts for the month ahead, updated every half month, are issued for each district.

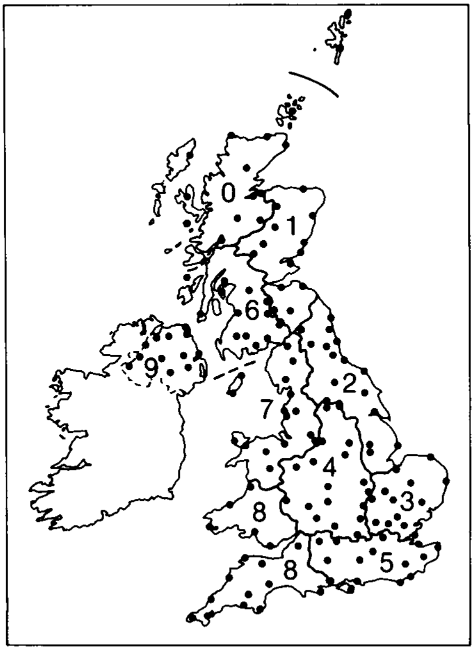


Figure 3. Positions of daily weather monitoring stations and forecast districts.

Fig. 4 shows how a typical forecast is structured (February 1986 was chosen because it was an extremely interesting month, being one of the coldest Februarys recorded). The average pressure at mean sea level (PMSL) pattern near the United Kingdom is forecast separately for the first 5 days of the month ahead ('medium range'), the remainder of the first half month ('mid-range') and the second half month ('long range'). These forecast patterns are permanently recorded and from them the best estimate and probability forecasts of temperature anomaly and percentage of average rainfall (henceforth called rainfall percentage) are constructed for each district. The anomalies are expressed at present as departures from a 1951–80 average. Fig. 5 shows the subsequently observed PMSL patterns and district mean surface weather anomalies. The best-estimate forecasts are currently expressed in meteorological units (in °C and as a rainfall percentage) for each of the three periods. In the telex message that is

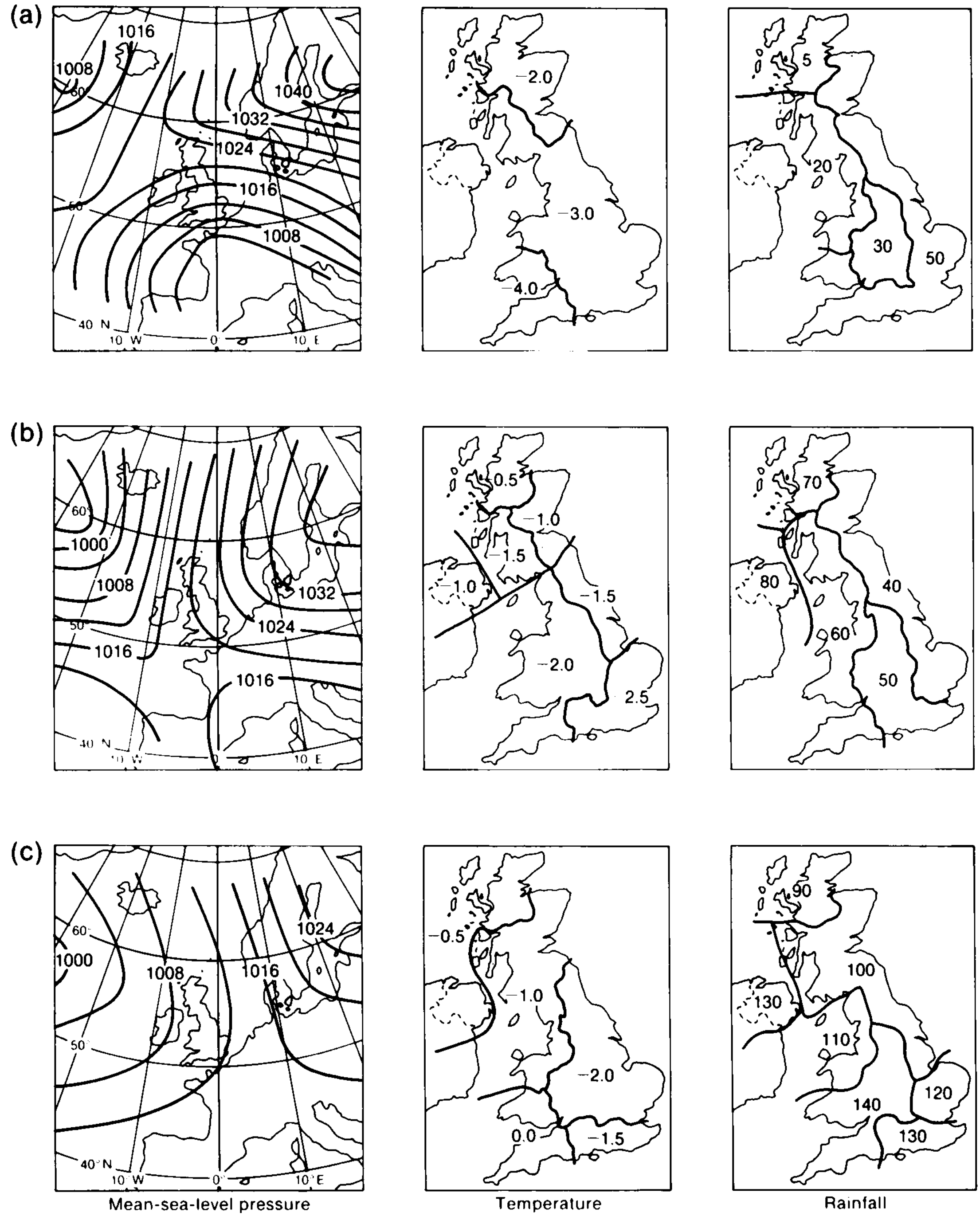


Figure 4. Typical example of a long-range forecast of pressure (mb), temperature anomaly (° C) and rainfall (% of normal) for (a) 1–5, (b) 6–15 and (c) 16–28 February 1986.

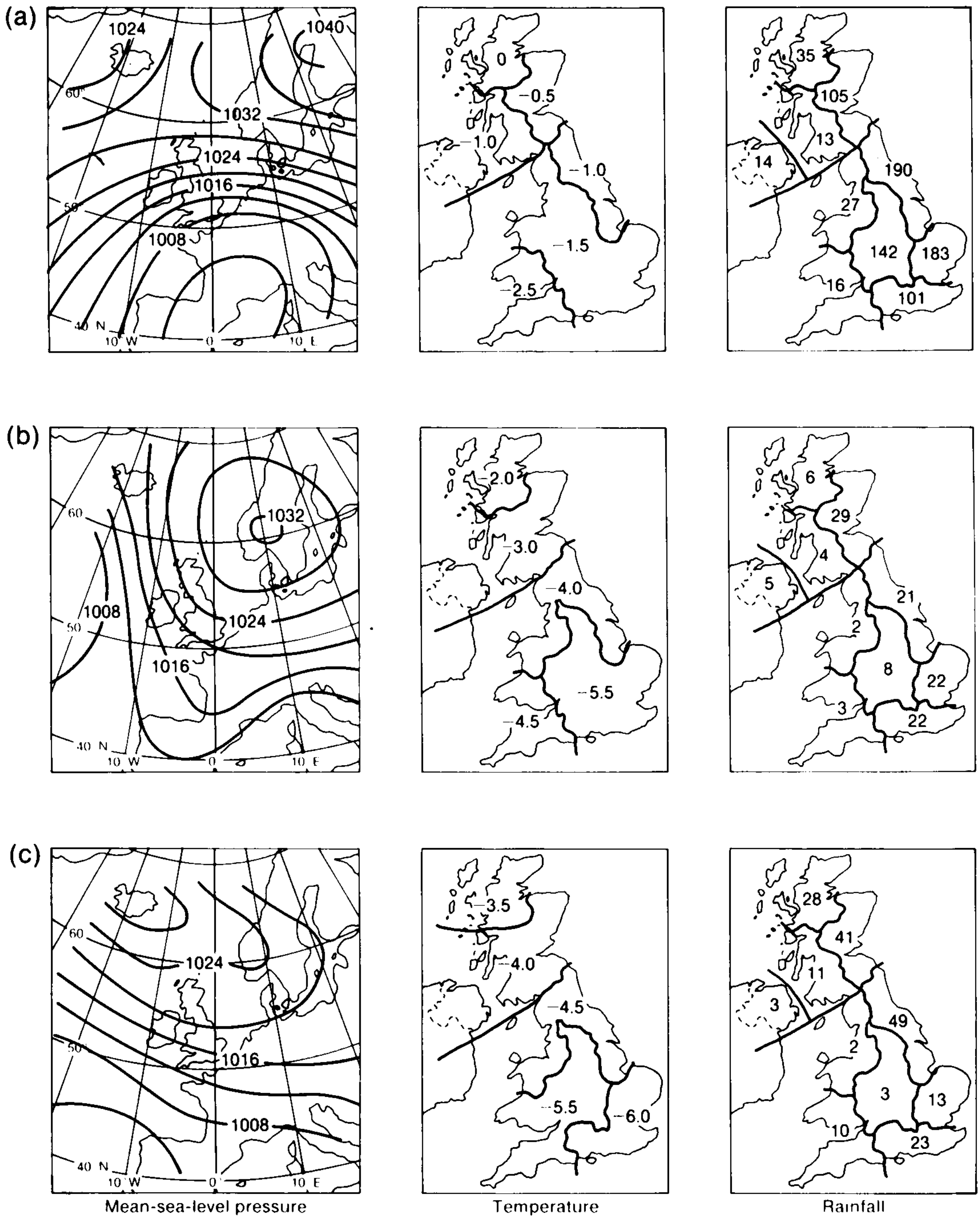


Figure 5. Observed presure (mb), temperature anomaly (°C) and rainfall (% of normal) data for (a) 1–5, (b) 6–15 and (c) 16–28 February 1986.

currently issued to recipients (see Fig. 6, which gives the February 1986 forecast, issued on 31 January) the medium- and mid-range periods are grouped together. Fig. 6 also shows that probability forecasts of temperature and rainfall are made for the month as a whole. The temperature forecasts for each district consist of a set of five probabilities, one for each of five climatologically equiprobable ranges of observed temperature for the given month. These are known as 'quints' and each has a long-term probability of occurrence of 0.2. Similarly the rainfall probability forecast consists of a set of three probabilities, one for each of three climatologically equiprobable ranges of observed rainfall, known as 'terces' (long-term probabilities of occurrence of 0.333).

FORECAST FOR THE PERIOD COMMENCING..1/2/86....ENDING..28/2/86.........
PART 1 BEST ESTIMATE FORECASTS:

TEMPERATURE (DEGREES C) AS A DIFFERENCE FROM NORMAL AND
RAINFALL AS A PERCENTAGE OF NORMAL FOR EACH DISTRICT
(1) FIRST 15 DAYS

DISTRICT	0	1	2	3	4	5	6	7	8	9
TEMP.	-1	-1.5	-2	-2.5	-2.5	-2.5	-2	-2.5	-2.5	-1.5
RAINFALL	50	45	45	45	45	50	45	45	55	60

CONFIDENCE: E

(2) REMAINDER OF PERIOD

DISTRICT	0	1	2	3	4	5	6	7	8	9
TEMP.	-0.5	-1	-2	-2	-2	-1.5	-1	-1	0	-0.5
RAINFALL	90	100	100	120	140	130	100	110	140	130

CONFIDENCE: E

PART 2 PROBABILITY FORECASTS FOR THE WHOLE PERIOD. (TEMP. AND RAINFALL)

TEMPERATURE PERCENTAGE PROBABILITY:

	MUCH BELOW AVERAGE	BELOW AVERAGE	AVERAGE	ABOVE AVERAGE	MUCH ABOVE AVERAGE
DISTRICTS: 0,1,9	20	30	25	15	10
2,3,4,5,6,7,8	35	25	20	15	5

RAINFALL PERCENTAGE PROBABILITY:

	BELOW AVERAGE	AVERAGE	ABOVE AVERAGE
DISTRICTS: 0,1,2,6,7	40	35	25
3,4,5,8,9	30	40	30

STRONG WIND EXPECTATION:

Average

DESCRIPTION OF WEATHER EXPECTED DURING THE PERIOD.
Much of the month will be cold or very cold and rather dry.
It is expected to become much wetter and milder in the last week

OVERALL CONFIDENCE: E

C CROWN COPYRIGHT

ORIGIN: MET O 13 BRACKNELL DATE/TIME
EXT: 2685 TELEX 849801
THIS FORECAST IS NOT TO BE QUOTED WITHOUT REFERENCE 31 Jan/1640
TO THE ORIGINATORS.

Figure 6. Example of the telex forecast message issued to users.

An important part of the issued forecast is a statement of the confidence that the forecasters express in the forecast at the time it is issued. This is expressed in principle on a scale from 'A' (highest confidence) to 'E' (lowest confidence) but the state of the art means that only the range from 'C' to 'E' is used at present. 'C' (most confident) is chosen if the various forecasting techniques are in broad agreement and the recent history of the skill of the forecasts is better than usual, especially the skill of the atmospheric circulation forecasts. 'E' represents a difficult forecast where synoptic judgement and more general considerations were prominent because of the strong disagreements between the forecasts given by the different techniques. The 'sharpness' of the probability forecasts is set by the confidence level in a subjective but predetermined way; thus a 'C' forecast would allocate a much higher probability to the most probable or 'best estimate' forecast quint or terce category than would an 'E' forecast. A general description of expected marked changes of weather type and the timing of the changes is added, together with a statement about the expected windiness of the month since one user is mainly interested in this information. It is important to remember that current statistical forecasting methods only forecast fields of PMSL, and that the temperature anomaly and rainfall percentage forecasts are inferred from them (see Section 5).

It should be noted that, whereas before 1981 the best-estimate temperature quint and rainfall terce forecasts were chosen directly, largely from the analogue forecasting techniques, they are currently automatically derived from the forecast temperature anomalies and rainfall percentages.

5. Techniques used to make the forecast

(a) *Statistical techniques for predicting PMSL patterns*

Cessation of the public service in long-range forecasts at the end of 1980 was accompanied by a substantial reduction of staff effort, so non-automated, labour-intensive, statistical techniques were set aside and only the most promising, largely automated, techniques retained.

The need to develop a new approach to statistical long-range forecasting was recognized in the Synoptic Climatology Branch of the Meterological Office in the mid-1970s. Long-range forecasts are always likely to be fundamentally probabilistic in nature and not truly deterministic, so a statistical approach that is deliberately designed to make forecasts of the probabilities of a range of possible future circulation patterns was felt to be a way forward. One such approach (not necessarily the best one in the long term) uses a multivariate statistical technique called linear discriminant analysis, and is the basis for the multivariate statistical forecasting technique (MVA) which is now the backbone of the UK statistical forecasting effort. It is described in detail by Maryon and Storey (1985), and by Folland and Colman (1986) who also provide recent tests of its skill. A fundamental discussion of MVA is also provided by Gilchrist (1986).

Briefly, MVA uses linear 'discriminant' equations derived from about 30 years of post-war data to forecast separately the probabilities of a predefined set of half-monthly mean PMSL patterns ('clusters') covering the North Atlantic and Europe in each half month of a monthly forecast using recently observed values of a set of atmospheric and sea surface temperature (SST) predictor variables. The atmospheric predictors consist of recent states of the lower troposphere in the northern hemisphere (north of 20°N), also averaged over half months, which are measured in the form of the strengths (eigenvector coefficients) of a set of covariance eigenvector patterns of 1000–500 mb thickness and PMSL. The set of regionally-averaged SST predictors consists of temperature anomalies averaged over the month preceding the forecast month in 15 key ocean regions. Examples of the eigenvectors are shown in Fig. 7 (adapted from Maryon and Storey (1985)) and the 15 SST predictor regions are shown in Fig. 8. The choice of region 2, for example, was guided by the pioneering work of Radcliffe and Murray (1970).

The use of eigenvectors is a method of describing past atmospheric fields in terms of statistically independent component fields each of which captures a part of the total variations of the past fields. Their validity as a representation of the atmosphere in the prediction step of a statistical forecasting model rests heavily on their ability genuinely to provide some predictive skill; the prediction will depend on the strengths of the eigenvectors deduced from recently observed data. Covariance eigenvectors of atmospheric anomalies provide the most straightforward mathematical representation of this type. If some of the eigenvectors represent dynamically coherent modes of atmospheric variation, the chances should be higher that the eigenvectors will have predictive skill. There is increasing evidence that the eigenvectors used here do have some predictive skill but may not provide the best method of representing dynamically coherent atmospheric patterns (Barnston and Livezey 1985 and Richman 1986). More complex forms of eigenvector analysis may be better; if so, the main advantage of eigenvectors, i.e. their ability to provide (nearly) statistically independent predictor patterns, is sufficiently great to make further investigation of this complex topic well worth while.

In MVA, the atmospheric eigenvector predictor strengths are currently measured separately over some or all of the four consecutive half months preceding the forecast period. Fig. 9 shows samples of

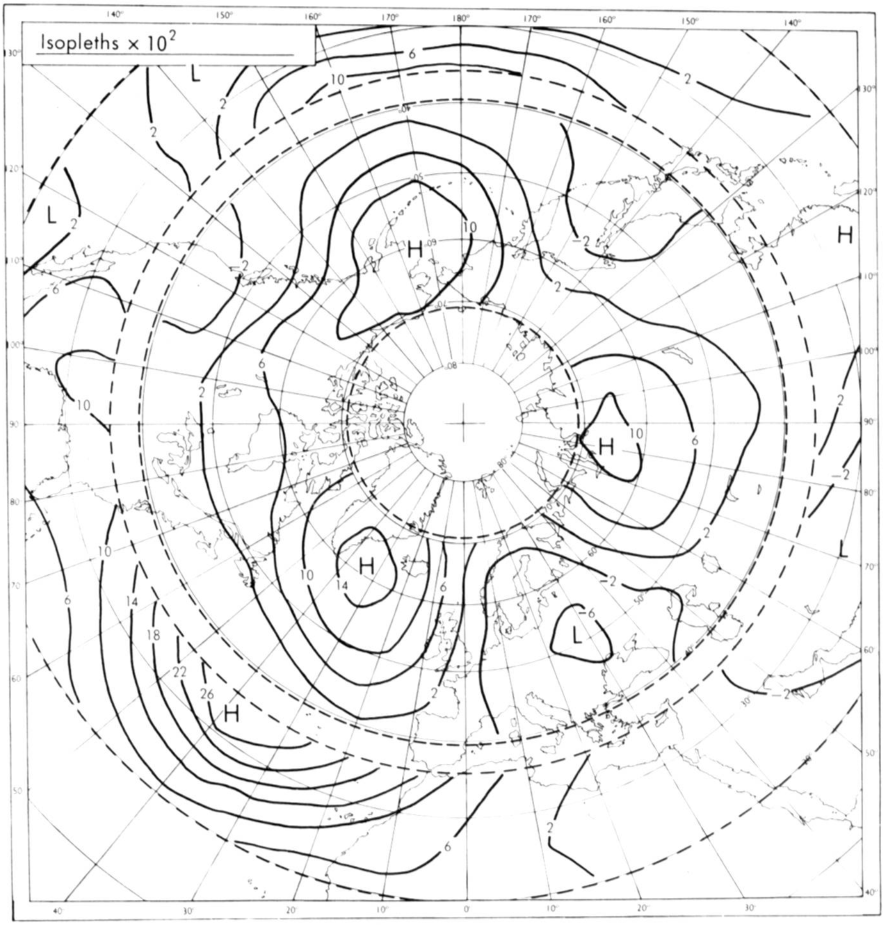


Figure 7. Sample predictor eigenvectors (standard dimensionless units): the second eigenvectors of both the northern and southern annuli of the northern hemisphere half-monthly mean-sea-level pressure for the pre-winter season (November–December).

the cluster patterns (for winter) whose probabilities (the 'predictands') are predicted in each forecast. The patterns are expressed here in the form of anomalies of PMSL calculated from a 1951–70 average.

The linear discriminant forecasting equations are created separately from historical data for the first and second half months of the forecast, and also for each of six 'natural' seasons, each two months long (i.e. January–February etc.). Special tests are used to ensure that only the most discriminating predictors are retained. The (predefined) cluster patterns change with the natural season but at present are always six in number in a given season. They do not occur equally often in the long run so their long-term probability of occurrence has to be estimated. It is assumed though that every half month can be classified into one of these clusters (see Maryon and Storey (1985) for details). Thus MVA consists of 12 similarly structured models each using a differently formulated set of linear discriminant prediction equations.

A second (regression) stage is currently used to 'fine tune' the forecasts of the most likely clusters, otherwise in each half month there are only 6 possible patterns to choose the forecast from. The regression equations contain a selection of similiar predictor variables as do the linear discriminant equations; however a few extra atmospheric predictors are included. Their purpose is to predict

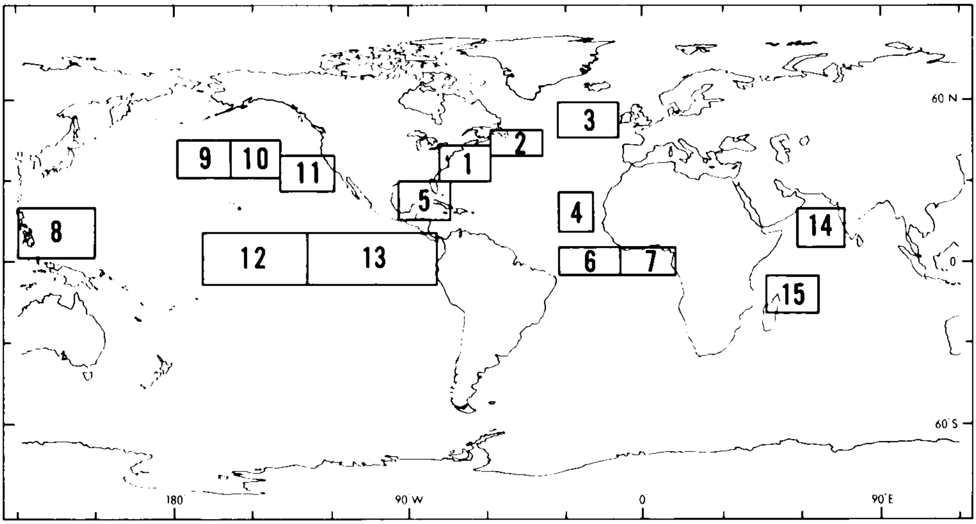


Figure 8. The 15 sea surface temperature areas currently used by the multivariate forecasting technique.

relatively small modifications to the most probable cluster patterns. This is done by predicting modest changes to the strengths of the most important eigenvectors that are used to represent each cluster pattern. In this way, modified PMSL patterns are created from the clusters; their probabilities of occurrence in the forecast period are assumed to be that of those clusters.

'Step-wise' statistical testing techniques are used to identify the most skilful predictors from those available in both the discrimination and regression stages; currently, this information is derived from a period of post-war data. Thus only a fraction of the predefined predictors are used in practice, and it is possible, for example, for a linear discriminant equation to contain few or none of the 15 'candidate' SST predictors.

In recent years, a range of the most skilful linear discriminant models has been used in practical forecasting, each containing a slightly different set of predictor variables. This approach provides an ensemble of sets of probability forecasts of the six clusters and therefore, as a by-product, of their 'tuned' (regressed) versions (Gilchrist 1986).

The ensemble approach considerably increases the information available from MVA; for example, the stability of the forecast probabilities can be assessed as the formulation of the linear discriminant equations is progressively altered by adding and subtracting variables. This particular use of an 'ensemble' of forecasts differs from that described by Murphy and Palmer (1986) during dynamical forecasting; in MVA the formulation (though not the basic structure) of the statistical model is progressively changed whereas Murphy and Palmer progressively change the initial data (equivalent to changing the MVA predictor strengths).

The only other statistical technique currently in use is the surface pressure eigenvector regression (SPEVR) (Maryon 1979). SPEVR is quite similar to the regression step of MVA but the predictors consist only of half-monthly mean covariance eigenvectors of PMSL. These are defined over much of the northern hemisphere and can include eigenvectors whose strengths are measured as much as one year before the forecast period. The predictands are the strengths of sets of covariance eigenvectors of PMSL anomalies over the North Atlantic and Europe defined over half months. There are two versions of SPEVR in each natural season (as with MVA), the first for one half month ahead and the second for two half months ahead. SPEVR is only capable of producing a single 'best estimate' PMSL pattern

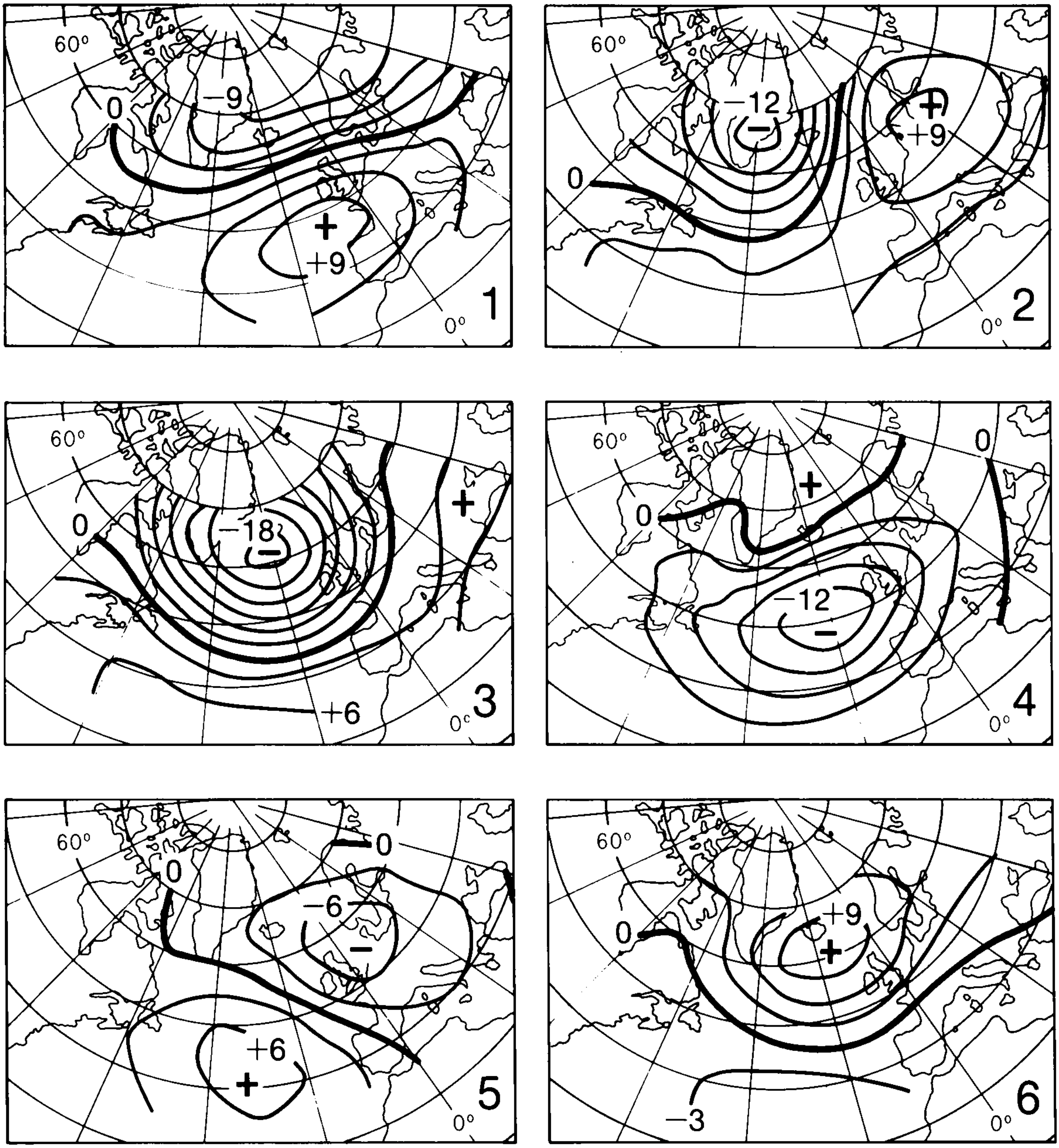


Figure 9. Mean-sea-level pressure anomaly patterns (mb) for the 6 clusters of the winter season (January–February), calculated from a 1951–70 average.

forecast. The ensemble approach is not used with SPEVR at present as staff resources have not been available to develop it. Maryon concluded that it was better to use a recent, post-war, historical period to construct the SPEVR prediction equations than a much longer historical period. Kates and Folland (1985) came to a similar conclusion when testing the skill of MVA. So SPEVR is currently based on historical data observed between 1950 and 1974. MVA, which has had much more attention, now uses data from 1949 to 1983 to construct its linear discriminant prediction equations.

(b) *Dynamical techniques in real-time long-range forecasting*

Dynamical long-range forecasting techniques have not yet made a large real-time impact, though the Meteorological Office 5-level general circulation model has in the past been used with some skill in winter (Mansfield 1986). Recently, occasional real-time use has been made of ensembles of forecasts from an 11-level general circulation model (Murphy and Palmer 1986). On the other hand, there has been a marked increase in the use of operational medium-range numerical weather forecasts; since December 1982 these have been available from the European Centre for Medium Range Weather Forecasts to day 10 of the medium-range period (usually day 8 or 9 of the long-range forecast). During days 1–5 of the long-range forecast the Meteorological Office 15-level model forecasts are usually available (almost always to day 4). At present both centres provide numerical forecasts of similar (and increasing) skill for the period for which they overlap. Differences between the numerical forecasts on individual occasions can, in conjunction with the statistical forecasts for the first half month ahead, be useful in judging the most likely developments during the mid-range period.

6. Derivation of district temperature and rainfall forecasts from PMSL forecasts

This aspect of long-range forecasting has probably changed most in the last 3–4 years. The recent availability of a reasonably long series of daily data of district averages of temperature and rainfall (commencing in 1951) has allowed fairly objective methods of deducing the district anomalies to be used, though judgement still plays a part.

(a) *Forecasts of rainfall percentage*

Two methods are now used. The first-guess forecast uses regression relationships between half-monthly mean rainfall anomalies and the PMSL calculated for the period 1951–85 for each district and calendar half month. Some smoothing of the regression relationships is carried out between adjacent half months (Legg, personal communication). Fig. 10 shows four of the regression lines, with their correlation coefficients, for south-west England. Over the medium-range period the judgement of the forecasters plays a dominant role, and these relationships only provide an approximate guide. The second-guess forecast of rainfall (in the mid-range or long range) is provided by an automatic search for historical PMSL patterns closely matching the forecast PMSL pattern just chosen (the 'matching technique'). The patterns are chosen from the same, or the two adjacent calendar half months observed since 1951; earlier years cannot yet be looked at as no analysed district mean climate data is available at present. The matching criteria include the similarity in PMSL values at four grid points around the United Kingdom and an index that provides a simple description of the forecast pattern shape (cyclonic westerly, anticyclonic, etc.). The forecasters then choose the 'best' pattern or patterns from these and read off the district rainfall percentages observed in the half months concerned. Judgement is used to combine the rainfall forecasts provided by the above methods for a given district.

Fig. 11 gives an example of the above procedure and shows the location of the four grid points. The two half-monthly mean PMSL fields, with their associated district mean rainfall anomalies, that were found to be most similar to the PMSL pattern forecast for 6–15 February 1986 (Fig. 4) are shown; these were the second halves of February 1972 and February 1981. The fields were selected from all the half-monthly fields since 1951 that were observed in the first half of February or in the adjacent half months, i.e. the second halves of both January and February. The fact that the period of interest in 1986 is only 10 days long and the 'matching' fields are 15-day averages is not considered a serious problem.

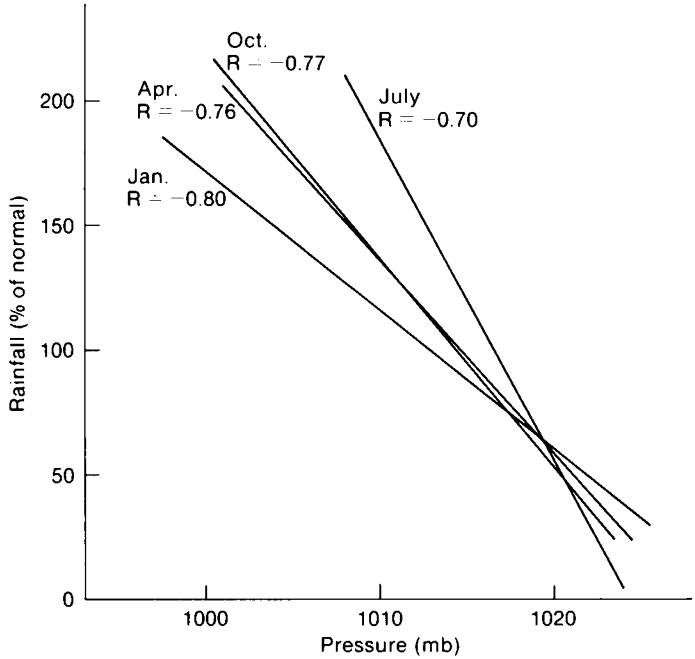
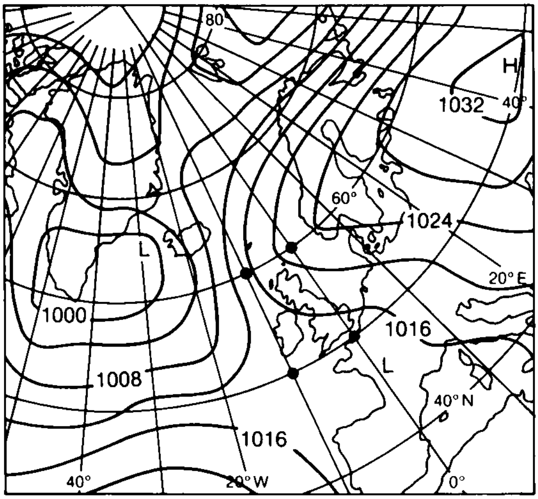


Figure 10. Selected regression relationships (R is the correlation coefficient) between mean-sea-level pressure and rainfall percentage for forecast district 8, calculated for the period 1951–85, for the first halves of the months shown.

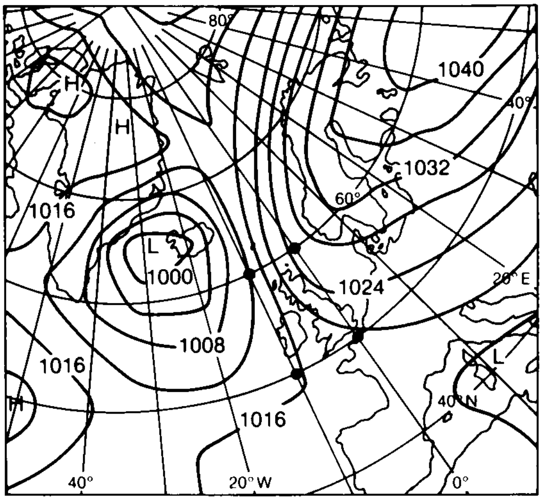
(b) *Temperature anomaly forecasts*

The availability of numerical 1000–500 mb thickness forecasts provides a very useful foundation for medium-range predictions of temperature. The PMSL pattern matching technique that is used as a second-guess procedure for deriving the rainfall forecasts becomes the main source of the forecasts of district temperature anomalies in the middle and long ranges. Information or surmises about snow cover or, in summer, surmises about soil moisture content also play a subjective part on all three forecast time-scales. Recently, analyses of historical monthly mean SST anomalies near the UK coasts have been used to modify the temperature forecasts subjectively. The SST data are described by Minhinick and Folland (1984). Thus when using the PMSL matching technique for temperature, the difference in observed SST anomalies accompanying the historical half months chosen as best PMSL matches would be noted and also that suggested by the most recent observations (usually the most recently available pentad). A further adjustment would then be applied, if need be, to the temperature anomalies extracted from the matching historical half months. Fig. 12 shows the SST charts that were used for the mid-range forecast for 6–15 February 1986. The top two are the monthly mean SST anomaly fields (near the United Kingdom) that overlapped with the best matching PMSL fields (half-monthly SST anomaly fields are not available). However, in recent years pentad mean SST anomaly fields have been calculated and are most useful in areas like those near the United Kingdom where data is most plentiful. The SST anomaly field for 26–30 January was the most recent available to the forecasters. The SST anomalies to



Second half of Feb. 1972

District	Temperature anomaly (°C)	Rainfall (% of average)
0	+0.2	26
1	+0.7	56
2	+0.7	53
3	+0.6	53
4	+0.6	60
5	+0.6	65
6	+0.7	45
7	+0.8	43
8	+0.4	101
9	+0.3	36



Second half of Feb. 1981

District	Temperature anomaly (°C)	Rainfall (% of average)
0	−0.8	8
1	−1.5	67
2	−2.0	85
3	−2.7	69
4	−2.8	82
5	−2.7	82
6	−2.2	41
7	−2.6	42
8	−2.3	108
9	−1.5	75

Figure 11. The two best mean-sea-level pressure (mb) matches to the forecast for 6–15 February 1986 with associated observed temperature and rainfall anomalies. (Large dots indicate the locations of the grid points used for the initial automated mean-sea-level pressure match.)

east and south-east of the United Kingdom were clearly the most important given the forecast PMSL pattern in Fig. 4. These anomalies were broadly similar to those observed for 16–28 February 1981; 16–28 February 1972 was only given a small weight as the origin of the air seemed to be further south than that indicated in Fig. 4. Allowing for the expected development of stronger negative SST anomalies over the North Sea owing to the expected blocked circulation pattern, the forecast district mean temperature anomalies derived from 16–28 February 1981 were finally given full weight. This illustrates the complex judgements that are made and the fact that the expected effect of local SST anomalies on a forecast depends on the dominant wind directions envisaged.

Variations of SST anomaly within about 1500 km of the UK coasts are quite large at most times of the year and since this technique was introduced in September 1985 there has been a noticeable impact on the quality of the hitherto poor mid-range temperature forecasts. Adjustments of 1 °C or more have quite commonly been made to district temperature forecasts initially derived from 'best PMSL matches'.

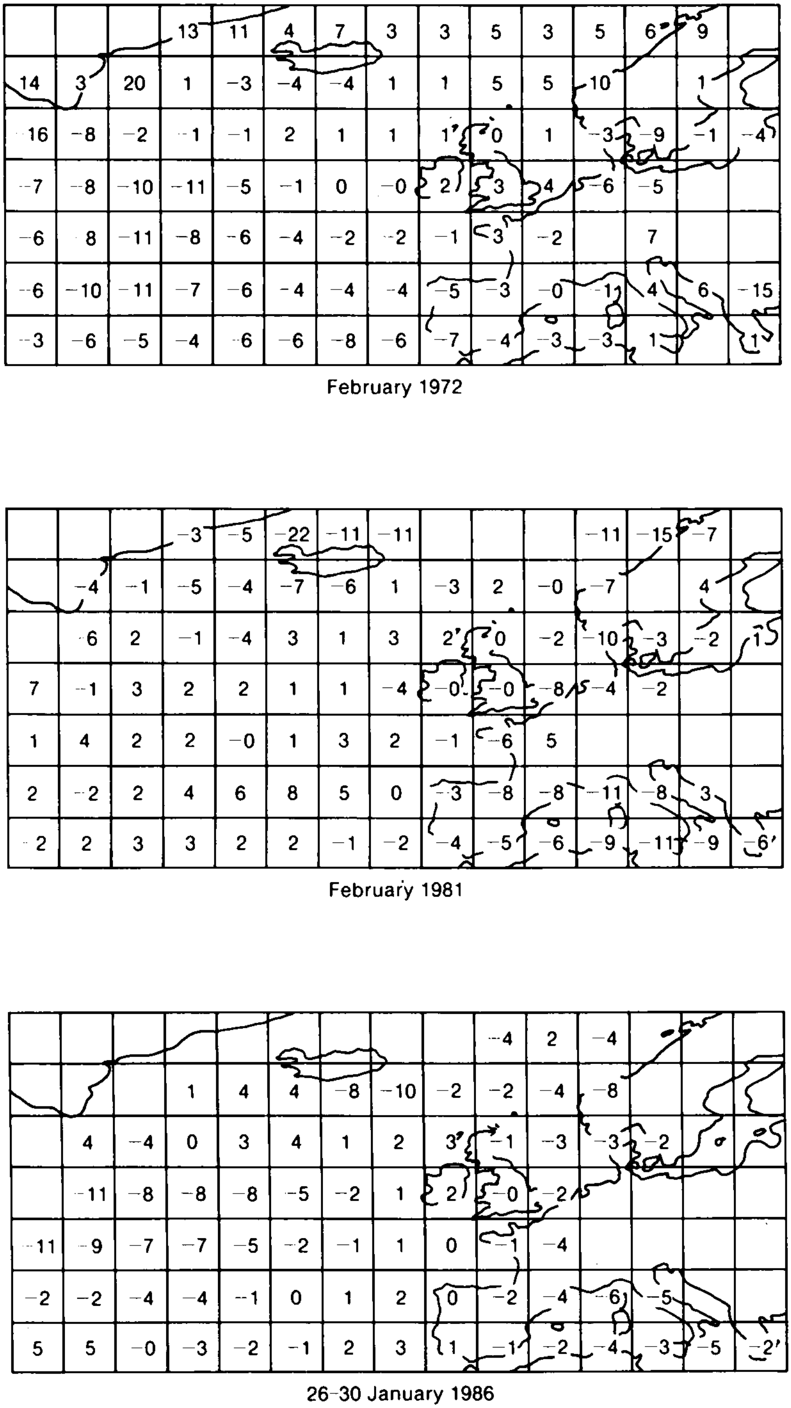


Figure 12. Sea surface temperature anomaly charts used for the mid-range forecast for 6–15 February 1986. Units are in tenths °C and are calculated from a 1951–80 average.

7. Conclusions

The long-range forecasting system is now substantially different from that used during the last few years of the public issue of the forecasts. Changes have been prominent both in forecasting techniques and in the methods of deriving forecasts of district surface weather anomalies from these techniques. The latter changes have been helped by the automatic analysis of surface climate information not previously readily available. In the near future we can expect further developments in the multivariate statistical forecasting technique and increased use of numerical long-range forecasts. A companion paper by Folland *et al.* (1986) will provide a provisional discussion of the complex impact of these changes on forecasting skill so far.

Acknowledgements

The authors are especially indebted to Roy Maryon for his original contributions to the development of statistical forecasting and to Mike Jackson for automating the analysis of the district surface climate data.

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Sea surface temperature images from Advanced Very High Resolution Radiometer (AVHRR) data

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Summary

An account is given of a pilot study to produce high-resolution polar stereographic images of sea surface temperature from Advanced Very High Resolution Radiometer data. Infra-red images at different wavelengths are combined to compensate for the attenuation of surface emission by the atmosphere, and to generate images of sea surface temperature for areas detected as cloud-free. Data from 14 overpasses of the British Isles by the NOAA-9 satellite during one week in April 1985 have been processed in this way. They have also been mapped into a polar stereographic projection and combined to give composite images for the week to illustrate how this or similar products might be provided operationally in future.

1. Introduction

Sea surface temperature (SST) data around the British Isles are currently available to forecasters in the form of a 5-day mean contour chart (Figs 1(a) and (b)) updated three times a week. These charts are produced from ship and buoy reports averaged over a 5-day period. Data from the Advanced Very High Resolution Radiometer (AVHRR) on board the TIROS-N/NOAA series of polar-orbiting satellites (Schwalb 1978) can potentially give a 5-day mean SST chart with a greatly improved spatial resolution.

The Meteorological Office plans to introduce a new computer system, AUTOSAT-2, to be used for processing digital satellite data. The availability of real-time High Resolution Picture Transmission (HRPT) data from the NOAA satellites, consisting of data from a number of instruments including

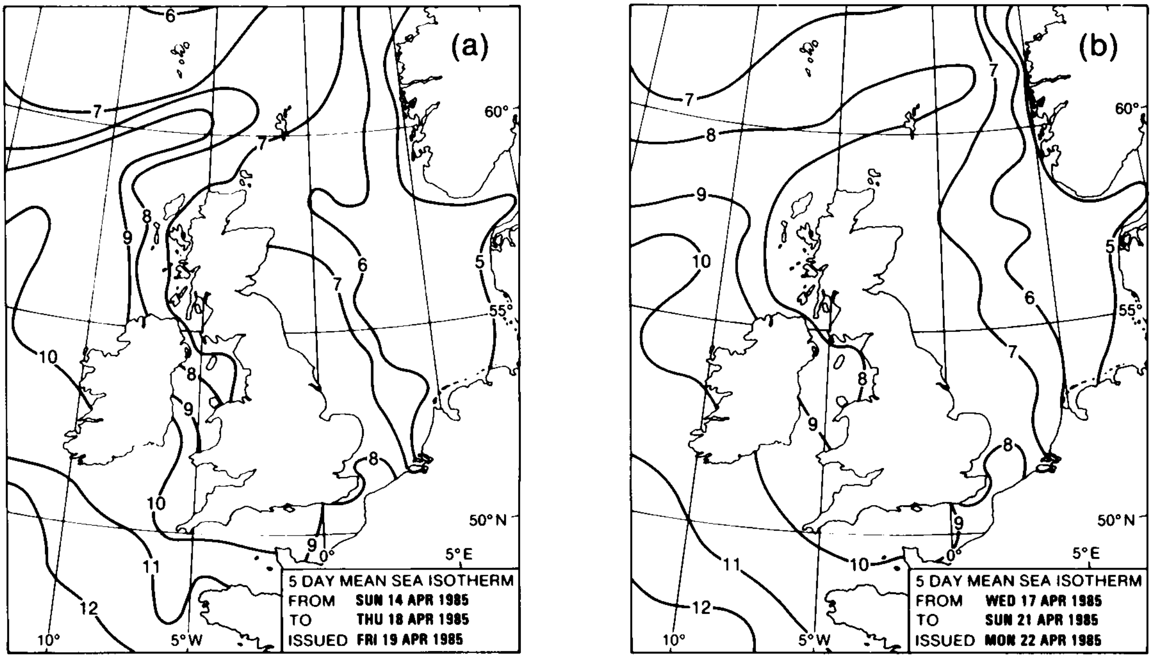

Figure 1. Conventional 5-day mean sea surface temperature (°C) charts for the seas around the British Isles for (a) 14–18 April and (b) 17–21 April 1985.

AVHRR, makes possible the generation of new operational products. The data would be received and processed at the Royal Aircraft Establishment ground station at Lasham and then transmitted to the Meteorological Office computer system at Bracknell over the METSATNET link (a new high-speed telecommunications link between Lasham and Bracknell). This paper describes an experimental scheme to produce a new SST product from the AVHRR data around the British Isles. It is intended to demonstrate how this or similar products could be derived by AUTOSAT-2.

2. Processing scheme

A general outline of the processing scheme is shown in Fig. 2 and is described in detail below. The details of the programs used on the Meteorological Office computers (HOMER and HERMES) to process the data are described by Pescod *et al.* (1986).

Reading AVHRR data

The raw input data are those received from the spacecraft as part of the HRPT data. They consist of upwelling radiance measurements made at five wavelengths (channels 1–5 centred at 0.53 μm, 0.85 μm, 3.7 μm, 10.7 μm and 11.8 μm respectively) over a field of view of about 1 km at the sub-satellite point. Each radiance is in the form of a 10-bit count, i.e. a value between 0 and 1023, but to facilitate computer processing the raw data stream is expanded from 10 to 16 bits for the channels required (1, 2, 4, and 5 for the day pass and 3, 4, and 5 for the night pass).

Computing brightness temperatures and radiances

The visible and near infra-red counts (channels 1 and 2) are converted to radiances. The infra-red counts (channels 3, 4 and 5) are converted to equivalent black body temperatures (brightness temperatures) using the scheme outlined by Lauritson *et al.* (1979), including the non-linearity correction given by NOAA (National Oceanic and Atmospheric Administration) for channels 4 and 5.

Computing earth location

Earth location information is also computed for the image. Because of the large amount of data in an AVHRR image, it is not practicable to compute the latitude/longitude of every pixel (picture element) in the image. As a compromise, the locations of every thirty-second pixel across and along the pass are calculated. These locations are computed by first predicting the position of the spacecraft above the earth at a known time from a recent set of orbital elements (received from NOAA over the Global Telecommunication System) and then applying the satellite scan geometry to determine the locations of pixels along a scan line. The predicted position of the spacecraft above the earth is usually in error by less than 10 km but occasionally errors in the along-track direction can be more than this. To correct for this error a coastline can be computed, which is then displayed over the image. Any offsets between the

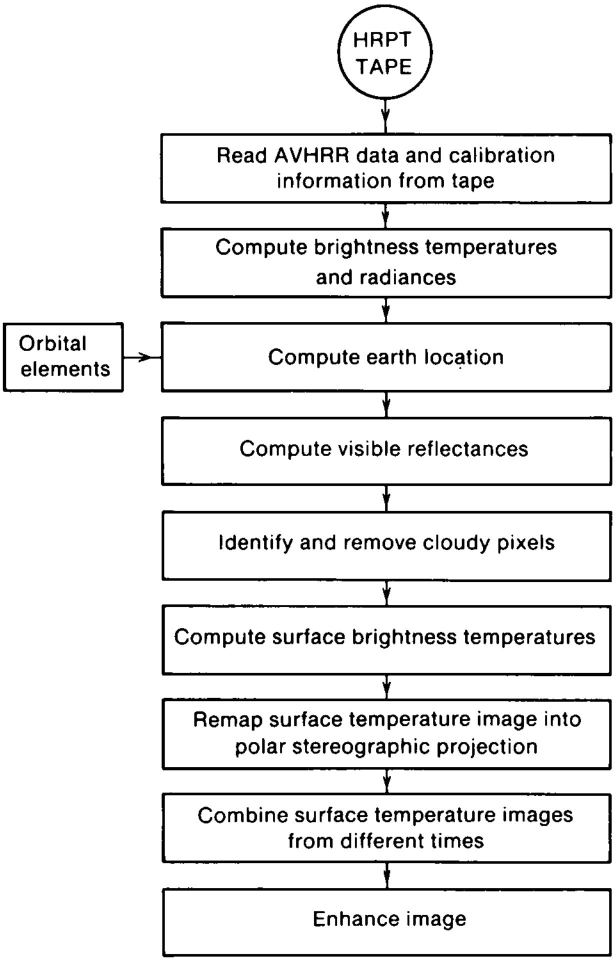

Figure 2. Flow diagram showing how AVHRR data taken from a High Resolution Picture Transmission (HRPT) tape is used to produce sea surface temperature images.

computed coastline and the actual coastline are then immediately obvious, and by interactively matching the two coastlines these offsets can be determined. The location information is then recomputed to include these offsets. Obviously this correction procedure is only possible when there is at least some cloud-free coast within the image. The corrected location information is used by most of the subsequent processing steps.

Computing visible reflectances

Reflectances are calculated from the visible and near infra-red channels by dividing the radiances by the incident solar radiation (at the appropriate time and location) within the filter response function of each channel. A value for the solar constant of 1365 W/m^2 is assumed (Lee *et al.* 1986) and the solar irradiance table of Neckel and Labs (1984) is used to compute the effective solar spectral radiance for each channel.

Identifying and removing cloudy pixels

The reflectances and brightness temperatures are used in a cloud detection scheme, which identifies cloud-free pixels, from which surface quantities can be derived. The scheme to detect cloud-free pixels is described in detail by Saunders (1986). Each pixel must pass five independent checks for cloud contamination. Different tests are applied according to whether it is day or night and on the type of underlying surface, i.e. sea, land or coast. The pixels which pass all of these tests are then assumed to be cloud-free.

Computing surface brightness temperatures

The cloud-free infra-red brightness temperatures are then converted to SSTs using the relationship described by Llewellyn-Jones *et al.* (1984) to remove atmospheric effects. This relationship takes the form of a linear combination of the 10.7 and 11.8 μm channels as follows:

$$SST = C_0 + C_1T_4 + C_2T_5$$

where SST is in Kelvin, and T_4 and T_5 are the brightness temperatures in channels 4 and 5. The regression coefficients C_0, C_1 and C_2 vary with 'air mass', i.e. secant of the satellite zenith angle. Values of SST are only computed for satellite zenith angles less than 60°, so that data at the edge of the scan lines (less than 100 pixels from the edge) are not used.

Remapping surface temperature image

The SST image of the earth as viewed by the AVHRR instrument is now remapped on to a polar stereographic projection plane (at 60° latitude). This projection was chosen to be compatible with the current operational charts. The details of the projection process are given by Pescod *et al.* (1986). The display device which has been used is a SIGMEX Advanced Raster Graphic System (ARGS) with a resolution of 1024 × 1024 elements. With this in mind the map area and scale of projection (in km/pixel) on the screen are chosen. In this experiment a final product was created for an area in polar stereographic projection bounded by latitudes 47° and 60° N and longitudes 12° W and 10° E, i.e. about 1400 × 1400 km. To select from one image all the pixels which may fall in this area, it is necessary to consider a swath of about 1600 pixels wide from the full AVHRR image.

The location of every thirty-second line and pixel is achieved as described above. The locations of all other pixels are then fixed by two-dimensional linear interpolation. The reprojection process allows a number of input images from different parts of a pass to be reprojected on to the same polar stereographic plane. With this simple scheme, it was sometimes found that more than one input pixel mapped to a single pixel in the output image and in these cases the pixel corresponding to the maximum surface temperature was the one used. Conversely, it was found that towards the edges of an AVHRR data swath, pixels in the reprojected image remained unfilled. This problem was overcome by assigning a pixel in the input image to as many as 9 pixels (as necessary) in the output image, for pixel positions in the input image greater than 824 pixels from the sub-orbital track.

Combining surface temperature images from different times

The next step merges the reprojected data from different passes on several days (seven in this case) into one composite SST image. The procedure chosen (from several possibilities) was to retain the maximum SST value encountered for each pixel in the output image during the seven days. This helped to remove spurious low temperatures due to any remaining undetected cloud contamination. This does have the disadvantage that if a strong diurnal thermocline is present, significant diurnal variations in SST can occur and go unrecorded, e.g. as seen by Saunders *et al.* (1982). This would bias the composite image to the warmest values and not give a true mean. With the advent of improved cloud detection algorithms, this limitation could be removed and a true mean SST value computed. A better method of detection and removal of spurious pixel values (for whatever reason) could also be devised if a background field was available.

Enhancing the image

To reduce the noise in the final image a median filter can be applied. This causes some reduction in the resolution of the product but is acceptable because of the low horizontal variability of SST. After combining seven days of data, it was found that the final image contained areas which had been cloud contaminated on all 14 passes. This resulted in some data voids. Voids of a few pixels were effectively removed by the median filter.

3. Results

The HRPT data used in this study were obtained on computer-compatible magnetic tapes from the University of Dundee. They consisted of one daytime and one night-time NOAA-9 pass over the British Isles during the week 14–20 April 1985, which corresponded to overpass times of approximately 0300 and 1330 GMT. The data used in this experiment were not a carefully selected set of cloud-free data, but seven days of contiguous data during which typical cloud cover was experienced.

The composite SST image produced by the processing scheme described above is shown in Fig. 3. For comparison two conventional 5-day mean SST charts for the same period, which were used operationally, are shown in Figs 1(a) and (b). These represent the bulk water temperature to a depth of about 1 m.

Comparing the conventional charts with the satellite product it can be seen that there is general agreement in temperature values between them, and that the major features are discernible in both. One such feature is the tongue of warmer water off north-west Scotland and Ireland. Another is the cold coastal strip of water off the Norwegian west coast as studied by Mork (1981). However, there is far more detail in the satellite plot than can be inferred from the conventional charts. For instance, the precise structure of the feature to the West of Scotland or the strong temperature gradients between the Irish Sea and the sea areas between Cornwall and south-eastern Ireland. A warmer (greater than 7 °C) patch of water on the Dogger Bank in the North Sea is also evident in the satellite data. One or two of the features, however, may still be artefacts caused by incomplete cloud clearing such as the plume of warm water reaching into the North Sea from the Dutch–German border. Fig. 4 shows the day/night

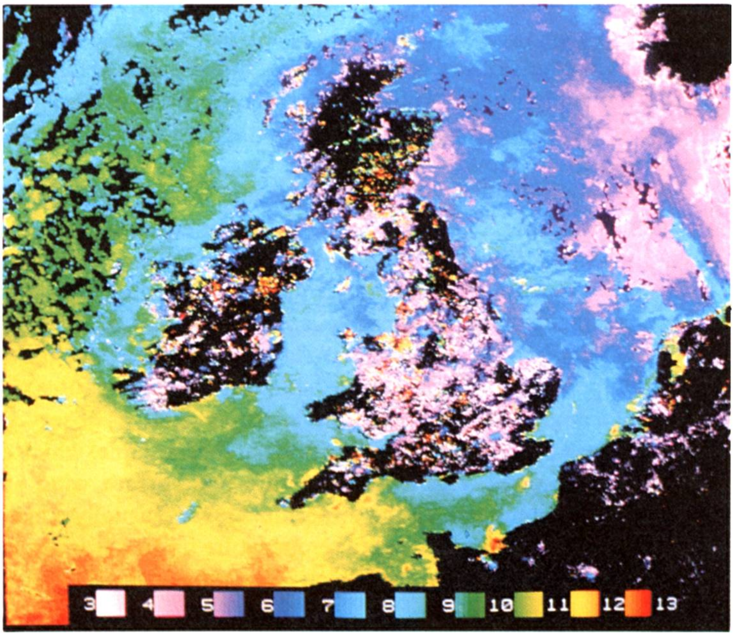

Figure 3. Composite sea surface temperature image which combines cloud-free AVHRR data from seven daytime and seven night-time passes for 14–20 April 1985. Over the sea, black areas remained cloud covered during all fourteen passes. Over the land, temperatures were mostly outside the range of the colour table and hence also appear black. The scale shows temperatures in °C.

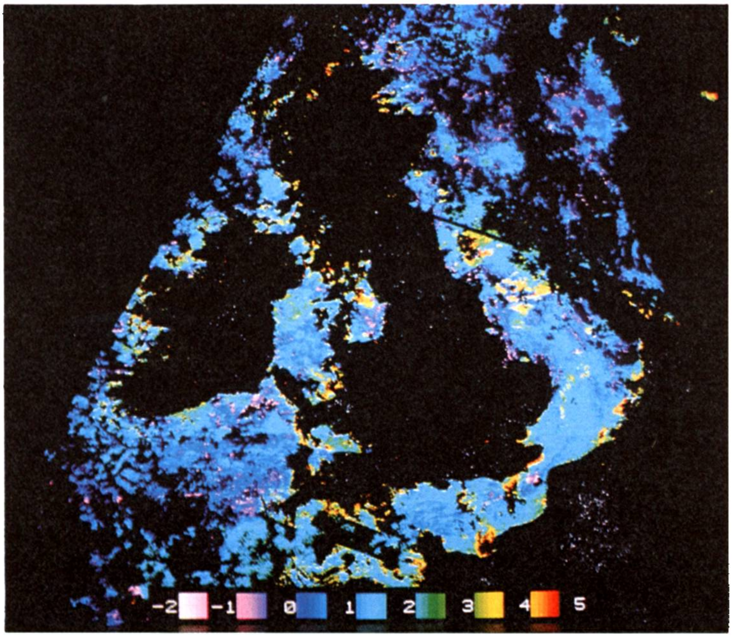

Figure 4. Day–night temperature difference image computed from AVHRR data for the period 14–20 April 1985. The scale shows temperature differences in °C.

temperature difference image for the seven days of data. In general the SST differences are close to zero but near to the coasts the daytime values are up to 4 °C warmer than the corresponding night-time values which would be expected over shallow coastal waters. The absence of large positive temperature differences over the open sea is evidence that a diurnal thermocline was not present during these 7 days. The small number of negative differences (i.e. where the night-time SST value is greater than the daytime value) is probably due to inadequate cloud clearing.

The absolute satellite SST values are in qualitative agreement with the conventional charts. A more comprehensive comparison of satellite SSTs, computed using the equation above, and ship SSTs was carried out by Llewellyn-Jones *et al.* (1984) and showed that the root-mean-square difference between the two was 0.53 °C with a bias of −0.10 °C. The satellite measures a surface skin temperature so the two measurements will only agree if the skin temperature is representative of the underlying bulk water temperature. There are two effects which can produce a significant difference between the bulk water temperature and the skin temperature. The first is the 'skin effect' which causes the skin temperature normally to be a few tenths of a degree colder than the bulk temperature, as observed by Robinson *et al.* (1984). The second effect is caused by the formation of a diurnal thermocline, which occurs when the top layers of the ocean are not well mixed, e.g. when there are low surface wind speeds. Under these conditions the incident solar radiation heats up the uppermost layers (usually a few tens of centimetres thick) of the sea surface. This results in a surface skin temperature up to a few degrees warmer than the bulk water temperature during the early afternoon which is the time of the NOAA-9 daytime overpass.

4. Conclusions

An SST image was produced from data from 14 passes of NOAA-9 during the period 14–20 April 1985. However, even over this 7-day period some pixels in the output image were cloud contaminated for every pass. More NOAA-9 passes per day could be processed rather than just the two used here, which would improve the extent and density of coverage a little. When the second NOAA polar-orbiter satellite is operational then data from this satellite may help reduce the number of cloud-contaminated areas. Compared with conventional charts, the satellite product gives good agreement in absolute SST values but shows far more detail. It is questionable whether most forecasting applications need such a high-resolution product, but for upgrading the conventional chart by filling in data void areas where there are no ship reports this product would undoubtedly be useful. In addition, this new satellite product would be useful for such applications as deriving a local high-resolution SST climatology and the location of ocean fronts (for fisheries and other applications). Although this scheme was designed for use over the sea it has been used with some success over land though differences between land and sea, such as surface emissivity and atmospheric profile structure, lead to larger uncertainties. It is therefore possible to obtain high-resolution land surface temperatures from these data. However, the interpretation of composite products is complicated — different areas contribute to the composite on different days, and the product is biased because it applies only to cloud-free cases. Nevertheless, surface temperature is just one example of a product which may be derived from AVHRR data; high-resolution climatologies of cloud cover, snow cover, surface albedo and other parameters could also be generated using a similar approach.

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An account of the International Conference on Polar Lows, Oslo, 21–23 May 1986

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1. Introduction

The recent extension of offshore operations to high latitudes, especially off the coast of Norway, has led to increased interest in weather conditions in these areas. Much of the interest has been directed towards polar lows which form close to the edge of the Arctic ice sheet and move southwards with associated severe weather (gale force winds and snow) and high waves. Owing to their small size (a few hundred kilometres in diameter), and their rapid movement and development in regions of sparse observations, it is difficult to forecast polar low evolution with the accuracy necessary for offshore operations.

A three-year project was recently undertaken, on behalf of a consortium of operators with licences for operations north of 62° N, by several groups including the Norwegian Meteorological Institute (DNMI) and the Oceanographic Company of Norway (Oceanor). Support for field projects was also provided by groups outside Norway including the National Oceanic and Atmospheric Administration (NOAA) and the Meteorological Office. The subjects included in the project were the climatology of polar lows, case studies, dynamical theories, numerical modelling, observing systems, forecasting, and ocean waves associated with polar lows.

To mark the completion of the project the International Conference on Polar Lows was held near Oslo to bring together experts, not confined to participants in the project, to assess the current state of knowledge. The conference was opened by Arne Grammeltvedt and Magne Lystad of DNMI who outlined the main findings of the project, especially the climatological aspects and the range of techniques used to forecast polar lows. It was shown that although 20–30 polar lows with observed winds up to 35 m s^{-1} are experienced each year in the area between Norway and Spitzbergen, they do not present the most stringent design problems. However, forecasting and operational problems are posed by the rapid movement of polar lows and the notice required to stop certain crucial operations.

After the introductory session, the conference followed the general areas of interest included within the Norwegian polar-low project.

2. Climatological studies

A range of detailed climatological studies was presented. Erik Rasmussen (University of Copenhagen) described five archetypes of polar lows including some with the appearance of lee vortices and others which appeared more baroclinic, e.g. when the low-level thermal wind opposed the surface northerly flow. It was suggested that the deepening occurred in three distinct phases with rapid deepening following initial triggering by baroclinic instability. Kari Wilhelmsen (DNMI), in an analysis of 76 Norwegian Sea polar lows, showed that although the peak period for their formation was in winter and spring there was a pronounced minimum in February, probably due to the general circulation being influenced by very cold land surface temperatures and a displacement of the main baroclinic zone. In general, the atmosphere above 800 mb was relatively dry, and warming was associated with both surface exchanges and differential advection. In contrast to this Norwegian Sea analysis, Steve Businger (University of Washington) presented results from the Gulf of Alaska where there is no February minimum in the frequency distribution. His analysis suggested that polar-low outbreaks lasting several days sometimes occurred. Polar lows were associated with cold anomalies at 500 mb (6 K deficit) and formation was often associated with the movement of the cold anomaly over warm sea surfaces.

Ingolf Kanestrøm (University of Oslo) described some promising attempts to identify conditions favourable to polar low development based on pressure differences between certain key locations and the presence of anomalies at 500 mb. Michael Bilello (US Army Research Laboratory) then presented results from a survey of surface lows that identified key areas for formation and signatures of rapid deepening and which also appeared to have some predictive capability.

3. Case studies

Detailed case studies of rapidly deepening lows were presented by Fred Saunders (Massachusetts) and by Mel Shapiro (NOAA, Boulder). The former presented a composite study of rapid cyclogenesis off the east coast of the USA making use of synoptic data. It was shown that rapid deepening was associated with the region of maximum sea surface temperature gradient on the cold side of the Gulf Stream. At the time of rapid deepening, the region of maximum upper-level vorticity advection was about 300 km behind the surface centre. Upper-level vorticity advection, rather than the position of the vorticity maximum, appeared to provide the best discriminator between explosive and less rapidly deepening systems. Similar patterns were also associated with a rapidly deepening low over Lake Superior when a long-wavelength upper trough coincided with a small surface feature over the warm water. Shapiro presented the results of an analysis of aircraft data obtained in a polar low north-east of Iceland on 27 February 1984; this remains the only case where detailed aircraft observations have been obtained in a polar low. The data show a warm core structure, two strong shear lines, an intensity which decreases with height, and maximum winds close to the surface with gusts to 40 m s^{-1}. Analysis suggested that the air was unstable to ascent along absolute momentum surfaces and that the surface sensible heat flux of 500 W/m^2 was comparable with the latent heat flux. Total Ozone Mapping Spectrometer (TOMS) data suggested that the tropopause descended to low levels in this system.

Other case studies were presented by Åsmund Rabbe (DNMI) who presented an analysis based on synoptic data of a polar low which developed two days later than that reported by Shapiro and which formed part of a 'system' of developing polar lows, and by Businger who described a Gulf of Alaska storm. Both of these case studies exhibited features similar to the case on 27 February with evidence of important baroclinic processes.

A paper in this session by Peter Aakjaer (Danish Meteorological Institute (DMI)) included results from a grid-point model reproducing an observed case but using simplified atmospheric profiles. It was shown that adequate surface fluxes were crucial to obtaining realistic simulations and that boundary-layer convergence was a major source of moisture in this example. R.A. Brown (University of Washington) showed how the atmospheric boundary-layer structure changed when moving downwind from the ice edge.

Use of satellites for the study of polar lows was described by Michael Steffensen (University of Copenhagen) who demonstrated the importance of using radiosonde data in deriving profiles by regression techniques, and by Anke Thoss (Free University of Berlin) who outlined the problems associated with wind retrieval from Meteosat cloud images, but suggested that useful data could be obtained at medium or high levels even at 70° N.

4. Dynamical theories and modelling

Dynamical ideas and numercial modelling were treated together in the third session. Dick Reed (European Centre for Medium Range Weather Forecasts) presented several results which suggested that baroclinic instability was the major mechanism for rapid deepening with upper-level vorticity maxima but limited surface heating. However, other examples were much shallower with greater surface fluxes, but these were also often associated with strong local baroclinicity. Hans Økland (University of Oslo), however, described a CISK (Convective Instability of the Second Kind) model with time and space dependent heating. Analysis showed that growth rates of instabilities were modest for a 500 mb deep model, but increased when heating was confined below 800 mb. It was considered that CISK may develop within a larger scale baroclinic system and some observations, e.g. pressure traces, supported the suggestion of a 'two scale' structure for polar lows.

The model presented by Kerry Emanuel (Massachusetts Institute of Technology) suggested that forced ascent of warm moist boundary-layer air, even though soundings were stable, could release energy to spin up a polar low, with the necessary ascent forced by larger-scale baroclinic instability. The model (an air–sea interaction model) was thermodynamically consistent and an axisymmetric numerical model suggested that it was dynamically possible to produce rapid cyclogenesis in this manner.

Numerical simulations of polar lows were presented by Erik Haugen (DMI) who undertook sensitivity studies with idealized flows demonstrating the importance of the initial horizontal scale of the disturbance, and by Sigbjørn Grønas (DNMI) who showed that a forecast model with 25 km resolution could predict the occurrence of polar lows up to 48 hours ahead but tended to over-predict the occurrence and underestimate the depth. Thor Nordeng (DNMI) showed that the inclusion of a parametrization of slantwise convection could in some cases improve the simulation of the depths of polar lows, while T.S. Pedersen showed that conversion of thermal to kinetic energy was most efficient about 3 km above the surface and that the efficiency was increased if the heating was concentrated in space.

5. Polar-low forecasting

Forecasting of polar lows requires adequate data and this was discussed by L. Fedor (NOAA, Boulder) who showed methods of improving the presentation of satellite data to improve the early identification of polar lows, and Grammeltvedt who described the current observation network in the Norwegian coastal areas including buoys, the use of satellite data and the possible future use of a network of three radars covering the area between the Norwegian coast and Björnöya (south of Spitzbergen). Peter Jonas (Meteorological Office) took up the latter point and showed how radar data could be used to derive the movement of intense mesoscale features and, by tracking shallow precipitating convective cells, to estimate peak gusts in exposed locations. Methods of identifying conditions likely to lead to polar-low formation were discussed by Knut Midtbø (DNMI) who obtained good results by applying statistically-derived criteria to numerical forecast charts.

Lars Eide (Norsk Hydro) identified the critical problems concerning offshore drilling operations, pointing out that for such operations the necessary lead time required to restore rigs to a stable state where they are insensitive to high winds could be as much as 5 hours. Most operations could be undertaken at wind speeds up to force 8 but above this speed some operations were impossible. Christian Zick (Free University of Berlin) and Per Gloersen (National Aeronautics and Space Administration, Greenbelt) showed films of satellite data which demonstrated respectively the detailed development and decay of two polar lows, and the strong seasonal dependence of disturbed conditions together with the rapid variations in ice cover.

6. Polar lows and ocean waves

The final session was devoted to discussion of the effects of polar lows on sea state. Duncan Ross (University of Miami) showed that directional wave spectra associated with the passage of polar lows differed from model predictions when the storms were moving rapidly. It was often necessary to use models with a grid of 10 km or less to obtain realistic spectra. In many examples, focusing and defraction of the waves by currents or topography, especially near coasts, had a significant effect on the wave spectra. Alf Harbitz (University of Tromsø) showed how resonance between the movement of waves of certain wavelengths could give large waves over a narrow band of wavelengths despite the apparently short fetch (much less than the 1000 km or so normally required to reach maximum amplitude). These ideas were also supported by laboratory experiments reported by Torkild Carstens (Norwegian Hydrotechnical Laboratory).

Ken Davidson (US Navy Postgraduate School) described plans for the next Marginal Ice Zone EXperiments (MIZEX) in early spring 1987. While the programme was largely oceanographic, making use of remote-sensing techniques to examine sea state and ice cover, an extensive meteorological programme was also envisaged to characterize the relationships between surface fluxes and cyclogenesis, and the relationships between mesoscale meteorological features and the surface state. At present the meteorological programme was hampered by the lack of upper-air observations which could, perhaps, be provided by dropsondes.

Dag Gjessing (Norwegian Environmental Surveillance Programme) showed how new radar signal processing techniques could be used to obtain wave spectra related to specific types of forcing, while Ole Houmb (Oceanor) showed how the waves produced by polar lows were often of higher frequency than those associated with other depressions, but that the maximum significant wave heights were generally lower than those from other storms owing to the limited fetch.

7. Summary

The meeting demonstrated that considerable progress is being made towards improving polar-low forecasting but that numerical forecasts of polar lows are often not sufficiently accurate or unambiguous to provide adequate warning for offshore operators. New sources of data appear to offer some chance for improved forecasts particularly when used subjectively, but the basic mechanism for the rapid development remains uncertain although it is probably a combination of causes which may differ in relative importance between different examples.

The meeting was very successful in bringing together 66 scientists with a range of backgrounds (forecasters, theoretical meteorologists, observationalists and oceanographers) and, by concentrating on a specific topic, discussion was both uninhibited and constructive. Definitions of polar lows were almost as numerous as the participants and it is probably true that the term includes a range of systems with different mechanisms. Basic research is still hampered by the limited observations of polar lows formed under different conditions, and further detailed observations are essential if the basic mechanisms are to be clarified and reliable forecasts produced.

551.551.5

Prolonged clear air turbulence over the British Isles on 4 September 1985

By L.A. Hisscott

(Meteorological Office, Ronaldsway Airport, Isle of Man)

Summary

Clear air turbulence (CAT) is normally a transient and localized phenomenon. An unusual outbreak of moderate to occasionally severe CAT, which covered a large area and persisted for several hours, is described. The occurrence was associated with diffluence and anticyclonic turning below a warm frontal zone.

Clear air turbulence (CAT) is important to aviation from the point of view of both safety and passenger comfort. Usually it is localized in space and short-lived in time. However, extensive and prolonged CAT occurred over the British Isles on 4 September 1985. The existence of this phenomenon over a large area and its persistence for several hours are extremely rare.

Manx Airlines flight 303 departed from Ronaldsway at 0740 GMT, and arrived at London/Heathrow about 0900 GMT. The same Viscount aircraft and crew returned as flight 304 to arrive back at Ronaldsway at 1100 GMT. The captain, with many years of military and commercial flying experience, returned to the meteorological office to report that they had encountered moderate, occasionally severe, turbulence continuously on both legs of the trip, and that it was the roughest flight he had ever experienced. The outward leg was operated at a flight level of 14 000 ft (FL140) and the return leg at FL100, both in clear air just below thick layer cloud.

Fig. 1 shows the surface synoptic situation at 0600 GMT on 4 September 1985, with a ridge over the British Isles ahead of a depression west of Ireland, and a warm front just advancing into south-west Ireland. The air mass over the south of the British Isles gave broken stratus and stratocumulus cloud layers, the base generally at about 1000 ft (but 200–400 ft on windward coasts) and the top at about 5000 ft, and thick layer cloud, associated with the overrunning warm air, above 14 000 ft, which lowered as the warm front approached. Fig. 2 shows winds at 14 000 ft and 10 000 ft reported at 0600 GMT by upper-air stations in the British Isles and near continent. The 700 mb contours have also been drawn, by interpolating between the 0000 and 1200 GMT data.

The area in which CAT was reported can be associated with deceleration and anticyclonic turning of the west-south-westerly airstream, factors often relevant to the occurrence of CAT. In fact there was a ridge pattern in the contours at all levels over the British Isles at the time, with a SIGMET* of severe

* A SIGMET is an in-flight warning of certain significant weather phenomena.

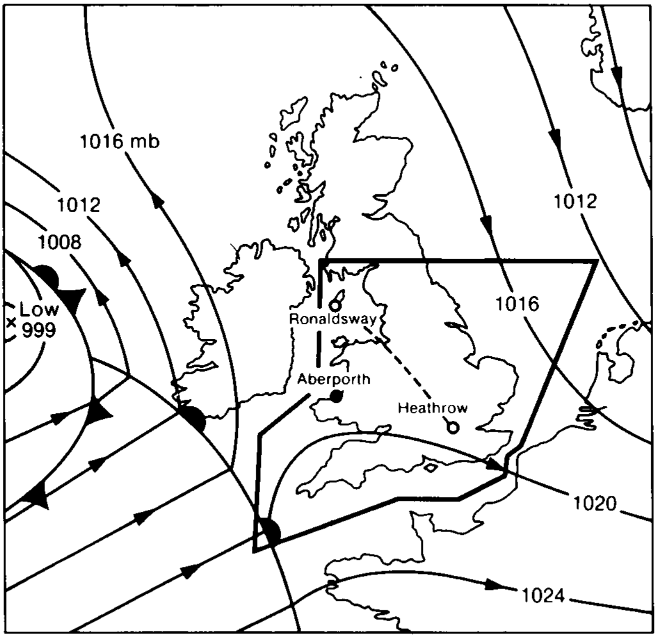

Figure 1. Surface analysis at 0600 GMT on 4 September 1985 showing route of Ronaldsway-Heathrow-Ronaldsway flight. The bold lines show the area covered by the London Flight Information Region.

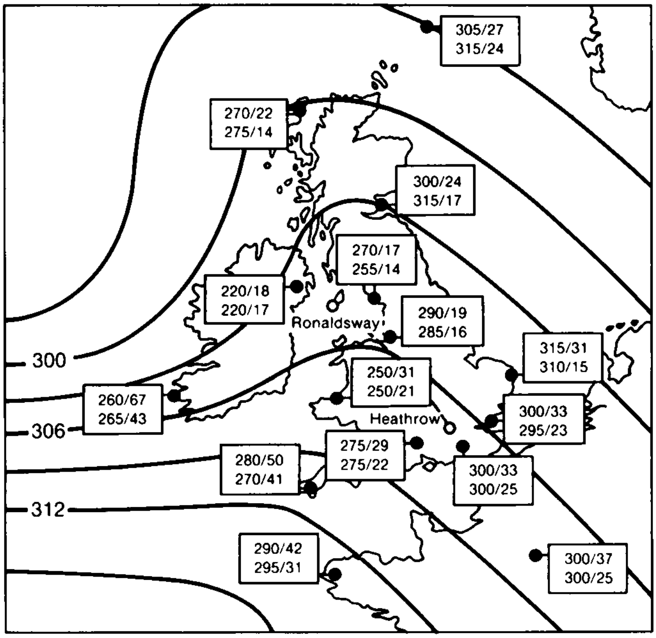

Figure 2. Interpolated 700 mb contour chart at 0600 GMT on 4 September 1985. Dots indicate upper-air stations and connected boxes contain 0600 GMT winds at 14 000 ft (upper figure) and 10 000 ft (lower figure). Contours are in decageopotential metres and wind speeds are in knots.

CAT between FL180 and FL420 in operation for the London Flight Information Region (see Fig. 1). However, the unusual feature of this case is that the reported extensive turbulence occurred below the frontal zone within the weak upper ridge. The dry unstable layer below the warm frontal zone, shown by the almost dry-adiabatic environmental lapse rate between 700 and 615 mb on the Aberporth ascent (Fig. 3), indicates strong mixing in this layer due to the severity and longevity of the turbulence. However, the continuous production of this intensity of turbulence over such a long period must be due to the broader-scale dynamics of the situation. There is a region of marked diffluence ahead of the 700 mb trough at 0600 GMT (Fig. 2) that moved east-north-east. The associated ascent of the air applied to the Aberporth sounding could presumably have maintained and deepened the instability for the return flight, but it is still difficult to understand why the moderate to occasionally severe CAT lasted so long.

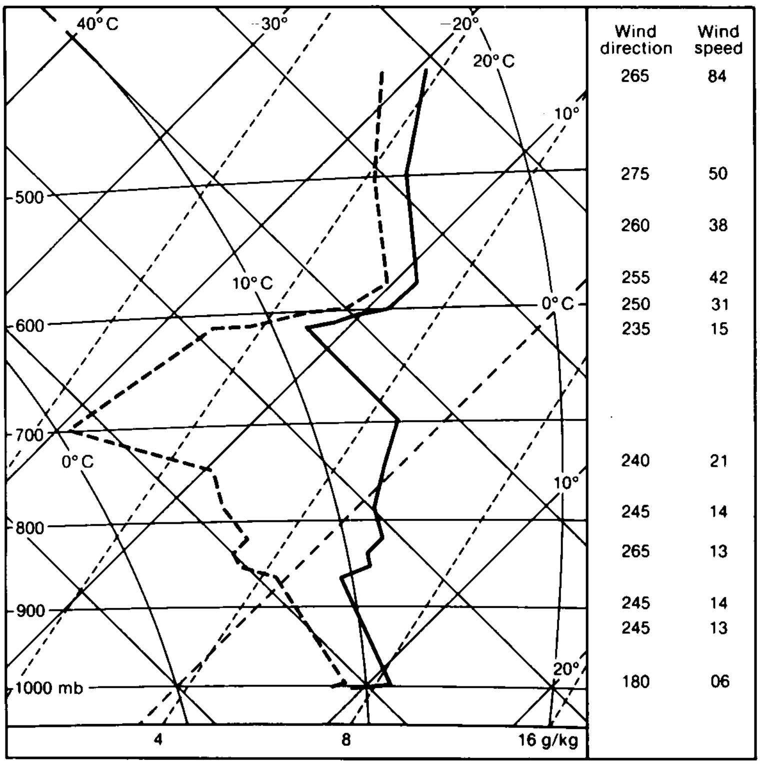

Figure 3. Aberporth radiosonde ascent at 0600 GMT on 4 September 1985 (wind speeds in knots).

Acknowledgements

I would like to thank Captain R. Coker of Manx Airlines for reporting this incident, the Senior Forecaster at Ronaldsway for permission to publish the data, and Mr M. Dutton of the Central Forecasting Office at Bracknell for his useful comments.

Notes and news

Workshops about the middle atmosphere

Two workshops entitled 'Middle atmosphere of the southern hemisphere' and 'Gravity waves and turbulence in the middle atmosphere' will be held consecutively at the University of Adelaide between 18 and 22 May 1987. Each workshop will contain invited reviews and contributed papers. Among the topics to be covered are:

Middle atmosphere of the southern hemisphere —

- Inter-hemispheric differences
- Intercomparison of observations and analysis
- Climatology and seasonal evolution
- Large-scale waves and wave–mean flow interactions; sudden warmings and final warmings
- Coupling of troposphere and middle atmosphere
- Dynamics of equatorial regions and inter-hemispheric coupling
- Transport of middle atmosphere constituents
- Numerical modelling

Convenor: Dr A. O'Neill (Meteorological Office, United Kingdom)

Gravity waves and turbulence in the middle atmosphere —

- Theory, modelling and parametrization
- Climatologies of gravity waves and turbulence
- Spectral studies; observational and theoretical interpretations
- Sources, propagation and saturation
- Gravity wave and turbulence variability; mechanisms
- Observational and data-processing techniques

Convenor: Dr D.C. Fritts (University of Alaska, USA)

Further information is available from the convenors or from Dr R.A. Vincent, Physics Department, University of Adelaide, PO Box 498, Adelaide 5001, Australia.

Advisory group on greenhouse gases

Radiatively active constituents in the atmosphere, including aerosols, which tend to increase the temperature of the lower atmosphere are sometimes referred to as greenhouse gases. In recent years there has been increasing interest in the assessment of the role of these gases, particularly carbon dioxide (CO_2), in climatic variations. This interest has led to the establishment of an Advisory Group on Greenhouse Gases (AGGG) by the International Council of Scientific Unions, the United Nations Environment Program and the World Meteorological Organization.

At its first meeting in Geneva on 1–2 July 1986, the AGGG strongly supported the statement from the 1985 Villach Conference on the 'Assessment of the Role of Carbon Dioxide and other Greenhouse Gases in Climatic Variation and Associated Impacts' that the effects of increases in CO_2 and other trace gases that cause the greenhouse effect (such as methane, chlorofluorocarbons (CFCs) and oxides of nitrogen) could produce an increase in global mean temperature of between 1.5 and 4.5 °C in the first half of the next century; the corresponding rise of sea level might reach between 20 and 140 centimetres.

The AGGG stressed the need to improve the basic understanding of the climate system and its response to both natural and man-made forcing mechanisms. Since the ozone depletion problem and the greenhouse gas problem are interlinked through the impact of the same chemicals, the Group urged that the study of these two problems be combined. They also suggested that there are two preventive measures that should be considered to alleviate the problem:

(i) The introduction of energy conservation schemes especially those that increase the efficiency of energy use.

(ii) Substitution for CFCs in a number of uses for which alternatives are available.

Formation of an Association of European Climatologists

For a number of years British and Greek climatologists have arranged joint scientific meetings. At the last such meeting in Athens climatologists of both countries agreed to try to set up an Association of European Climatologists. The aim of the association is to foster the study of pure and applied climatology within the whole of Europe, and to promote collaboration between European climatologists. Full membership of the association is open to professional climatologists and those working in allied and associated professions; associate membership is available to amateur climatologists. Further information about the association is available from Dr A.H. Perry, Department of Geography, University College, Swansea, Wales.

Reviews

Fields, currents and aerosols in the lower troposphere, by R. Reiter. 150 mm × 240 mm, pp. xix + 714, *illus.* A.A. Balkema, Rotterdam, 1986. Price £29.75.

This well-produced book by Reinhold Reiter represents an extensive report of an observational programme at a network of mountain stations in the Bavarian Alps (particularly the Zugspitze massif). The work mainly spans the years 1950–61 and involves measurements of atmospheric electricity, aerosol concentration and radioactivity, both natural and artificial (man-made), together with more conventional meteorological observations. The book is No. 71 in the Natural Sciences Series, a collection of scientific research reports originally published in German in 1964, and published in English for the first time over 15 years later.

The material is weighty, both literally (714 pages and 1.25 kg) and in its scientific content. As the author admits, he had to drop the idea of including all the latest literature when producing the English version in order to preserve the original character of the book as a specific report of ten years of research. This is reflected in the references, about 50% of which were published between 1950 and 1960. Indeed, the recent references, that is post-1970, refer almost exclusively to the results of the Bavarian observational programme in the 1950s, and a significant portion of these are attributed to the author. Hence, one must not approach this text expecting to find a balanced 'state of the art' review, although there are many references to work from 20 or more years before the observational programme which provide a sound historical perspective.

The treatise begins with a justification for making measurements at fixed mountain stations as opposed to those made using probes in the free atmosphere. This section eventually comes to the correct conclusion, that the techniques are complementary, but frustrates the reader with its needlessly tedious argument. The relationship between atmospheric electricity and radioactivity is stated, and the order in which topics are to be discussed is justified. There follows an excellent review of the environment and nature of the observing stations and the measurement techniques employed, including the interesting use of what is termed a 'movement diagram', constructed by plotting measurements from a valley station against those made at a mountain station.

The diurnal and seasonal variations of the electric field and radioactivity of different elements, the relationships observed between wind speed and direction, humidity, precipitation and aerosol concentrations and electrical field and radioactivity, are all unfolded from the observations. At times the reviewer felt almost overwhelmed by facts and figures as each page was turned. Nevertheless, the standard of translation is high, although there are occasionally rather strange statements (for example, on page 23: 'It is known that the local climatic factors influence the relationship between atmospheric electricity and radioactivity more or less strongly, and . . .'), and there are few typographical errors, all of which makes the text easy to read. The main criticism is that one does not know quite what to expect from page to page; theory interrupts observations, special observations from short field projects precede or follow long-period observations.

The section on radioactivity convincingly explains observed variations in terms of the following: variations of weather type — convective or frontal; meteorological parameters, particularly wind direction from areas of naturally occurring radioactivity in Alpine rocks; and the occurrence of known atomic explosions during the period, in the Sahara and elsewhere. Some tantalizing suggestions are made regarding the speed of transport of nuclear-fission products between the mountain top and the valley bottoms, and the presence of such material on glaciers, in grass and in animal organs, all of which is particularly topical in the wake of the recent Chernobyl disaster.

The author is certainly not understating his findings when he concludes by saying 'We find a mosaic of individual facts and observations before us.' There is much in this book to interest, indeed stimulate, those concerned with atmospheric electricity and radioactivity. The reader should be aware, however, that the observations often prompt further questions. This is a book that most meteorologists will find very interesting, and some will find in it invaluable source material to be confirmed or challenged. It may be, as the publishers suggest, that this book will become recognized as a major reference work.

C.G. Collier

Weather at sea, by D.M. Houghton, 180 mm × 240 mm, pp. 64, *illus*. Fernhurst Books, Steyning, 1986. Price £5.50.

This book has been written in consultation with the Royal Yachting Association (RYA), and is therefore likely to be used as a supporting text for the meteorological component in RYA certificate courses in sailing and navigation. The book assumes no knowledge of meteorology, but does appropriately assume some knowledge of sailing and navigation. It is directed at yachtsmen who are likely to do most of their sailing in coastal waters, the emphasis being mainly on coastal weather typical of the British Isles. Some of the book's content can also be found in another recent book by D.M. Houghton (*Wind strategy*, Fernhurst Books, Steyning), but is here presented in a slightly more condensed and simplified form.

Early sections of the book deal mainly with weather basics, comprising short chapters covering the general circulation, pressure/wind relationships, stability and air mass concepts, clouds, and middle-latitude weather systems. In parts, the presentation is either too precise or too incomplete to make much sense, as in the opening section on global wind systems where the text does not actually explain the accompanying diagram depicting south-westerlies at our latitude; whilst elsewhere there are a few inconsistencies and odd usages which are likely to confuse some readers. The author's choice of the term 'pressure-gradient wind' (later 'gradient wind') in place of 'geostrophic wind' is questionable; not so much on semantic grounds as on the grounds that yachtsmen are likely to come across the more conventional term elsewhere without necessarily being aware that it is synonymous.

Following a well-presented section on clouds and how they can be used to identify weather type, the author introduces some of the terminology of synoptic weather systems, ending with an observation to the effect that fronts are relatively rare phenonema (in what sense, where, and at what time of year are not stated). Some readers might find that statement apparently inconsistent with the following chapter describing depressions as essentially frontal phenomena, along with a 'classical' description of warm, cold and occluding frontal structures. Although the difficulties involved are appreciated, it is a pity that the author relies almost entirely on a vintage model for middle-latitude development without any reference to more recent concepts. For example, yachtsmen frequently ask why the strongest surface winds are usually associated with cyclonic circulation patterns. The model used by the author cannot really answer that important question, mainly because it insists on describing development of the surface circulation in terms of a geostrophic response *due* to changes in pressure, without being able to account for the pressure change itself. It also puts too much emphasis on the role of moisture, given that we now know that latent heat is rarely a major energy source in mature Atlantic depressions. The chapters on weather systems should have given some space to a discussion of the relationship between the intensity of surface development and season, given that this is an important factor to consider when planning sailing activities around the British Isles.

The second half of the book is mainly concerned with the more practical aspects of weather and sailing, covering the interpretation and use of weather forecasts and bulletins, observing weather at sea, coastal and offshore wind variations, weather hazards, and the interactions between wind and tide, and wind and waves. The chapter on using weather bulletins contains a concise but comprehensive account of how to interpret information in shipping forecasts, though I am not sure about the implication here that constructing an isobaric analysis from the forecast and coastal reports is an easy task. In my experience most yachtsmen find it an extremely difficult task except for relatively simple synoptic situations; it is perhaps significant that the RYA syllabuses no longer require that this skill be examined. The following sections on coastal and offshore variations of surface winds (including sea-breezes) present highly simplified but nevertheless quite detailed descriptions of factors influencing the type of sub-synoptic wind variations which are of special relevance to coastal sailing, and clearly reflect the author's expertise and practical sailing experience. Most yachtsmen should find these sections fascinating reading, and thus be encouraged to perceive local weather variations as being consistent with, rather than exceptions to, the general synoptic conditions described in weather forecasts.

Overall, the book is clearly written and well produced, with attractive illustrations and plenty of clear line diagrams. Better use might have been made of some of the illustrations through the addition of suitable captions, and the examples at the end of the book might have been extended to include short descriptions of coastal weather conditions as might be observed in association with the analysed weather maps. A course direction given in the first example as 'SW' should read 'SE' to make sense. However, these are minor criticisms, and despite my reservations concerning some of the background material, I believe that the book does on the whole succeed in presenting meteorology at just about the right level for the intended readership, while at the same time giving a more than adequate coverage of most essential topics.

M.A. Pedder

Books received

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

Prediction of solar radiation on inclined surfaces, edited by J.K. Page (Dordrecht, Boston, Lancaster, D. Reidel Publishing Company, 1986. £59.50, US $85.00, Dfl 180.00) presents methods for the mathematical prediction of values of solar radiation falling on inclined planes under clear conditions in climates of differing atmospheric clarity and also under overcast conditions. The chapters are a collection of individual European research projects and the whole programme has been extensively checked against practical measurements of actual inclined surface radiation in Europe. Instructions for the manual calculation of the solar radiation are included along with other applications of the European Community Solar Radiation Model.

Oceánic whitecaps and their role in the air–sea exchange processes, edited by E.C. Monahan and Gearóid MacNiocaill (Dordrecht, Boston, Lancaster, D. Reidel Publishing Company, 1986. £40.25, US $64.00, Dfl 145.00) comprehensively describes the current state of knowledge about one of the most elusive physical features of the ocean surface — the whitecaps which form when a wave breaks. Among the many whitecap-related topics treated are wave-breaking, the sub-surface bubble clouds, and the production of sea-salt aerosol as a result of the bursting of whitecap bubbles. The role of whitecaps in sea surface electrostatic charge separation and in air–sea gas exchange are discussed, as is the effect of whitecaps on the remote-sensing signatures of the sea surface. Over 20 papers are included, which were presented at the first International Whitecap Workshop.

Cloud investigation by satellite, by R.S. Scorer (Chichester, Ellis Horwood Ltd, 1986. £39.50) consists of over 600 pictures and photographs which illustrate the language of satellite imagery of the atmosphere. The introductory chapters include a review of the mysterious Channel 3, and discussion on desert dust and sea-glint designed to help interpret the pictures which accompany the text. There are basic discussions of cellular convection, fog and stratus, cirrus, mountain waves, cyclones and anticyclones; and treatment of regional phenomena with individual and peculiar flow patterns, as well as aircraft and ship trails.

An introduction to the theory of climate, by A.S. Monin (Dordrecht, Boston, Lancaster, D. Reidel Publishing Company, 1986, £45.75, US $64.00, Dfl 165.00) presents, in a concise form, the basic concepts, ideas and methods dealing with the contemporary physical theory of climate. An important part of the book is devoted to the discussion of mathematical models related to the climatic system as a whole. Other subjects such as the transfer of radiation in the atmosphere, carbon dioxide, aerosol and ozone cycles, stratospheric circulation, oceanic thermocline, upper layer of the ocean, filtration of moisture in the ground, sea ice, etc. are also discussed in relation to climate. This book will be of value to specialists and graduate students in many different fields.

The atmosphere and ocean: a physical introduction, by N. Wells (London, Philadelphia, Taylor and Francis Ltd, 1986. £15.00 paperback, £29.00 hardback) is an introduction to the physical processes of the atmosphere and ocean for science students. Both systems are described and compared, and examples are given of how the atmosphere and ocean interact. The diverse concepts and ideas of meteorologists, atmospheric physicists and oceanographers are brought together into a single account of the environment, placing the emphasis on physical ideas and mechanisms rather than on mathematics, and thus providing the student with a much better understanding of the atmosphere and the ocean, and an appreciation of their close relationship.

Meteorological Magazine

GUIDE TO AUTHORS

Content

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Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

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 referred to 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.

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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 difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

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Meteorological Magazine

October 1986

Vol. 115
No. 1371

CONTENTS

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ISBN 0 11 727838 6 ISSN 0026–1149

Printed for HER MAJESTY'S STATIONERY OFFICE
by Delco Printing Co Ltd 10/86 Dd. 0739131 1425

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S
STATIONERY
OFFICE

November 1986

Met.O.971 No. 1372 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1372, November 1986, Vol. 115

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Experimental monthly long-range forecasts for the United Kingdom

Part II. A real-time long-range forecast by an ensemble of numerical integrations

By J.M. Murphy and T.N. Palmer*
(Meteorological Office, Bracknell)

Summary

The use of an ensemble of integrations for long-range prediction has been studied with a hemispheric version of the Meteorological Office 5-level general circulation model. Some results, showing the potential of the technique, are described. The method is now being used with the global 11-level model to produce real-time long-range forecasts for the long-range forecasting conference in the Synoptic Climatology Branch of the Meteorological Office. Results from the first of these real-time ensemble forecasts are discussed.

1. Introduction

The short-range predictive skill of numerical weather prediction (NWP) models has steadily improved over the years. Despite this, attempts to use such models to forecast the instantaneous state of the atmosphere a month into the future have not enjoyed much success. The fundamental reasons for this lie not only with deficiencies in the numerical models, but also with the very equations of motion which the models integrate.

Specifically, the difference between two or more integrations of an NWP model whose initial states differ by a small amount (representing, say, analysis error) will increase with time until at some stage the integrations are completely independent of one another, in the sense that they can be thought of as random states in some climatological distribution. This suggests that the atmosphere has some 'limit of deterministic predictability' and attempts to estimate this (e.g. Lorenz 1982, Mansfield 1986) suggest that, on average, it is considerably less than 1 month. This limit can be extended by considering the model's forecast of only the planetary-scale modes and/or time-averaged fields (Shukla 1981), though this approach ignores a fundamental problem that forecasting on the monthly time-scale has a marked probabilistic element, and is not strictly deterministic. The multivariate statistical model (Maryon and Storey 1985, Folland and Woodcock 1986), the backbone of the operational long-range forecasting system in the Meteorological Office, has this notion built into its basic formulation; it does not predict one pattern of surface pressure, but assigns probabilities to a number of pre-defined patterns.

* Now on secondment to the European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading.

One way of approaching the probabilistic nature of long-range forecasting using dynamical models is through the method of 'ensemble' forecasting, where the model is integrated, not from one initial state, but from a set of equally possible initial states, consistent, say, with known analysis errors. A priori each forecast from this ensemble of initial states is treated as equally likely. If, after a month of integration, each member of the ensemble has totally diverged from each of the others then no useful information can be obtained from the forecasts. If, however, subsets of the ensemble forecast tend to 'cluster together', then probabilities can be assigned to each cluster and a probabilistic forecast given.

Over the past 2 years the ensemble forecast method has been developed in the Synoptic Climatology Branch of the Meteorological Office (Mansfield 1986, Murphy 1985). This work, based on the Meteorological Office 5-level model (Corby *et al.* 1977), has shown that under certain circumstances useful information can be obtained from the ensemble technique, even out to 1 month. Some of this work is summarized in section 2. Encouraged by this research, it was decided to attempt to use the ensemble forecast technique in real time for the regular long-range forecasting conferences.

The first of these attempts took place at the mid-September 1985 conference. To the best of the authors' knowledge this was the first occasion that an ensemble of integrations of an NWP model has had a direct impact on the production of a real-time long-range forecast. The following is an account of the method used to produce this forecast, the forecast itself, and an assessment of its skill.

2. Potential impact of ensemble forecasting

Before attempting a practical real-time ensemble forecast, it was necessary to establish whether, in principle, this technique could be used to give an improvement in long-range forecast skill. If the notion of a probability distribution of forecasts, each arising from initial conditions compatible with a given initial analysis, is valid, then the mean of a finite ensemble of such forecasts should, on average, be closer to the true atmospheric evolution than should an individual forecast from within the ensemble.

To test this idea, eight 50-day ensemble forecasts, each containing seven individual integrations, were made from winter initial conditions using, in this case, the 5-level model. The ensembles were created by adding spatially correlated random perturbations to a given observed state to simulate the effects of analysis error. The method used was to take a linear combination of the observed state with an independent analysis such that the difference between the resulting perturbed state and the observed state corresponded to a typical root-mean-square (r.m.s.) analysis error of 30 metres at 500 mb. Each ensemble forecast was verified both against observations and against an additional 'nature' integration, also produced using the above perturbation technique. The purpose of the latter was to test the ensemble method under the (unrealistic) assumption that the model has no systematic biases. With this so-called 'perfect-model' assumption, the additional integration can be thought of as a possible realization of the real atmosphere and used to verify the forecasts (see Fig. 1). The predictability limit under a perfect-model assumption can be thought to provide an upper bound to the model's actual predictive skill.

Fig. 2 shows results averaged over the eight ensembles under this perfect-model assumption. All the curves refer to results for the 500 mb geopotential height field in the area 30–85° N. The skill score is defined by the 'anomaly correlation coefficient'. To calculate this, model fields are calculated relative to an estimate of the model climatology obtained by averaging over the eight 'nature' runs.

As discussed above, it is expected that, on average, the ensemble-mean forecast would yield an improvement in predictability relative to an individual forecast. However, as mentioned in the introduction, some improvement in skill may also be gained by removing the least predictable scales of motion by spatial or temporal filtering.

The curves in Fig. 2 show the relative effects of spatial filtering and ensemble averaging on forecast skill. An improvement in skill is obtained if only the long-wave component, represented by zonal waves

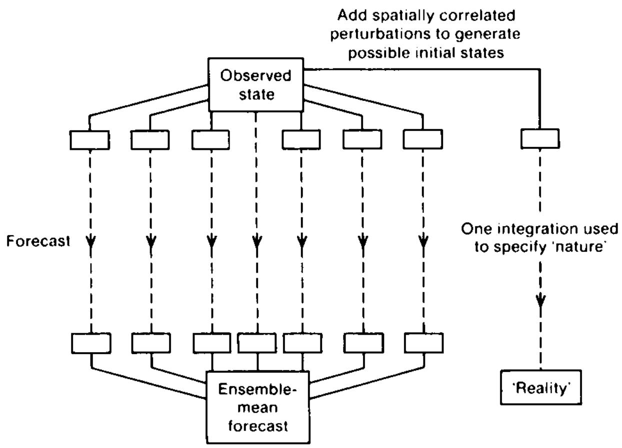

Figure 1. Schematic diagram showing the construction of a 5-level model ensemble forecast, together with the 'nature' integration used for the perfect-model evaluation of predictability.

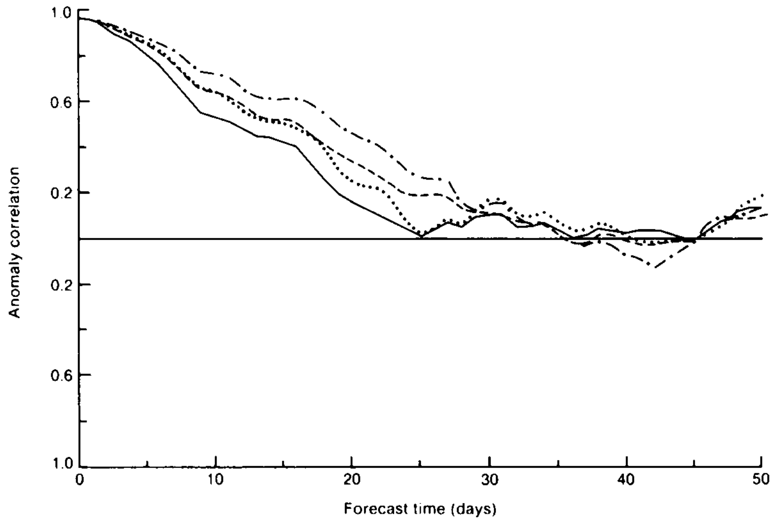

Figure 2. Average perfect-model forecast skill for 500 mb geopotential height, 30–85°N, for 5-level model integrations: ——— daily unfiltered individual forecast, ······· daily individual forecast, zonal waves 0–3 only, – – – – daily ensemble-mean forecast, —·—·— daily ensemble-mean forecast, zonal waves 0–3 only.

0–3, in an individual forecast is considered. However, if the long-wave component of the ensemble-mean forecast, formed by averaging the seven individual forecasts in a given experiment, is considered, the skill is improved still further. In terms of the predictability limit, the spatially filtered ensemble-mean forecast offers an improvement of almost 50% when compared with the unfiltered individual forecast —19 days for an individual forecast and 28 days for the spatially filtered ensemble-mean forecast.

A substantial improvement in skill can also be observed in the time-averaged ensemble-mean forecast when compared with the time-averaged individual forecast (Murphy 1985). When verified against real data, however, the ensemble-mean forecast is, on average, no better than an individual forecast. This essentially indicates that, in general, the rate of divergence of the real atmospheric evolution from the ensemble-mean forecast is much larger than the rate of divergence of individual model forecasts from the ensemble mean.

However, even though the effect of ensemble averaging on forecast skill is negligible on average, an improvement is obtained in cases when individual forecasts show greater than average skill. In particular, in two of the eight cases, the individual forecasts were found to show skill well beyond the model's average limit of predictability (Mansfield 1986). In these two cases the ensemble-mean forecast showed a substantial improvement in skill. To investigate this further, another three random perturbation ensemble forecasts were produced for three independent situations where an individual forecast, run previously, had shown an unusually high degree of skill. In two of these three cases, the average skill of individual forecasts within the ensemble remained positive throughout, and the ensemble-mean forecast again showed a significant increase in skill. Fig. 3 illustrates the average improvement in skill given by the ensemble-mean forecast in these four unusually predictable cases compared with the effect in the other seven cases where the model did not show any skill beyond the normal predictability limit.

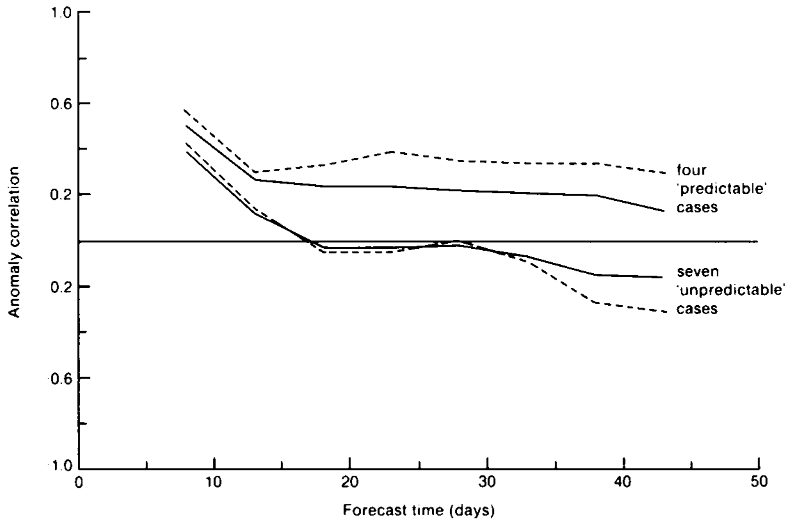

Figure 3. Practical forecast skill for four 'predictable' 5-level model forecasts and seven 'unpredictable' forecasts for the 500 mb geopotential height, 30–85° N: ——— 15-day mean individual forecast, – – – – 15-day mean ensemble-mean forecast.

3. Methodology for the real-time forecast

Having shown that increased predictability could be obtained by ensemble averaging a number of individual forecasts under perfect-model conditions, the next step was to see if a similar improvement could be obtained in reality by attempting a practical long-range ensemble forecast using a more skilful model.

The model used for the real-time integrations was the global 11-level climate model developed in the Dynamical Climatology Branch and is described in detail by Slingo (1985). The model, similar in many respects to the 5-level model, has a regular latitude–longitude grid with $2\frac{1}{2} \times 3\frac{3}{4}°$ resolution. The 11-level model was designed for long-period integrations and has an energy-conserving finite difference scheme as well as sophisticated physical parametrizations. For these reasons, it was decided that this model was the most appropriate available for long-range forecast integrations. Whilst it was not designed primarily as an NWP model, *de facto*, it is treated as such in this paper.

Instead of the spatially correlated random perturbation technique used to generate the 5-level model ensembles, seven consecutive operational analyses at 12-hour intervals between 00 GMT on 12 September 1985 and 00 GMT on 15 September 1985 inclusive were used for initial conditions for the real-time forecast. The correspondence between this 'time-lagged' technique for generating initial conditions for an ensemble and the random perturbation method depends on the forecast skill of the model, and it is still an open question as to which technique is more appropriate in practice.

The initialization dates were chosen to be as close as practicably possible to the date of the long-range forecasting conference on 17 September. As in section 2, results are expressed as anomalies with respect to an estimate of the model's autumn climatology. The latter was formed from a set of eight integrations employing a selection of initial conditions at least 10 days apart from September and October of 1983 and 1984. These integrations used climatological sea surface temperatures (SSTs).

For the forecast integrations, fixed SST anomalies, based on operational SST analyses averaged over the 10 days preceding the initialization date of the first of the forecasts, were added to an SST climatology, which was updated every 5 days during the integrations. From each forecast, time-mean fields were produced corresponding to the 5-day period immediately following the long-range forecasting conference (18–22 September), the next 10-day period (23 September–2 October), and the following 15-day period (3–17 October). (Clearly these fixed verification periods correspond to different model forecast times in each of the seven integrations.)

Results from the ensemble of forecasts (see next section) were considered, together with the multivariate statistical model, in the production of the mid-September long-range forecast.

4. Discussion of forecast

The 5 days 18–22 September represent a medium-range period of the forecast, during which there was a small spread between the ensemble members and there was a reasonable degree of skill in their predictions. Fig. 4 shows the ensemble-mean 500 mb geopotential height anomaly for this period compared with the verifying actual anomaly. Most of the major centres have a counterpart in the

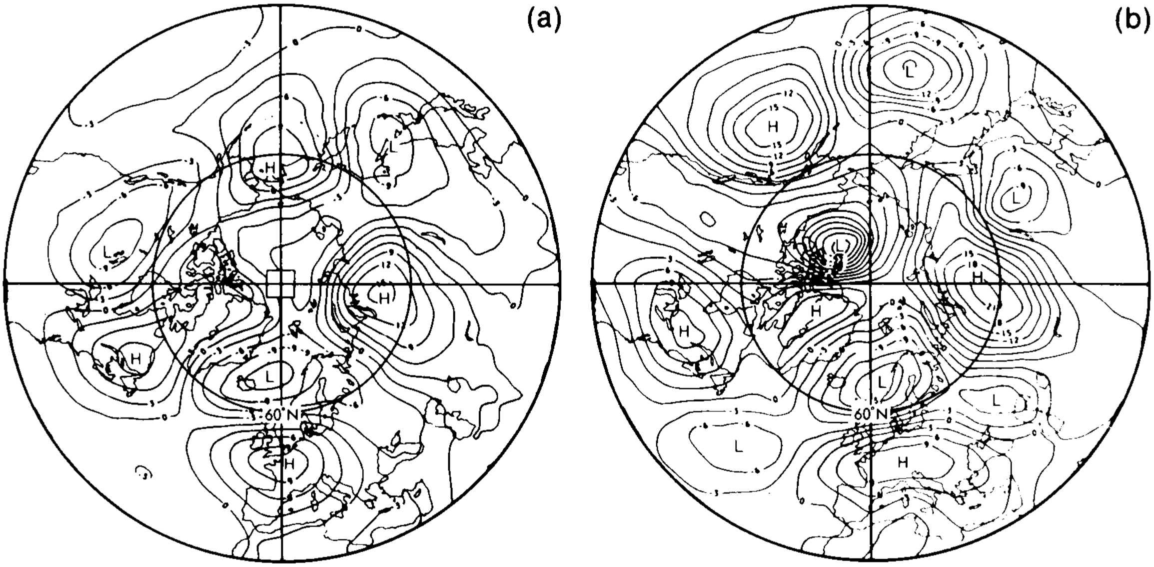

Figure 4. Ensemble-mean forecast (a) and observed (b) 500 mb geopotential height anomaly (dam) for 18–22 September 1985.

ensemble mean, the most notable exception being the deep low of −30 decametres centred near the pole. There is a fairly close correspondence between the individual forecasts in most areas at this stage (not shown); for example, all seven integrations show evidence of the high–low anomaly dipole over western Europe, a feature which corresponds well with the observed pattern in this region.

The correlation between the ensemble-mean and observed anomaly patterns, for the northern hemisphere north of 15° N, is 0.49 (Table I) — a slightly disappointing score in view of the above remarks. At this range the skill could of course be improved somewhat by weighting the more recent individual integrations more highly when forming the ensemble mean, as they are likely, on average, to be more skilful than the earlier ones (Table I confirms this in the present case). However, since the main interest is in the long-range forecast periods, for which the integrations can essentially be treated as equally likely realizations, such a procedure was not used.

The ensemble-mean forecast for the 10-day period 23 September–2 October and the actual anomaly are shown in Fig. 5. The considerable reduction in the intensity of the ensemble-mean anomaly compared with that shown in Fig. 4(a) reflects the spreading of the ensemble towards complete loss of predictability. Nevertheless, a degree of coherence still appears to exist between the individual patterns (not shown). To determine objectively whether the ensemble-mean anomaly represented anything more than random noise would require a series of point-by-point statistical Student's *t*-tests on the ensemble-mean anomaly to ascertain whether the number of points at which the anomaly was significant was greater than that expected by chance (Murphy 1985).

Table I reveals that all the individual forecasts retain a positive anomaly correlation at this stage,

Table I. *Anomaly correlations for forecast 500 mb geopotential height anomaly fields, 15–90° N for the three periods of the long-range forecast*

Integration	Forecast period 18–22 Sept.	23 Sept.– 2 Oct.	3–17 Oct.
1 (00 GMT 12 Sept.)	0.09	0.16	−0.01
2 (12 GMT 12 Sept.)	0.21	0.10	0.08
3 (00 GMT 13 Sept.)	0.14	0.01	0.05
4 (12 GMT 13 Sept.)	0.46	0.18	−0.05
5 (00 GMT 14 Sept.)	0.51	0.34	0.09
6 (12 GMT 14 Sept.)	0.65	0.21	0.02
7 (00 GMT 15 Sept.)	0.60	0.23	−0.07
1–7 average individual forecast	0.38	0.18	0.00
1–7 ensemble-mean forecast	0.49	0.25	−0.12

although the level of correlation is low with an average score of 0.18 compared with 0.25 for the ensemble mean. This difference in skill, although modest, illustrates the principle of increasing the signal-to-noise ratio through ensemble averaging. Subjectively, most of the skill appears to lie in the eastern hemisphere, with successive centres between Europe and Kamchatka, eastern Russia corresponding quite well in position, if not intensity, with observed features. This impression is

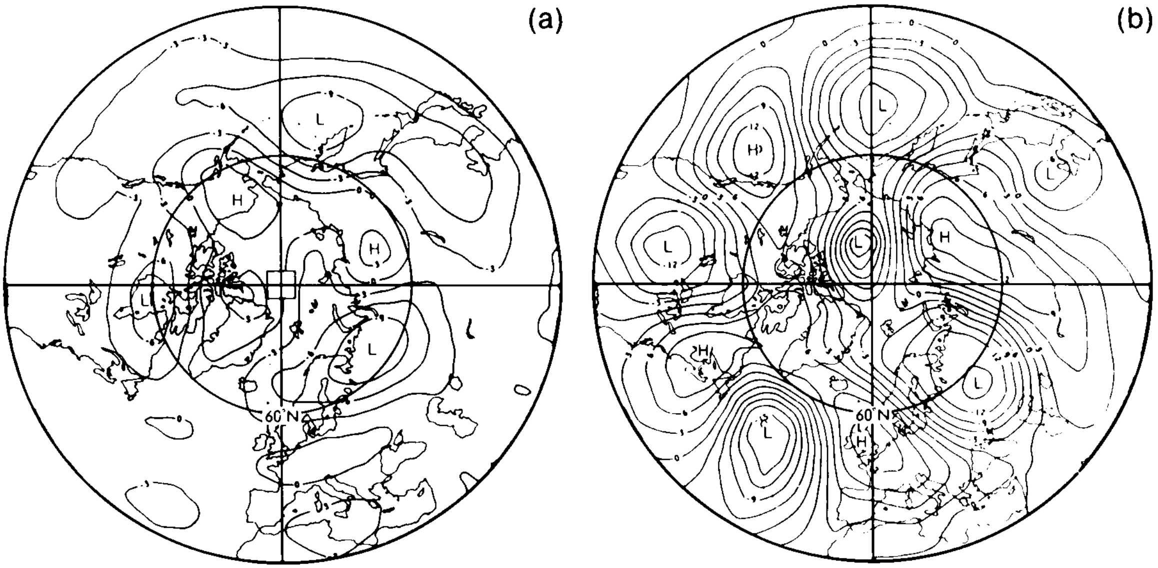

Figure 5. Ensemble-mean forecast (a) and observed (b) 500 mb geopotential height anomaly (dam) for 23 September–2 October 1985.

corroborated by limited-area anomaly correlations obtained by splitting the area north of 30° N into three equal sectors. The score for the sector 180–60° W is −0.11, whereas the scores for the sectors 60° W–60° E and 60° E–180° W are 0.39 and 0.42 respectively. Fig. 6 shows the forecasts from each integration for the 15-day period 3–17 October together with the ensemble mean. The ensemble-mean pattern has a featureless 'washed-out' nature suggesting initially that the ensemble distribution has become essentially random by this point. It is certainly true that, as measured by anomaly correlation, the forecast has completely lost skill at this stage (Table I).

The impression of the time variation of the forecast skill is obscured somewhat by using different time-averaging lengths for the three forecast periods. Accordingly, in Table II, the individual and ensemble-mean anomaly correlations obtained by splitting the forecast span into successive 5-day periods have been recorded. In terms of model time a small degree of skill remains up to days 16–20, though one cannot infer too much about the model's long-range skill from just one case. Predictability is liable to vary considerably from one experiment to another (Mansfield 1986), and also from season to season (Bengtsson and Simmons 1983).

In section 2 only the full ensemble mean of all seven integrations was considered. If an ensemble forecast is always normally distributed about its mean this is an appropriate quantity to consider. However, if, as postulated in the introduction, ensemble distributions tend to cluster into a small number of distinct groups, the full ensemble mean may become less meaningful and, alternatively, 'sub-ensemble means' should be formed from the members of each separate cluster, presenting the final forecast as a series of probabilities based on each of the sub-ensemble means.

Interestingly, there does appear to be some evidence of such clustering among the individual integrations in Fig. 6. In integrations 5–7 there is a pattern showing areas of low anomaly centred in the Pacific and near Hudson Bay with an area of high anomaly in between, somewhat similar to the winter-time Pacific/North American (PNA) pattern of Wallace and Gutzler (1981). In contrast, integrations 1–4 show no sign of this pattern, but all show a low anomaly centred near Alaska. Thus it

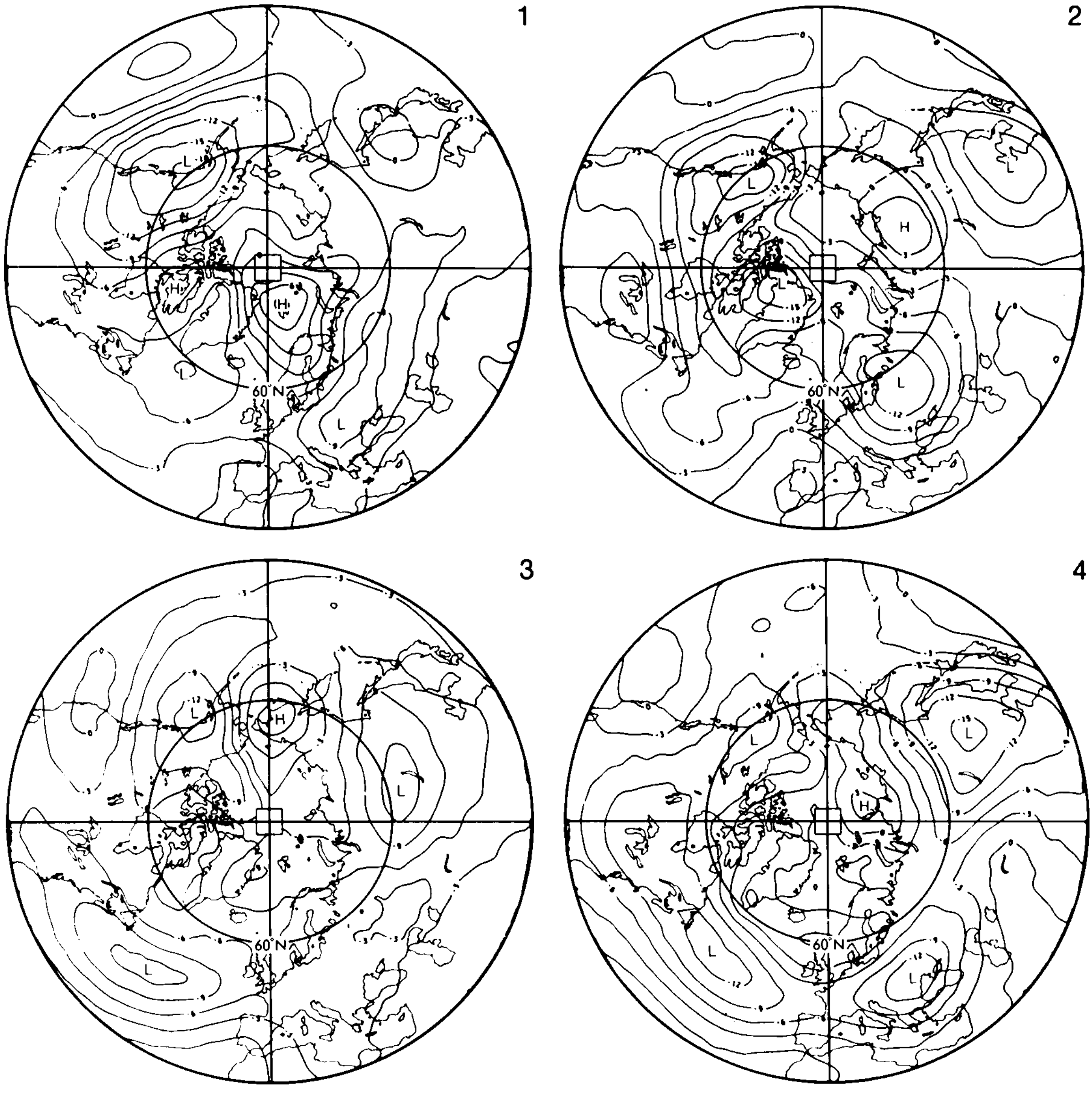

Figure 6. Individual (from integrations 1–4) forecast 500 mb geopotential height anomaly (dam) for 3–17 October 1985.

could be considered that, at least in the Pacific/North American region, the integrations have split into two definite groups. The two relevant sub-ensemble means are shown in Figs 7(a) and (b). Despite the slack pattern of the full ensemble mean this clustering suggests that the ensemble distribution has not yet become randomly distributed. Furthermore, the actual atmospheric anomaly pattern (Fig. 7(c)) in the Pacific/North American area does show a structure similar to that of the 5–7 sub-ensemble mean. However, since the latter incorrectly predicts high anomalies in polar regions and also underestimates the broadness of the high part of the pattern at lower latitudes, the correspondence in type does not show

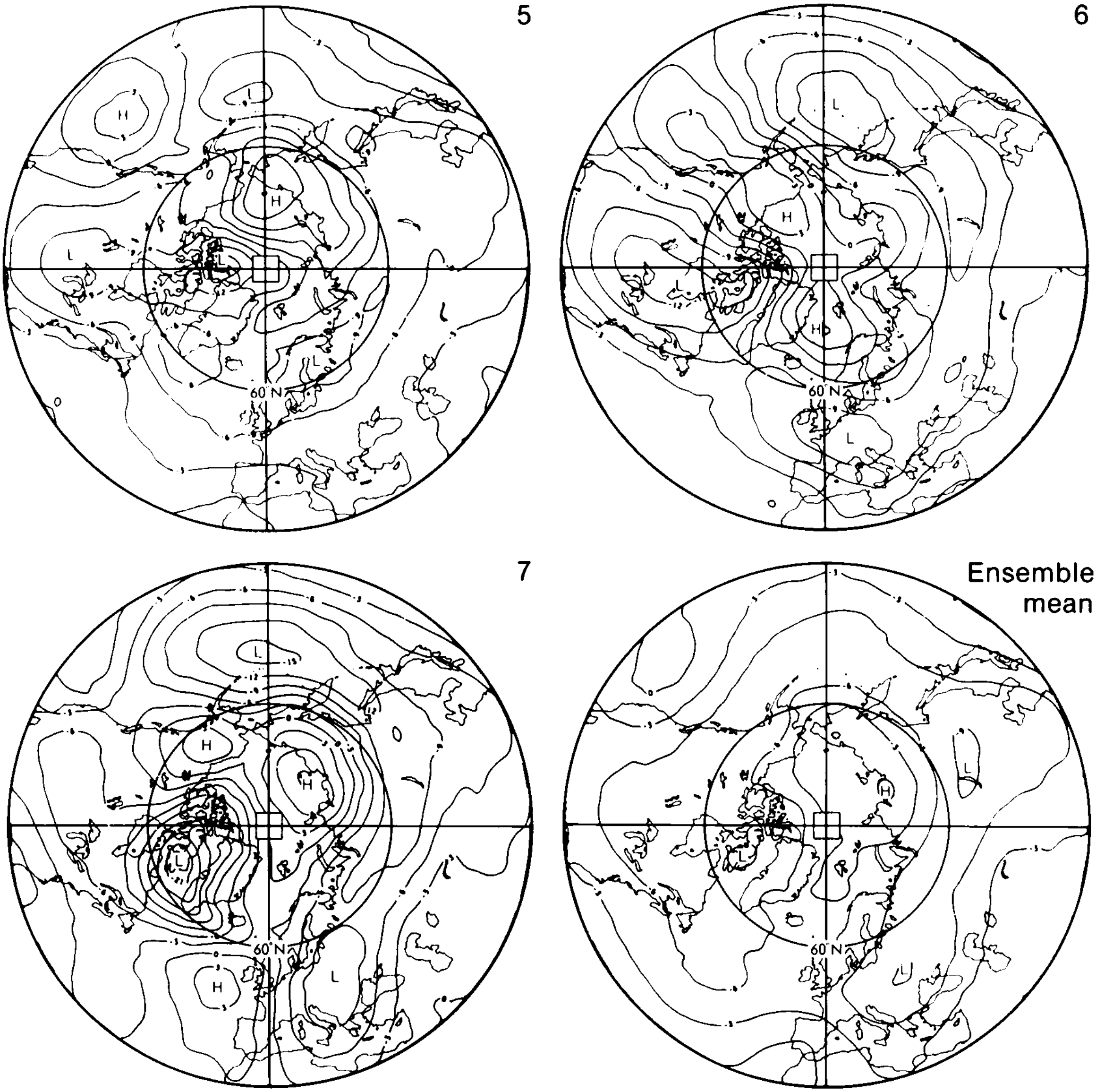

Figure 6 continued. Individual (from integrations 5–7) and ensemble-mean forecast 500 mb geopotential height anomaly (dam) for 3–17 October 1985.

up in terms of objective skill. Nevertheless, it is certainly encouraging that the actual pattern seems to bear a notable subjective resemblance to that which defines one of the two subsets predicted by the ensemble forecast.

The question arises as to whether the clustering can be traced back to earlier stages of the forecast. In the preceding period, 23 September–2 October, a similar pattern was again evident in integrations 5–7, it being displaced somewhat to the west in the sub-ensemble mean (not shown). Integrations 1–4 again show no sign of this PNA-like pattern.

Table II. *As Table I but with forecast divided into successive pentad means*

Integration	Forecast period 16–20 Sept. (day 1–5)	21–25 Sept. (day 6–10)	26–30 Sept. (day 11–15)	1–5 Oct. (day 16–20)	6–10 Oct. (day 21–25)	11–15 Oct. (day 26–30)	16–20 Oct. (day 31–35)
1 (00 GMT 12 Sept.)	0.31	0.03	0.21	0.10	−0.03	−0.01	−0.05
2 (12 GMT 12 Sept.)	0.47	0.02	0.01	0.03	−0.08	0.11	−0.17
3 (00 GMT 13 Sept.)	0.44	0.07	0.24	0.26	−0.21	0.05	0.05
4 (12 GMT 13 Sept.)	0.73	0.22	0.22	0.08	−0.19	0.03	−0.11
5 (00 GMT 14 Sept.)	0.75	0.40	0.34	0.27	0.23	0.04	−0.25
6 (12 GMT 14 Sept.)	0.82	0.46	0.28	0.06	0.23	−0.07	−0.10
7 (00 GMT 15 Sept.)	0.82	0.30	0.34	0.07	−0.02	0.10	0.08
1–7 average individual forecast	0.62	0.21	0.23	0.12	−0.01	0.04	−0.08
1–7 ensemble-mean forecast	0.73	0.30	0.32	0.16	−0.01	0.05	−0.10

Fig. 8 illustrates the development of differences between the sub-ensemble means 5–7 and 1–4 during the first 10 days of the forecast. Even at day 1 there is a low centre in the Pacific with a downstream high off the coast of North America and a further low to the north-east. Although the day 1 difference shows other features just as pronounced as these, the important point is that the aforementioned pattern remains more or less stationary throughout the first 10 days, whereas other areas of difference shift their position and disappear after a few days. This suggests that, while these latter differences are due to transient systems, the pattern in the Pacific/North American area seems to represent a genuine difference in the quasi-stationary large-scale circulation, implying that the migration of integrations 5–7 into a separate cluster can be traced right back to the initial conditions.

To demonstrate such behaviour objectively would require a method of cluster analysis, possibly based on a criterion of maximizing the phase correlation between cluster members rather than the more conventional one of minimizing the r.m.s. difference. It is intended to develop such a method to aid the investigation of this intriguing phenomenon in future long-range ensemble forecast experiments.

5. Conclusions

Having demonstrated the potential of the ensemble forecast technique to increase long-range predictability using a perfect-model approach, attempts at producing real-time operational monthly forecasts using a global 11-level climate model have commenced in the Synoptic Climatology Branch. The first such experiment was carried out for the operational long-range forecasting conference on 17 September 1985, for which an ensemble of seven integrations, initiated from consecutive analyses at 12-hour intervals between 00 GMT on 12 September 1985 and 00 GMT on 15 September 1985, was produced. The results show that all the individual model forecasts retain a small degree of skill out to 20 days, and the ensemble-mean forecast improves somewhat on the average individual forecast skill over this period.

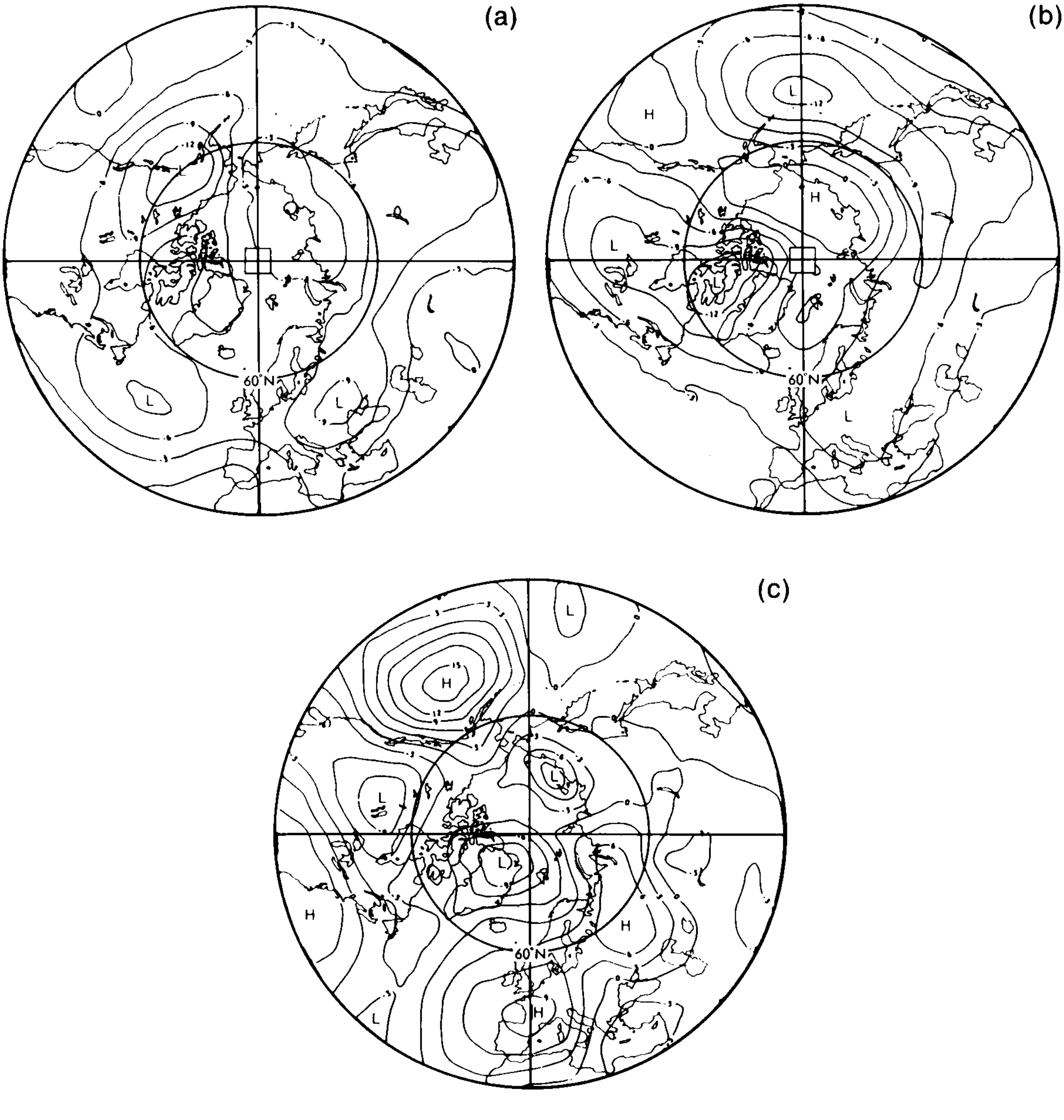

Figure 7. 500 mb geopotential height anomaly (dam) for 3–17 October 1985: (a) sub-ensemble-mean forecast formed from integrations 1–4, (b) sub-ensemble-mean forecast formed from integrations 5–7 and (c) observed.

An interesting feature concerns the apparent splitting of the integrations into two distinct clusters with respect to the forecast circulation patterns for the Pacific/North American region. This is most noticeable during the later part of the forecast, at which point the actual atmospheric pattern in the area bears some resemblance to one of the cluster patterns, but the development of the clustering may be traced back to the initial stages of the forecast. If typical of the manner in which ensemble forecast

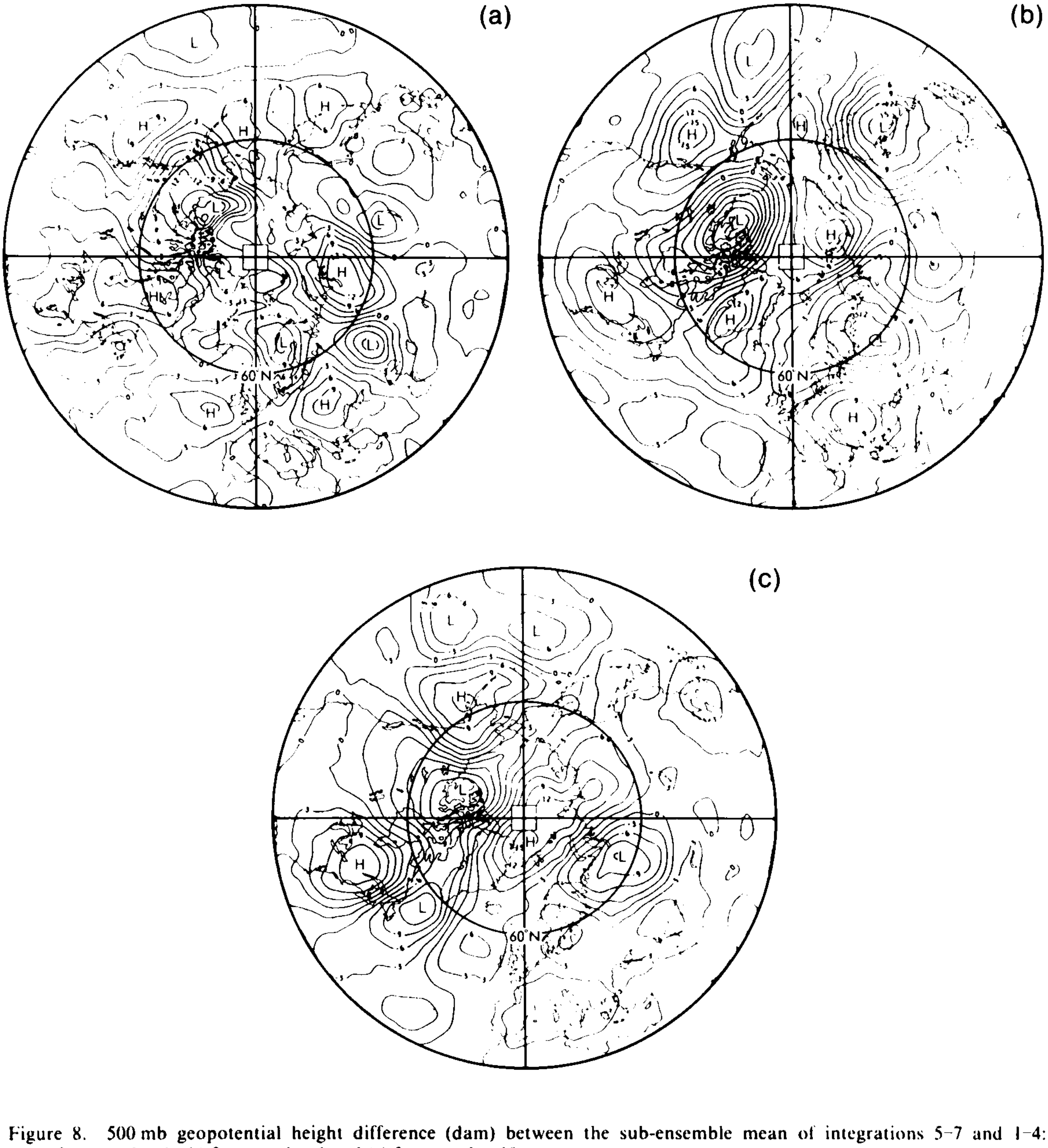

Figure 8. 500 mb geopotential height difference (dam) between the sub-ensemble mean of integrations 5–7 and 1–4: (a) forecast day 1, (b) forecast day 6 and (c) forecast day 10.

distributions evolve, such behaviour would have important implications for the interpretation and presentation of long-range ensemble forecasts in terms of probabilistic estimates of the occurrence of certain configurations of the quasi-stationary waves in the atmosphere. It is anticipated that these real-time ensembles of forecasts will be run at least once a quarter and will have a major impact on the operational requirements of the Synoptic Climatology Branch.

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551.515.4(46):551.509.326

The Spanish plume — testing the forecaster's nerve

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Summary

An example is described of a spectacular development of thunderstorms arising out of dynamical interaction between a typical mid-latitude upper cold trough and a reservoir of hot air over Iberia. Prediction of the development by the Meteorological Office 15-level numerical fine-mesh model is also described.

1. Introduction

Experienced forecasters will all agree that the most difficult weather situations to predict with any accuracy are those in which development is a feature of the evolution rather than translation of existing weather. One weather situation which readily falls into this category is the development over Iberia and western France of widespread thunderstorms which spread to the United Kingdom. This weather pattern, which usually occurs at least once or twice during the summer months between May and September, is known as the 'Spanish plume'. A good example of this phenomenon occurred during 19 and 20 May 1986 and, despite the fact that the evolution was extremely well forecast by the Meteorological Office operational numerical weather prediction model, the writer is aware that some forecasters were very sceptical of the predicted evolution at the time. For this reason alone it seems very desirable that the Spanish plume should be documented in the literature as a lesson for the unwary and for inexperienced forecasters of the future.

2. Mechanics of the development

The main conditions for development of a Spanish plume include an upper trough slowly advancing towards Biscay and Iberia, and a zone of strong temperature gradient in the lower troposphere over Iberia. The baroclinic zone on the forward side of the upper trough is usually identified with a moderately active cold front whilst the baroclinic zone over Iberia is initially dynamically inactive. As the upper trough advances towards Iberia a number of dynamical forces come into play (see Fig. 1). These can be deduced subjectively using the quasi-geostrophic omega equation to link vertical motion to the thermal and vorticity advection (see, for example, Morris 1972). The pre-existing upper flow over Iberia takes up the cyclonic curvature of the encroaching flow and causes limited dynamical ascent and falling surface pressure over Iberia. This in turn causes thermal advection to develop within the baroclinic zone flanking the hot cell; in particular warm air advection causes enhancement of the dynamical ascent with further falls in surface pressure. The adjusting low-level wind creates cold air advection in the western coastal zone so that a well-marked discontinuity in thermal advection is created over Iberia with ascending air ahead of the sharpening thermal ridge and descending air to the rear; the Spanish plume is born.

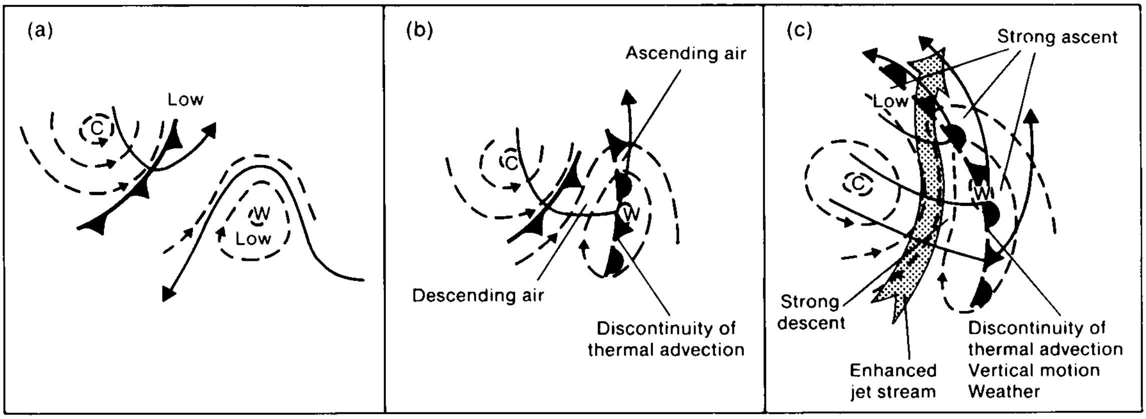

Figure 1. The development of the Spanish plume. Solid lines indicate surface flow, dashed lines thermal flow. For description of development see text.

From this point on the plume is capable of a quasi-independent dynamical evolution. However, the organization of the thermal wind on the forward side of the upper trough causes an intensification of the thermal gradient and an increase in wind strength aloft. This in turn intensifies the vorticity advection along with a corresponding increase in the magnitude of vertical motion on the forward side of the trough. (Often there is an enhanced cold exit region to the south-south-west jet with associated cyclogenesis and widespread precipitation.) The plume effectively becomes the main frontal zone and the old cold front associated with the upper trough tends to lose its identity under the influence of the adjusting dynamical forces.

3. An example: 19 and 20 May 1986

Using initialized fields from the Meteorological Office numerical weather prediction 15-level fine-mesh model, Figs 2(a), (b) and (c) depict the synoptic situation at 00 GMT on 19 May 1986. Fig. 2(a) is a composite of the mean-sea-level pressure (mslp) and 850 mb wet-bulb potential temperature (θ_w). Note the zone of strong θ_w gradient over north France, Biscay and Iberia and also the weak gradient

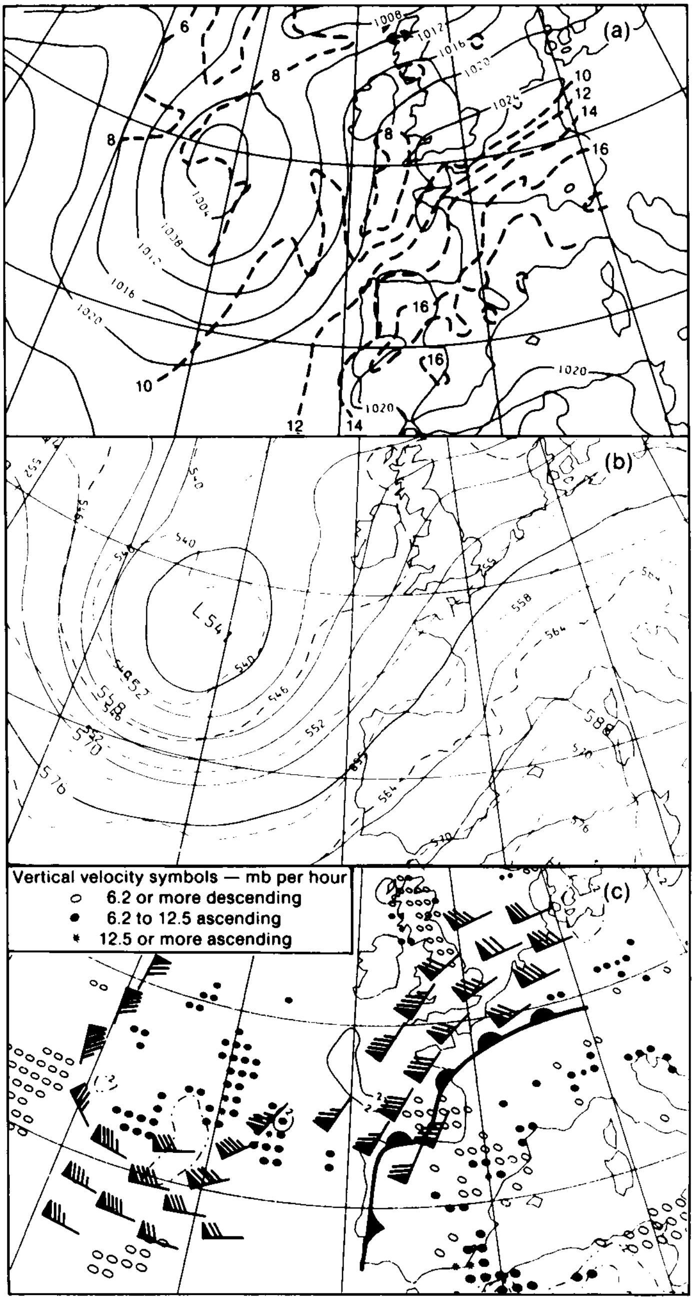

Figure 2. The synoptic situation at 00 GMT on 19 May 1986: (a) mean-sea-level pressure (mb) (solid lines) and 850 mb wet-bulb potential temperature (°C) (dashed lines), (b) 500 mb geopotential height (dam) (solid lines) and 500–1000 mb thickness (dam) (dashed lines) and (c) composit showing maximum winds, warm edge of 850 mb wet-bulb potential temperature, vertical velocity (see key) and thermal advection (°C per 6 hours) (solid lines, warming, dashed lines, cooling). In (c) vertical velocity and thermal advection are each meaned over the 850–500 mb layer.

associated with an Atlantic cold front. Fig. 2(b) is a composite of the 500 mb geopotential height and 1000–500 mb total thickness — note the broad zone of thermal gradient from the vortex to Iberia and France. A composite consisting of the maximum wind, thermal advection and vertical velocity (the latter two each meaned over the 850–500 mb layer) is shown in Fig. 2(c). The warm edge of the 850 mb θ_w gradient (denoted by frontal symbols) is also included for completeness. At this stage the main dynamical ascent is closely associated with the strongest flow flanking the upper vortex. The composite is a diagnostic analysis of the type prepared daily as an experiment in the Central Forecasting Office (CFO) at Bracknell with the objective of displaying the most essential dynamical functions on one chart to explain cause and effect in the distribution of weather. Developments in the troposphere over western Europe during the subsequent 36 hours will be largely illustrated by composites of the format depicted in this figure.

Fig. 3(a) illustrates the dynamical situation at 12 GMT on 19 May. The upper trough has advanced closer to Iberia whilst downstream the jet axis has been transferred north across the United Kingdom and has weakened somewhat. Ascending air is now more widespread over Iberia, and both warm and cold air advection is in evidence in this region. Note that the warm air advection over south-west Britain is not associated with any significant ascent (i.e. ≥6.2 mb per hour) due probably to lack of support from the vorticity advection aloft. Strong ascent is evident west of Ireland in the cold exit region of the south-south-west jet. Fig. 3(b) depicts the distribution of cloud at 1200 GMT derived from Meteosat; significant weather reported at the surface is also shown. At this time there was a band of high cloud across Iberia but no evidence of cumulonimbus activity. It was this picture which gave rise to the scepticism. Six hours later Meteosat revealed quite a different picture (Fig. 3(c)) while considerable convective cloud and thunderstorms were reported in northern Spain.

Fig. 4(a) depicts the dynamical situation at 00 GMT on 20 May. Ascent is now indicated widely over south-west Britain and a further broad area of ascent appears centred just to the north-west of Iberia. There are warm air advection fields in both regions and positive vorticity advection is probably contributing to ascent just to the rear of the upper ridge axis (north) and ahead of the upper trough axis (south). The rapid northward advance of rain and thunderstorms to north-west France is revealed in Fig. 4(b) although there is a curious phase difference between this and the model analysis of ascending air to the north. This aspect will be discussed further in section 4. As Fig. 4(c) shows, the thundery rain has spread to most of England by 06 GMT.

By 12 GMT on 20 May cold air advection is broadly established across Biscay and extreme western France with warm advection covering eastern Britain and the North Sea (Fig. 5(a)). Ascending air extends broadly from north-east Spain across north France to Scotland. Note the increase in strength of the maximum wind on the forward side of the advancing upper trough. Fig. 5(b) illustrates the distribution of cloud and significant weather for the same time. By this stage the old cold front is dynamically inactive, thermally weak and without evidence of any significant weather.

4. The numerical model forecast

The characteristics of the Meteorological Office 15-level numerical weather prediction model were described in special issues of the *Meteorological Magazine* recently (Meteorological Office 1985a, b). The fine-mesh T+12-, T+24- and T+36-hour forecasts of mslp and instantaneous local rainfall rates, based upon initial conditions at 00 GMT on 19 May, are shown in Figs 6(a), (b) and (c). The main features of the evolution were very well predicted with the only significant error being the timing of the movement of rain across northern England and southern Scotland during the first 24 hours. Figs 7(a), (b) and (c) depict the corresponding forecasts of vertical motion and thermal advection. It is interesting to see how the T+24- and T+36-hour fields look slightly more consistent with the observed significant

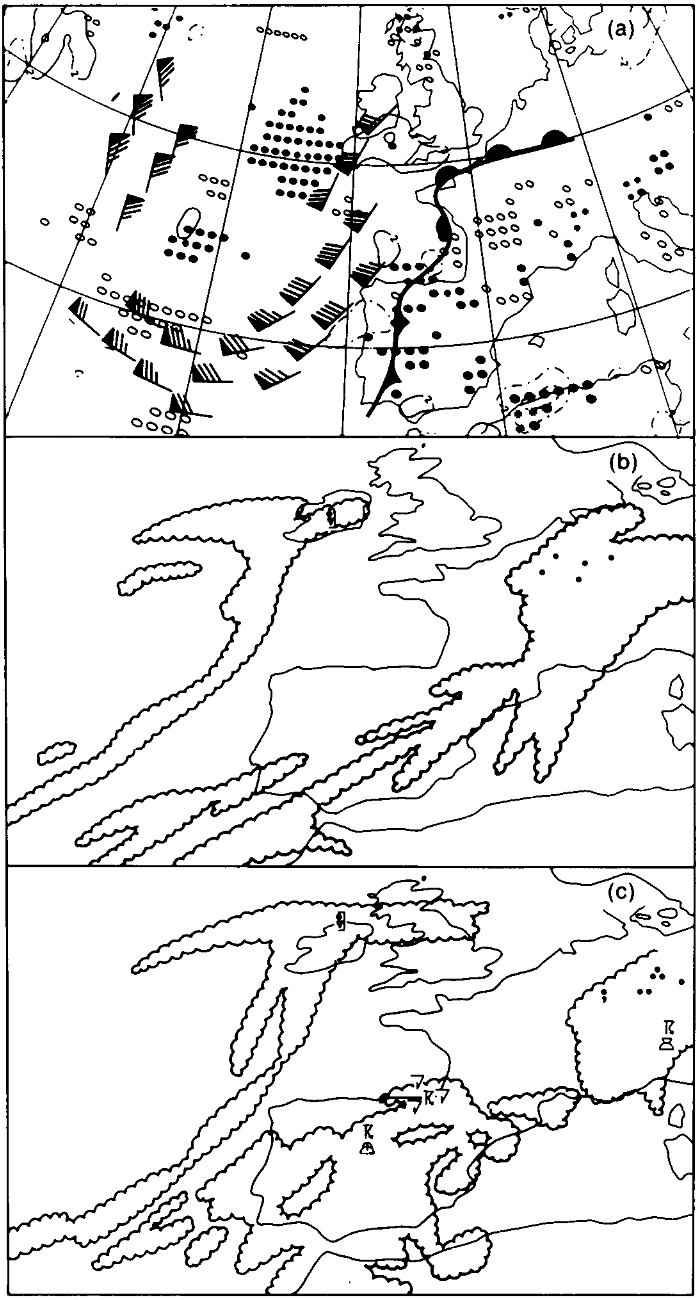

Figure 3. (a) Same as Fig. 2(c) but for 12 GMT on 19 May 1986, (b) distribution of cloud at 12 GMT on 19 May 1986 derived from Meteosat, and significant weather reported at the surface for the same time and (c) as (b) but for 18 GMT.

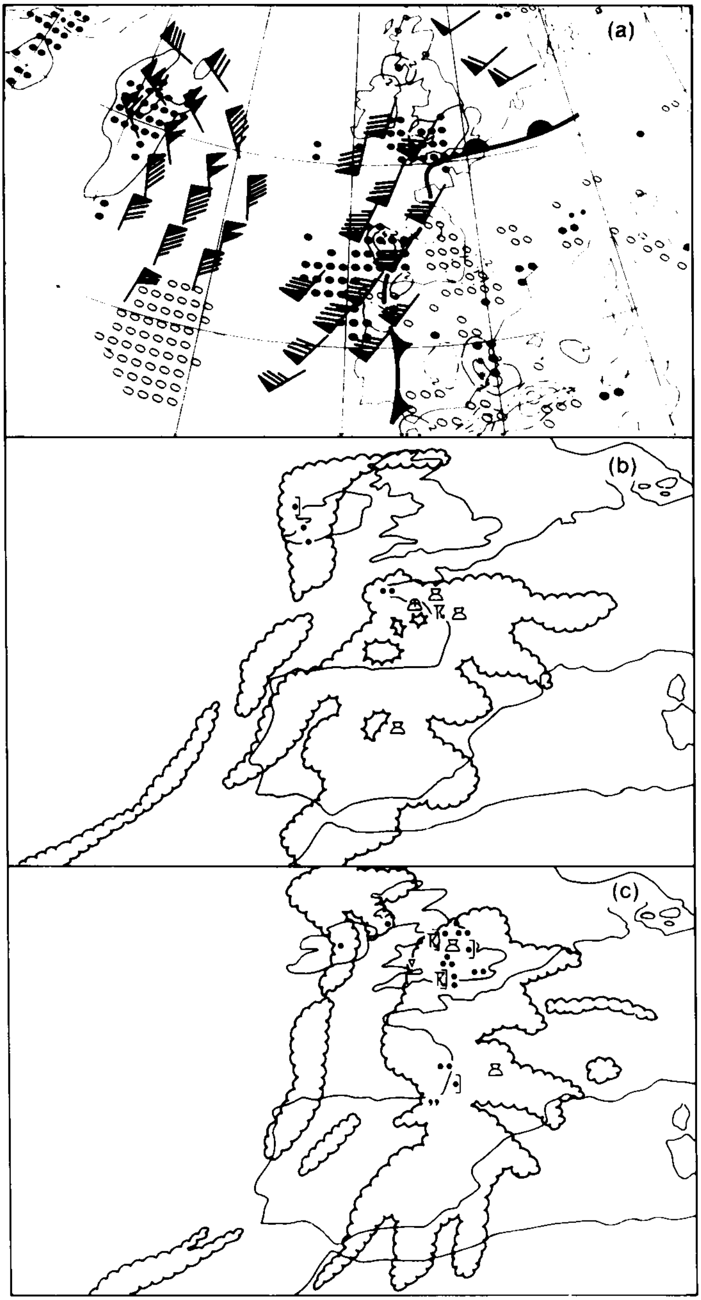

Figure 4. Same as Fig. 3 but for 00 GMT on 20 May 1986 ((a) and (b)) and 06 GMT on 20 May 1986 (c).

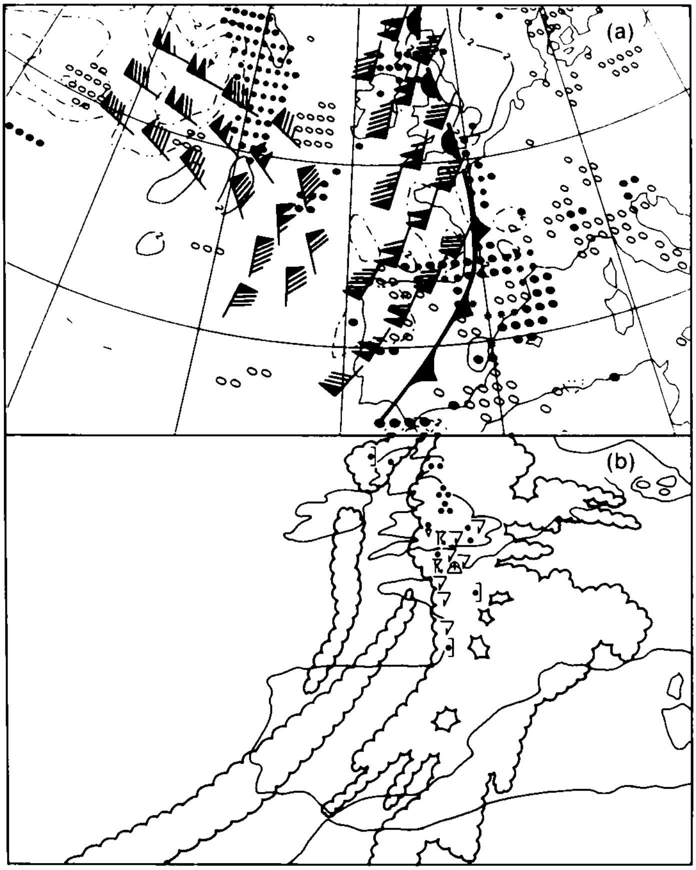

Figure 5. (a) Same as Fig. 3(a) but for 12 GMT on 20 May 1986 and (b) same as Fig. 3(b) but for 12 GMT on 20 May 1986.

weather than the corresponding analysis fields (Figs 4(a) and 5(a)). There is a possible explanation for this; the assimilation of fresh data is quasi-continuous in the model analysis scheme and so the solutions to the equations are constrained by the need to fit real observations at the main analysis times. This can introduce spurious solutions locally for variables that are not directly observed. The forecasts are not so constrained, however, and smoother, dynamically more consistent solutions should be obtained.

One of the most useful new products derived from the fine-mesh operational suite is the distribution of convective cloud tops (see Davies 1986). Fig. 8 depicts the T+36-hour forecast verifying at 12 GMT on 20 May. Most of the cumulonimbus cloud tops in the thundery area were forecast to be above a flight level of 30 000 ft (FL 300) with several places above FL 350 and one point in south-east England above FL 400. This output is used operationally by the International Civil Aviation Organization Regional Area Forecast Centre located within CFO.

5. Concluding remarks

One of the most significant aspects of this case is the way in which the evolution is amenable to human perception using quasi-subjective reasoning. Even without the benefit of modern numerical models the discerning forecaster could expect some development of a weather system to occur between Iberia and southern England. Of course there would be doubts — would the ascent of air be enough, would the air

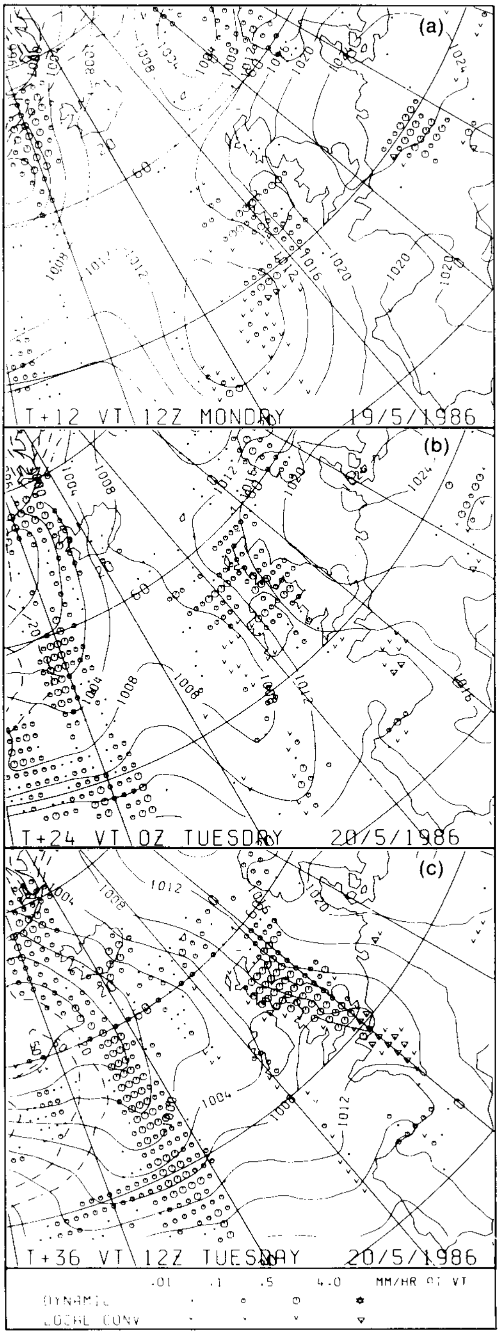

Figure 6. Fine-mesh 15-level numerical model forecast of mean-sea-level pressure (mb) (solid lines) and rainfall (see key) for (a) T+12, (b) T+24 and (c) T+36 hours, all based upon data time 00 GMT, 19 May 1986.

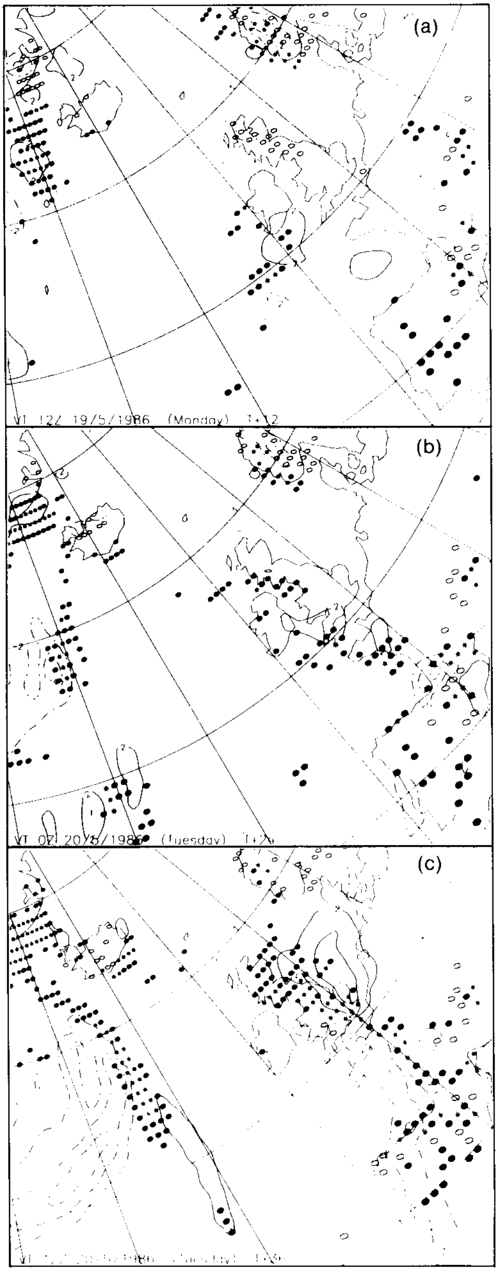

Figure 7. Fine-mesh 15-level numerical model forecast of vertical velocity and thermal advection (see Fig. 2 for key) for (a) T+12, (b) T+24 and (c) T+36 hours, all based upon data time 00 GMT, 19 May 1986.

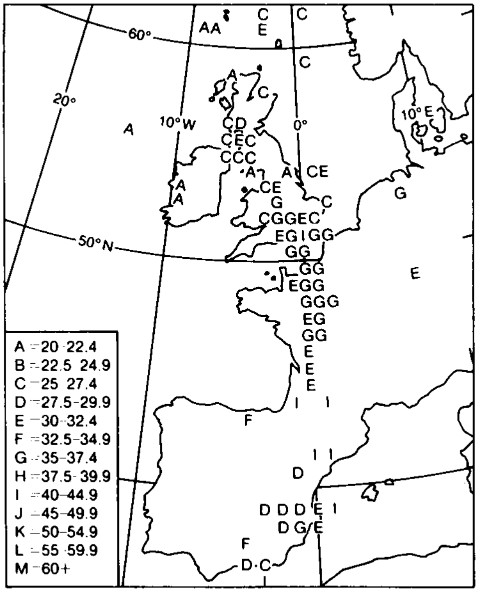

Figure 8. Fine-mesh 15-level numerical model T+36-hour forecast of convective cloud tops above 20 000 ft (key gives heights in thousands of feet) for 12 GMT on 20 May 1986.

be sufficiently moist and would the air be convectively unstable? It is these aspects that test the forecaster's nerve, given the innocuous weather conditions prevailing at the time he has to make up his mind. The ability of the 15-level numerical model to predict the evolution so successfully should increase the forecaster's confidence, but model forecasts are not always so accurate (for a variety of reasons, e.g. poor analysis in some crucial areas) — why otherwise did some forecasters doubt the predicted evolution? In such cases the successful forecaster, who doesn't lose his nerve, is the one who uses his discerning and perceptive logic to understand how the numerical model has produced its solution.

Browning and Hill (1984) describe a mesoscale convective system which, if not exactly the same, looks very similar in development to the example discussed here. It would be interesting to see how the current numerical model, with the range and versatility of output described here, would predict the evolution of that system.

References

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Morris, R.M.	1972	The trowal, an important feature of frontal analysis. *Meteorol Mag*, **101**, 150–153.

551.526.6:551.465.7

Ocean and atmosphere interact!

By S.J. Foreman

(Meteorological Office, Bracknell)

Summary

A brief description is given of the coupled ocean–atmosphere model developed by the Dynamical Climatology Branch of the Meteorological Office. Some characteristics of the first experiment performed with this model are discussed.

1. Introduction

The Dynamical Climatology Branch of the Meteorological Office uses numerical models of the atmosphere to simulate the climate. One of the strongest constraints on the atmosphere is its interaction with the oceans through the sea surface temperature (SST). To date, SSTs have been specified from observations for investigations of present-day climate. However, for studies of climate change, it has been necessary either to impose arbitrary perturbations of the SSTs, or to use a simple heat balance model of the upper layers of the ocean. Clearly such procedures are unsatisfactory if, as often happens, it is suspected that the climate to be modelled differs markedly from that of the present day. In these circumstances a better approach would be the simulation of SSTs using an explicit calculation of the ocean circulation during the integration of the atmosphere model. This is now possible using a general circulation model for the oceans which has been developed in recent years.

2. The models

(a) *Atmosphere*

The 11-layer model, as its name implies, calculates values of atmospheric variables (temperature, humidity, winds) for 11 layers in the vertical (using pressure divided by surface pressure as the vertical coordinate) on a uniform 2.5 × 3.75° latitude–longitude horizontal grid; it is described in more detail by Slingo (1985). The model includes a comprehensive 'physics' package similar to that of the operational fine-mesh model. Synoptic features are resolved by the 11-layer model, which produces realistic simulations of the present-day climate. Adjustments of the atmospheric circulation to changes in the SSTs occur over time-scales of the order of months.

(b) *Ocean*

The ocean model is based on that of Bryan (1969) and produced by Cox of the Geophysical Fluid Dynamics Laboratory, Princeton (Cox, personal communication), though it has been extensively modified to allow it to run alongside the atmosphere model. In the form used for the experiment described below, the model has 12 layers in the vertical and uses the same horizontal grid as the atmosphere model. It calculates values for the current velocity, temperature and salinity (which strongly influences the density) of the water by solving the equations of motion, and the equations describing the conservation of heat and salt. These are solved using numerical techniques similar to those used in atmosphere models. Eddies in the ocean are more than an order of magnitude smaller than anticyclones and depressions, their counterparts in the atmosphere. As the model is unable to resolve these eddies it is necessary to include strong lateral diffusion. Time-scales in the ocean are much longer than in the atmosphere, so that the upper layers of the ocean take tens of years to reach equilibrium with changes in the surface forcing, while in the deep oceans this process may take millennnia. Ocean simulations must therefore be run for much longer periods than atmospheric ones if equilibrium is to be attained.

(c) *Coupling of the models*

The two models are coupled through their interactions at the sea surface. Wind stress and fluxes of sensible and latent heat are calculated by the atmosphere model and passed to the ocean model for use at its upper boundary, as are the radiative fluxes and the amounts of precipitation and evaporation. These quantities are accumulated during 5 days of integration of the atmosphere model, and then passed to the ocean model which uses them as boundary conditions for the same 5 days. Calculated ocean model temperatures for the top model layer are then passed back to the atmosphere model, and are used as the SSTs for the following 5 days. This cycle continues throughout the simulation, and is illustrated in Fig. 1.

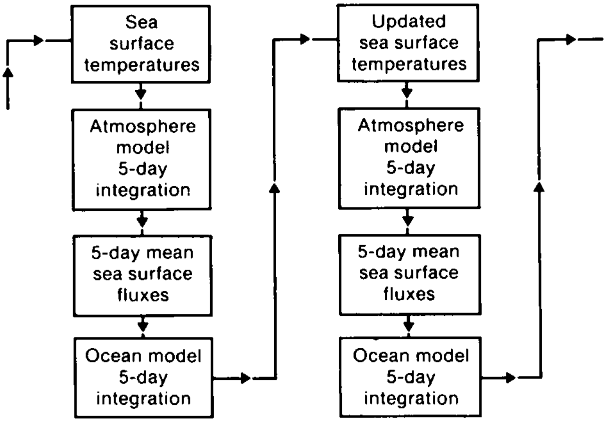


Figure 1. Schematic diagram of the integration cycle for the coupled model.

This process would be too expensive to run to equilibrium. Instead, a technique known as 'asynchronous coupling' is used. In this the ocean and atmosphere models are run coupled as above for a number of years ('synchronous coupling') during which the fluxes at the ocean surface calculated by the atmosphere model are stored. The ocean model is then run using this forcing for several more years, following which the two models are again run synchronously. Since this approach accelerates the system's approach to equilibrium and the ocean model requires fewer resources than the atmosphere model this process makes it possible to run to a steady climate.

A further complication which arises is the treatment of sea ice. A comprehensive sea-ice model is being developed, but was not ready in time to be included in the first experiment using the coupled ocean–atmosphere model. Therefore, climatological sea-ice extents have been used instead.

3. A preliminary experiment

A preliminary experiment, to run the coupled model synchronously for 18 months, has been initiated. This was started from atmospheric data for the last day of April derived from a previous 'atmosphere-only' simulation of the present-day climate which used climatological SSTs, and the quasi-equilibrium state of an 'ocean-only' experiment which used annual mean climatological forcing at the sea surface. The two were merged at the start of the integration; the initial temperatures for the top ocean layer were taken from an appropriate climatology to remove gross differences between the ocean annual mean simulation and the seasonal climatology.

As the coupled system would take about 10 years to reach a near-equilibrium state for the atmosphere and upper layers of the ocean, and far longer for the deep ocean, the present experiment can only be expected to indicate trends in the evolution of the coupled system.

Interaction between the two models takes place at the sea surface. Inevitably, fluxes calculated by the atmosphere model will differ from climatological fluxes, resulting in modifications to the ocean circulation when compared with climatology; likewise the SSTs calculated by the ocean model will not be the same as those derived from climatology, so modifying the atmospheric flow. As a result it should be expected that the simulations of ocean and atmosphere would differ from those obtained using climatological fluxes and SSTs. The simulated SSTs are subject to both the dynamics of the ocean model and to the atmospheric forcing, and therefore provide a suitable indication of the behaviour of the coupled system.

Simulated and observed distributions of SST for the winter months (December, January, February), after 10 months' simulation, are shown in Fig. 2. The coupled model maintains the general pattern of

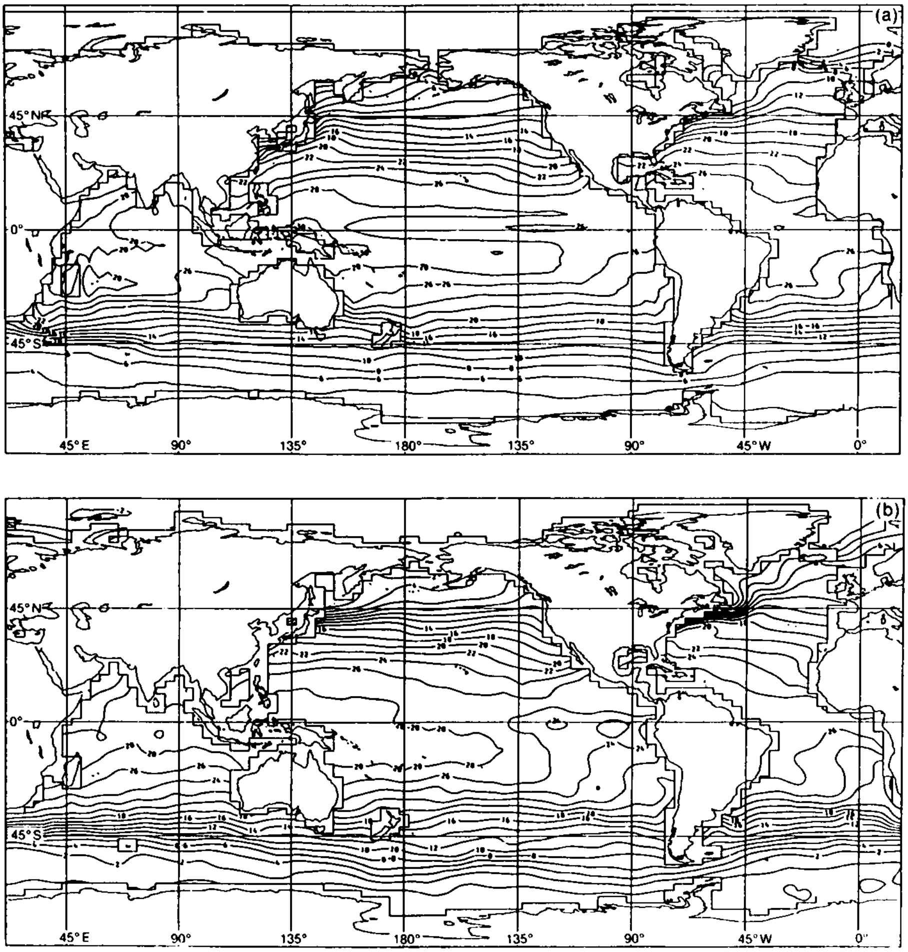


Figure 2. Sea surface temperatures (°C): (a) the coupled model experiment and (b) climatology (from Levitus 1982) for the winter months (December, January, February).

SST, including the minimum along the equator, and the contrast between the warm water in the west of the tropical oceans and the cooler water in the east. Certain errors are apparent, however. For example, the water along the equator is too cold in the Atlantic, Indian and western Pacific oceans; these errors are being investigated further using a high-resolution tropical Pacific model. Also areas of ocean upwelling off the western coasts of continents tend to be too warm, notably near Peru and western north Africa, while western boundary currents are too cool due to the coarse resolution of the ocean model. In the southern hemisphere the mid-latitude SSTs tend to be too cool as a result of the thick top layer, which cannot represent the shallow mixed layer (a feature also found in the northern hemisphere during its summer) and at higher latitudes the SSTs are too warm as a result of deficiencies of the initial conditions used for the ocean. Gradients are too weak as a result of the strong lateral diffusion used in the ocean model.

4. Future developments

The present experiment has proved that the system for running the coupled model works, and has indicated areas in which improvements in model formulation are necessary. Further experiments will be performed during the next year which will use a version of the ocean model with higher resolution in the vertical to enable the mixed layer to be represented and start from ocean conditions derived from seasonally varying forcing. The interactive sea-ice model should also be available. In addition to the simulation of the present-day climate necessary to validate the results from the models, perturbation experiments to investigate the climatic aspects of increased atmospheric carbon dioxide are planned.

5. References

Bryan, K.	1969	A numerical method for the study of the circulation of the world ocean. *J Comput Phys*, **4**, 347–376.
Levitus, S.	1982	Climatological atlas of the world ocean. NOAA Prof. Paper No. 13.
Slingo, A.	1985	Handbook of the Meteorological Office 11-layer atmospheric general circulation model. Volume 1: Model description. (Unpublished, copy available in the National Meteorological Library, Bracknell.)

551.593.653(4)

Noctilucent clouds over western Europe during 1985

By D.M. Gavine

(Leith Nautical College, Edinburgh)

Table I summarizes noctilucent cloud (NLC) reported to the Aurora Section of the British Astronomical Association (BAA) during 1985, from Finland (F), Denmark (D), Great Britain (G), one experienced observer, Mr van Loo, at Itegem, Belgium (B), and Mr Kaye at the meteorological station in Detmold, Federal Republic of Germany. Also received was a list of positive sightings from Alberta, Canada, by Mr Zalcik, Mr Brown and Mr Kushniryk.

Times (UT) in the second column of the table are of reported sightings, not necessarily the duration of a display. Maximum elevations of the upper border are given, with limiting azimuths where possible. Coordinates of the observing stations are given to the nearest half-degree. No routine hourly reports of sky cover are now received from meteorological stations, so estimates of the 'negative' nights, (i.e. clear or slight cloud with no visible NLC) are based on prolonged watches by experienced amateur observers.

Contributions to the year's survey were received from 17 British amateur observers and 6 meteorological stations. There are now four regular observers in Denmark, co-ordinated by Mr J.Ø. Olesen; their colour photographs, especially of panoramas of major displays, are of a very high standard and have been exhibited at BAA meetings. The Finnish network, whose reports are compiled by Mr V. Mäkelä, now has 24 observers spread widely over the country, their data being handled by microcomputer. The Section is very much indebted to Finland's highly efficient and enthusiastic team, which now has plans to encourage NLC observing in neighbouring countries.

Of a total of 42 definite NLCs reported over Europe, 26 were seen in Finland, 14 in Britain, 10 in Denmark, 2 in Belgium, and in addition 10 displays and one 'suspect' were observed in Alberta. In one of the worst summers this century, Britain suffered very badly from tropospheric cloud, and the fact that NLC was visible on so many of the clear nights may indicate a high incidence of the phenomenon in 1985. No parallactic photography was possible because of cloud.

The statistics reveal a curious anomaly between the occurrence of NLC in the United Kingdom/Denmark and in Finland. From mid-May up to 4/5 July only two displays were seen in Finland despite a relatively quiet geomagnetic field, and in this period there were 32 negative nights; yet in the same period Britain and Denmark experienced 12 displays, 4 of them major. Finnish observers then continued to see NLC frequently until 16/17 August, with two suspect appearances in the last week of that month.

The Aurora Section offers thanks to all observers, amateur and professional, for helping to keep the survey going in the interests of continuity of data, to the staff of the Department of Meteorology, University of Edinburgh for forwarding reports, and to Dr Michael Gadsden (University of Aberdeen), Mr Ron Livesey (Director, BAA Aurora Section) and Mr Neil Bone (Aurora Director, Junior Astronomical Society) for helpful collaboration.

Immediate NLC news is announced in *The Astronomer* monthly magazine. Instructions for observing NLC, and report forms, may be obtained from the Section Assistant Director, Dr D.M. Gavine, 29 Coillesdene Crescent, Edinburgh, EH15 2JJ.

Table I. *Displays of noctilucent clouds over western Europe during 1985*

Date night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev. (degrees)	Limiting azimuths (degrees)
5/6 May		No NLC (F)				
6/7	2340–0105	Faint veil and bands at Kuopio.	63° N 27.5° E	2340	20	090–150
				2350	22	100–170
7/8 to 8/9		No NLC (F)				
9/10	2330–0105	Medium bright veil and bands at Kuopio, reddish-white, suspect NE movement.	63° N 27.5° E	2330	No NLC	
				2350	20	125–240
				0015	24	125–250
				0055	54	105–210
				0105	NLC suspect	
12/13 to 14/15		No NLC (F)				
15/16	2300–0005	Faint bands and billows at Kuopio, no NLC at Helsinki.	63° N 27.5° E	2300	No NLC	
				2340	16	010–035
				2350	13	010–035
				0005	NLC suspect	

Date night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev.	Limiting azimuths
					degrees	
16/17 to 17/18		No NLC (F)				
20/21		No NLC (F)				
26/27 to 27/28		No NLC (F)				
28/29 to 30/31		No NLC (B, F)				
31 May to 3/4 June		No NLC (B, F, G)				
4/5 to 6/7		No NLC (B, F)				
8/9		No NLC (B, D)				
9/10		No NLC (D, F)				
10/11		NLC in Alberta. No NLC (F).				
11/12		No NLC (F)				
12/13		No NLC (G)				
13/14	2214–2307	Faint bands and NLC patches at Helsinki, very faint bands visible with binoculars at Rønne.	60° N 24.5° E	2214	14	340–000
				2219	35	340–005
				2230	18	000–005
				2249	NLC suspect	
			55° N 14.5° E	2110	12	000–022
				2208	15	000–045
				2315	NLC suspect	
14/15	2217–0330	Bands, billows and whirls observed throughout Britain, Belgium, Denmark. Bands and billows in Alberta.	56° N 03° W	2340	8?	350
				2345	10?	340–350
				0000	15	015–040
				0015	20	Cloud–060
				0030	20	Cloud–090
				0045	NLC	Cloud
			56° N 04.5° W	2256–0035	15+	Cloud
			56° N 10° E	2233	13	288–008
				2330–2352	22	300–350
			55° N 01.5° W (Morpeth)	2217	NLC trace	
				2235	30	330–052
				2245	24	336–046
				2300	20	345–050
			55° N 01.5° W (Newcastle)	0140–0330	80?	290–335
			55° N 14.5° E	2240–2250	12	315–045
			54.5° N 06° W	0005	5	060–078
				0025	5	058–076
			54° N 02.5° W	0145	10	000
			52° N 02° W	2230	8	340–030
			51° N 04.5° E	0135	9	346–072
				0155	9	347–072
				0215	8	348–070
15/16	2345–0245	Extensive display of pronounced billows, medium brightness, visible only in N Britain after cloud clearance.	57.5° N 03.5° W	2345	8	340–040
				0015	10	340–080
				0100	25	330–100
			56.5° N 03° W	0040	10	
			56° N 03° W	0130	45	010–100
				0140	80	000–100
				0150	100	000–100
			56° N 04° W	0100	12	350–050
				0110	12	Cloud–050
				0122	40	
				0130	60	Cloud
			55.5° N 04.5° W	0100–0130	19	355–090
			55° N 01.5° W	0130	36	336–086
				0145	50	332–120

Date night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev	Limiting azimuths
					degrees	
15/16 (contd)				0200	90+	
				0215	90+	158
				0245	Dawn	
16/17	2140–0100	Faint bands visible in trop. clouds, Britain, Denmark and Alberta. No NLC in N Finland.	56° N 03° W	2320	5?	315
				2345	4	000–030
				0005	4	340–030
				0030	5	000–035
			55.5° N 12.5° E	2140	15?	000–045
			55° N 01.5° W	0000	5	020–031
				0015	10	005–037
				0030	10	004–045
				0045	11	000–045
				0100	Low	Cloud
			52° N 00.5° W	0049	Low	045
17/18		Bands and billows at Edmonton (Alberta). No NLC (F).				
18/19	2333–0100	Very faint veil, possible band and billows, Scotland and N England. No NLC (F).	56° N 04° W	2333	10	
			56° N 03° W	0015	10	320–030
				0100	NLC suspect	
			53.5° N 03° W	0000	5	330–015
19/20	2220–0100	Billows and whirls at Kinloss, faint bands and patches in trop. cloud, S Scotland and N England.	57.5° N 03.5° W	0015	17	020–065
			57° N 04° W	0040–0100	20	015–045
			56° N 03° W	2245	30	330–000
				2320	15	330–020
				0000–0100	20	Cloud
			55° N 01.5° W	2220	40	
				2250	NLC faint	
				2320	46?	
				2325	10	326–047
20/21	2220–2250	Very faint parallel bands in haze at Morpeth. Faint bands at Edmonton. No NLC (F).	55° N 01.5° W	2220	44	320–070
				2235	43	060
				2240	35?	
				2250	No vis. NLC	
21/22		No NLC (F)				
22/23		No NLC (D, F)				
23/24	2215–0145	Bright display, all forms, observed in N England. Scotland overcast. No NLC (F).	55° N 01.5° W	2230	25	Cloud
				2325	8	336–018
				2340	7+	Cloud
				2355	8+	340–003
				0010	Cloud	
			54° N 01° W	0045	9	350
				0145	13	345
			53.5° N 03° W	2225	25	315
				2230	20	260–040
				2330	Low	270–030
			53.5° N 02° W	2215	20	000–020
				2230	20	310–320
				2300	10	
				2330	Cloud	
			53.5° N 01.5° W	2225	15	310–030
				2245	18	310–030
				2300	12	
				2315	9	350–020
				2345	8	000
24/25		No NLC (F)				
25/26	2215–0225	Moderately bright bands and whirls in N England, billow development about 0130. Faint bands at Jämsä, Finland. Major display at Edmonton — all forms, very bright, alt. 90° at 0400 local time.	62° N 25° E	2215–2300	40	000–030
			54° N 01° W	2315	3	000–030
				2330	3	000–030
				2345	7	340–030
				0001	7	340–030
				0015	9	330–030
				0045	8	320–040
				0100	9	320–050
				0115	10	320–050

Date night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev.	Limiting azimuths
					degrees	
25/26 (contd)				0130	12	320–030
				0145	11	330–030
			53.5° N 01° W	2315	10	000
				2350		350–010
				0040	15	335–045
				0120		315–060
				0150	15	315–070
				0210	Fade	030–060
				0225	No NLC	
			52° N 00.5° W	0045	5	000–050
				0145	NLC above fog	
26/27	2100–2140	Billows in broken trop. cloud, Sjælland and Bornholm. Patch of billows at Edmonton. No NLC (F).	56° N 12.5° E	2100–2125	30	045
			55° N 14.5° E	2140	22	000–022
28/29	0110–0210	Very faint parallel bands at Morpeth, seen only with binoculars.	55° N 01.5° W	0110	4	020–035
				0125		356–045
				0140	5	350–070
				0155	6	000–070
				0210	No NLC	
29/30		No NLC (F)				
30 June/1 July	2258–2311	Bands and billows in trop. cloud gaps, Edinburgh. No NLC (F).	56° N 03° W	2258	12	–030
				2311	32	335–020
3/4	2200–2230	Faint veil in trop. cloud gaps, Jämsä. No NLC anywhere else in Finland, or Alberta.	62° N 25° E	2200–2230	20	355–010
5/6	1920–0246	Extensive display, bands, billows, whirls; Finland, Britain, Denmark. No NLC in Alberta.	63° N 27.5° E	2130	24	015–050
				2150	NLC visible	
				2230	24	005–042
			62.5° N 27.5° E	2120	No NLC	
				2150	NLC suspect	
				2215	16	000–040
				2235	30	005–045
				2300–2315	36	000–290
			62° N 25° E	2200–2245	40	035–050
			60.5° N 25° E	2215	No NLC	
				2300	20	280–000
				2315	22	280–010
				2330–2345	22	280–350
			60.5° N 22° E	2230	15	300–330
				2245	20	245–050
				2300	22	245–055
				2315	22	245–035
				2330	25	250–090
				2345	15	250–090
			56° N 12.5° E	1920–2215	Bands	000
			56° N 09° E	2315	12	338–042
				2355	20	326–060
				0035	25	316–062
				0100	46	296–038
				0115	27	298–048
				0130	18	274–022
				0140	11	272–006
				0145	Faint NLC	
			56° N 03° W	0040–0200	30	330–060
			56° N 04.5° W	2252–2330	45	330–015
			55.5° N 04.5° W	0125–0131	25	000
			54° N 01° W	0045–0115	NLC present	
			52° N 01° W	0040	3	
				0246	16	
6/7	2230–2240	Faint bands at Rønne, NLC observed at Fort McMurray, Alberta. No NLC (F, G).	55° N 14.5° E	2230–2240	13	315–022
7/8	2144–2155	Very faint bands and billows at Itegem. No NLC (D, F).	51° N 04.5° E	2144	10	343–006
				2155	NLC with binocs.	
8/9		No NLC (B, F)				
9/10	2300–2345	Very faint NLC patches among cirrus suspected at Edinburgh. No NLC (B, F).	56° N 03° W	2300	45	330–030
				2315	50	300–055

Date night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev. *degrees*	Limiting azimuths
9/10 (contd)				2330	55	330–055
				2345	NLC suspect	
10/11	2045–0000	Brilliant and extensive display throughout Finland except far north. All forms visible well into southern sky. SSE movement.	65.5° N 24.5° E	2200–2230	No NLC	
			65° N 25.5° E	2200–2230	No NLC	
			63° N 23° E	2130–2230	No NLC	
			62.5° N 27° E	2200	166	240–120
				2215	166	240–120
				2230	160	250–140
				2245	NLC present	
			62° N 25° E	2145–2245	35	350–045
			61° N 29° E	2145	150	190–100
				2215	150	210–120
				2245	150	210–090
				2300	150	210–090
			61° N 21.5° E	2045–2115	No NLC	
			60.5° N 27° E	2100–2130	50	160–080
			60.5° N 22.5° E	2100	No NLC	
				2120	Bands	270
				2145	145	220–120
				2200	145	230–080
				2215	140	260–080
				2230	125	220–080
				2245	130	250–135
				2300	145	260–100
				2315	160	250–140
				2330	140	260–110
				2345	155	255–140
				0000	140	235–100
			60° N 25° E	2050–2310	NLC extensive	
11/12	2020–2330	Bands in SW Finland but negative reports from rest of country.	61° N 23.5° E	2020–2100	22	210–270
			60.5° N 23.5° E	2145	22	011–055
				2200	40	320–050
			60° N 25° E	2200–2330	NLC suspect	
12/13		No NLC (F, G)				
13/14		No NLC (B, D)				
14/15	2040–2340	Minor display, bands and billows, Finland. SW movement.	62.5° N 27° E	2215	NLC present	
				2230	162	250–105
				2245–2315	160	235–170
			62° N 25° E	2150	60	340–045
				2210	65	330–045
			61° N 21.5° E	2200–2230	No NLC	
			60° N 25° E	2040–2340	45	
15/16	2025–2225	Minor display, bands and billows, Copenhagen and Alrö. No NLC (B).	56° N 10° E	2125	30	270–045
			55.5° N 12.5° E	2205–2225	7	000
16/17	2030–2330	Extensive, moderate to bright display over Finland. All forms, SW movement.	63° N 27.5° E	2200	36	250–090
				2230	40	170–230
				2305–2330	70	190–100
			63° N 23° E	2100–2130	25	240–260
			62.5° N 27° E	2045	NLC present	
				2145	160	210–120
				2200	160	190–150
				2230	35	265–090
				2245	90	240–120
			62° N 25° E	2150	70	240–060
				2220	50	250–065
				2240	40	270–050
				2310	60	250–045
			61° N 29° E	2115	60	170–010
				2130	80	185–020
				2145	90	000–190
						275–340
				2200	90	130–100
			61° N 23° E	2020–2140	No NLC	
			60.5° N 22.5° E	2030	No NLC	
				2100	NLC present	
				2130	90	220–060

Date night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev.	Limiting azimuths
					degrees	
16–17 (contd)				2145	85	250–065
				2200	70	260–080
				2215	45	285–030
			60° N 25° E (Helsinki)	2100–2130	45	290–045
			60° N 25° E (Kaivopuisto)	2121–2300	45	250–335
17–18	0125–0240	Faint bands and billows in trop. cloud, Morpeth. No NLC (B, D).	55° N 01.5° W	0125	8	Cloud–038
				0140	9	340–035
				0155	12	336–035
				0210	15	–040
				0225	14	330–036
				0240	14	335–020
18–19	2030–2339	Moderate display, all forms, Finland.	65.5° N 24.5° E	2145–2230	No NLC	
			63° N 27.5° E	2205	24	290–340
				2215	26	280–340
				2230	35	250–340
				2250	24	260–330
			63° N 23° E	2115–2230	15	350–000
			62.5° N 27° E	2200	32	265–340
				2215–2300	NLC present	
			62° N 25° E	2130–2300	30	280–010
			61° N 29° E	2030–2130	No NLC	
			60.5° N 22.5° E	2100	No NLC	
				2130	15	340–020
				2230	15	330–030
			60° N 25° E	2100–2130	No NLC	
				2140	NLC	330
				2200	8	320–000
				2215	13	305–015
				2230	15	295–015
				2245	17	300–005
				2307	22	283–010
				2331	28	280–000
19–20	2015–2210	Veil suspected at Illo (Finland). Other Finnish stations negative. No NLC (B, D, G).				
20–21	2000–2345	Bands reported at Helsinki, other Finnish stations negative. No NLC (D, G).	60° N 25° E (Helsinki)	2130–2250	No NLC	
				2300	30	330–015
				2321	NLC faint	
			60° N 25° E (Kaivopuisto)	2300–2330	NLC present	
			60° N 25° E (Konala)	2115–2140	50	270–000
21–22	0005–0100	Faint bands Vildbjerg, also Edmonton.	56° N 09° E	0005	6	342–020
				0030	8	342–022
				0100	Trace	000–010
22–23	2000–0015	Bright and extensive display over Finland, all forms. Possible SW drift. No NLC (G).	65.5° N 24.5° E	2200–2232	25	270–325
			65° N 25.5° E	2200	No NLC	
				2210	60	310–060
				2245	No NLC	
			63° N 27.5° E	2140	16	340–050
				2200	20	310–020
				2225	24	280–010
			62.5° N 27.5° E	2115	16	010–040
				2200	18	290–030
				2215	30	280–025
				2245	30	306–330
			62.5° N 27° E	2115	15	315–000
				2145	20	300–020
				2215	30	321–015
				2245	8	300–045
				2300	12	290–040
				2315	8	290–040
				2330	10	285–040
				2345	8	345–020
				0000	NLC present	
			62.5° N 25.5° E	2120–2235	25	

Date night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev. (degrees)	Limiting azimuths (degrees)
22/23 (contd)			62° N 25° E	2200	30	320–025
				2220	25	315–010
				2235	20	310–000
				2330	15	315–350
			61° N 23° E	2020–2050	No NLC	
			60.5° N 22.5° E	2125	NLC present	
				2145	9	330–040
				2200	10	325–035
				2215	10	325–025
				2230	12	325–025
				2245	13	320–020
				2300	13	320–025
				2315	8	310–020
			60° N 25° E	2045	NLC low	
				2119	NLC present	
				2127	7	348–005
				2150	8	346–005
				2200	10	335–010
				2224	10	331–005
				2237	10	322–005
				2300	5	320–330
				2322	2	352
				2330	7	315–000
				0012	NLC present	
23/24		No NLC (F)				
24/25		No NLC (D, F)				
25/26	2040–0150	Very bright and extensive display, all forms, Finland and Denmark	65.5° N 24.5° E	2200–2245	No NLC	
			65° N 25.5° E	2200	145	005–120
				2240	155	280–005
				2305	30	020–090
				2320	25	015–070
			63° N 27.5° E	2100–2115	40	330–045
			63° N 23° E	2115–2245	30	000–090
						270–300
			62.5° N 27° E	2045	NLC present	
				2145	110	300–120
				2215	95	270–120
				2230	NLC in cloud	
			62° N 25° E	2100	30	300–045
				2120	40	280–050
				2140	35	270–055
				2200	30	270–045
				2230	30	300–040
			61.5° N 23.5° E	2102	20	300–048
				2130	20	300–055
				2145	20	312–055
				2205	22	336–048
				2225	22	336–060
				2245	20	310–060
			61° N 23° E	2040–2150	60	240–350
			60.5° N 22° E	2110	NLC	NE and NW
				2130	15	280–050
				2145	15	280–055
				2200	15	280–045
				2230	17	285–060
				2300	18	300–090
				2330	35	280–095
				0000	60	280–115
			60° N 25° E	2115	15	N
				2255	6	002–010
				2320	23	327–060
				2340	57	290–080
				2355	61	280–095
				0000	61	
			60° N 24.5° E	2100	8	320–050
				2130	12	290–035
			56° N 10° E	2055–0110	15	315–090
			56° N 09° E	2115	10	334–040
				2145	11	330–038
				2215	11	342–028

Date night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev. *degrees*	Limiting azimuths *degrees*
25/26 (contd)				2245	6	340–040
				2315	6	340–030
				2345	7	332–032
				0015	12	338–046
				0045	13	338–048
				0100	12	340–064
				0130	10	356–035
				0150	10	002
26/27		No NLC (F)				
27/28	2045–2345	Small patch of bands very low at Edinburgh. Fairly small display of bands and billows, Finland.	63° N 27.5° E	2130	65	000–030
			62° N 25° E	2045–2110	No NLC	
			60° N 25° E	2121	10	WNW
				2312	NLC	N
				2328	8	337–340
				2334	8	330–005
				2342	8	325–000
			56° N 03° W	2243	3	035–040
				2300	3	010–040
				2315	3	356–040
				2345	3	Cloud
28/29	2040–2300	Faint to moderate bands over USSR, seen from Finland. All forms at Rautalampi.	63° N 27.5° E	2100	15	045–070
				2125	17	060–080
				2145–2200	8	350–050
			62.5° N 27° E	2215	14	000–070
				2245	NLC present	
			61.5° N 23.5° E	2040–2130	No NLC	
			61° N 29° E	2100	10	010–050
				2115	12	030–040
				2145	No NLC	
			60.5° N 22.5° E	2045–2125	No NLC	
29/30 to 30/31		No NLC (F)				
1/2 Aug	2115–2345	Bands visible in trop. cloud gaps, E Finland.	63° N 27.5° E	2115–2130	34	340–000
			62.5° N 27° E	2330–2345	10	010–050
2/3	2015–2230	Moderate to bright display, all forms, Finland. SW drift.	63° N 23° E	2030–2230	No NLC	
			62.5° N 27° E	2030–2105	No NLC	
				2115	18	340–030
				2130	20	320–030
				2145	20	330–030
				2200	20	320–040
				2230	26	305–040
			61.5° N 23.5° E	2040	No NLC	
				2120	9	330–030
				2135	11	312–024
			61° N 29° E	2045	10	000–020
				2130	10	320–025
				2200	10	320–025
			61° N 21.5° E	2015–2100	No NLC	
3/4		No NLC (B, F)				
4/5	2030–0000	Faint bands in trop. cloud gaps, Rautalampi.	62.5° N 27° E	2300–2315	12	020–030
				2345–0000	15	350–015
			62° N 25° E	2030–2200	No NLC?	
			61° N 21.5° E	2030–2130	No NLC	
5/6		No NLC (F)				
9/10	1900–2330	Slight bands at Maksamaa and Lapua, W Finland.	65.5° N 24.5° E	2230–2330	No NLC	
			63.5° N 22° E	2220–2245	15	315–000
			63° N 23° E	2200–2230	10	340–000
			60.5° N 27° E	1900–2100	No NLC	
10/11 to 11/12		No NLC (F)				
12/13	2215–2340	Small moderately bright NLC, bands and billows, E Finland. Patches of billow suspected at Detmold despite moon.	65.5° N 24.5° E	2245–2340	15	000–030
			63° N 28.5° E	2300–2330	10	000–040

Date night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev.	Limiting azimuths
					degrees	
12/13 (contd)			63° N 27.5° E	2215–2245	12	010–030
			52° N 09° E	2300	NLC?	
13/14	1930–0234	Faint bands and whirls at Rautalampi. Short-lived and faint NLC at Viby (Funen).	65.5° N 24.5° E	2115–0045	No NLC	
			63° N 23° E	2000–2245	No NLC	
			62.5° N 27° E	2010	NLC present	
				2015	150?	210–090
				2030	NLC present	
			62.5° N 24.5° E	1940–2030	45	270–000
			62° N 25° E	2000–2130	45	310–030
			61.5° N 23.5° E	2050	9	300–012
				2100	9	324–000
			60.5° N 22.5° E	1930–0100	No NLC	
			55.5° N 10.5° E	0232	NLC trace	N
14/15	1945–0100	Small veil suspected at Tampere. 4 other Finnish stations negative.	61.5° N 23.5° E	2115–2125	5	300–000
15/16		No NLC (F)				
16/17	2000–2300	Faint bands and billows at Kemi. 2 other Finnish stations negative.	65.5° N 24.5° E	2230–2300	10	335–010
17/18 to 20/21		No NLC (F)				
23/24	1900–2100	Small brightish bands at Lapua.	63° N 23° E	2000–2100	30	
			62° N 25° E	1900–2000	No NLC	
24/25		No NLC (F)				
26/27 to 28/29		No NLC (F)				
29/30	1830–2230	Faint veil at Illo? No NLC at Helsinki and Kemi.	61° N 23° E	1830–1910	20	330–000
30/31	1900–2230	Brightish veil suspected at Pertteli, no NLC at 3 other Finnish stations.	60.5° N 23.5° E	1900	32	280–045
				1910	45	270–049

Photographs

13/14 June	2238	Rønne	J.Ø. Olesen
14/15	0005–0021	Edinburgh (Blackford)	N. Bone
	0015–0045	Edinburgh (Joppa)	D. Gavine
	2317–0145	Morpeth	A. McBeath
	2249, 2338	Vildbjerg	H. Andersen
15/16	0015–0045	Milngavie	A. Simmons
	0100–0136	Stirling	A. Smeaton
	0130–0147	Edinburgh	D. Gavine
	0130–0245	Morpeth	A. McBeath
23/24	2235	Wakefield	M.D. Taylor
	2240	Heswall, Wirral	P. Irons
5/6 July	2315	Milngavie	A. Simmons
	0040, 0100	Vildbjerg	H. Andersen
15/16	2210	Rønne	J.Ø. Olesen
17/18	0125–0255	Morpeth	A. McBeath
18/19	2307	Helsinki	D. Frydman
22/23	2207–2249	Helsinki	D. Frydman
25/26	2311–2336	Helsinki	D. Frydman
	2215–0015	Vildbjerg	H. Andersen
	0040	Rønne	J.Ø. Olesen
27/28	2254–2303	Edinburgh (Blackford)	N. Bone
	2300–2315	Edinburgh (Joppa)	D. Gavine

551.509.324.1

Convective cloud forecasts from the Meteorological Office fine-mesh model

By T. Davies
(Meteorological Office, Bracknell)

Since March 1986, charts showing convective cloud tops and depths, as produced by the fine-mesh 15-level numerical model, have been available in the Central Forecasting Office (CFO) of the Meteorological Office. Two sets of charts are produced for the analysis time (T) and for each 6 hours of the forecast from T+18 to T+36, and cover the area of the fine-mesh model (30–80° N, 80° W–40° E). The charts are specifically tailored to the needs of the aviation forecasters in the International Civil Aviation Organization Regional Area Forecast Centre located within CFO.

One set of charts indicates where convective cloud tops are above 20 000 ft and depths are in excess of 10 000 ft. These are used to determine those regions where cumulonimbus clouds are thought likely to penetrate to significant flight levels (25 000 ft and above). Examples of the part of these charts covering the British Isles are shown in Figs 1 and 2 for cloud tops and depths respectively. The second set of charts shows the position of clouds with tops between 10 000 and 20 000 ft, and depths in excess of 5000 ft, and these are of particular use for lower-level flights.

The two sets of charts can be used to build a picture of the model's convective cloud. This can help to assess the convective component of rainfall in some situations since, for output purposes, dynamic (i.e. large-scale) rainfall symbols are printed in preference to convective symbols when both types of rainfall occur. Fig. 3 shows the conventional model output of surface pressure and rainfall valid at the same time as the cloud tops and cloud depths given in Figs 1 and 2. Notice that only dynamic rainfall symbols appear over England whereas the convection charts show that there is a convective element to the rain.

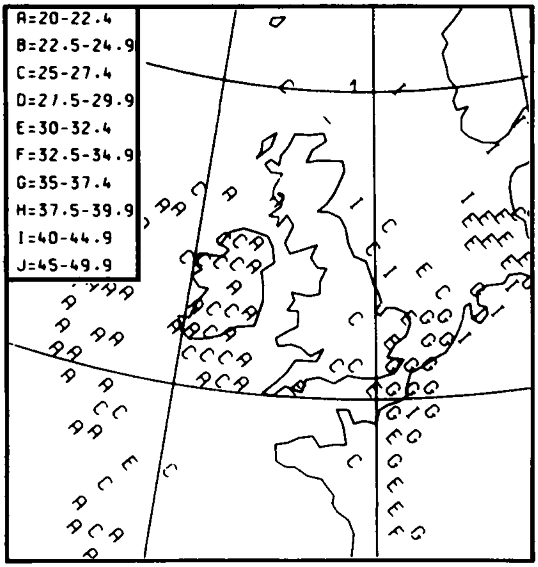


Figure 1. Fine-mesh 15-level numerical model T+18-hour forecast of convective cloud tops (key gives heights in thousands of feet), based upon data time 00 GMT, 3 August 1986.

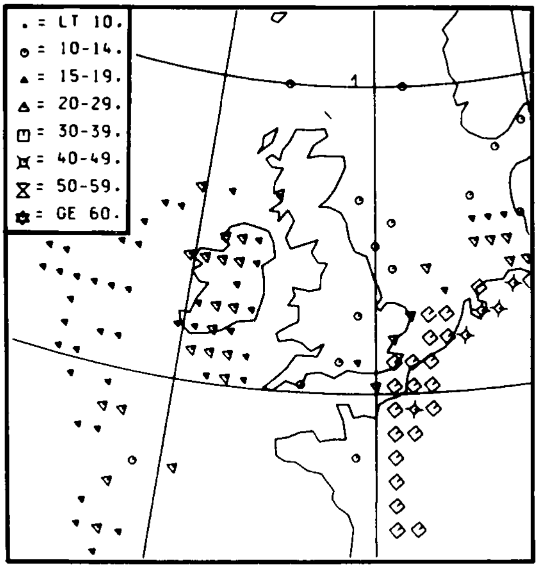


Figure 2. As Fig. 1 but for convective cloud depths (key gives depths in thousands of feet).

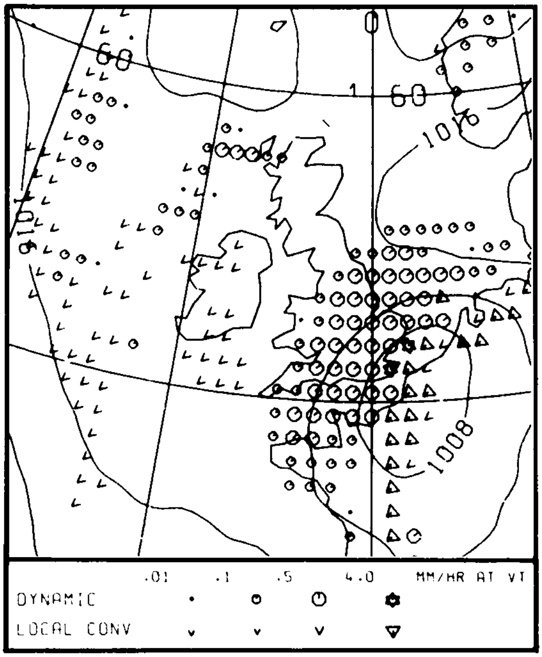


Figure 3. As Fig. 1 but for surface pressure (mb) and rainfall (see key).

The information displayed in the convection charts is obtained from the model's deep convection scheme which is based on parcel theory modified by entrainment. The cloud base is defined as the bottom of the first model layer for which moist convection takes place. A buoyant parcel is assumed to rise through the unstable atmosphere, gradually losing mass by detrainment, until it is no longer buoyant — this level is taken to be the cloud top. In the model it is possible for convection to restart after terminating at a lower level, but the cloud charts identify only the lowest convective layers at a particular grid point.

The charts have been well received by the forecasters who find them very useful in preparing significant weather charts and for issue of SIGMETs (warnings of severe weather to aircraft in flight).

Acknowledgement

The convective cloud chart output for CFO was developed by Mrs A.J.K. Small.

Notes and news

EUMETSAT

On 18 June 1986 a special inter-governmental meeting was convened in Paris to consider the status of EUMETSAT (EUropean METeorological SATellite organization). Sixteen European states agreed that the organization should be authorized to begin its work immediately. A few days later the first meeting of the EUMETSAT Council appointed John Morgan, then Assistant Director (Satellite Meteorology) in the Meteorological Office, as its first Director; it was also decided that the headquarters should be located in Darmstadt, Federal Republic of Germany.

EUMETSAT has been created to establish, maintain and exploit European systems of operational meteorological satellites. Its first task will be to carry overall responsibility for the Meteosat Operational Programme, though this programme will be operated by the European Space Agency on behalf of EUMETSAT. Furthermore it will evaluate existing and future programmes, and will contribute to the development of space meteorology techniques and meteorological observing systems that use satellites.

The Professor Dr Vilho Vaisala Award

The World Meteorological Organization (WMO) has agreed to a trust fund being set up to finance an annual award entitled the 'Professor Dr Vilho Vaisala Award' which is named after the well known meteorologist and instrument maker. The purpose of the award is to encourage and stimulate interest in research concerned with instruments and methods of observations which support WMO programmes. It is awarded for the best published paper on these topics during the previous 18 months.

The Executive Council of WMO selected Chris Collier, until recently Assistant Director (Operational Instrumentation) in the Meteorological Office, to be the first recipient of the award. It was given in recognition of his paper on the 'Accuracy of rainfall estimates by radar' published in the *Journal of Hydrology* in 1986. In Part I of the paper the provision of radar data for both rainfall and flood forecasting is discussed. In particular the accuracy of the gauge-calibrated radar estimates of rainfall, when compared with data from rain-gauges, is considered over river sub-basins of up to 200 km^2. An analysis is described in Part II of the way in which radar data, together with data from telemetering rain-gauges, should be used for flood forecasting. In Part III a simple hydrological model is used to assess the effects of errors in estimates of rainfall made by radar on predictions of river flow.

The award was presented to Mr Collier on the 50th Anniversary of Vaisala OY in Helsinki, Finland on 5 September 1986.

Reviews

Air: composition and chemistry, by P. Brimblecombe. 170 mm × 240 mm, pp. viii + 224, *illus*. Cambridge University Press, 1986. Price £25.00 (hardback) £8.95 (paperback).

In recent years a number of textbooks on atmospheric chemistry have been published and perhaps the natural question to ask is whether we really need another one. This book is aimed at the level of the young scientist or perhaps interested meteorologist compared with the more learned works by G. Brasseur and S. Solomon (*Aeronomy of the middle atmosphere*, Dordrecht, D. Reidel Publishing Company, 1984), R.P. Wayne (*Chemistry of atmospheres*, Oxford University Press, 1985), and that edited by J.S. Levine (*The photochemistry of atmospheres. Earth, the other planets and comets*, London, Academic Press, 1985).

The book is divided into nine chapters which give a broad brush treatment of virtually the whole subject area from gas phase chemistry to the atmospheres of the planets. In general, I felt that the more simple the concept, the more irksome the description became. For example, on page one the reasons for supposing the air to be a mixture of gases as opposed to a single compound are somewhat laboured and the statement that, 'if it were a compound the formula would be $N_{15}O_4$ and this seems rather unlikely' does not seem to be very scientific. Later in the same chapter the concept of average residence time for species is not as clear as it could be with the word 'average' not properly defined. More worrying, though, was the statement that, '... where the environment cools less rapidly with height than the adiabatic lapse rate an inversion is said to have formed' (page 118).

The author has taken the step of giving just a few references on the subject matter of each chapter and I think in general this has worked well. However, there are two major omissions — the book by Brasseur and Solomon from the references of Chapter 8, and the book by Levine from the references of many chapters but especially of Chapter 9. In fact Chapter 8 is quite inadequate in scope when one considers the biological effects of potential damage to the ozone layer due to anthropogenic activities, and the whole concept of interaction between chemistry and dynamics in the middle atmosphere is not raised at all. In Chapter 9 omission of references to the book by Levine, which describes the chemistry of the other planets in much more depth, is equally serious. Levine's book, though, quotes methane concentrations on Jupiter and Saturn some 2½ and 5½ times greater. This is confusing bearing in mind that both sets of figures are presumably based on the same Voyager data. There are also small differences in some other constituents.

I think the book could also have been improved by the addition of two more chapters —one on the theoretical techniques of chemical modelling and another on the techniques of measuring minor constituents. As regards chemical modelling the nearest that the author gets to it is in discussing reaction rates in Chapter 3 on gas phase chemistry; and in discussing the reaction $2NO + O_2 \rightarrow 2NO_2$ a factor of 2 finds itself on the wrong side of several equations. Despite reading every word of the book (I from insomnia!) suffer I could find few references to measuring techniques.

The best parts of the book are Chapters 6 and 7 dealing with the sources and effects of air pollution which, on the basis of their length (together they cover over one third of the book), are the author's main areas of expertise. Here some very interesting facts on the effects of pollution on human health may be found. For example, cigarette smoke contains about 400 parts per million by volume of carbon monoxide which lies in the category whose health effects include headaches and nausea. As a cautionary note, although the pollution chemistry of the troposphere is described in much more detail than topics in other chapters, I wonder whether some clarity in the scientific concepts has been lost. For example, a paradox such as why does nitric oxide destroy ozone in the stratosphere but produce ozone in the troposphere is not brought out in the text whereas I think a book at this level should raise such questions.

Despite these criticisms the book is quite appropriate, in general, to the audience to which it is addressed (students taking courses in environmental sciences, ecology and chemistry) but would probably not appeal very much to active researchers in the field. So the answer to the question raised in my first paragraph, i.e. do we really need another textbook, is, I think, a qualified 'yes'.

J. Austin

World survey of climatology, Volume 1A: General climatology, 1A, by A.Kessler. 217 mm × 300 mm, pp. xii + 224, *illus*. Elsevier Science Publishers, Amsterdam, London, New York, Tokyo, 1985. Price US $55.50, Dfl 150.00.

This fine book is divided into several sections; firstly a historical résumé of climatology (the earliest reference is 'Halley 1687'), then a chapter on the earth–atmosphere heat and radiation budget, which was unfortunately unread as pages 5 to 20 inclusive were missing in the reviewer's copy. The book is historical in another aspect, since printing was delayed by a change of editor and 'slow' contributors, hence one may get some feel for the growth of the science during the last 15 years.

Subsequent chapters on the net radiation, latent heat flux and sensible heat flux (all at the earth's surface) are thoroughly explored including their diurnal and annual variability, on a global scale, with consideration being given to types of surface and the vegetation thereon. Many tables and diagrams are used to support the text, all neatly displayed, but some of the captions are, of necessity I suppose, rather cumbersome. I especially liked Figure 15 which is a fold-out (usually frowned upon) of the net radiation at selected sites around the world, displayed by month and hour of day with a helpful inset showing the location of the places and their relative positions. This helps comparison, but the author's discussion occurs ten pages later.

Finally, there is a chapter on heat flux into the surface, with all the complications of ablation, biomass and oceanic transport investigated. For oceanic heat flux, the author states (with surprise) that the sign changes three times at Ship 'V' between 1956 and 1970; in fact I made it even more surprising at six times — perhaps a case of different interpretation. It is hereabouts that a few tentative remarks are made about climatic changes and the oceans' importance to them. In this chapter there is also an interesting discussion about the variable ground-water temperature associated with urbanization (Cologne is used as the example) and a statement about the water temperature at 28 metres beneath the Paris Observatory having risen by nearly 2 °C during this century up to 1969.

There are comprehensive reference sections and appendices, with Appendix III being a conversion table to 'modern' SI units, since the energy unit used in the book, which is one of a large series, is calories and is to be used throughout the series for consistency. The subject index is disappointing after the earlier thoroughness, mainly seeming to concern itself with various types of earth cover.

With over 70 figures and over 70 tables scattered throughout the book, it might have been better to have arabic numerals for tables as well as for figures, and/or keep a section at the end of the book for tables. Many times one is confused, for example on page 182 one is referred to Tables LVIII and XLIII and Figure 46 simultaneously, when Figure 73 is on the current page and Table LXX is on the previous page, which becomes rather frustrating and wearing on the pages.

Nevertheless, the book has been compiled with great care, accuracy and enthusiasm in good readable English and, despite the weighty subject, it is entertaining, albeit possibly unconsciously as in the sentence, 'The climate of the small isolated island is extremely maritime'. What else?

I am reviewing the book as a non-expert, but would recommend it, to anyone interested in meteorology, for browsing or reference.

S.H. Barker

Books received

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

Physics and chemistry in space, Vol. 13: Photochemistry of the atmospheres of Mars and Venus, by V.A. Krasnopolsky (Berlin, Heidelberg, New York, Tokyo, Springer-Verlag, 1986. DM 240.00) gives a detailed description of the chemical structure of the atmospheres of Mars and Venus, and the chemical and physical processes that define the properties of these atmospheres. It compiles experimental and theoretical data collected over the last decade in ground-based observations and, by Soviet and American flyby systems, orbiters and descent probes. The author reviews various methods for determining the chemical composition of planetary atmospheres, discusses the reliability of the experimental results critically, and compares these results with predictions based on photochemical modelling.

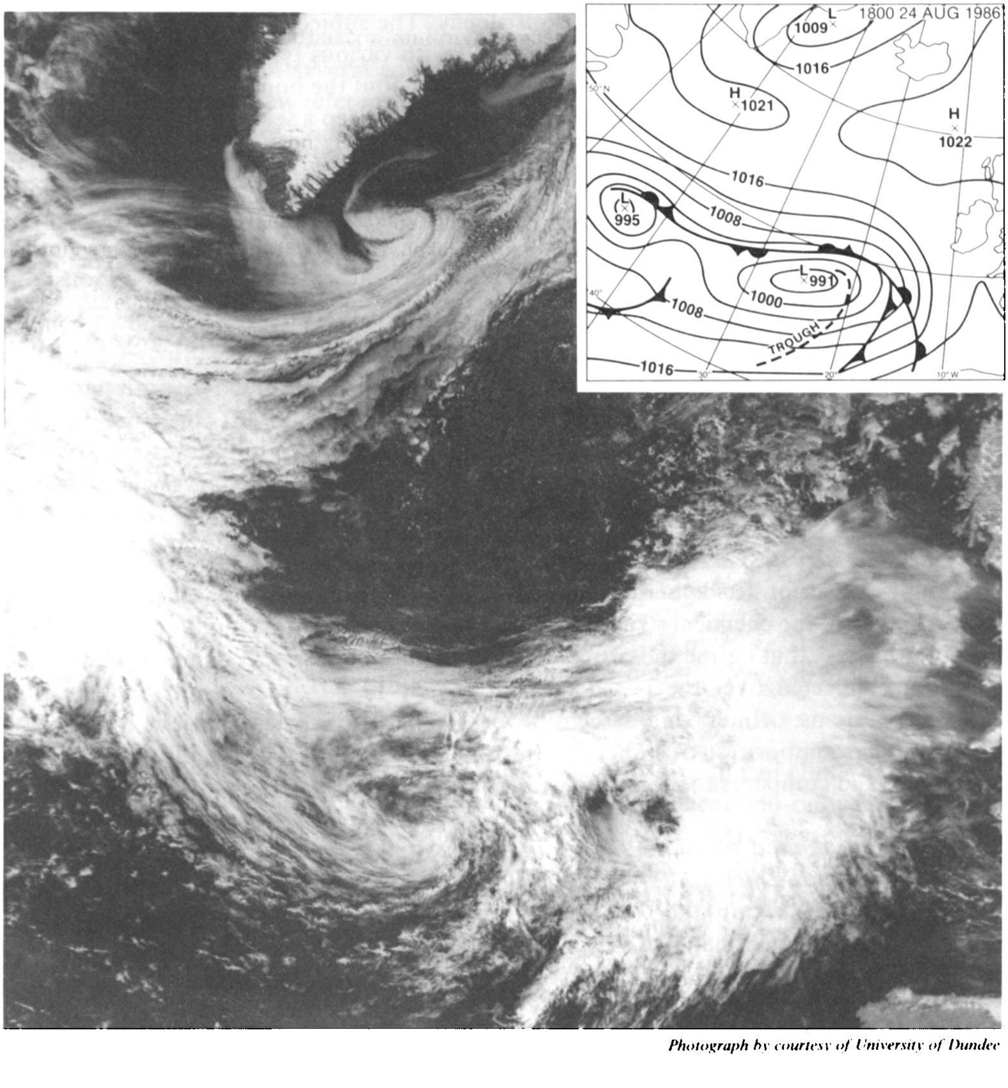
Notes on numerical fluid mechanics, Vol. 13: Proceedings of the Sixth GAMM-Conference on numerical methods in fluid mechanics, edited by D. Rues and W. Kordulla (Wiesbaden, Friedr. Vieweg and Sohn, 1986. £31.00) contains the 51 papers presented at this conference which was held at Göttingen in the Federal Republic of Germany on 25–27 September 1985. The papers cover a broad range of topics from the mathematical development and investigation of algorithms to applications to fluid mechanical problem in acoustics, aerodynamics, car aerodynamics, gas dynamics, hydrodynamics, meteorology, oceanography, turbomachinery, etc. A report on the GAMM-Workshop 'The efficient use of vector computers with emphasis on computational fluid dynamics' is included.

Satellite photograph — 24 August 1986 at 1552 GMT

The satellite picture is a NOAA-9 visible image over the mid-Atlantic (British Isles extreme right). Two vortices are defined by low-level clouds — a shallow low near the tip of southern Greenland, and a less well-defined swirl showing the remains of ex-hurricane Charley (centre bottom).

A vast 'head' of cloud is present well in advance of Charley, composed of mostly thick middle- and upper-level cloud, although the forward portion is largely transparent cirriform cloud. Similar cloud heads are often observed prior to rapid cyclogenesis.

Subsequent satellite images suggest that the cloud swirl associated with the hurricane weakened, whilst the intense circulation that brought severe gales and considerable rainfall over England, Wales and the Republic of Ireland on 25 August was probably associated with a new low that formed several hundred kilometres to the north-east.



Photograph by courtesy of University of Dundee

Meteorological Magazine

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Meteorological Magazine

November 1986

Vol. 115
No. 1372

CONTENTS

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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.

ISBN 0 11 727839 4 ISSN 0026–1149

Printed for HER MAJESTY'S STATIONERY OFFICE
by Delco Printing Co. Ltd. 10/86 Dd. 739131 C14.25

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

December 1986

Met.O.971 No. 1373 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1373, December 1986, Vol. 115

551.509.53 .542(41 4):551.509.332

Experimental monthly long-range forecasts for the United Kingdom

Part III. Skill of the monthly forecasts

By C.K. Folland, A. Woodcock and L.D. Varah

(Meteorological Office, Bracknell)

Summary

Evidence is shown for a recent fairly sudden, though modest, improvement in the skill of the monthly forecasts, especially those of temperature extremes and rainfall. These forecasts are derived from forecast patterns of pressure at mean sea level (PMSL) made for three periods within the month. A first analysis is given of the skill of the derived monthly mean PMSL forecasts and preliminary analyses of the recent skill of the temperature and rainfall forecasts for several distinct periods within the month ahead, including the second half-month, to help indicate whether the forecasts have skill on the purely 'long-range' time-scale.

1. Introduction

This paper concentrates on the skill of the issued forecasts which are based on the contributions of all the forecasting techniques described in Folland and Woodcock (1986). (Folland and Colman (1986) provide a preliminary discussion of the skill of the most important statistical technique, the multivariate forecasting technique.) A discussion about the skill of the forecasts of pressure at mean sea level (PMSL), temperature and rainfall issued in the medium range (first 5 days of the month ahead), mid range (remainder of the first half-month) and long range (second half-month) since July 1982 is included.

2. General remarks on the skill of the forecasts

The forecasts of monthly mean temperature anomalies for each district are given in terms of the 'best-estimate' of whether it will be very cold, cold, average, warm or very warm. In the long term the probability of each of these 'quints' is the same. Similarly, forecasts of percentage of average rainfall (hereafter referred to as rainfall percentage) are categorized according to whether it will be dry, average or wet, where each 'terce' is equally likely in the long term. A map of the ten districts for which forecasts are issued is given in Folland and Woodcock (1986). Until 1979 the forecasts were usually only made for the single most probable quint or terce category which is called the best-estimate forecast. The current system also forecasts the probabilities of each of the quints and terces, and is designed so that one of the quints or terces is forecast to have the highest probability and this is regarded as the best-estimate forecast. Thus best-estimate forecasts can be continuously assessed from 1964 to date. Assessment of the skill of the complete set of probability forecasts is more difficult, though important, and will be tackled in a later paper.

Since July 1982, a full record of best-estimate forecasts of temperature anomaly and rainfall percentage has been kept separately for the medium, mid and long ranges. In addition, forecasts of PMSL have also been analysed since July 1982 for six grid points near the United Kingdom (four of the points are shown in Folland and Woodcock (1986) with the two additional points at 55° N, 10° W and 55° N, 00° W) though only the skill of forecasts for the month as a whole, and its first and second halves, is available at present. These objectively made assessments cannot, of course, be taken as complete measures of the value or utility of the long-range forecasts. However, the assessments of the skill of recent PMSL forecasts do at least start to tackle the problem of estimating the value of what used to be called 'additional information', i.e. the worded part of the forecast that describes the expected sequence of circulation types and the general characteristics of the associated weather. From a scientific point of view the assessments of the forecast PMSL patterns are therefore fundamental, since the temperature and rainfall forecasts, as well as the additional information, are now largely derived from these patterns.

3. Skill of the temperature and rainfall forecasts

(a) *General problem of assessing long-range forecasts*

The assessment of the skill of forecasts is a very difficult matter. Each user of the forecasts has a different sensitivity to their content largely because their value (or 'utility') depends on the way the forecasts are phrased, their level of detail and on whether the user has an effective way of using the forecasts and monitoring their utility. The very act of receiving the forecasts, almost irrespective of their content, can be beneficial, as the background meteorological information supplied about district climatological averages etc. is of considerable potential value in its own right. For some users this information may be more useful than the low skill that the forecasts currently have in predicting deviations from these averages. On the other hand, some users may regard an individual forecast as essentially correct when an objective assessment shows little or even negative skill relative to a random chance level. For example, consider a forecast that predicts a change of circulation type, and a marked increase in temperature, in the second half of the month ahead. If the change actually occurs but was delayed for a few days after the beginning of the second half-month, a set of extremely cold observed temperatures at the beginning of the period may render the second half-month as a whole rather cold even though most of it was rather mild. Indeed, small timing errors of this kind may be imperceptible to many users interested in planning on the basis of the general nature of the weather over 2 weeks. This lack of sensitivity is itself influenced by the current non-availability of more detailed forecasts of good accuracy. Thus more detailed and accurate forecasts, if they become available, might appreciably influence the mode of operation of some users, quite apart from any increase in their number. Presumably, the occasional serious forecasting failures would then be much more damaging than is possible at the present time. So at this stage we have confined our assessments of forecasts to methods that help researchers into long-range forecasting to monitor their own performance. Every forecast assessment system is rooted in a need to create indices of the skill or information content of the forecasts relative (in most cases) to a measure of what is achievable by following some fixed, simpler strategy such as random chance forecasts ('guesswork'), climatology, or forecasts of the persistence of some recently observed weather anomaly.

The technique currently in most frequent use in the Synoptic Climatology Branch of the Meteorological Office for assessing UK long-range forecasts of temperature and rainfall of the best-estimate type is known as the Folland–Painting or FP system. As described in section (d), other measures of skill are also found to be useful for assessing the PMSL forecasts. This is not surprising as any assessment system has scientific value if it provides self-consistent answers to well-posed questions about forecast performance.

A final problem for all measures of forecast skill is the need to define, in an appropriate way, the climatological averages from which the anomalies are being forecast. Long-range forecasts are currently made in anomaly form but the climate continually fluctuates. In the United Kingdom this problem has been quite acute in recent decades (Gilchrist 1982, Folland, *et al.* 1985), especially for temperature averages in April and October. The traditional approach is to define 'average' over a recent period of 30 years which is regarded as representative of the current climate. This convention has been adopted here but its limitations should be borne in mind. Its use has consistently led to an excessive number of observations of colder than normal conditions in the north-west of the United Kingdom since 1964, especially in the north and west of Scotland, possibly related to the cooling of the North Atlantic to the west of Scotland since about 1955, a cooling which has only recently ceased (Folland and Parker 1986).

(b) *The FP forecast assessment system*

The basic ideas underlying the system are described in Appendix 1. Table I shows the FP scoring tables for (a) temperature quints, (b) 'grouped' temperature quints (here the cold, average and warm quints are grouped together) and (c) rainfall terces. The quint and terce boundaries are defined separately in each district and for each of the overlapping 24 calendar monthly periods for which forecasts are made each year. Table II shows the 'Sutcliffe' scoring tables (Freeman 1966) which had previously been the most important assessment technique and which are still in limited use.

Table I(a). *The Folland–Painting scoring table for assessing forecasts of temperature quints*

Forecast		Observed					Chance scores for forecast categories
		Very cold A_1	Cold A_2	Average A_3	Warm A_4	Very warm A_5	
Very cold	F_1	5.2	1.0	−1.2	−2.4	−2.6	0
Cold	F_2	1.0	3.4	−0.2	−1.8	−2.4	0
Average	F_3	−1.2	−0.2	2.8	−0.2	−1.2	0
Warm	F_4	−2.4	−1.8	−0.2	3.4	1.0	0
Very warm	F_5	−2.6	−2.4	−1.2	1.0	5.2	0
Chance scores for observed categories		0	0	0	0	0	

Table I(b). *As Table I(a) but for grouped temperature quints*

Forecast		Observed			Chance scores for forecast categories
		Very cold A_1	Cold to warm A_2	Very warm A_3	
Very cold	F_1	8.5	−1.5	−4.0	0
Cold to warm	F_2	−1.5	1.0	−1.5	0
Very warm	F_3	−4.0	−1.5	8.5	0
Chance scores for observed categories		0	0	0	

Table I(c). *As Table I(a) but for rainfall terces*

Forecast		Observed Dry A_1	Observed Average A_2	Observed Wet A_3	Chance scores for forecast categories
Dry	F_1	4.7	−1.3	−3.4	0
Average	F_2	−1.3	2.6	−1.3	0
Wet	F_3	−3.4	−1.3	4.7	0
Chance scores for observed categories		0	0	0	

Table II(a). *The Sutcliffe scoring table for assessing forecasts of temperature quints*

Forecast		Observed Very cold A_1	Observed Cold A_2	Observed Average A_3	Observed Warm A_4	Observed Very warm A_5	Chance scores for forecast categories
Very cold	F_1	4	2	0	−2	−4	0
Cold	F_2	1	4	1	−2	−4	0
Average	F_3	−3	1	4	1	−3	0
Warm	F_4	−4	−2	1	4	1	0
Very warm	F_5	−4	−2	0	2	4	0
Chance scores for observed categories		−1.2	0.6	1.2	0.6	−1.2	

Table II(b). *As Table II(a) but for rainfall terces*

Forecast		Observed Dry A_1	Observed Average A_2	Observed Wet A_3	Chance scores for forecast categories
Dry	F_1	4	0	−4	0
Average	F_2	−2	4	−2	0
Wet	F_3	−4	0	4	0
Chance scores for observed categories		−0.67	1.33	−0.67	

Tables I(a)−I(c) are designed so that the chance score is always zero no matter what the observed (outcome) category. By contrast, the Sutcliffe tables have a positive chance score for average or near-average outcome categories (i.e. quints 2, 3 and 4) and a negative chance score for extreme outcome categories. This structure tends to give an artificially (slightly) higher score during a run of near-average conditions than during a run of extremes. For individual forecasts, a more serious problem with the Sutcliffe tables can be seen when comparing Table II(a) with Table I(a). Consider a forecast of quint 5 (F_5) followed by an outcome of quint 3 (A_3); the Sutcliffe system gives a score of 0 points. For a forecast of quint 3 (F_3) followed by an observation of quint 5 (A_5), the score is now −3 points. The FP system gives −1.2 points in both situations; this seems more logical as the 'error' in both situations is the same. Another difference between the tables is that a correct forecast of a quint or terce category gains the same maximum score in the Sutcliffe system no matter what the category is; in the FP system correct forecasts of extreme categories have a higher score than correct forecasts of a near-average category.

It should be noted that the values of the quint and terce boundaries and the estimates of observed anomalies in each district have been recalculated back to 1964 and therefore differ from the values published in the old *Monthly Weather Survey and Prospects* during the period of public issue. This development has been made possible by the construction of a new district-average climate data base that commences in January 1951 and which is regularly updated in an automatic way using quality-controlled data files created by the Advisory Services Branch. These data were still found to be inadequate in amount to revise satisfactorily the (previously rather uneven) rainfall terce boundaries. So it was decided to use the very comprehensive automated statistical model of the climate of extreme rainfall totals, calculated for the United Kingdom on monthly (and longer) time-scales by Tabony (1977) and converted into a regular grid-point format by Colgate (personal communication). The result is to provide quint and terce boundaries at fixed values of temperature anomaly or rainfall percentage that vary smoothly through the calendar year and between adjacent districts. The averages about which the anomalies are calculated (for a fixed set of stations) vary according to the epoch when the forecast was made.*

(c) *Assessments of monthly forecasts for 1964–86*

Table III (a) shows the annual mean FP skill scores for best-estimate monthly forecasts that were issued from 1964 to 1985. Table III(b) shows the equivalent results from the Sutcliffe system for comparison with previous papers, e.g. Ratcliffe (1970), Jenkinson (1975) and Hardy (1980). For both systems the skill, SK, of a given forecast is derived from the scores, S_d, for individual districts as follows:

$$SK = 100 \frac{\Sigma S_d}{\Sigma S_d^{max}} \quad \text{for } \Sigma S_d > 0$$

$$SK = 100 \frac{\Sigma S_d}{\Sigma |S_d^{min}|} \quad \text{for } \Sigma S_d < 0$$

where S_d^{max} and S_d^{min} are the maximum and minimum possible scores (e.g. S_d^{max} is the score that would be obtained if the outcome was correctly forecast). Thus SK varies between ± 100%. For example, if the observed and forecast quints for two districts are (A_5, F_4) and (A_4, F_2), then their combined skill score is −16%(see Table I(a)). If an annual mean value of skill is required, the sum of the scores, ΣS_d, is taken over all ten districts and 24 overlapping forecast months in a year (starting in January and finishing in mid-December to mid-January). SK can, of course, be calculated over any period and choice of districts.

* The averaging periods used to calculate district mean anomalies for use with Tables I(a)–I(c) are as follows:

Period of forecasts	Temperature	Rainfall
1964–75	1931–60	1941–70
1976–80	1941–70	1941–70
1981–86	1951–80	1951–80

The 1931–60 temperature averages for the ten districts are estimates based on changes in Central England Temperature between 1931–60 and 1941–70.

Table III(a). *Annual skill scores (percentages) of issued forecasts for 1964–85 compared with persistence, for all districts, using the Folland–Painting system (I = issued and P = persistence forecasts)*

	Temperature (quints)		Temperature (grouped quints)		Rainfall (terces)	
	I	*P*	*I*	*P*	*I*	*P*
1964	1	−23	−1	−6	2	12
1965	18	29	−4	29	6	−2
1966	12	−9	8	−5	4	−2
1967	5	16	12	9	0	−19
1968	5	−14	6	−14	−8	−11
1969	23	16	7	17	14	0
1970	20	13	4	13	0	−4
1971	−18	−14	11	−1	−1	−11
1972	1	11	5	11	14	12
1973	−9	1	5	−6	11	10
1974	7	23	−2	14	1	18
1975	9	−7	10	7	5	2
1976	7	25	3	34	9	15
1977	−7	0	−1	−3	1	19
1978	−15	−15	−4	−13	15	9
1979	13	23	17	30	10	−8
1980	−5	−25	−2	−17	−16	−3
1981	14	−16	4	−4	9	−9
1982	−11	−7	−2	−18	−3	2
1983	15	17	24	25	19	0
1984	14	−8	17	0	22	12
1985	13	−3	15	−7	15	3
1964–85 mean	7	4	6	7	6	3
Twice the standard error*	4	6	3	6	4	4

* Assuming each year is independent of the next, calculated from twice the standard error of the underlying annual scores, only then converted to skill.

Table III also shows skill scores for forecasts based on the use of persistence, i.e. a forecast of the same quint or terce category as was observed in the most recently observed non-overlapping month-long period. There is clearly a large variability in skill as well as a small overall positive 'bias' in the Sutcliffe quint skill values (because slightly more positively biased quint 2, 3 and 4 categories were observed between 1964 and 1985 than the chance expectation of 60%).Over the whole period, issued forecasts averaged over all districts have statistically significant annual skill while persistence forecasts show significant annual skill for grouped quints only.

Figs 1–3 show 4-year running-mean graphs of skill calculated from the FP system, where skill has been updated for each 2-month natural season. The diagrams show that it is almost certain that real variations have occurred in the skill of both issued and persistence forecasts. (The FP scores have been summed over running 4-year periods before converting them to skill.) Fig. 1 indicates an appreciable variation in skill of forecasts of the persistence of temperature quints (persistence from the previous month), a peak in skill of issued temperature forecasts in the 1960s and a recent sharp, though modest, recovery of the skill of issued temperature and rainfall forecasts from low values in much of the 1970s.

Table III(b). *As Table III(a) but using the Sutcliffe system*

	Temperature (quints)		Rainfall (terces)	
	I	*P*	*I*	*P*
1964	5	−22	2	21
1965	26	32	9	2
1966	14	−5	5	−1
1967	11	25	2	−18
1968	10	−9	−10	−13
1969	24	10	17	4
1970	25	14	1	−2
1971	−18	−14	4	−3
1972	4	16	13	11
1973	−1	9	11	11
1974	6	24	6	21
1975	12	−8	5	2
1976	8	29	4	11
1977	−8	−4	2	20
1978	−20	−17	14	7
1979	12	24	12	−3
1980	2	−20	−16	−3
1981	15	−20	7	−11
1982	−5	2	−5	0
1983	15	16	17	−4
1984	18	−5	20	10
1985	17	−1	17	5
1964–85 mean	9	6	7	4
Twice the standard error	5	6	3	4

Fig. 2 (grouped quint assessments) places more emphasis on extremes (quints 1 and 5) being correct; until recently, forecasts categorized into grouped quints showed less skill than did those categorized into quints.

Fig. 3 indicates that the rainfall forecasts have increased in skill to the same extent as those for temperature both in absolute skill and relative to persistence. In fact the skill of the three-category forecasts of rainfall (terces) and temperature (grouped quints) changes in a rather similar way throughout 1964–86. Fig. 2 suggests that a rather sudden marked improvement in predictions of extreme temperature occurred quite recently. Fig. 4(a) throws light on this result. It shows the 4-year running mean of the ratio of the number of quints 1 and 5 observed to the number forecast, irrespective of whether the forecasts were correct. This ratio increased suddenly from a near-constant value of about 0.2 between 1964 and 1980 to over 0.8 in 1982–85, i.e. the 'boldness' of the best-estimate temperature forecasts has recently quadrupled. Despite the increased boldness in 1982–85, the probability that a forecast of an extreme quint was correct was about the same as in 1964–80. The net result was a four-fold increase in the number of correct forecasts of quints 1 and 5 (Fig. 4(b)). This is encouraging, as skilful forecasts of extremes are probably of most use to customers. Note that the problem of lack of boldness in the forecasts and the need to tackle it was well recognized in the period of public issue, especially by Jenkinson (personal communication).

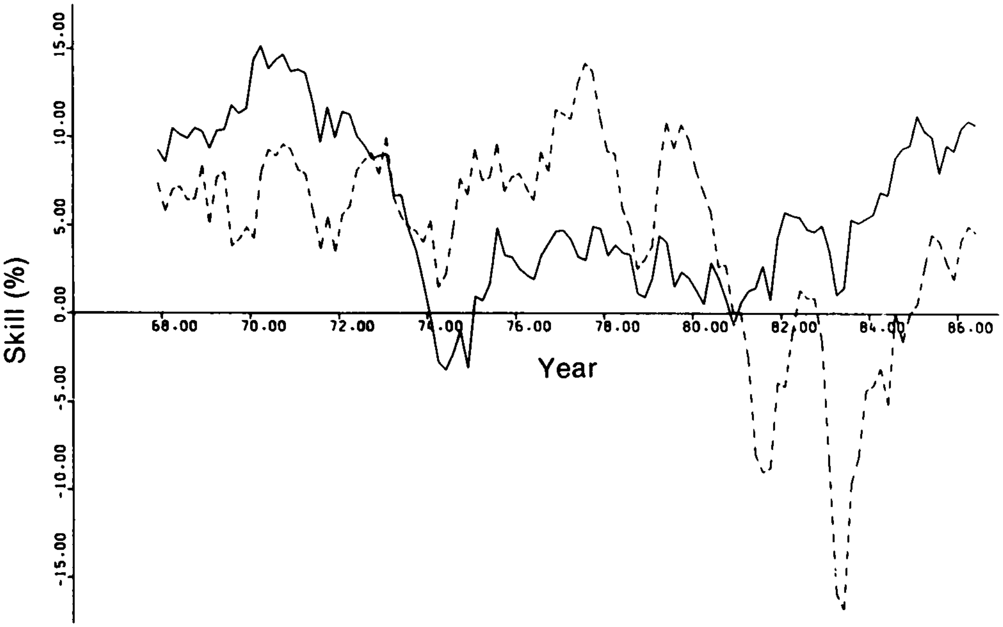


Figure 1. Four-year running mean skill of issued (——) and persistence (– – –) forecasts of temperature quints, based on the Folland–Painting system, plotted every two months. The last point plotted is for season 4 of 1982 to season 3 of 1986.

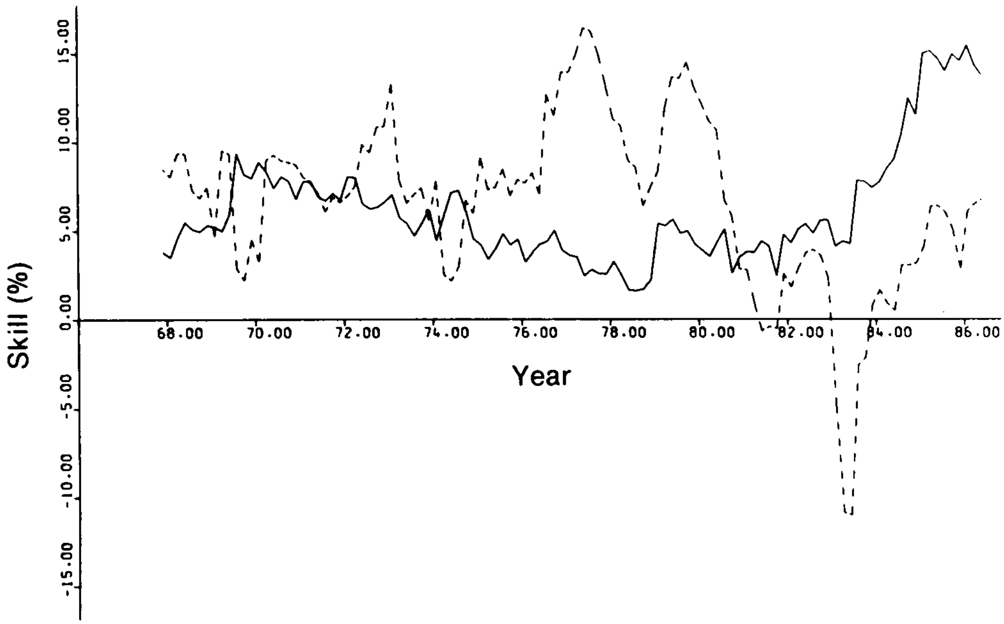


Figure 2. As for Fig. 1 but for grouped temperature quints.

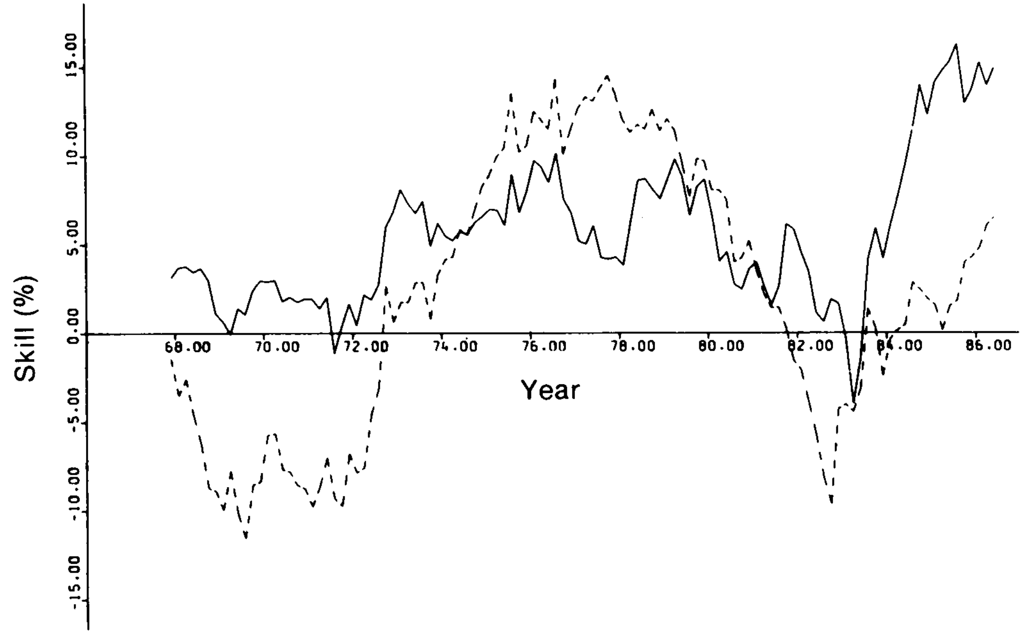
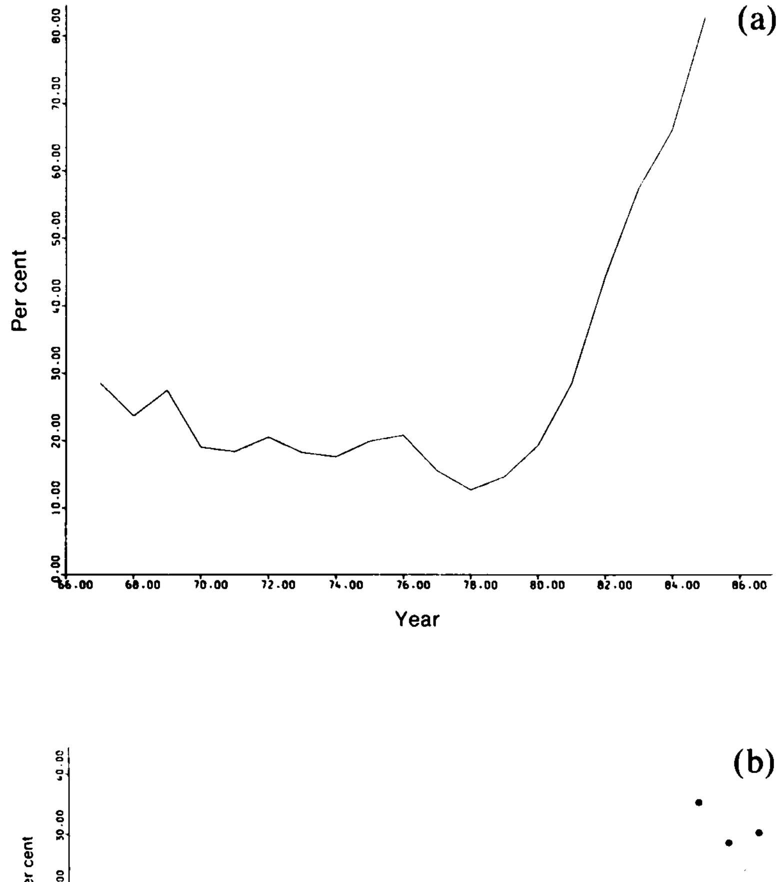


Figure 3. As for Fig. 1 but for rainfall terces.

There is still a strong tendency to forecast too many occasions of near-average rainfall (i.e. terce 2). Thus in 1982–85 the number of forecasts of terces 1 and 3 was only about 70% of the number observed — a percentage which was only a little more than in the period of public issue. Despite this, the likelihood that a forecast of terce 1 or terce 3 is correct appears to have increased (Fig. 5). Note that the chance percentage of such forecasts that are correct varies (mostly) with the number of terces 1 and 3 observed, though in the long run the chance percentage will be very near 33.3%.

Figs 6(a)–6(c) show how the skill of the issued forecasts has varied over individual districts. Four-year running-mean skill scores for all ten districts are shown, but for clarity only two are identified; district 5 (south-east and central southern England) and district 1 (eastern Scotland). District 5 has tended to have the least successful forecasts, especially in the 1970s. District 1 has generally more successful forecasts especially in the 1970s. Recently the skill scores have tended to vary less between the districts. The differences in the 1970s are important as Nap *et al.* (1981) and Baker (1982) draw rather over-pessimistic conclusions about the performance of UK long-range forecasts as a whole by analysing data only from district 5 during the 1970s.

The skill of monthly long-range forecasts also tends to vary with season (Table IV). Over the whole period 1964–86, the variations are not quite statistically significant, but they are appreciable. The correlation between the seasonal mean values of skill for temperature (quints) and rainfall (terces) is 0.85, which is statistically significant at the 5% level. It is too early to draw firm conclusions about recent trends in the pattern of seasonal forecast skill. So far, though, forecasts for the traditionally most skilful natural seasons (summer and winter) have contributed most to recent increases in skill, especially forecasts of temperature in winter and rainfall in summer. Over the last few years forecasts in spring have been least successful.



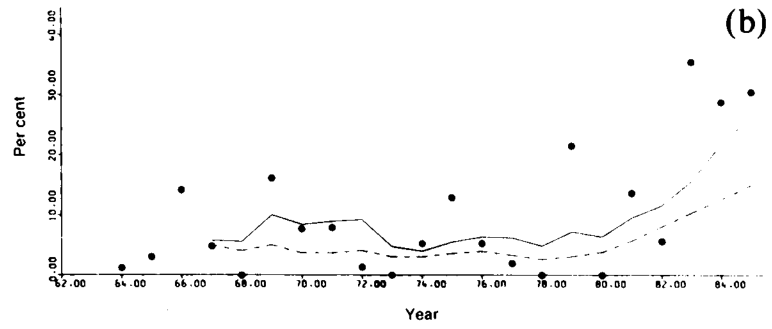


Figure 4. (a) Percentage of quints 1 and 5 forecast compared with number of quints 1 and 5 observed and (b) the percentage of observed quints 1 and 5 which were correctly forecast: individual years (•), four-year running mean (——), four-year running mean of chance percentage of correct forecasts of quints 1 and 5, given the number of quints 1 and 5 forecast (– – –).

(d) *PMSL forecasts for six grid points near the United Kingdom*

For each month, PMSL forecasts for the constituent medium-, mid- and long-range periods have been appropriately averaged to provide forecasts of mean monthly and half-monthly PMSL and PMSL anomalies (from a 1951–70 average) at each of the six grid points. Because the period available for testing is brief (the 4 years from July 1982 to mid-June/mid-July 1986) only a short summary of the results is given (Table V).

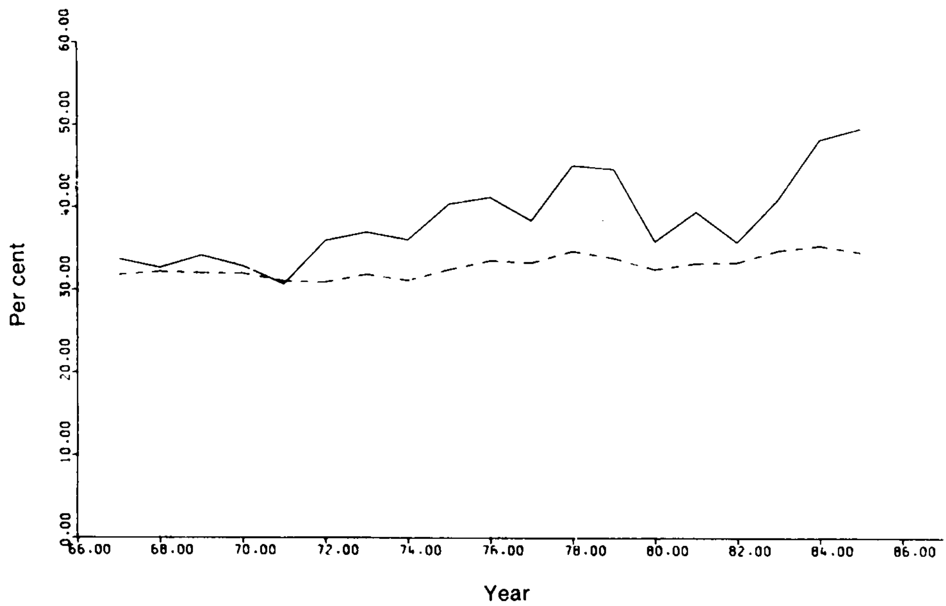


Figure 5. Four-year running mean of percentage of forecasts of rainfall terces 1 and 3 that were correct (——) and that expected by chance to be correct given the number observed (– – –).

The skill of the PMSL anomaly forecasts has been categorized according to the confidence levels C, D or E that accompany each forecast (the confidence scale runs from A (highest) to E (lowest), but only the range C to E is currently used) to provide an indication of whether these expressions of confidence made when the forecast is issued are meaningful. Four measures of skill are shown:

(i) A measure of the skill of the PMSL anomaly forecasts in predicting correctly the observed sign of the PMSL anomalies. This is called the 'sign skill' and is defined by:

$$SS = 100 \frac{(N_c - N_i)}{T}$$

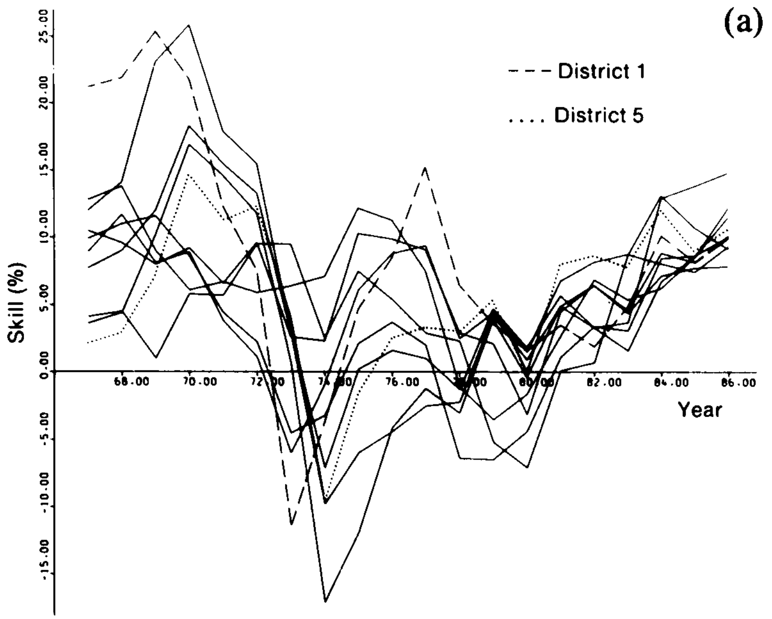
where N_c and N_i are the number of correctly and incorrectly forecast grid points respectively, and T is the total number of grid points forecast. This index has a value of zero when the numbers of correct and incorrect forecasts are the same. *SS* provides the same measures of skill as does the FP system when applied to two equi-probable observed and forecast categories (climatological probability 0.5 for each category).

(ii) The root-mean-square error of the PMSL anomaly forecasts, $(RMS)_F$ in millibars.

(iii) The root-mean-square error of forecasts assuming persistence of the PMSL anomaly observed in the previous month, $(RMS)_P$ in millibars.

(iv) The mean correlation, r_A between the forecast and observed PMSL anomalies. This is calculated as the grand average of correlations calculated for individual monthly forecasts (using Fisher's *z* transformation to help calculate the average (e.g. Snedecor and Cochran 1973)).

It appears that there is significantly more skill in the forecasts overall when the forecasters have most confidence (confidence C) in them at the time of issue. It is encouraging that the PMSL forecasts,



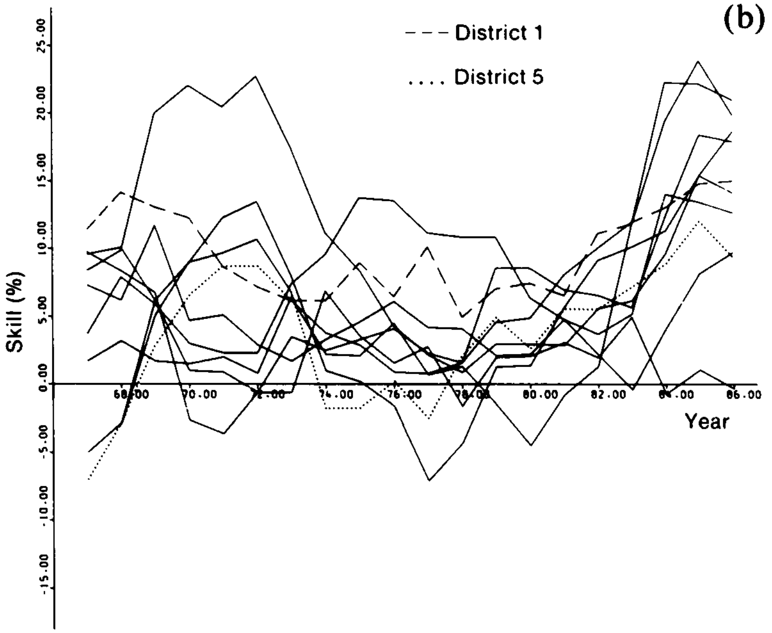


Figure 6. Four-year running mean skill of forecasts for all ten districts of (a) temperature quints, (b) grouped temperature quints and (c) rainfall terces. Districts 1 and 5 are highlighted.

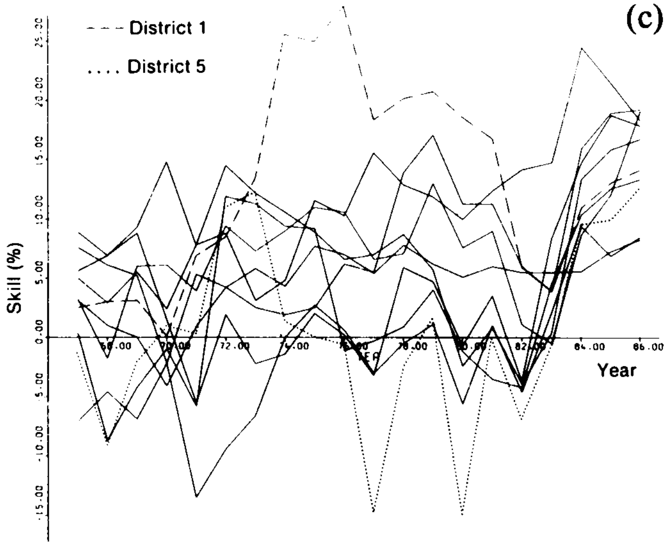


Figure 6 continued.

Table IV *Seasonal skill scores (percentages) of issued forecasts between 1964 and pre-summer 1986 compared with persistences, for all districts, using the Folland–Painting system*

Natural seasons (two months)	No. of forecasts*	Skill	Persistence skill
(a) Temperature (quints)			
Winter (Jan., Feb.)	92	10	5
Spring	92	5	6
Pre-summer	92	1	4
Summer	88	18	16
Autumn	88	2	3
Pre-winter	88	4	−8
(b) Temperature (grouped quints)			
Winter	92	11	3
Spring	92	6	16
Pre-summer	92	1	4
Summer	88	18	20
Autumn	88	−1	4
Pre-winter	88	1	−5
(c) Rainfall (terces)			
Winter	92	6	4
Spring	92	4	−2
Pre-summer	92	3	1
Summer	88	16	12
Autumn	88	7	5
Pre-winter	88	1	−3

* There are four overlapping monthly forecasts in each season in each year and a forecast for the ten districts in a given month is counted as one forecast.

Table V. *Summary of various skills for different confidences of forecast during recent years (see text for explanation of notation)*

	Confidence C	D	E	All	Twice standard error	Significance*
(a) Monthly mean PMSL forecasts						
No. of forecasts	17	46	33	96		
SS	75	23	16	30	19	1%
$(RMS)_F$ (mb)	4.31	6.21	6.32	5.96		
$(RMS)_P$ (mb)	6.82	8.21	8.79	8.19		
$(RMS)_F/(RMS)_P$	0.63	0.76	0.72	0.73		
r_A	0.34	0.16	0.27	0.23	0.17	
(b) Monthly temperature and rainfall — Folland–Painting skill scores						
Temperature (quints)	29	3	11	11		
Temperature (grouped quints)	23	6	17	14		
Rainfall (terces)	40	15	2	15		1%

* Using an analysis of variance on the three categories, and assuming $N/2$ independent monthly forecasts, where N = number of forecasts.

Note: $(RMS)_C$, the root-mean-square error of a forecast of climatology, is about $0.75 \times (RMS)_P$ in principle, so is harder to improve on than persistence. However, the values of *SS* and r_A for climatology forecasts are in principle zero, illustrating the difficulty of scoring long-range forecasts expressed in ordinary scientific units.

Twice the standard error is calculated assuming $N/2$ independent monthly forecasts.

especially, hint at this relationship. Table V indicates, therefore, that an overall measure of consistency exists between the skill of the different elements of the forecasts and the quality of the evidence used to construct them. This is perhaps one of the best pieces of scientific evidence so far available that long-range forecasting can be done at all, that predictability does vary and that the user, to a limited extent, can decide on which forecasts to place more reliance. However, the user is most likely to benefit from applying this knowledge over an extended period.

4. Variation of skill throughout the monthly forecast

High skill in the medium range (days 1–5) will clearly tend to raise the skill of the forecasts averaged over the month as a whole. So a false impression could be gained of trends in skill in the truly long range from changes in monthly average skill alone. Table VI gives a preliminary indication of the variation of sign skill, *SS*, for different periods within the monthly forecasts since the data were first available in a homogeneous form (July 1982). *SS* is applied to best-estimate forecasts of temperature anomaly and rainfall percentage on the medium, mid (day 6–mid-month) and long (second half-month) ranges and to PMSL forecasts for the two individual half-months and for the whole month. *SS* is a very basic measure of skill, being based on only two categories, and will generally give larger values of skill than a more searching terce or quint scheme. It is adequate to show, though, whether skill exists at all.

To increase the number of forecasts available for assessment, the forecasts for each district are used. However, adjustments have then been made to the nominal number of district forecasts to allow for their lack of statistical independence. These adjustments are made separately for temperature and rainfall forecasts and allow for the correlation of observed district-averaged anomalies (a) in space (between districts) and (b) in time (due to the persistence and, sometimes, overlap of observed conditions in successive forecast periods); the details are described in Appendix 2. The procedure entails the introduction of the factor f_i, whose form is derived in Appendix 2, which is used to reduce the apparent number of forecasts summed over all districts; f_i is shown in Table VI for each forecast period i within the month.

Table VI. *Sign skill (SS) of forecasts for periods within a month for the period July 1982 to mid-June/mid-July 1986 (see text for explanation of notation)*

	Medium range	Mid range	First half-month	Second half-month	Mid and long ranges	Whole month
(a) PMSL*						
SS	—	—	34	8	—	30
(b) Temperature						
SS	43	6	21	8	9	16
Significance	10^{-3}%	—	2%	—	—	10%
f_i	0.115	0.109	0.109	0.110	0.103	0.102
(c) Rainfall						
SS	35	13	26	20	20	25
Significance	5×10^{-4}%	10%	2×10^{-1}%	1%	5%	1%
f_i	0.117	0.151	0.149	0.149	0.136	0.133
D_iN_i	960	960	960	960	960	960

* No significance tests available.

Note: The percentage of forecasts having the correct signs of their anomalies is given by 50 + 0.5 *SS*.

Table VI shows that, on the monthly time-scale, the number of statistically independent district forecasts is typically only about 10–15% of the number issued . This number (for a month) is considerably less, for example, than that cautiously assumed by Hardy (1980). Estimates of the statistical significance of *SS* are based on two tests. Firstly a χ^2 test (Snedecor and Cochran 1973) is used to indicate whether the tendency to forecast correctly the sign of the observed anomalies is statistically significant after allowing for the actual number of observations and forecasts, of both signs, of the anomaly. For rainfall, the two categories of opposite sign are above and below 100% of average rainfall respectively. Allowance was also made for a marked tendency to forecast exactly 100% of average rainfall or zero anomaly of temperature in the mid range or long range. These are regarded, in principle, as neither correct nor incorrect.

A second test, based on the binomial distribution, is used to show whether the observed fraction of forecasts having the correct sign of the anomaly is significantly larger than the chance value, which is assumed to be 0.5. Both tests give similar results and only their average indication of statistical significance is reported.

The following important conclusions can be deduced from Table VI:

(i) There can be no doubt that the forecasts have appreciable skill in the medium range (days 1–5 of the forecast which are in practice usually days 2–6 or 3–7 ahead). The skill value of 43% observed for temperature implies that over 71% of the district temperature forecasts had the correct sign between July 1982 and mid-June/mid-July 1986 (since January 1985 the number with correct sign has averaged nearly 80%).

(ii) The rainfall forecasts tend to be better than the temperature forecasts except in the medium range: Table VI has the advantage of providing the same, if very basic, measure of skill for both parameters so that a direct comparison of skill is possible. The extra skill of the rainfall forecasts is clearer in the second half-month ahead (long range), when it is apparently statistically significant. However since summer 1985 the temperature forecasts have been more skilful, possibly related to the increased use of information about sea surface temperature anomalies near the UK coast (Folland and Woodcock 1986).

(iii) The average structure of sign skill through the monthly forecasts is unexpectedly complex. Thus the skill of the rainfall forecasts on the monthly time-scale is unexpectedly large (25%) when compared with the medium-range time-scale (35%) and is unexpectedly small (smallest) in the mid range (13%). However, mid-range skill has apparently improved over the last year. There is a marked overall tendency for the skill averaged over a longer forecast period to be larger than its weighted average over constituent shorter periods. This is a regular feature even in tables (not shown) for individual years constructed in the same way as Table VI, despite large interannual variations in other details of the skill. This tendency may result from timing errors in the forecasts which are likely to reduce skill more strongly on shorter time-scales than on longer ones — a feature worth closer scrutiny since it could affect the perception of 'predictability' and the design of future forecasting systems.

5. Conclusions

Despite a substantial reduction in staff effort, the use of a small number of improved forecasting techniques and the creation of a more structured forecasting procedure appear to have recently resulted in a modest improvement in skill. Skill of course is still low and it remains to be seen whether the improvement can be maintained; past history demonstrates that fluctuations in skill are almost inevitable in the future. It is hoped that current efforts to (a) introduce regular dynamical forecasts in the longer ranges, (b) to intensify research into the dynamics and statistical description of low-frequency weather variability and (c) to exploit information contained in world-wide sea surface temperature anomaly patterns, may allow further slow improvements in technique and performance to take place.

6. Acknowledgements

The authors would especially like to thank K. Shone, B.N. Parker and J. McCoy for their past help in developing the computerized assessment system and D.E. Jones and N. Ward for numerous discussions about the performance of long-range forecasts.

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Appendix 1 *The FP scoring system for long-range forecasts*

The fundamental basis for the FP system arose from an unpublished suggestion by Kirk around 1970 that information theory might provide a more flexible and satisfactory approach to assessing long-range forecasts. This is currently a matter of debate (e.g. Daan 1985). The initial development of Kirk's ideas was carried out by Painting (personal communication) in 1975. The FP system can provide a variety of diagnostics about forecast performance (both best-estimate and probability forecasts). Here attention is concentrated on deriving the Tables I(a)–I(c) used to estimate the skill of best-estimate forecasts.

Fig. A1 shows a hypothetical probability distribution of, say, monthly mean temperature in a given district and calendar month derived from many years of historical data. A best-estimate forecast, X_F, is made in one of the categories shown (which need not have the same size) and the category in which the verifying observation, X_A, falls is noted. The 'distance' between X_F and X_A is defined as the area, S_{FA}, under that part of the probability curve that lies between, and includes, the categories into which X_F and X_A fall. The information content of the forecast is then defined as:

$$I = -\log_e (S_{FA}). \qquad \text{(A1.1)}$$

This definition is related to the idea of the 'self information' of an event in information theory (Jones 1979). It is possible to calculate I for all combinations of forecast and observed values to provide a table of information values. Table A1 shows the resulting information values I_{ij} ($i = 1$ to 5, $j = 1$ to 5) for (equi-probable) forecasts and observations of quints. Note that $I = 0$ for a forecast of quint 5 and an observation of quint 1 which, quite naturally, has no information content.

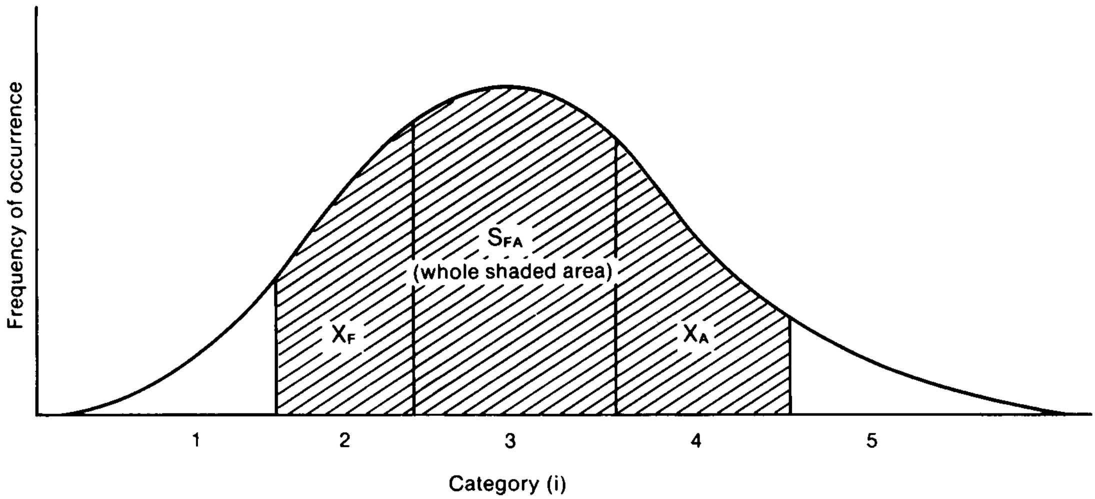

Figure A1. The basis of the Folland–Painting system using a probability curve. X_F and X_A are respectively the forecast and observed values for a variable X, and S_{FA} is the area under the probability curve that lies between, and includes, the categories into which X_F and X_A fall. The five categories (i) into which X_F and X_A fall do not necessarily have equal areas under the probability curve.

Table A1. *Information scores for forecast and observed quints using the Folland–Painting system*

Forecast	Observed 1	2	3	4	5
1	1.61	0.92	0.51	0.22	0
2	0.92	1.61	0.92	0.51	0.22
3	0.51	0.92	1.61	0.92	0.51
4	0.22	0.51	0.92	1.61	0.92
5	0	0.22	0.51	0.92	1.61

It is desirable for scientific purposes to provide a set of information values I'_{ij} whose average would be zero if the forecasts were unrelated statistically to the observations. This can be done, e.g. for a set of quint categories, by making a long series of forecasts where the quint categories of successive forecasts are chosen using a random number generator which operates on a uniform distribution of numbers in the range 1 to 5. The expected result of this operation can be achieved using a standard mathematical result:

$$I'_{ij} = I_{ij} - \frac{\sum_{i=1}^{5} P_{ij/j}.I_{ij}.\sum_{j=1}^{5} P_{ij/i}.I_{ij}}{\sum_{i=1}^{5}\sum_{j=1}^{5} P_{ij}.I_{ij}} \quad \ldots \ldots \ldots \ldots \ldots \quad \text{(A1.2)}$$

where P_{ij} is the chance probability of an observation of category i and a forecast of category j, $P_{ij/j}$ is the chance probability of category ij happening given that the forecast category j occurred etc. We note also that in the quint table:

$$\sum_{i=1}^{5} P_{ij/j} = \sum_{j=1}^{5} P_{ij/i} = 1. \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad \text{(A1.3)}$$

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THE METEOROLOGICAL MAGAZINE

1986 *Volume 115*

INDEX

	Pages		Pages
January	1–36	July	189–228
February	37–64	August	229–268
March	65–100	September	269–300
April	101–132	October	301–336
May	133–160	November	337–376
June	161–188	December	377–412

Published for the Meteorological Office by Her Majesty's Stationery Office

The resulting values, I'_{ij}, are called the 'effective information gain' values above a (random) chance level. To help comparison with the older Sutcliffe scoring system, we normalize the effective information gain values to a new set, S_{ij}, so that the long-term average score for a correct forecast is 4 (allowing for the long-term probabilities of each correct category; in a quint scheme these are 0.2 for each correct category). Tables I(a)–I(c) result from appropriate applications of this procedure, and assume that the forecasts and observations of each category are made with their expected probabilities (i.e. 0.2 for forecasts and observations of quints and 0.333 for those of terces). In recent years these assumptions have been reasonably acceptable for quints but before 1981 the number of forecasts of extreme temperature (quints 1 and 5) was consistently much too low, only about 1/5 of the number observed (see also section 3(b)). The problem will be discussed in a future paper; it is enough to note that the FP system can automatically be adjusted (via equation (A1.2)) to deal with this problem. Flood and Weller (1969) provide an interesting discussion of the possible consequences for skill when the Sutcliffe scoring system is not adjusted to allow for an insufficient number of forecasts of extremes.

Appendix 2 *Calculation of the equivalent number of independent district forecasts*

Let there be N_i forecasts for a given period i within the month (including the month itself) made over a period of time for D_i districts. The total of D_i times N_i forecasts is modified to an equivalent number of independent forecasts N'_i given by:

$$N'_i = a_i D_i b_i N_i = f_i D_i N_i$$

where $f_i = a_i b_i$ and b_i is the reducing factor that estimates the effective number of independent forecasts made through time for a given district due (mainly) to the persistence of observed anomalies between successive forecasts, and a_i is the reducing factor that estimates the effective number of independent districts mainly because of the high spatial correlation of observed anomalies between districts. Thus $a_i < 1$ and $b_i < 1$. The high spatial correlation of temperature and rainfall anomalies means that the number of truly independent districts is much less than the ten for which forecasts are made. Using data for the period July 1982 to mid-June/mid-July 1986, estimates of a_i were made using the formula (Yevjevich 1972):

$$a_i = \frac{D_i}{K_i(D_i - 1)\,\bar{r}_i + 1}$$

where $\bar{r}_i$ is the average correlation of the observed anomalies in each district with those in every other district and K_i is a complex factor that allows for the variation in the standard deviation of the temperature anomalies or rainfall percentages between districts and between different months of the year and has a value of a little below unity. The value of a_i varies only slowly with the choice of forecast period i and averages rather over 0.1 for temperature and about 0.15 for rainfall. The value of b_i has been estimated from the following approximate expression adapted from Yevjevich (1972):

$$b_i = \frac{N_i}{1 + 2(\bar{r}_{1i}{}^2 + \bar{r}_{2i}{}^2 + \bar{r}_{3i}{}^3)}$$

where $\bar{r}_{1i}$ is the average correlation (over all districts) of observed anomalies (for given forecast period length i) in successive forecast periods, $\bar{r}_{2i}$ is the average correlation of observed anomalies with those in the next but one forecast period, etc. Values of $\bar{r}_{4i}$ and beyond were insignificantly different from zero for all lengths of forecast period within the month and so were not used.

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Snow forecasts from the Meteorological Office fine-mesh model during the winter of 1985/86

By T. Davies and Olive Hammon
(Meteorological Office, Bracknell)

Summary

The performance of the Meteorological Office fine-mesh model in forecasting snow during the winter of 1985/86 is examined. The snow predictor currently used in the model is compared with other possible predictors to see whether an alternative predictor could provide more precise guidance.

1. Introduction

The fine-mesh model is one of the important sources of guidance for forecasters in the United Kingdom and, in his assessment of the current state of short-range weather forecasting, Woodroffe (1984) states that the model is the best tool at the forecaster's disposal for forecasting snow 24 hours or so ahead. A basic description of the fine-mesh model can be found in an article by Gadd (1985).

The forecasting of snow is a two-stage process. The first stage is to decide whether or not precipitation is likely, and the second stage is to forecast the temperature structure of the near-surface layer of the atmosphere. This second stage compounds the forecasting problem since small temperature errors may imply the wrong form of precipitation. The main purpose of this paper is to examine the performance of the fine-mesh model with regard to the second stage, but firstly, a few remarks are required as to the quality of the model's precipitation forecasts.

The fine-mesh model is a grid-point model with a grid length over the United Kingdom of about 75 km. As a result of approximations used in the modelling process, accurate detail cannot be achieved on a scale below one or two grid lengths, about 100 km. The enhancement of precipitation due to orographic effects and local convection cannot therefore be simulated realistically by the model.

Errors of about one grid length in forecasting precipitation are often unimportant as the movement of systems makes them appear as minor timing errors. However, in slow-moving or quasi-stationary situations, such an error can imply the wrong character of weather for a whole region, but even with this degradation, the fine-mesh model has proved to be very useful in assessing the general distribution and amounts of rain. Up to the winter of 1985/86 there was no regular objective verification of precipitation forecasts from the model, though since 1962 a partially objective statistic has been produced in the Central Forecasting Office (CFO) at Bracknell based on the forecast of precipitation for London made by the senior forecaster (Woodroffe 1984, Flood 1985). This statistic shows that the skill of the forecast does appear to have improved in recent years and this improvement is mainly attributed to the increased accuracy of fine-mesh model guidance.

2. Snow prediction

Whether snow melts or not before reaching the ground depends on the temperature and humidity near the surface and the rate of precipitation. Forecasting the low-level atmospheric structure is difficult and to overcome this, attempts have been made to identify snow predictors which can be forecast more readily. For example Boyden (1964) examined a number of predictors giving the probability of snow and recommended the use of the 1000–850 mb thickness corrected for mean-sea-level pressure (MSL) by adding a factor (MSL−1000)/4; this predictor will be referred to as 1000–850 P henceforth. A further correction for station height is also required (arrived at by subtracting station height in metres divided by 30).

The 1000–850 P has become one of the most widely used predictors chiefly because it is usually not too difficult to predict the 1000–850 mb thickness. With the advent of the 10-level model, and in particular the limited-area version (the rectangle), it was appreciated that the model forecast of the 1000–850 mb thickness was reliable enough for the predictors to be displayed as part of the model output. Therefore the 1000–850 P was used to show the probability of snow occurring by adding lines of snow probability (80%, 50% and 20%) to the form of output used by the forecaster. The use of the snow-probability lines based on 1000–850 P has continued with the introduction of the higher-resolution fine-mesh model. The snow-probability lines are mean-sea-level values which need to be adjusted to suit local terrain. However the fine-mesh model orography is too smooth (because the grid length is insufficient to resolve local detail) to make realistic adjustments to the snow probability at each grid point. Fig. 1 shows the orography currently used by the fine-mesh. There are many places where the model orography differs substantially from reality. Note for example, the absence of valleys.

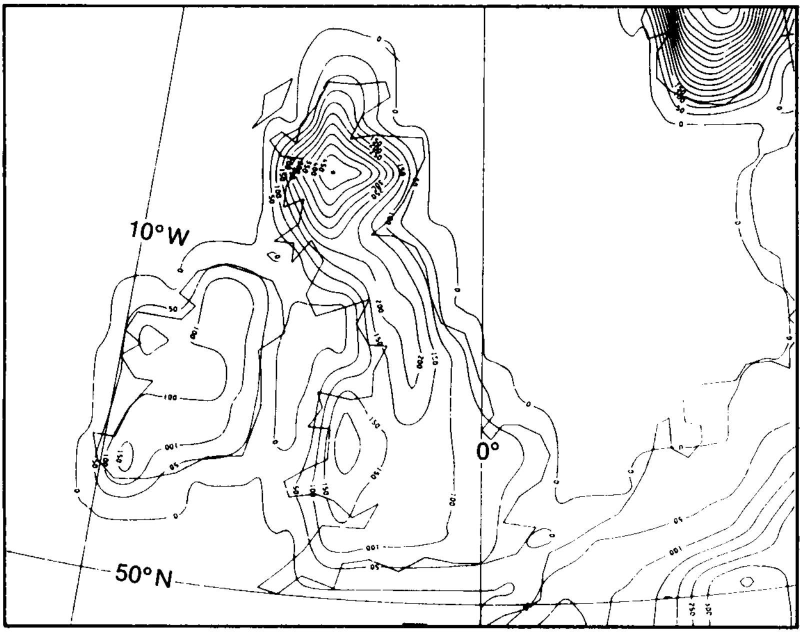

Figure 1. Part of the operational fine-mesh orography. Lines drawn every 50 metres.

Forecasters in CFO have recognized for some time that in the case of precipitation ahead of active warm fronts, the 1000–850 P predictor underestimates the probability of snow. The 20% snow-line in such instances is usually interpreted as defining a 50% actual probability of snow (Hunt 1985). The discrepancy is not a result of model errors in forecasting the 1000–850 mb thickness. Indeed, since the 1000–850 mb thickness of 1300 gpm (corresponding to a 20% probability of snow when MSL is 1000 mb) is considered to be important, the forecaster in CFO has forecast charts of 1000–850 mb thickness available so that they can be examined in marginal situations and used for forecasting snow over high ground.

Boyden pointed out possible reasons for the failure on some occasions of 1000–850 P as a predictor. Firstly, the layer of air above the freezing level contributes to the thickness but is not relevant to the form of precipitation. Secondly, the 1000–850 mb thickness is relatively insensitive to the lowering of the freezing level caused by melting snow. Both factors taken together are important when considering active warm fronts, particularly in situations where an inversion just above the surface is undercut by very cold air.

The efficacy of 1000–850 P as a predictor is partly due to the experience and skill of the user. However, major snowfall events are often finely balanced, particularly in southern Britain on occasions when warm air from the south-west comes up against very cold and dry continental air. When using 1000–850 P, many forecasters compensate for warm fronts as well as attempting to assess the likely structure of the low-level air by studying upstream dew-points and temperatures.

In practice a single-valued predictor would be more helpful. If a representative upper-air ascent is available or the low-level structure can be forecast, many forecasters choose to use the wet-bulb freezing level as a predictor. In an operational trial of snow predictors, Lowndes *et al.* (1974) suggested that the wet-bulb freezing level was the most efficient predictor. To make effective use of wet-bulb freezing level or any other predictor relying on information close to the surface in a numerical model requires an accurate simulation of the near-surface layers. Before the winter of 1985/86, forecast surface and boundary-layer temperatures from the fine-mesh were not accurate enough, but the introduction of a scheme for modelling the soil heat flux has improved the forecast temperatures markedly. It is therefore worthwhile examining some other predictors to see whether their performance matches that of 1000–850 P.

3. A comparison of snow predictors using the fine-mesh model

The only routine verification of snow forecasts produced by the fine-mesh model is a subjective assessment made by the senior forecaster in CFO of the 24-hour forecast. The assessment is based on the position of the snow-probability lines over the United Kingdom and on the forecast precipitation area. It is made only when the forecast pressure pattern is considered to be good, so that cases of incorrect model evolution over the United Kingdom are excluded. The performance of the model during the period 26 December 1985 to 7 April 1986 is summarized in Table I.

Table I. *CFO subjective assessment of fine-mesh snow forecasts at T+24 hours, during the period 26 December 1985–7 April 1986*

Score	Criteria	Number of forecasts
A	Snow well forecast	28
B +/−	Snow slightly over/under estimated in amount or extent	47
C +/−	Snow badly over/under estimated in amount or extent	29

Considering the 29 forecasts scored as 'C', 14 underestimated amounts of snow, 8 overestimated and the remaining 7 were a combination of precipitation error and forecast thickness error. The majority of forecasts scored as 'C' were due mainly to errors in precipitation rather than thickness, and several others to the model's underestimation of areas of very light snow during February. These results show an encouraging degree of skill (over 70% score A or B, excluding cases with major evolution errors) in the prediction of snow.

It was not possible to reproduce the above verification using other predictors so an objective comparison has been made using 11 cases from the period covered by the above assessment. These

11 cases were chosen because on each occasion the forecasting of significant snowfall was finely balanced. The predictors examined were as follows:

(a) 1000–850 P.
(b) Dry-bulb freezing level.
(c) Wet-bulb freezing level.
(d) Mean temperature of the lowest 100 mb above the ground.

Table II shows the probability of snow for particular values of the first two predictors derived by Boyden. The difference between 30% and 70% snow probability using 1000–850 P is less than 10 gpm. For this predictor to be useful, the fine-mesh model needs to forecast the 1000–850 mb thickness within 1% accuracy. The forecast values at T+24 hours of the 1000–850 mb thickness at nine UK/Irish upper-air stations were compared with the actual radiosonde values in the 11 cases assessed. The mean error was found to be 1.5 gpm and the root-mean-square (r.m.s.) error 6 gpm — comfortably within the range required. In one case thickness errors greater than 10 gpm were found to be due to an inaccurate evolution.

Table II. *Snow probabilities derived from values of the 1000–850 mb thickness and dry-bulb freezing level*

Percentage probability of snow	90	70	50	30	10
1000–850 P (gpm)	1281	1290	1293	1298	1303
Dry-bulb freezing level (mb)	12	25	35	45	61

To use the dry-bulb freezing level as a predictor, the model needs to predict the freezing level to within 20 mb. Lowndes *et al.* (1974) derived values for wet-bulb freezing levels for showery and non-showery precipitation which show even less margin for error. Comparison of forecast dry- and wet-bulb freezing levels at T+24 hours with radiosonde values for the 11 chosen cases gave the following results. For the dry-bulb freezing level the mean error was found to be 15 mb and the r.m.s. error 26 mb; for the wet-bulb freezing level the mean error was found to be 20 mb and the r.m.s. error 29 mb. The percentage of forecasts correct within 20 mb was 72% for the dry-bulb freezing level. These figures demonstrate that the freezing level in the model is not sufficiently reliable to use as a predictor for snow.

The mean temperature of the lowest 100 mb above the ground, (known as M100 henceforth) has recently been suggested as a possible snow predictor. However M100 would need to be corrected if the fine-mesh orography differed significantly from the actual orography. Suggested values for this predictor, derived from comparison with observations by W. Hand (personal communication) are shown in Table III.

Table III. *Mean temperature of lowest 100 mb above ground used to predict type of precipitation at the surface*

Mean temperature of the lowest 100 mb above ground (°C)	Precipitation type at surface
Less than −1.5	Snow
−1.5 to 0.5	Sleet
More than 0.5	Rain

In tests using M100, the 0.5 °C isotherm gave useful guidance for the position of the rain/sleet boundary, but −0.5 °C seemed more appropriate for the sleet/snow boundary than the −1.5 °C suggested. This is perhaps evidence of a slightly warm bias in the model at low levels.

4. The predictors in action — fine-mesh model case study, 7 January 1986

By 06 GMT on 7 January, a warm front was approaching south-west England, bringing moderate or heavy rain and sleet to southern Cornwall. As the front continued to push slowly northwards, the rain soon turned to snow and sleet inland, especially over the higher ground in southern England and Wales. The snow reached the Midlands during the afternoon and extended into East Anglia and north-west England during the evening. Over southern England and South Wales the snow did not last long and was followed by rain or sleet, but further north the snow persisted. Fig. 2 shows the synoptic situation at 18 GMT, with the heaviest snow over the Midlands. During the evening, the warm front became quasi-stationary from Sussex to central Wales, with moderate or heavy snow to the north of this line.

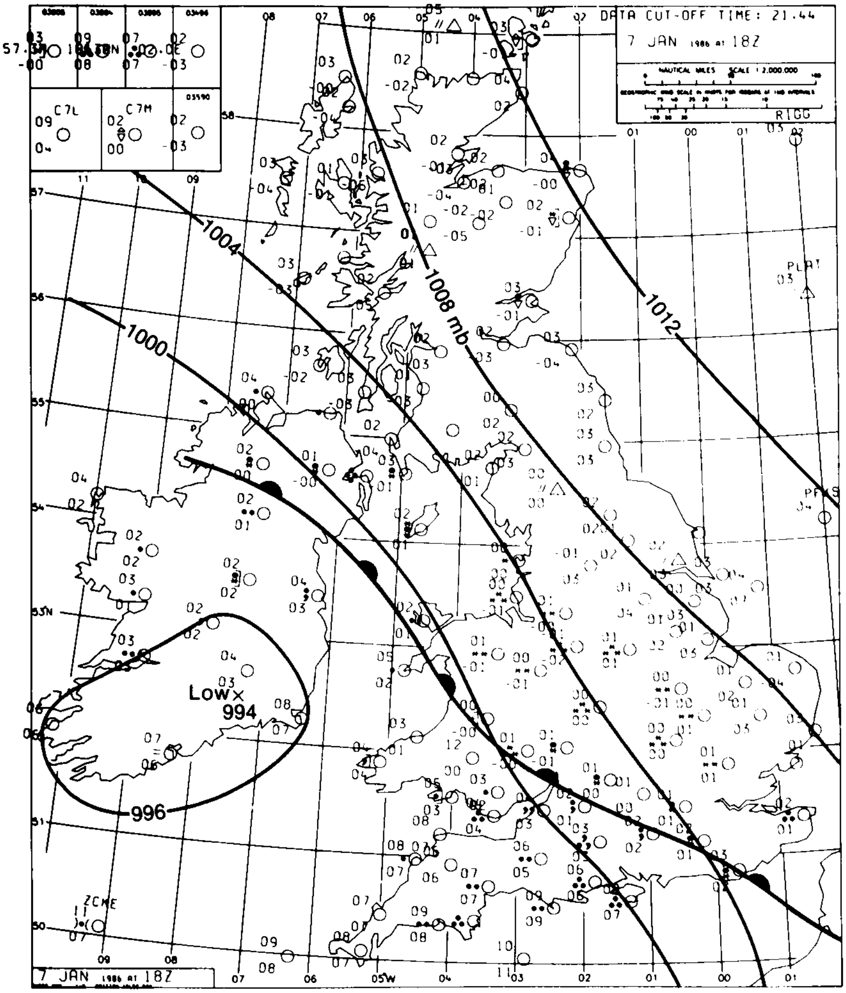

Figure 2. The synoptic situation at 18 GMT on 7 January 1986.

The fine-mesh forecast from data time 12 GMT on 6 January predicted these developments and enabled forecasters to issue advanced warnings of snow with a high degree of confidence. Fig. 3 shows the fine-mesh model's forecast precipitation area and snow-probability lines for 18 GMT on 7 January.

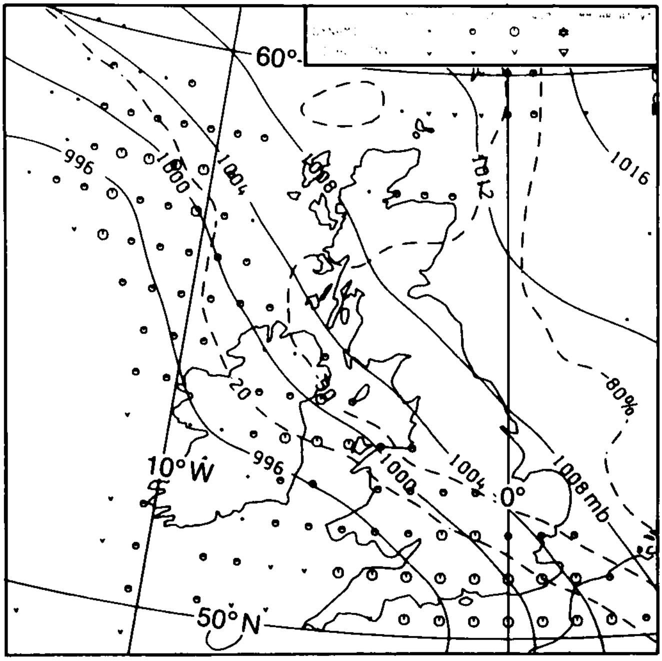

Figure 3. Fine-mesh 30-hour forecast of surface pressure and intensity of precipitation for 18 GMT on 7 January 1986. The pecked lines are snow probabilities.

This was a very good 30-hour forecast from the fine-mesh model with an accurately forecast precipitation area. The only defect is that the area of heavier precipitation does not extend far enough northwards into the Midlands, but the model is only one grid length in error. The evolution is correct and errors in the forecast 1000–850 mb thickness at 12 GMT on 7 January and 00 GMT on 8 January were very small. From Figs 2 and 3 it can be seen that the observed snow area lies between the forecast positions of the 20% and 50% snow-probability lines. For the area of heaviest precipitation over the Midlands, a correction of 1 to 4 gpm must be subtracted from the 1000–850 P to allow for station height above mean sea level. This effectively increases the forecast probability of snow to 50% or more and is excellent guidance for the Midlands, received more than 24 hours in advance. Figs 4 and 5 show the model's prediction for the height above mean sea level of the dry- and wet-bulb freezing levels respectively. Values greater than 2000 feet have been shaded to indicate areas of low risk of snow. Over the Midlands, for example, both the dry- and wet-bulb freezing levels are less than 1000 feet, giving an indication of the wintry precipitation expected. The main error is over Sussex and Kent, where forecast freezing levels of 1500 to 2000 feet indicate that the model had pushed the warm air slightly too far east. The fine-mesh model's 1.5 m screen temperature forecast for 18 GMT is shown in Fig. 6. Only the 0–3 °C isotherms have been shown, with the shaded area indicating temperatures greater than 3 °C. Forecast temperatures over the Midlands and much of Wales were 0–1 °C; an accurate forecast which would have helped to confirm the probability of snow rather than rain. Fig. 7 shows the critical values of the M100 snow predictor. The forecast positions of the 0.5, −0.5 and −1.5 °C isotherms are shown,

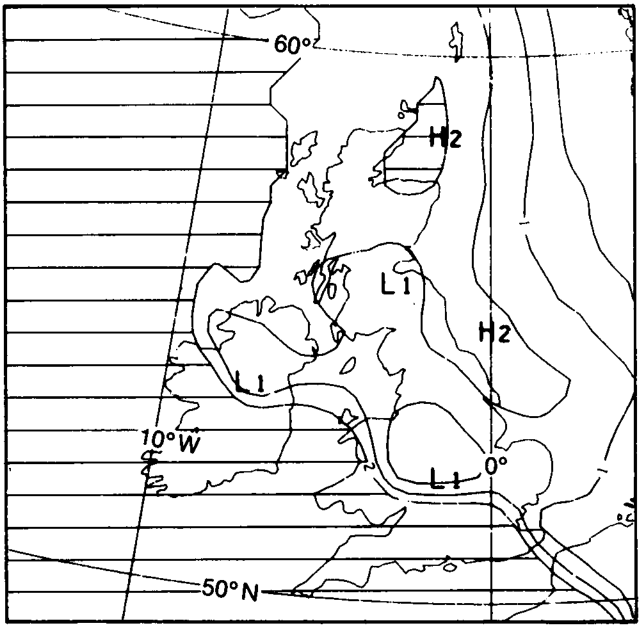

Figure 4. Fine-mesh 30-hour forecast of the height of the dry-bulb freezing level for 18 GMT on 7 January 1986. Isopleths are labelled in thousands of feet with the shaded area > 2000 feet.

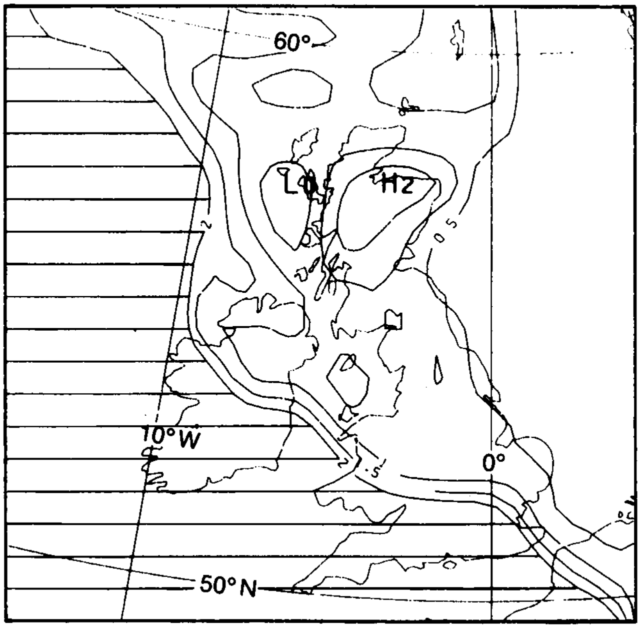

Figure 5. As Fig. 4 but for wet-bulb freezing level.

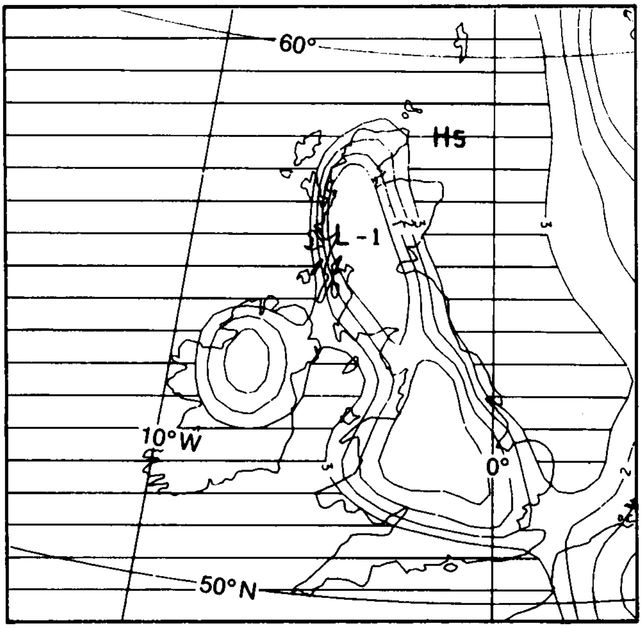

Figure 6. Fine-mesh 30-hour forecast of the 1.5 m temperature for 18 GMT on 7 January 1986. Isopleths are degrees Celsius and shaded area > 3° C.

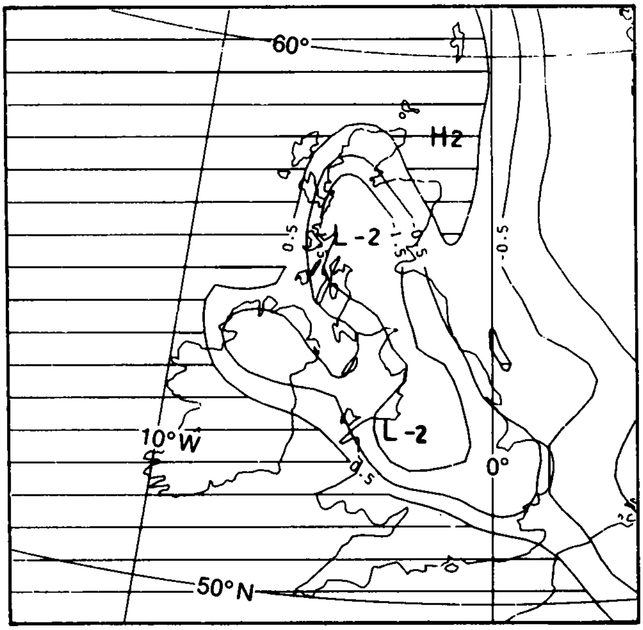

Figure 7. As Fig. 6 but for mean temperature of the lowest 100 mb. Shaded area is > 0.5 °C.

whilst the shaded area indicates a temperature of more than 0.5 °C. Bearing in mind that a small negative correction must be made to the value over Wales due to inaccurate fine-mesh orography, the position of the 0.5 °C isotherm accurately marks the boundary between rain and sleet, whilst the −0.5 isotherm gives the sleet-snow boundary. The −1.5 °C isotherm suggested from comparison with observations is too far north in this case.

This was one of the best fine-mesh snow forecasts of the winter and it gave good guidance of probable snow areas 24 hours in advance. The main error was over Sussex and Kent where the model guidance was for rain rather than sleet. However, the borderline nature of the weather in this area was indicated by the report of moderate to heavy sleet on the south coast with a temperature higher than at Manston in Kent where moderate rain was reported.

5. Conclusion

The 1000–850 mb thickness, adjusted for mean-sea-level pressure, appears to be the most useful predictor of snow when used with the fine-mesh model. The main advantage over other predictors is in the model's accuracy in forecasting the 1000–850 mb thickness. However, because there is a wide range of values over which the transition from rain to snow may occur, much of the success of 1000–850 P depends upon the experience of the user. The other predictors examined have a smaller range of values over which the transition from rain to snow may occur, but the fine-mesh model is not yet able to forecast these predictors as accurately as 1000–850 P.

Further improvements in the modelling of the boundary layer are envisaged in the near future, and the performance of the predictors will be re-examined. On the scale of the fine-mesh, it is unrealistic to expect a definitive solution in finely balanced situations. This may be of small comfort to the airfield forecaster, forecasting for more than 12 hours ahead, but the advent of higher-resolution mesoscale models may improve matters.

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551.594.52

Report on the sighting of aurora borealis at Royal Air Force Lyneham

By P.J. Smith

(Meteorological Office, Royal Air Force Lyneham)

Auroras are caused by a stream of charged solar particles (the solar wind) being focused by the earth's magnetic field. As the particles enter the high atmosphere they collide with the molecules of the various atmospheric gases which then become 'excited', i.e. the molecules change their internal energy state. When they subsequently decay to their normal energy state they emit packets of energy at visible wavelengths, usually red, green or yellow. This release of energy is often organized and the resulting patterns are in the form of rays or curtains of coloured light. A more detailed discussion of auroras can be found in Falck-Ytter (1985)*.

Auroral displays are usually found in the zone between 65 and 70° latitude. Occasionally they form at lower latitudes, but it is rare for displays to be clearly visible in southern England. It was therefore with great interest that I watched a spectacular auroral display from Lyneham Meteorological Office (51° 30′N, 01° 59′W) during the night of 8/9 February 1986. There was little cloud and the visibility was good, between 6 and 10 km. I was the only observer, with obligations to Air Traffic Control, so my observations of the aurora are necessarily simplified and generalized with only approximate times. Also, since the aurora displayed a great variety of activity, I have endeavoured to report only the major changes.

At 2020 GMT a homogeneous arc appeared from the west-north-west to the north-east, faint, white in colour and at an elevation of about 5°. By 2035 GMT the display had developed into a rayed arc, moderately bright, pale green in colour and with several small rayed bands separate to, but overlapping, the base of the arc (Fig. 1(a)). At 2100 GMT it faded to a faint homogeneous arc, north-north-west to

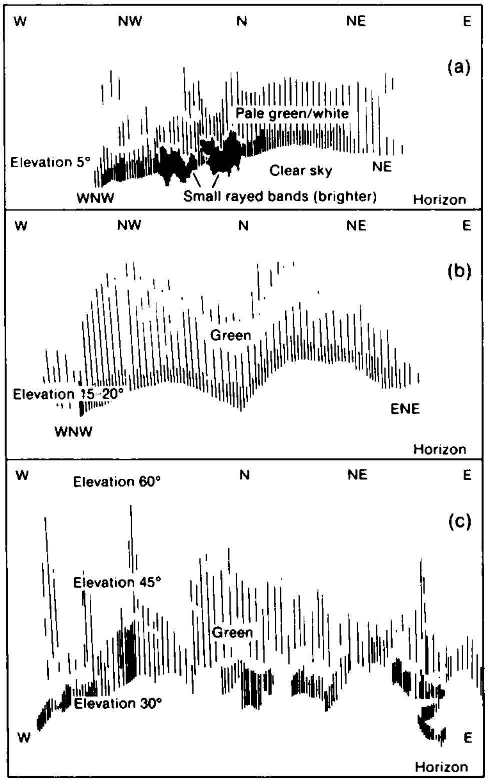

Figure 1. Sketches of auroral displays (a) at 2035 GMT, (b) at 2200 GMT and (c) around 2330 GMT.

north-north-east, and rose to 10° elevation. However, by 2145 GMT the display had developed again into a homogeneous band, of moderate brightness, greenish hue, orientated west-north-west to east-north-east, with the base having risen slightly to 15–20° elevation. At this time one or two rays began to

* Falck-Ytter, H.; *Aurora. The northern lights in mythology, history and science*, Floris Books, Edinburgh, 1985.

appear and by 2200 GMT had developed into two prominent rayed areas (Fig. 1(b)). The aurora continued to rise, eventually reached 30° elevation and stretched almost from east to west. It continually changed form, occasionally breaking into 'curtain-like' formations, with frequent single rays reaching up to 60° (Fig. 1(c)). The aurora continued in this manner until 2330 GMT. There was also considerable meteor activity with one remarkable sighting at 2130 GMT of a very bright green meteor that appeared briefly in the west at 30° elevation.

From 2330 GMT onwards, the aurora varied in activity, sometimes becoming almost homogeneous, but remaining as a broad band, moderate in brightness and faintly green. At 0130 GMT it faded to a faint homogeneous arc, 30° in elevation, occasionally displaying some rays, but probably partially obscured by thickening haze. By 0200 GMT it had disappeared.

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High absolute humidities in Ireland, 12–13 July 1983

By S.D. Burt

(Sandhurst, Berkshire)

Summary

An occasion of prolonged high absolute humidities in central and western Ireland during July 1983 is described. It is suggested that the event is probably the most extreme of its type on record for the British Isles.

A recent note in this magazine (Lewis 1986)* drew attention to the occurrence of high absolute humidity in parts of England on 1 July 1968. Readers may be interested in a more recent occasion of even higher, and longer-lasting, high absolute humidity — not in England on this occasion, but over central and western Ireland on 12–13 July 1983.

The synoptic situation at 1200 GMT on 12 July 1983 was as illustrated in Fig. 1. The British Isles lay under the influence of an anticyclone centred between Iceland and Scotland; surface winds were light north or north-easterly in most districts. Over all but the extreme north and west of Scotland (where a weak cold front had introduced cloud and rain) and a narrow strip down the east and north-east of England (where fog and low stratus prevailed) the day was exceptionally warm. Afternoon temperatures exceeded 30 °C over the whole of England and Wales away from the coast (reaching 32 °C in the Southampton area and in south Wales) and even 31 °C in southern Scotland.

Over Ireland the weather was also hot, but in the south, cloudier weather with scattered thunderstorms had developed overnight, somewhat in advance of another weak cold front associated with a depression to the west of Spain. Humidities were already high, and mist and low cloud developed widely as temperatures fell. Even so, night temperatures were uncomfortably high; at Birr the overnight minimum was 17.0 °C, and at Roche's Point 16.9 °C (see Fig. 2 for locations). However, as the day wore on, the mist and low cloud cleared and further breaks in the medium cloud cover, together with a westward drift of warm air from England and Wales, allowed temperatures to rise quickly. Meanwhile, the cold front advancing slowly north-east continued to spread moist Atlantic air before it over southern and central Ireland. As a result central and western districts of Ireland experienced exceptionally high absolute humidities for most of the day.

* Lewis, R.P.W.; An occasion of high absolute humidity in England: 1 July 1968, *Meteorol Mag*, **115**, 1986, 115–117.

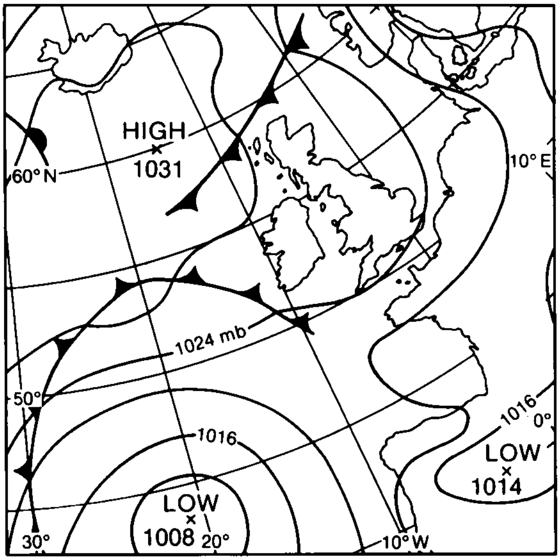


Figure 1. Surface analysis for 1200 GMT on 12 July 1983.

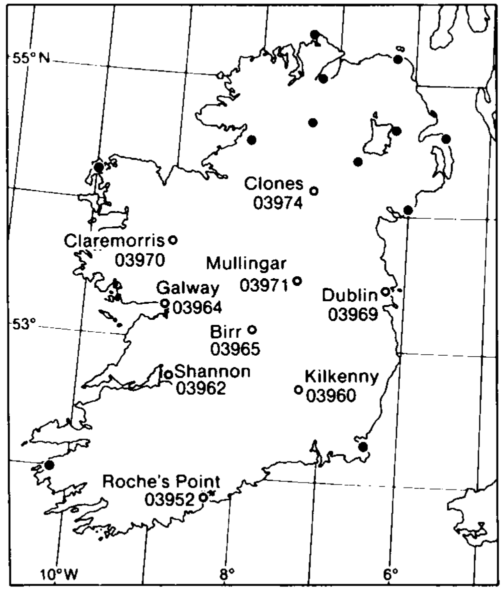


Figure 2. Locations of places referred to in the text. Other synoptic stations in Ireland are marked but not individually identified.

The first report of a dew-point in excess of 20 °C came from Kilkenny at 0900 GMT — 21.3 °C with a dry-bulb temperature of 24.7 °C, under clear skies with only 3 knots of wind. By 1200 GMT dew-point temperatures at Kilkenny, Birr, Galway, Claremorris, Mullingar and Clones were all above 20 °C; at Birr 23.2 °C was reported, associated with a dry-bulb temperature of 26.0 °C, under 6 oktas stratocumulus cover, with mist (visibility 2000 metres) — in conditions of flat calm. At this site the dew-point remained above 20 °C for 16 consecutive hours, although it did not subsequently exceed the

1200 GMT value. Most other sites, however, reported their highest values of dew-point during the late afternoon or early evening. Fig. 3 shows the surface observations for 1800 GMT; by this time the surface cold front had been omitted from the Atlantic analysis, although a consideration of the wind and dew-point fields would seem to indicate its remains across southern Ireland at about 52.5° N.

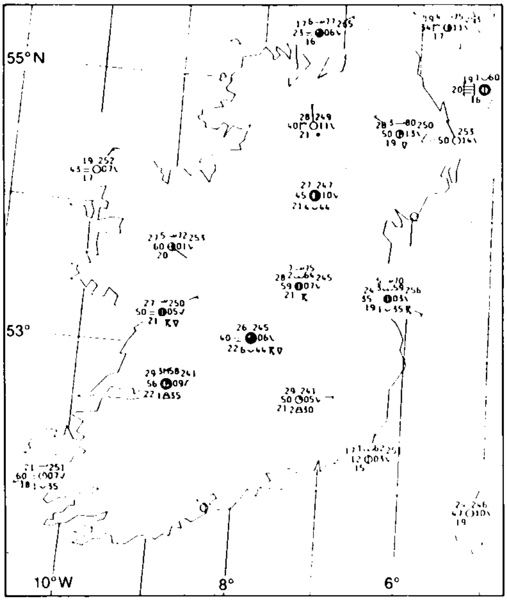


Figure 3. Surface observations at 1800 GMT on 12 July 1983.

At 1900 GMT Shannon reported the highest dew-point temperature for the British Isles known to the author, namely 23.8 °C. At this observation, the dry-bulb temperature was 28.1 °C (wet-bulb temperature about 25.1 °C, relative humidity about 77%, vapour pressure about 29.5 mb), with 3 oktas altocumulus floccus, and a 5-knot north-easterly breeze. The heavy thunderstorm that broke within the next hour must have brought welcome relief; at 2000 GMT the temperature was down to 24.0 °C, accompanied by an 18-knot easterly breeze.

Table I lists dry-bulb and dew-point temperatures for eight sites in central and western Ireland for 24 hours commencing 0600 GMT 12 July, while Fig. 4 presents a sequence of observations made at Kilkenny, Shannon and Birr over the same period.

Temperatures and humidities remained high throughout the night of 12/13 July and for most of the following day (although generally not as extreme as on 12 July). At Birr the overnight minimum was 18.9 °C, with thick fog by morning (Fig. 4), while at 0800 GMT the dew-point had climbed to 21.5 °C, and thence to 21.6 °C at 1000 and 1100 GMT. At 1000 GMT a dew-point of 21.8 °C was reported from Claremorris. As late as 2000 GMT the dew-point was still as high as 21.1 °C at Kilkenny, while the last report of 20 °C or more (20.2 °C) came from Mullingar at 2200 GMT. Not until overnight 13/14 July did values of absolute humidity fall below exceptional levels, after what was probably a spell of unprecedented length. At Birr the dew-point remained at or above 18 °C from 0700 on 12th until 2100 on 13th inclusive, an unbroken period of 39 hours, including 33 consecutive hours at or above 19 °C and 17 hours in all above 21 °C. Frequency-duration data of dew-point temperatures above specified thresholds for eight of the stations identified on Fig. 2 appear in Table II. While this table is probably complete for the highest values, the only data available to the author are for the 48 hours ending

Table I. *Dry-bulb (T_{dry}) and dew-point (T_{dew}) temperatures (°C) at various sites in Ireland, 12–13 July 1983 (extracted from synoptic observations as received at the Meteorological Office)*

Time GMT	Kilkenny 03960		Shannon 03962		Galway 03964		Birr 03965		Dublin 03969		Claremorris 03970		Mullingar 03971		Clones 03974	
	T_{dry}	T_{dew}	T_{dry}	T_{dew}	T_{dry}	T_{dew}	T_{dry}	T_{dew}	T_{dry}	T_{dew}	T_{dry}	T_{dew}	T_{dry}	T_{dew}	T_{dry}	T_{dew}
0600	*18.3*	*17.7*	16.3	15.2	17.0	17.0	17.6	16.8	17.5	15.3	17.2	17.0	16.7	15.2	17.2	15.9
0700	19.4	18.6	17.4	16.4	17.6	17.4	18.8	18.0	17.6	15.7	19.2	18.1	18.5	16.5	18.2	16.7
0800	20.9	19.1	18.5	17.4	19.0	18.2	20.0	19.2	19.5	16.9	20.0	18.6	20.1	17.0	20.1	17.3
0900	24.7	**21.3**	20.1	17.9	20.3	18.4	*21.3*	*20.3*	21.3	17.2	*22.0*	*19.0*	23.1	18.2	22.0	17.7
1000	25.6	21.1	19.9	18.1	22.2	19.6	22.7	21.5	23.0	17.8	24.0	19.4	25.1	19.9	24.2	18.7
1100	26.0	20.9	20.6	18.0	24.0	20.2	24.2	22.1	24.0	17.6	25.4	20.5	26.5	19.5	25.2	19.5
1200	27.4	21.1	22.6	19.3	24.8	20.6	26.0	**23.2**	**25.9**	**19.1**	26.0	20.4	27.8	20.3	26.6	20.6
1300	28.4	20.4	25.4	20.7	23.5	20.5	25.2	22.8	25.1	18.5	27.0	20.5	27.9	19.7	25.3	21.0
1400	29.0	20.3	*26.9*	*20.7*	23.8	19.8	23.5	22.0	24.5	**19.1**	27.4	20.8	**28.4**	20.0	26.0	20.9
1500	29.1	20.0	28.4	20.7	25.5	20.8	24.7	22.8	23.0	18.6	26.0	20.5	27.1	21.4	27.5	19.9
1600	**29.6**	19.8	29.0	21.6	25.9	20.4	25.8	20.9	24.0	18.7	27.2	**21.5**	27.1	21.7	**27.8**	19.5
1700	29.5	20.0	**29.3**	22.7	**26.5**	21.0	26.4	21.7	24.2	18.9	**27.7**	20.6	28.1	21.2	27.6	20.0
1800	28.7	**21.3**	29.0	22.1	**26.5**	**21.3**	26.4	22.4	23.8	18.7	27.3	20.2	27.6	20.5	27.3	21.1
1900	26.7	**21.3**	28.1	**23.8**	26.0	**21.3**	**26.5**	22.6	22.9	18.4	26.6	20.3	26.6	22.0	27.4	**21.2**
2000	25.2	20.7	24.0	18.1	25.5	21.0	25.5	22.3	22.6	18.2	25.4	20.9	25.1	**22.1**	26.1	20.6
2100	24.0	20.8	23.1	17.3	23.5	21.0	24.9	22.4	22.4	17.9	23.6	20.9	23.7	21.2	24.1	20.9
2200	22.5	20.2	21.9	19.0	22.5	20.8	23.7	22.2	21.2	18.5	22.2	20.4	21.6	20.4	23.1	20.3
2300	20.6	19.6	21.5	18.9	22.5	20.5	22.4	21.0	20.6	18.0	20.2	19.2	20.8	19.7	21.9	19.6
0000	19.0	18.2	20.7	18.1	22.1	**21.3**	21.6	20.5	21.2	17.6	19.5	18.7	20.4	19.6	20.5	17.8
0100	18.9	17.8	20.7	18.8	20.2	19.2	20.7	19.7	19.7	17.6	18.9	18.3	19.7	19.1	19.2	17.1
0200	18.8	18.0	20.8	17.9	20.4	19.6	21.1	20.1	19.0	17.9	18.0	17.4	18.7	18.1	18.5	16.5
0300	18.6	18.1	20.0	18.7	20.5	19.9	20.5	19.7	18.7	17.1	17.0	16.7	18.3	18.0	17.9	16.2
0400	17.6	17.3	18.9	17.8	20.0	19.4	20.0	19.8	18.5	17.1	16.6	16.4	17.8	17.5	17.3	15.6
0500	17.5	17.0	18.8	17.7	19.3	18.8	19.3	19.1	18.4	17.2	17.0	16.8	17.8	17.5	17.1	15.2
0600	17.5	16.9	18.7	17.9	18.5	18.5	19.5	19.3	19.0	17.6	18.8	18.5	18.7	18.4	17.4	15.3

The highest values in each column are printed in bold. Figures in italics denote linear interpolations between observations on either side of the missing hour for observations not received.

Table II. *Frequency-duration of dew-point temperatures above specified thresholds for eight stations in Ireland for the 48 hourly observations commencing 0000 GMT on 12 July 1983. The figures in parentheses denote the longest continuous spell within that period.*

Dew-point °C	Kilkenny		Shannon		Galway		Birr		Dublin		Claremorris		Mullingar		Clones	
⩾23.0	0		1		0		1		0		0		0		0	
⩾22.0	0		3	(3)	0		10	(5)	0		0		2	(2)	0	
⩾21.0	6	(2)	4	(4)	6	(5)	17	(7)	0		4	(2)	10	(3)	4	(2)
⩾20.0	20	(7)	9	(7)	18	(10)	23	(16)	2	(2)	20	(12)	23	(9)	13	(6)
⩾19.0	32	(16)	18	(8)	30	(19)	36	(33)	6	(4)	27	(15)	33	(17)	19	(13)
⩾18.0	35	(18)	27	(11)	37	(37)	40	(39)	17	(9)	33	(19)	37	(19)	25	(14)

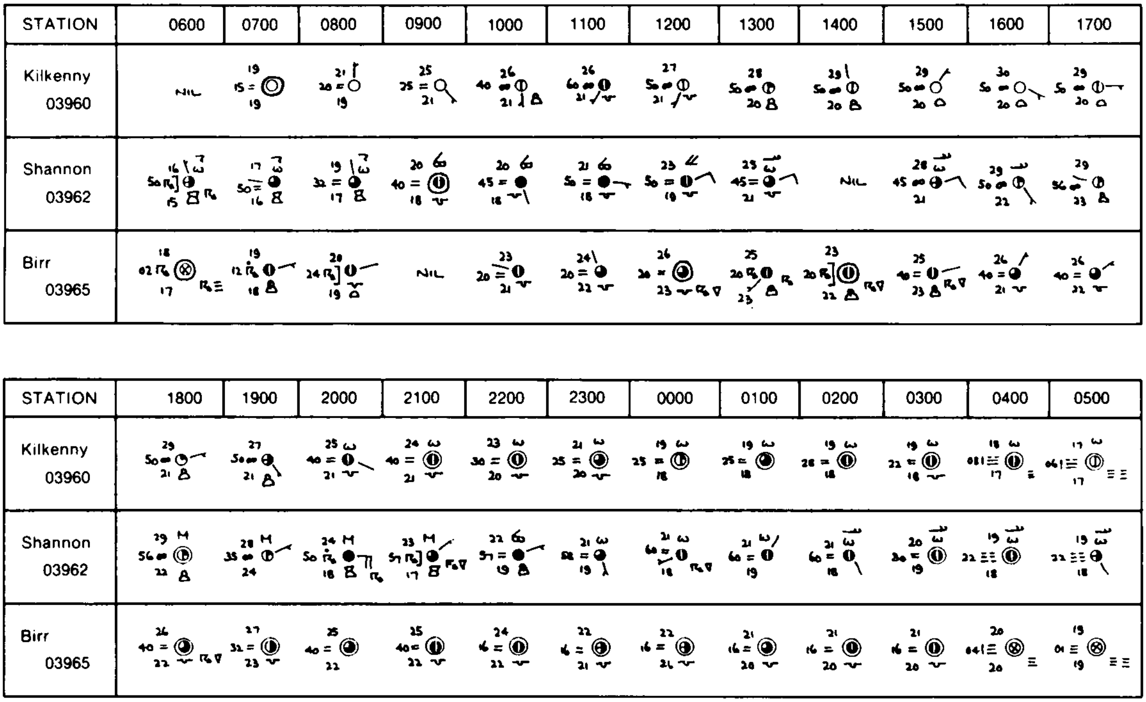


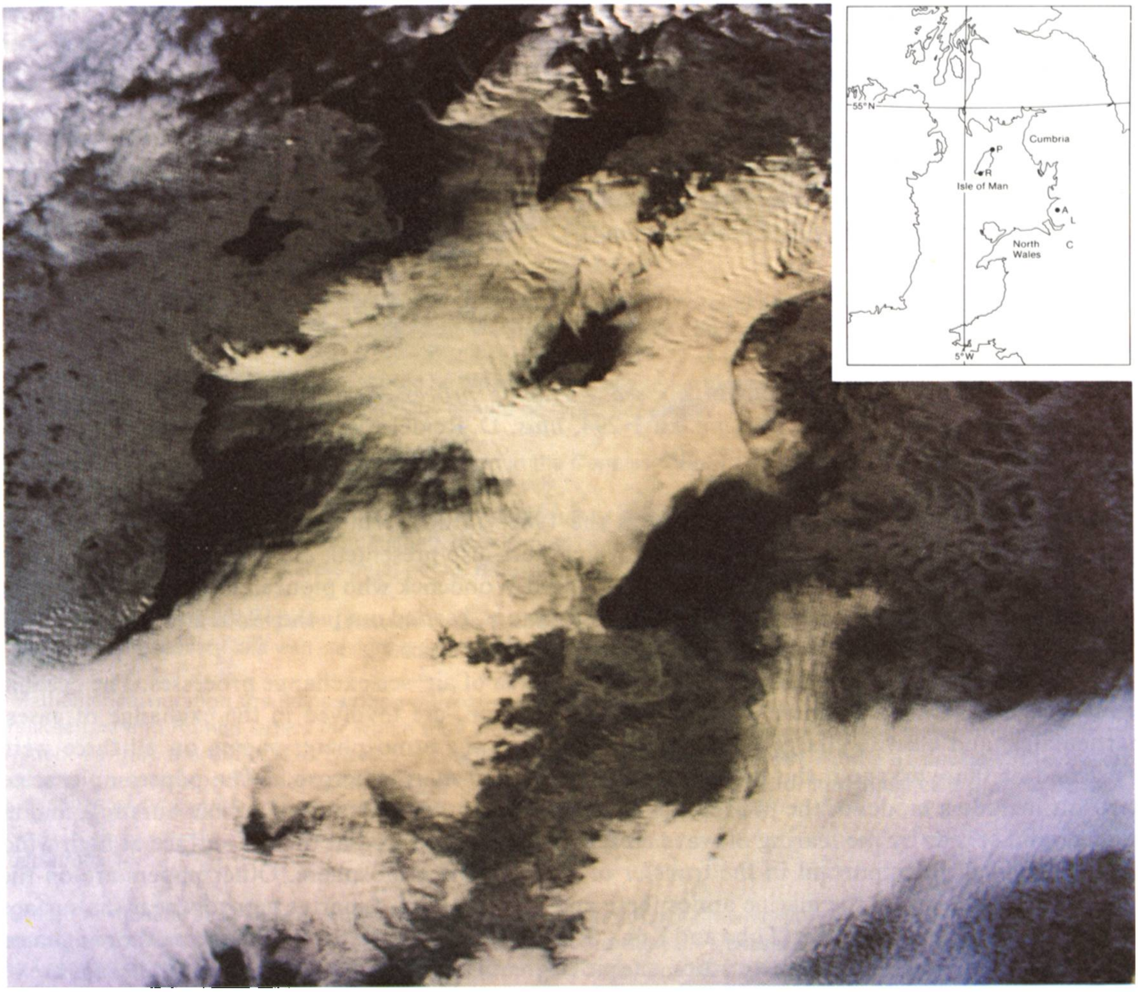
Figure 4. Simplified plot of observations made at Kilkenny, Shannon and Birr over the 24 hours commencing 0600 GMT on 12 July 1983.

2300 GMT on 13 July. At this time, dew-points at the eight stations ranged between 19.2 °C (at Mullingar) and 17.1 °C (at Dublin) and accordingly it is certain that consideration of observations for 14 July would increase some of the spell lengths given in Table II.

The month of July 1983 provided many occasions, in almost all parts of the country, of steamy heat of an intensity almost unknown in the British Isles but, so far as the author is aware, the degree and persistence of absolute humidity that prevailed over central and western Ireland on the 12/13 July was not surpassed. If any readers are aware of any other occasions (in July 1983 or otherwise) when authenticated dew-points at any station or stations within the British Isles are known to have reached or exceeded the values reported in this article, would they please forward details to the author.

Satellite photograph — 30 September 1986 at 1412 GMT

The high-resolution NOAA-9 visible image displayed on the Meteorological Office HERMES (High-resolution Evaluation of Radiances from MEteorological Satellites) system shows the distribution of fog and low cloud over central Britain beneath a pronounced low-level inversion which, according to the 1100 GMT radiosonde ascent (see Fig. 1) from Aughton (marked 'A' in inset map), is 300 m above sea level. Following several days of anticyclonic conditions, a weak south-south-westerly airflow had become established over the British Isles. Cloud originating over the sea is seen to dissipate over the high ground of North Wales and the Isle of Man. However, cloud appears to be largely deflected



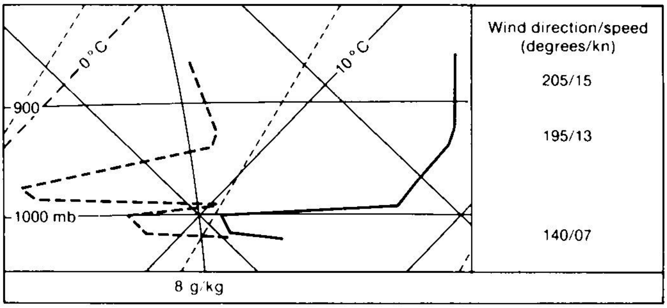


Figure 1. Part of the Aughton radiosonde ascent at 1100 GMT on 30 September 1986.

around Cumbria, although tongues of fog do appear to reach the coast, where surface observations indicate weak sea-breezes. Over the Isle of Man, Ronaldsway (R) in the south had a sunless day with intermittent drizzle and fog, whilst Point of Ayre (P) in the north had a dry day with 9.6 hours of sunshine.

The cloud top shows considerable structure, with lee wave patterns in the north, in particular downwind of the Isle of Man where a 'herring-bone' pattern is apparent. Over the land, there is evidence of banding along the wind direction, particularly within the narrow band of cloud that reaches Lancashire (L) via the low-lying Cheshire Plain (C).

Review

Oceanic whitecaps and their role in air–sea exchange processes, edited by E.C. Monahan and G. MacNiocaill. 168 mm × 247 mm, pp. xii + 294, *illus.* D. Reidel Publishing Company, Dordrecht, 1986. Price £40.25, US $64.00, Dfl 145.00.

This book contains 22 papers presented at the 1983 Galway Whitecap Workshop. Abstracts of 18 poster papers (in some cases with figures), which were also presented, are included at the end. The book is introduced with a short biography of Dr Alfred Woodcock who pioneered the measurement of aerosols in the marine boundary layer during investigations, carried out in the 1940s and 1950s, into the role played by salt particles in the formation of rain in the tropics.

The papers cover a wide range of topics within the area of air–sea exchange processes. The oceanic whitecaps, which were the main concern of the workshop, are involved in the exchange of gases, particulates, and electric charge between the ocean and the atmosphere; papers on all three were presented at the workshop, the greatest number being on marine aerosols. The papers on marine aerosols include a model of the production of droplets at the sea surface by bubble bursting, and at higher wind speeds by the tearing of wave crests. Droplets produced at the sea surface at high wind speeds may well be important in the transfer of water to the atmosphere. Other papers are on the modelling of aerosols in the marine atmosphere and observations of marine aerosols near the surface and from satellites. Two papers (Toba and Koga, Hasse) discuss the relationship between the roughness of the sea surface and wave characteristics, a topic of great interest to meteorologists. Whitecaps are of interest here since they indicate that wave breaking is occurring.

The workshop was not concerned only with the atmosphere, and papers on the characteristics of waves, whitecaps and bubbles are well represented. The final papers in the volume are concerned with satellite sensing of whitecaps, either because of possible effects (through changes to the surface albedo or emissivity) of whitecaps on the retrieval of other quantities (e.g. the aerosol content, discussed in another paper) or as indicators of the near-surface wind speed.

The style of the papers is the same as that found in scientific journals, while the quality is generally higher than is normally found in the proceedings of conferences or workshops. Although some time has elapsed between the workshop and the appearance of this volume, I would agree with the editor's opinion that the papers still provide an up-to-date review of this area. To help make this a valuable source book, the editors have also included a large supplementary bibliography of papers which they feel are pertinent to the subject but which are not referenced by the other contributors.

A. Grant

Meteorological Magazine

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Meteorological Magazine

December 1986

Vol. 115
No. 1373

CONTENTS

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ISBN 0 11 727840 8

ISSN 0026–1149

Printed for HER MAJESTY'S STATIONERY OFFICE
by Delco Printing Co Ltd 11/86 Dd. 739131 1425