The Meteorological Magazine

February 1990

Heavy snowfall event
Exeter temperatures

HMSO

Met.O.992 Vol. 119 No. 1411

The
Meteorological
Magazine

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Vol. 119 No. 1411

551.578.45:551.553.11:551.547.5:551.513.2(420+261.26)

Persistent coastal convergence in a heavy snowfall event on the south-east coast of England

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Summary

A detailed investigation of the heavy coastal snowfall during the period 11–13 January 1987 is presented, accompanied by an explanation of the sequence of events.

1. Introduction

General insurance losses associated with severe weather and heavy snowfalls in south-east England during January 1987 have been assessed at £285 million. Taking account of inflation, this is the third-largest figure for natural disasters affecting all of the United Kingdom since 1975, ranking only after the £2000 million (approximately) for the Great Storm of October 1987 and the arctic conditions during the winter of 1981–82 (which cost near £327 million) in terms of total losses sustained by the main UK insurance companies (Jackson 1988).

Small-scale (i.e. large area coverage) synoptic charts plus NOAA-9 and NOAA-10 AVHRR satellite pictures have already been published to illustrate accounts of the bitterly cold polar continental outbreak over the period 10–15 January 1987, when both extremely low 1000–500 mb thickness values and daytime temperatures were recorded on the 12th (Mortimore 1987, Brugge 1987, Webb 1987).

The heavy but localized snowfalls during this period near coasts bordering the southern North Sea and the English Channel have been well-described by (chronologically) Bacon (1987), Selfe (1987), Van den Berg (1987), Monk (1987), Kain (1988) and Lumb (1988, 1989). Three of these authors mention coastal convergence between over-land and over-sea airflows as being a significant cause of the localized snowfalls.

This paper aims to pursue their ideas, using analyses of satellite and surface observations, and present larger-scale synoptic charts drawn at 6-hourly intervals to illustrate mesoscale features. Concern has been expressed regarding the adequacy of synoptic charts with isobars drawn at 4 mb intervals in mesoscale analysis; in this work isobars at smaller intervals are used which reveal more clearly important features present in the surface synoptic situation during this period.

Fig. 1 locates most of the places referred to in the text.

2. The Synoptic situation

The general situation was, at first, dominated by a powerful anticyclone which reached its maximum central pressure over the Central Norwegian Massif during the evening of the 11th, 1055.0 mb (corrected to mean sea level) being recorded at Bråtå (61° 54′N, 7° 52′E, alt. 710 m) at 18 UTC. Thereafter, pressure fell steadily over the United Kingdom as a depression began to develop and move eastwards over France during the 13th.

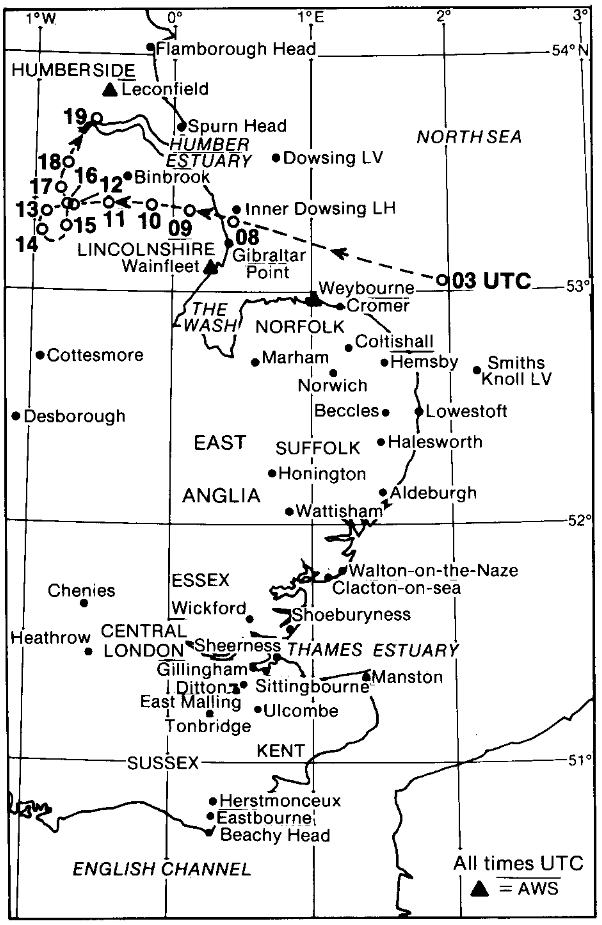


Figure 1. Location of most of the places referred to in the text. Also shown is the track of a small disturbance on 12 January 1987, numbers are times (UTC).

However, during the first evening of this cold outbreak on 10 January, surface wind reports from The Netherlands and East Anglia indicated that a trough was beginning to form where increasingly cold polar continental air was advecting from the east over the relatively warm southern North Sea. This trough is not readily apparent in surface charts drawn at 4 or 5 mb intervals as, for example, in Brugge (1987). Fig. 2(a) suggests that by 03 UTC on the 11th, this trough was well developed; a sequence of these large-scale synoptic charts (Figs 3(a)–3(h)) underlines its persistence, which spanned some 66 hours, until late on the 13th. The marine trough appears to have been thermally maintained from the surface, and independent of the movement overhead of minor 'cold airmass' troughs, such as that shown crossing East Anglia from the north-east later on the 11th in Figs 3(a)–3(c).

Therefore, this offshore trough may be regarded as a quasi-stationary wintertime marine feature associated with relatively warm water, in its formation similar to the summertime thermal depression (or, more familiar heat low) which develops, often over the warmest ground inland.

Troughing over the sea has an important effect, particularly in this instance along the east Suffolk–Essex coastline (and also on 12 January 1987 off southern Cornwall), through backing the pressure gradient precisely where the onshore wind could make a smaller angle with that coastline than would otherwise have occurred in a straightforward easterly airflow.

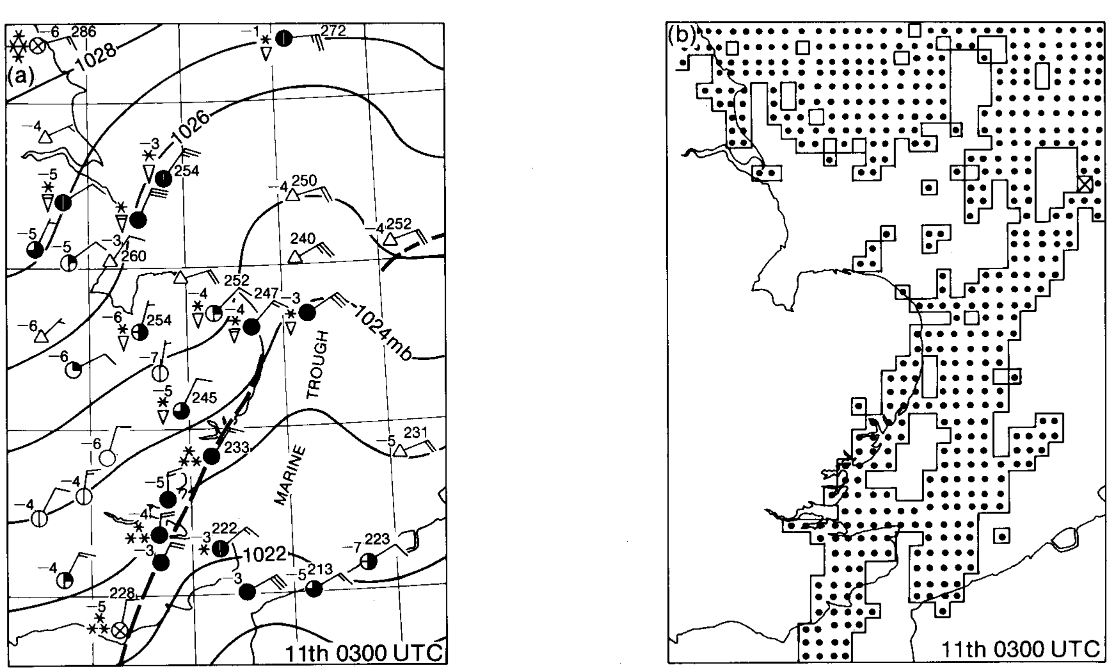


Figure 2. Situation at 03 UTC on 11 January 1987; (a) surface observations (usual symbols with triangles denoting automatic weather stations), isobars (thin continuous lines), air-mass trough (thick continuous line), convergence lines/coastal fronts (dashed lines), (b) areally averaged (for 10 km × 10 km squares) Meteosat cloud-top temperatures, open above −20 °C or no cloud, dotted −20 °C to −30 °C, hatched −30 °C to −40 °C, solid below −40 °C.

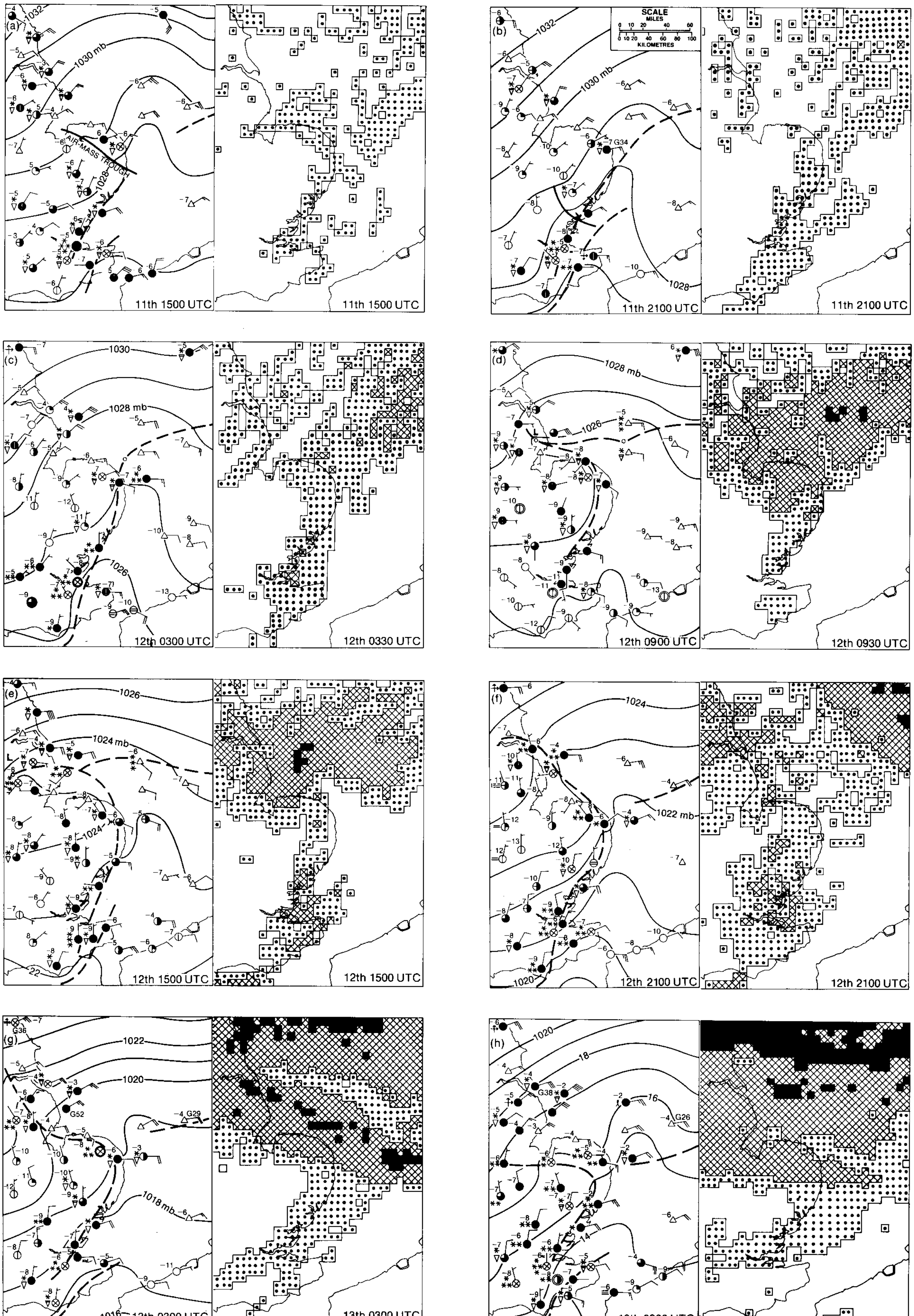


Figure 3. As Fig. 2, but for the sequence of times shown.

3. Coastal frictional convergence

Coastal zones are particularly subject to frictional convergence of low-level airflow, due to roughness difference between the land and sea surfaces. Excluding thermodynamic effects, frictional convergence in itself leads to sometimes-pronounced upward air motion, which has been found to have a maximum when an appreciable (i.e. stronger than moderate) onshore wind makes a shallow angle (between 14° and 25° clockwise) with the coastline (Bergeron 1949, Roeloffzen *et al.* 1986).

The effects of these conditions were greatest along the east Suffolk–Essex coastline early in the cold outbreak period when the gradient wind was stronger (Fig. 2(a)), probably leading to the continuous moderate snow that was being reported by 03 UTC on the 11th, not only from Walton-on-the-Naze and Sheerness, but also from Herstmonceux, indicating that the cloud and precipitation had extended downwind (between 020–035° / 25–30 kn at the 800 mb level) towards the Beachy Head area of Sussex. Fig. 2(b) confirms that a belt of colder-topped (higher) cloud stretched south-south-westwards from Lowestoft at this time. Also, allowing for a slight existing cover, snow depths measured at 09 UTC on the 11th (Fig. 4) verify that the heaviest overnight falls occurred just downwind of the east Suffolk–Essex coast in north-west Kent (e.g. Ulcombe 18, Keycol 15 and Wigmore 13 cm).

However, continued development of the offshore trough slackened the pressure gradient locally near the East Anglian coast where, as a result, onshore winds over much of 11–13 January 1987 were only moderate (see Figs 3(a)–3(h)). Van den Berg (1987) describes how thermodynamic effects in the boundary layer (i.e. due to temperature and stability differences) become more important than differential surface friction in coastal frontogenesis as the onshore winds moderate.

4. The quasi-orographic effect of cold air stagnating over East Anglia

As they had done locally the previous night, temperatures fell more widely to −10 °C in East Anglia by 21 UTC on 11 January 1987, particularly since winds had fallen to light, and strong radiational cooling was occurring beneath clearing skies. Lower temperatures still were recorded over snow-covered ground, a minimum of −14.8 °C was recorded at Marham, with a grass minimum of −22.2 °C. While clear skies persist, a stagnating pool of cold, stable air is likely to form inland (see Roach and Brownscombe 1984).

Fig. 3 also shows Meteosat infra-red imagery interpretations which may be taken as closely comparable in terms of time and area covered with the surface charts. They indicate that, although some cells moved through the pattern, there was remarkable persistence of clear skies inland while a band of cloud parallel to the coastline appeared to be stationary near the East Anglian coast (especially where east Suffolk and Essex border the North Sea). Whether cloud penetrated well inland on the 12th at 21 UTC is uncertain because the

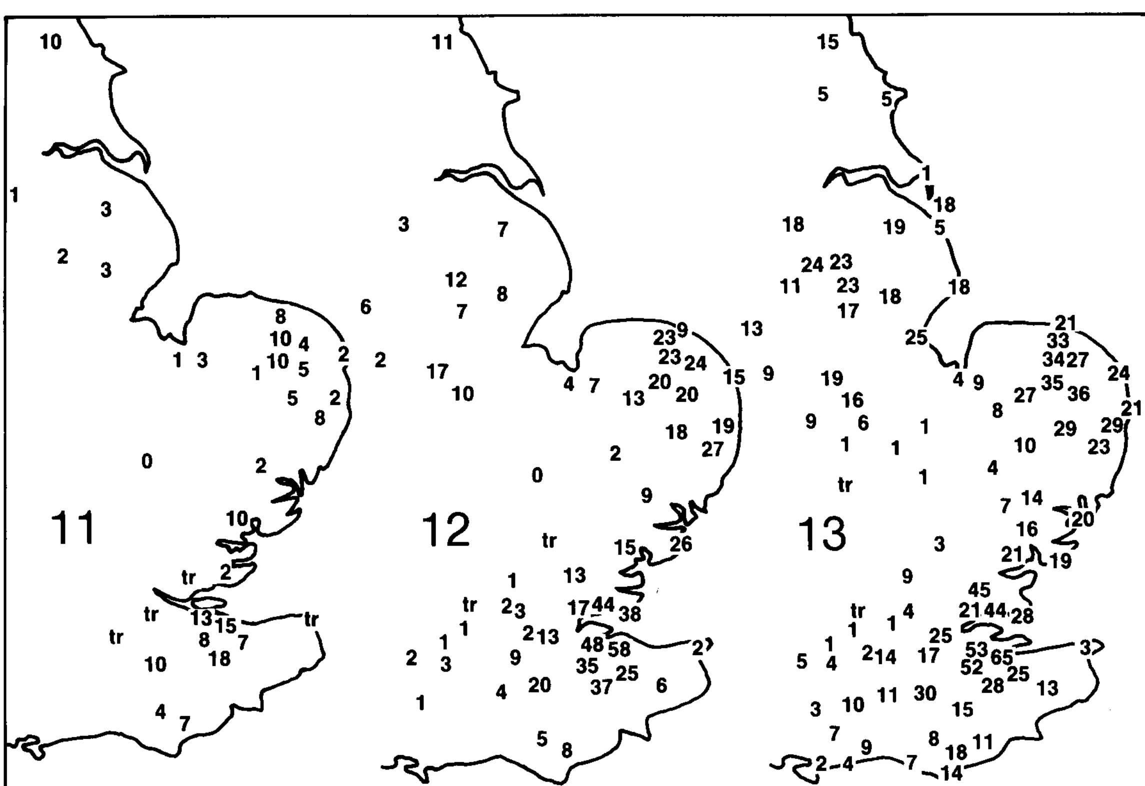


Figure 4. Snow depths (cm) measured at 09 UTC on the dates shown (11, 12, 13) January 1987.

infra-red radiometer might have been registering very low ground temperatures, below −20 °C at that time. Bacon (1987) produced an unconfirmed thermograph trace from Desborough, Northamptonshire, where the air temperature (in a sheltered, upland valley exposure) hovered close to 0 °F (−18 °C) between 1930 and 2045 UTC. Also, that evening, a grass minimum (over snow) of −24.6 °C was recorded at Cottesmore.

When investigating enhanced precipitation occurring just inland from the Dutch coast overnight on 17–18 November 1977, Oerlemans (1980) reasoned that while radiation formed a stable layer over land, instability had prevailed over the warmer North Sea. From reported surface wind variations, pronounced low-level convergence had occurred along the coast. While these conditions persisted, and the stable air inland remained undisturbed, a quasi-orographic effect was diagnosed, whereby a hill of stationary air forced uplift of onshore winds over otherwise flat country. Called 'The θ-hill effect', it was shown (by radar study) to have formed a relatively narrow belt of enhanced cloud and precipitation parallel to the coastline along a low-level convergence line which had remained quasi-stationary just inland from the coast.

Fig. 5 shows a remarkable series of observations from Coltishall and Hemsby in Norfolk on 12 January, with just 22 km between the stations. Wind directions were in almost-complete opposition between 06 and 18 UTC, with light land-breeze north-westerlies at Coltishall (indicative of the undisturbed air inland) while a moderate onshore east-south-easterly wind persisted at Hemsby, suggesting maintenance of a quasi-stationary convergence line between these two stations over more-or-less flat land, an unusually balanced situation aided by extremely cold air (see section 7) advecting over the sea to Hemsby. During the period 06–18 UTC on the 12th, thermal contrast was quite small, dry-bulb maxima being −5.6 °C (despite the sunshine and only isolated passing showers moving in from the sea) at Hemsby, and −6.4 °C (beneath cloud and in almost-continuous snow) at Coltishall.

The observational evidence suggests that a quasi-orographic hill of cold surface air remained undisturbed over East Anglia during the 12th, and persisted in the south of the region for a total of approximately 48 hours until the evening of the 13th (when both upper-cloud cover and surface wind increased). Fig. 3 and the averaged Meteosat data (which indicates cloud persistence/development areas) in Fig. 6 confirm the general maintenance of cloud, closely correlating with the East Anglian coastline.

5. Land-breezes

The land-breeze has become a well-known factor in the generation of lake-effect snowstorms in the vicinity of Lake Michigan, USA, and such events have been intensively studied since 1977. Lake Michigan is about 130 kilometres wide and, although not quite as far as the

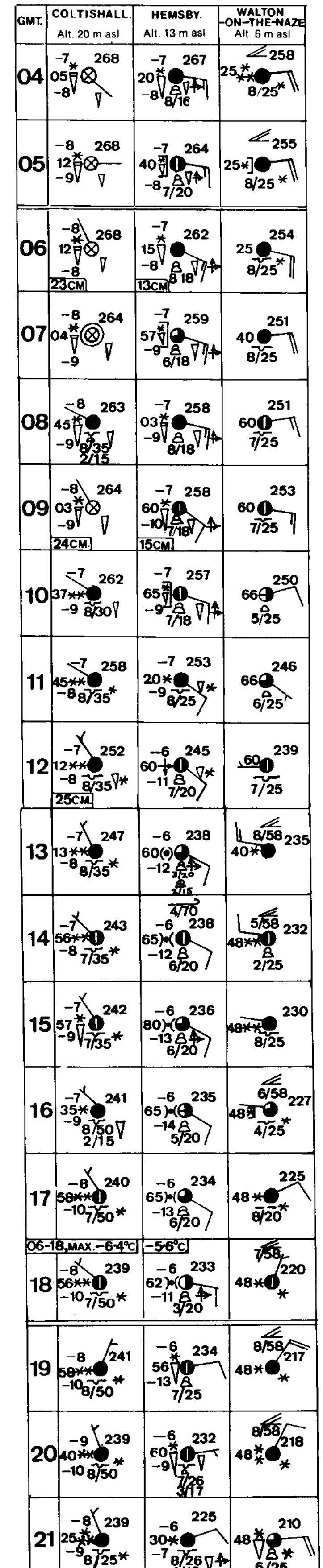


Figure 5. Hourly surface observations from Coltishall, Hemsby and Walton-on-the-Naze for the times shown on 12 January 1987.

distance from East Anglia to the Dutch coast, presents approximately the same fetch of warmer water to a cold easterly airflow as does the southern North Sea between East Kent and continental Europe at the Dutch–Belgian border. Arctic outbreaks are relatively common in the mid-western USA in January, therefore at least some of the American studies might have relevance to events in south-east England over the period 11–13 January 1987.

Two cases of snowfall on the western shores of Lake Michigan have similar aspects, and are discussed in Ballentine (1982), as is the role of the land-breeze in producing a nearly stationary band of precipitation (the snow band) parallel to the western shoreline. Both Ballentine (1982) and Schoenberger (1984) mention that the radar studies of Passarelli and Braham (1981) had demonstrated: (a) a vital role played by the land-breeze in forming cloud and precipitation bands parallel to the shoreline, and (b) these bands sometimes consisted of discrete cores of heavier precipitation embedded within the more uniform precipitation band, the intense cores or cells tending to move in a direction parallel to the axis of the belt, resulting in very little movement of the band itself. Schoenberger (1984) defined the land-breeze as a 'shallow density current' and described the land-breeze cold front (when it pushed out over the water) as the line separating radiationally cooled over-land air from the warmer over-sea air.

What may be interpreted as a discrete line of isolated colder (higher) topped convective cells appeared from the Essex coast to north-west Kent by 0330 UTC on 12 January 1987 as in Fig. 3(c), indicating probable land-breeze involvement. These cells first appeared at 02 UTC over the Thames Estuary on the Meteosat infra-red imagery, where cloud tops had previously been lower.

Surface observations from Walton-on-the-Naze coastguard station (Figs 5 and 7) trace three probable land-breeze events there over the period 11–12 January 1987, each accompanied by outbreaks of snow associated with oscillations overhead of the coastal convergence line, and each featuring a temporary offshore wind from between north and west in direction. Interaction with a minor cold air-mass trough which was moving south-westwards (Figs 3(a) and 3(b)) appears responsible for

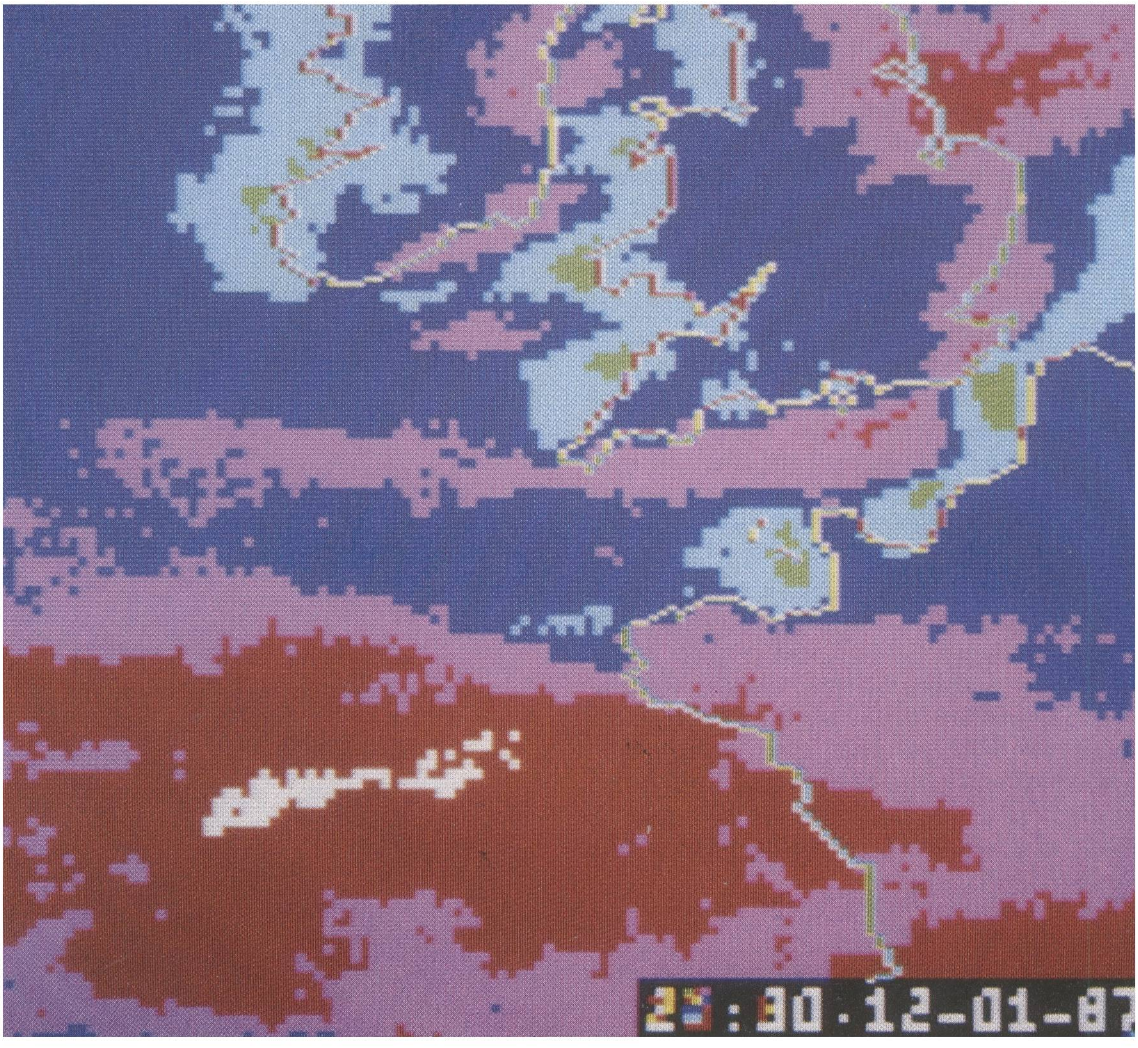


Figure 6. Cloud-top temperatures from Meteosat averaged infra-red imagery averaged over 10 km × 10 km squares for the period from 10 to 21 UTC on 12 January 1987.

the period of particularly heavy snow around 18–19 UTC on the 11th, but the renewed continuous snowfall between 01 and 04 UTC on the 12th appears to have been related purely to a land-breeze-induced oscillation of the coastal convergence line. Temperatures are not recorded at Walton, but nearby at Shoeburyness the thermograph trace clearly indicated temporary 2-hour duration dips of 2 °C and 1 °C which, although not all that great considering the snowfall, were probably associated with these two respective oscillations.

Off south-east Essex, the sea froze on 12 January 1987 in places from Shoeburyness to Westcliffe, and Brugge (1987) has mentioned that ice floes were seen half a mile out to sea, which is very shallow off Southend. But a

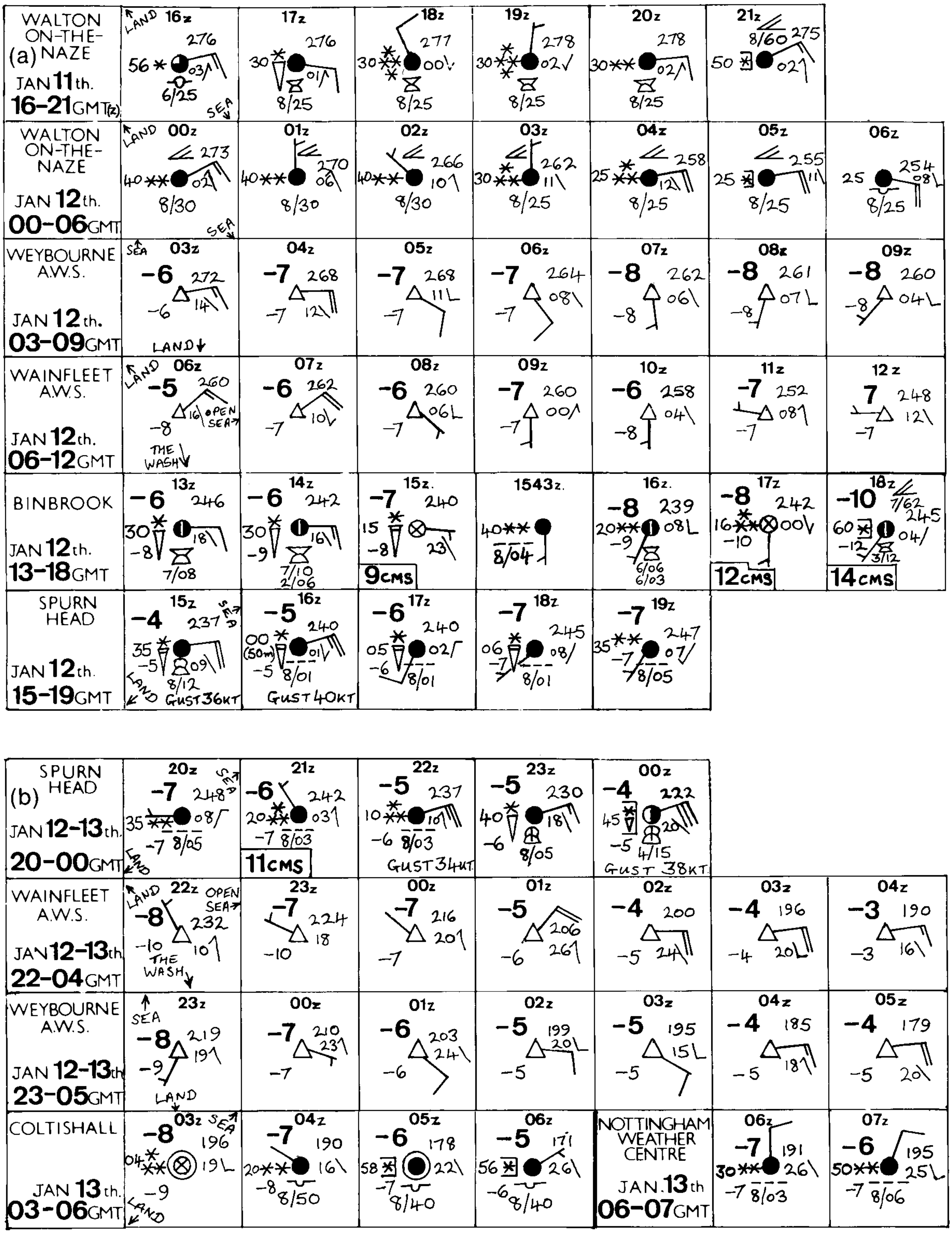


Figure 7. Further sequences of surface observations to illustrate passages of (a) the land-breeze cold front, and (b) the warm coastal front from 11 to 13 January 1987.

particular reason for ice formation here (suggested by isotherms of maximum temperature over the adjacent land in Fig. 8 and Bacon (1987), also by the reported surface wind directions) was that this area of Essex appeared to be beneath the main outflow of cold surface air where it was draining from over East Anglia as a land-breeze. From 09 to 18 UTC on the 12th, very cold maximum air temperatures of −9 °C were recorded on the coast at Southend and Shoeburyness. Observations from Walton-on-the-Naze (Fig. 5) clearly indicate that this land-breeze over Essex pushed the coastal convergence line there out to sea for a 4-hour period between 12 and 16 UTC on the 12th; however, this movement may have been aided by the development occurring further north.

6. A mesoscale circulation

As deeper cold air began to arrive, to the north-east of Norfolk a small circulation began to form in the developing marine trough from approximately 03 UTC on the 12th. Continuity of this disturbance's centre is given in Fig. 1, as it moved initially west-north-westwards over the sea towards Gibraltar Point, developing as an eddy vortex, (a) on the boundary (convergence) line propagating downwind westwards from the Dutch Wadden islands and (b) between fast flowing air over the sea to the north and slow moving air which was stagnating over East Anglia.

Interestingly, surface observations (Fig. 7) showed a *veering* of surface winds, where steady addition of the land-breeze to the synoptic scale east-north-easterlies occurs, at first on the Norfolk coast (between 04 and 07 UTC at Weybourne) then later in south Lincolnshire (gradually between 07 and 11 UTC at Wainfleet).

Fig. 3 shows the mesoscale centre tracking over-land into Lincolnshire by 09 UTC on the 12th, thereafter retarding and turning soon after midday to drift north-north-eastwards towards the Humber, where it lost its identity some 16 hours after first forming, having produced 15–20 cm of snow in its immediate vicinity (Fig. 4(c)). Associated with this centre and its change of track, the coastal convergence lines combined to move north-eastward over Lincolnshire as a land-breeze cold front, having developed a 2 °C thermal contrast (Fig. 3(e) and the detailed sequential observations in Fig. 7), passing through Binbrook close on 1530 UTC and reaching Spurn Head, some 25 km distant, about an hour later, although passage of the small depression nearby may have hastened this movement.

7. Extremely low 1000–500 mb thickness values

It should be emphasized that the heavy coastal snowfalls over the period 11–13 January 1987 occurred in association with extremely low 1000–500 mb thickness values for Britain. The height of 497 geopotential decametres (dam) recorded at Hemsby on the 12th at 12 UTC exactly equalled the previous lowest UK measurement, coincidentally also at Hemsby at 12 UTC on 1 February 1956. However, on that previous occasion, the coldest air moved southwards to the east of Britain, so therefore, there is every likelihood that 12 January 1987 saw extreme low values throughout southern England, and later also in South Wales as this particular cold pool untypically moved westwards (see Fig. 8 inset), albeit warming slightly with time.

During the early evening of 12 January, thickness values were probably near 495–496 dam overhead areas immediately south-west of The Wash, where clear calm conditions and a fresh snow cover together combined to produce the coldest surface temperatures seen in England since the 1981/82 winter, and caused the θ-hill effect to persist over East Anglia.

8. Discussion of the snowfalls

For forecasters based in the United Kingdom, early indications of coastal convergence, initially forming in the boundary layer and aligned east-north-east to west-south-west near the north Dutch Wadden islands, were given by observations from West Terschelling Lighthouse (see Fig. 8 and sketch map in Groenland, 1987), where the surface wind veered to a direction south of easterly (indicating addition of the land-breeze) accompanied by continuous snow from 18 UTC on 10 January 1987. When unusually cold polar continental air is advecting from the east, similar coastal snowfall may well begin to affect south-east England 3–6 hours hence. Van den Berg (1987) cites the Wadden Islands coastal front as having had a known history of producing large amounts of snow especially on Terschelling (e.g. over 40 cm in January 1985, and 50 cm in the early-February 1956 outbreak).

Groenland (1987) reported that, during a 60-hour accumulation period from 10–13 January 1987, 22 cm had fallen at Buren (Ameland) and 50 cm at Hoorn (Central Terschelling) by 06 UTC on the 13th, when a maximum of 56 cm was measured on West Terschelling. There was negligible snowfall at Groningen and further south in Friesland.

Van den Berg (personal communication) related that, typically, snow depths tend to increase rapidly from east to west over the Dutch Waddens, with only very limited penetration southwards over the mainland. He noticed that, this particular 10–13 Jan. 1987 event formed a persistent line of heavy snow showers on the boundary between clear air over land and showery air over the sea, which he describes as 'The North Sea Lake Effect'.

Snowfalls were particularly spectacular around the Thames Estuary during the early hours and again over late afternoon–evening of 11 January. Thirty-three centimetres of snow (including a fresh 20 cm since the 09 UTC observation) was measured at 2130 UTC in Wigmore, near Gillingham, with snow still falling heavily. Just 10 km to the east at Keycol, 11 cm had fallen between 16 and 19 UTC; with a further 15 cm by 22 UTC, which can be interpreted as continuous and often heavy snow falling at a rate of up to 5 cm hr^{-1} (a

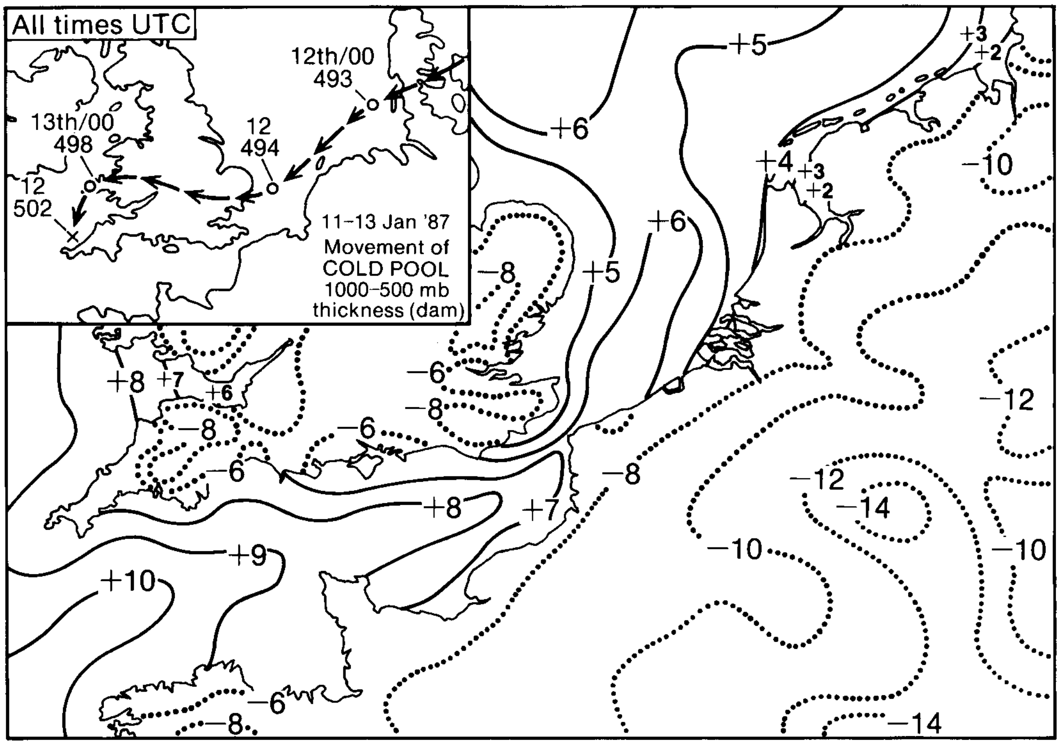


Figure 8. The 5-day mean sea surface temperature (°C) chart for 11–15 January 1987. The dotted lines over land are isotherms of maximum daytime temperatures (°C) on 12 January. Inset shows continuity of the movement of the centre of the 1000–500 mb cold pool, with central value.

rate only exceeded in north-east Norfolk around 02 to 04 UTC on the 12th). Therefore, it was hardly surprising that British Rail were unable to keep its routes through north Kent operating, since a traction system depending on good 'ground-contact' with the conductor-rail for electrification is perhaps the most vulnerable of all to heavy snow accumulating in very cold conditions.

It has been remarked that such heavy accumulations as occurred had not been adequately predicted (Prichard 1988), although for the most part Monk (1987) has successfully defended the UK mesoscale forecast model's precipitation distribution simulation, on a chart presented for 09 UTC on 13 January 1987. However, this was after the event, and snowfall amounts in north and east Norfolk were generally underestimated by a factor of 3, and the heaviest falls in north-west Kent by a factor of 2.

Observations of water equivalents of the overnight snowfalls (that were made early on the 12th at Keycol, Wigmore, and Leigh-on-Sea, Essex) indicate the new, powdery, dry snow, 35–45 cm deep, yielded only between 28 and 32 mm; which suggests that one source of model error was probably the assumption of a 1:10 ratio between rainfall and snow depth, which could well have been nearer 1:12 in the unusually cold conditions. At Braemar, Thompson (1963) showed 1:12 to be the most frequently-found ratio in water equivalents of snow when the air temperature fell into the −5 °C to −8 °C range (as experienced in south-east England).

Prichard (1988) also observed that the Thames Estuary snowfalls had been inadequately represented on radar displays from the Chenies (London) radar. Relevant Hemsby ascents and hourly Meteosat infra-red data (Fig. 3) indicate that the heavy snow falling on the 11th in areas bordering the Thames Estuary, emanated from a cloud band lying parallel to the Essex–east Suffolk coast with tops below 12 000 ft (i.e. tops warmer than −30 °C did not exceed the 650 mb/3.5 km level until 02 UTC on the 12th). Assuming Chenies to be 70 km from this precipitating cloud band, the radar beam would be elevated about 900 m high at this range. Therefore, it would not see the lowest portion of cloud (or beneath, in the boundary layer) where the largest snowflakes would almost certainly be concentrated.

Although a new radar has been commissioned near Lincoln recently, an installation located east of London in Kent or Essex may well be an answer to under-estimation of precipitation in easterly airstreams, especially in extremely cold winter weather when dryness of falling snow may well combine again with modest vertical development of cloud to exacerbate the problem.

The shallowness of coastal snow-producing cloud-systems in Sweden has been remarked upon by Bergeron (1949), who investigated two snowfalls which built up over about a week in two successive Januarys over flat land of the Stockholm peninsula. Both cases produced 35–40 cm of snow falling in a belt parallel to the shoreline, approximately 15–20 km wide, with its axis (and maximum falls) situated approximately 20 km from the outlying islands of eastern Sweden. Bergeron believed these events to have been partly caused by frictional convergence and lifting within an onshore wind, and partly by the sudden increase of vertical mixing at the coastline. The apparently stratiform cloud systems responsible for the snowfalls were, in reality, low and untypical, dwarflike, cumulonimbus clouds fused into a more-or-less continuous cloud deck, forming within the lowest unstable layer at the coastline.

Roeloffzen *et al.* (1986) confirmed theoretically that the effects of differential friction alone (given a strong onshore wind over a fairly flat coastline) produced maximum upward motion, in the order of 400–500 m vertically over some 25 km from the coast, when the geostrophic wind made a small ($\approx 20°$ clockwise) angle with the coastline, and least upward motion when near perpendicular to it.

Figs 3 and 4 indicate that the areas of greatest snow depth by 13 January 1987 followed an approximate shape of the East Anglian coast, if this were moved 20–30 km south-south-westwards. Snowfall charts in Bacon (1987) and Lumb (1988) confirm this idea. Historically, Bosart *et al.* (1972) originally linked the physical coastal configuration with convergence line or frontal orientation in USA Eastern Seaboard case studies, and Draghici's Black Sea coastal frontogenesis study (1984) confirmed this hypothesis.

The author had to make a return journey to London (from Newbury) on the 12th, and concluded that the climate of London was similar to Calgary (if only for a day). There was an unfamiliar absence of thawing snow where normally, underground sources of heat should have at least some effect. Along the M4 motorway, snow became apparent on the landscape from the vicinity of Heathrow Airport eastwards. In the West End of London, traffic wardens were nowhere to be seen, probably due to the extreme cold, and road markings in Piccadilly area (double yellow lines etc.) had been obscured by 3 cm of snow. A 15-minute walk early that evening to the car produced severely-chapped lips.

Skies had remained almost clear during the day in London, and there is a theoretical diurnal minimum in coastal convergence activity towards midday as thermal contrast between land and sea diminishes temporarily, due to solar heating of the ground. Apart from near the small centre over Lincolnshire, there did appear to be a temporary abatement of snowfall elsewhere in south-east England between 10 and 14 UTC on the 12th. Skies cleared almost completely over north-west Kent (Fig. 9) from about 06 UTC, with an observer at East Malling noting the cloud returning around 1330, snowfall re-commencing at 1410 UTC and continuing thereafter.

Water equivalent and snowfall maxima occurred in the Gillingham–Sittingbourne–Southend area. Before drifting in strengthening winds occurred, an average depth of 65 cm had built up by 09 UTC at Keycol, and 61 cm was measured in Wigmore at 1515 UTC (both in north-west Kent) on the 13th. However, on the Essex and east Suffolk coast, several reported snow depths were less on the 13th than on the 12th at 09 UTC (e.g. at Shoeburyness, Clacton, and at Halesworth), with observers noting that the snow had become more compact. Reductions here and at other locations near the sea were most probably due to stronger winds causing drifting, and ablation by salt particles.

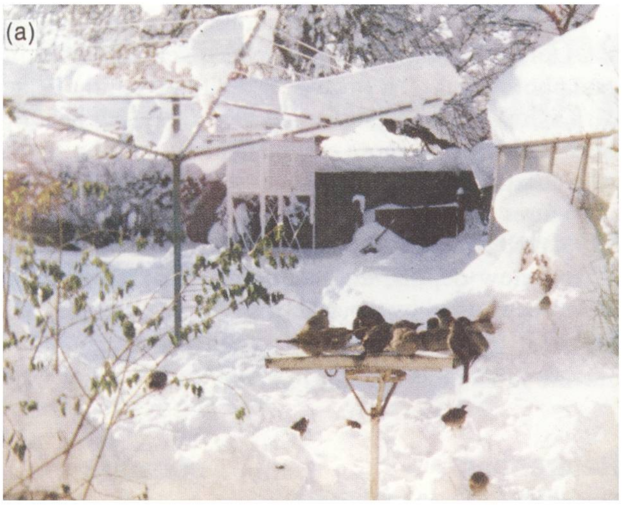
Illustrating the dry, powdery nature of the snow cover, a helicopter pilot, cautiously attempting a landing into wind at Wickford, Essex, at 1335 UTC on the 13th, was so disorientated by the machine's downwash which caused all external references to be lost in rotor-blown snow (estimated to have been 45 cm deep), that the helicopter was inadvertently flown through a hedge before coming to rest in an adjacent field. Although the aircraft suffered substantial damage, fortunately no one was hurt — from *Department of Transport Air Accident Investigation Branch Bulletin*, March 1987.

To demonstrate how closely the convergence zone had been associated with the east Suffolk–Essex coast since the 11th, Fig. 4(c) shows that places 40 km to the north-west and to the south-east (notably Stansted and Manston, each with 3 cm) were only reporting a thin cover at 09 UTC on 13 January 1987; Cambridge Botanical Gardens reporting no snow at all until then, when 1 cm was recorded. Meanwhile, there was turmoil around the Thames Estuary, where the Isle of Sheppey had become cut off and supplies were brought in either by sea, by helicopter, or by the Army on skis. Over the week 11–17 January 1987, Kent's newly-opened Radio Invicta Helpline received a record 23 000 telephone calls from motorists and householders requesting aid or advice in conditions described as the worst in living memory by the automobile associations — from *IBA Yearbook*, 1988.

9. The coastal front moves inland during 13 January 1987

At 21 UTC on the 12th, a light south-easterly wind at Leconfield AWS (just north of the Humber in Fig. 3(f)) indicates that this was the northernmost extent of the land-breeze cold front which, from observations, did not reach the outer Dowsing Light Vessel.

After halting, this land breeze front began to return south-westwards as a warm coastal front, whose passage was typically marked by a surface wind increase and veer (to a more easterly point) with a dry-bulb temperature rise over 1–2 hours of at least 1 °C hr^{-1}. The coastal frontal passage may also be regarded as terminating the θ-hill effect. The front arrived (Fig. 7 shows sequential observations) dramatically at Spurn Head by 22 UTC, with gusts to 34 kn); reaching Weybourne and Binbrook by 00 UTC on the 13th; Wainfleet by 01 UTC; Scampton in Lincolnshire by 04 UTC; Coltishall between 05 and 06 UTC; and Nottingham Weather Centre (the farthest inland frontal passage was still recognizable) between 06 and 07 UTC; then through Marham and Cottesmore by 09 UTC; Shoeburyness by 12 UTC; and Wattisham, also East Malling by 13 UTC.



Photograph courtesy of Mrs E. Taylor

Photograph courtesy of Mr W. Tribe

Figure 9. Snowfall on 12 January at (a) 0930 UTC near Sittingbourne, and (b) 1100 UTC near Maidstone.

The remarkable reluctance of the coastal front to finally detach itself from the Essex coastline appears to be directly due to an absence of the cloud cover which had overwhelmed the θ-hill effect much earlier further north, where in Norfolk and Lincolnshire, thick upper- and medium-level cloud was spreading over rapidly from the east at 03 UTC on the 13th (Fig. 3(g)).

10. General summary and conclusions

The location of snowfall maxima over south-east English coastal areas from Lincolnshire to north-west Kent over 11–13 January 1987 resembles those in the Swedish events investigated by Bergeron (1949); the snowfall on Terschelling in the north Dutch Wadden islands over the same days and also on 1–2 February 1956 (Van den Berg 1987); plus exhibiting distinct similarities to some lake-effect snowstorms seen on the western shores of Lake Michigan in the mid-west of the USA (see Passarelli and Braham 1981, Ballentine 1982).

As with the 1956 case in the northern Netherlands' islands, heavy coastal snowfalls were associated with extremely low 1000–500 mb thickness values arriving. The reading of 497 dam at Hemsby on 12 January 1987 at 12 UTC exactly equals the previous lowest UK record, and probably has a return period near 30 years. Given these unusual conditions, where exceptionally cold and quite unstable air flows over relatively warm waters, heavy snow showers may be expected to develop along the boundary line between clear air over cold land and showery air over the sea.

Around the Thames Estuary heavy snowfalls accumulated over 11–13 January 1987 because of coastal convergence of over-sea and over-land airflows persisting along one such boundary line near the east Suffolk–Essex coastline, and closely associated with it. Maximum falls were in excess of 60 cm (2 feet) deep in north-west Kent.

The coastal convergence here was brought about and enhanced by:

(a) Differential surface friction — rapid development and remarkable persistence (for over 60 hours) of an offshore marine trough over the relatively warm North Sea around East Anglia, with this trough providing a vital backing to north-easterly of the pressure gradient at the coast of Essex and east Suffolk in particular, where the geostrophic wind continued to make a shallow (15–30° clockwise) angle with the shore. With at least moderate wind force, these are conditions suitable for differential surface friction to produce maximum uplift of the onshore breeze just inland from the coast.

b) Thermodynamic effects — development of a mesoscale disturbance (like an eddy vortex) forming in the marine trough after 03 UTC on the 12th effectively slackened the pressure gradient over East Anglia, where a quasi-orographic hill of cold surface air stagnated inland, allowing land-breezes to develop near the coast.

Thermal contrast developing across the probably pre-existing frictional convergence line oscillates it either seaward as a land-breeze cold front or inland as a warm coastal front. Where the opposing forces balanced, the coastal convergence line lay quasi-stationary over north-east Norfolk between 06 and 18 UTC on the 12th.

A large surface temperature gradient (e.g. from Fig. 8, as existed on the 12th between the East Anglian Heights and the southern North Sea, resulted in land-breeze-induced oscillations of the coastal convergence lines/fronts which persisted near these large surface-temperature gradients, producing large amounts of snow in their immediate vicinity and just downwind.

While skies remained clear inland, the quasi-orographic θ-hill effect persisted over East Anglia, and perhaps this was the single most important factor in maintaining convergence near the east Suffolk–Essex coastline for some 66 hours, resulting in the heaviest snowfalls (65 cm) being reported immediately downwind in north-west Kent.

The land-breeze cold front reached to a maximum distance of 50 km out to sea north-east of The Wash at 15 UTC on 12 January 1987 (probably aided by movement of the small eddy-vortex, at that time over eastern England). The feature then halted, and returned westwards during the 13th as a warm coastal front, still being just recognizable as passing over Nottingham Weather Centre (Fig. 7) between 06 and 07 UTC, some 100 km inland.

Following Leslie's remarks (1988) on the closure of Binbrook concerning the limitations of synoptic automatic weather stations (SAWS), it may be concluded from Figs 3 and 7 that while the SAWS at Leconfield, Weybourne and Wainfleet give good additional records of surface pressure, temperature, wind speed and direction; they can at present offer no acceptable substitute for the human observation of snowfall.

The SAWS observations of surface winds veering rather than backing as the land-breeze takes over from the gradient wind (see section 6) could be an interesting area for future research.

Acknowledgements

To Meteorological Office staff: at Bracknell, particular thanks to the Nowcasting and Satellite Applications Branch (G.A. Monk) for supplying Meteosat data, also to the Advisory Services Branch for AWS data from Weybourne; and to the Library and Archives staff (particularly M. Wood) for their friendly help.

Extra observations from outstations came from J. Leslie (Binbrook), B. Morris (Manston), L. Gurney (Hemsby) and J. Davies (Frinton-on-Sea coastguard for Walton). Copies of autographic records were kindly supplied by M. Wickenden (East Malling) and S. Cardy (Shoeburyness), and correspondence came from R.J. Prichard and C.R. Burlton at LWC, Holborn.

Special thanks also to Dr Van den Berg for correspondence and kindly sending a copy of his Ph. D thesis on *Coastal Frontogenesis in The Netherlands* (now available in National Meteorological Library, Bracknell). Thanks to J. Webb of the Tornado and Storm Research Organization (TORRO) for the extra snow depths, to J.D. Bacon (Anglia TV, Norwich) for sending his paper on the snowfalls in East Anglia, to F.E. Lumb (Camberley) for prompting verification of the Marine Trough and to A. Sampson (Sheringham High School) for bringing the existence of Weybourne AWS to the author's attention. Also to Drs Meaden and Briscoe for supply of addresses of observers in Climatological Observers Link (COL).

In gratitude to the amateur observers, many being COL or TORRO members, who have sent observations and photographs (N. Brooks, R. Selfe, B. Smith, E. and N. Taylor, E. and W. Tribe, and D. Venuti) to help the author build up a more complete picture of the south-east coastal snowfalls on 11–13 January 1987.

Figures are by the author, based on information supplied by the Meteorological Office as detailed above. Extra snow depths, authenticated as far as possible, have been added by the author to Fig. 4, through COL and TORRO data supply.

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Exeter temperatures: monthly means from 1782 to 1839, and from 1985 to 1988

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Summary

A table of monthly mean temperatures representative of the vicinity of Exeter has been derived for the period from 1782 to 1839, linking with and completing the tables previously derived for 1840 to 1984.

1. Introduction

In an earlier paper (Hay 1985) monthly mean temperatures (MMTs) representative of the vicinity of Exeter for 1840 to 1984 were presented, based mainly on records kept at the Devon and Exeter Institution (DEI) and by the Revd Thomas Heberden (HEB) of Exeter Cathedral, and to a lesser extent, at several other stations in the neighbourhood. In this paper a description is given of the extension of the record back to 1782 and forward to 1988 (see Table I).

2. Derivation of the additional MMTs

The Heberden* records (undated) as available from 1782–1855 give monthly mean values of temperature for 0800 and 1400 clock time. The DEI record begun in 1817 similarly includes daily temperatures, taken at the fixed hours 0800, 1400 and 2200 clock time from 1817 to 1829, and daily maximum and minimum temperatures from 1830 onwards.

MMTs for DEI had not been computed in the original records, so these were next obtained from the daily values for 0800, 1400 and 2200. The following procedure was used to ensure that MMTs derived for the years before 1830 for HEB and DEI data, using only the fixed hourly data available, should be comparable with MMTs as obtained from mean monthly (MM) maximum and minimum temperatures for the later years.

The *Observatories' Year Book* for 1900 includes values of MMTs for Falmouth Observatory for each fixed hour 0000 to 2400, meaned for the 30-year period 1871–1900, together with MM maximum and minimum temperatures for the same period. (Falmouth was used as being the nearest station to Exeter where hourly data are available, and since both stations lie adjacent to the English Channel). Mean monthly ranges of temperature defined as (MM maximum−MM minimum) were then obtained over similar periods for Falmouth and Exeter for each month, and monthly ratios (MM range Exeter/MM range Falmouth) were derived. These ratios for each month were then used to multiply the MM differences of each Falmouth mean hourly temperature (0, 1, 2 .... to 24 hours) from the appropriate 24-hourly means for Falmouth to obtain derived Exeter MM differences to be expected at each hour (0–24 hours) from the appropriate 24-hour means for each month. The Exeter MM differences, derived here for 0800, 1400 and 2200 hours alone, were then used to obtain corrections to be applied to the MMs derived from $(T_{0800} + T_{1400} + T_{2200})/3$ to derive the MMs to be found from MM maxima and minima if these had been available. The same procedure was also applied to the Heberden records available from 0800 and 1400 hours.

The Heberden record between 1782 (when it was begun) and 1817 when the DEI temperature series begins, is unfortunately not supported by any other record, except for a record from Earnshill, Somerset (see Table II) which is complete between September 1798 and December 1804 inclusive. However when MMTs had been determined for Earnshill (EAR) from this record, and mean differences (EAR−HEB) between MMTs obtained over the 6 complete years available, it was decided not to use Earnshill to modify the Heberden data in deriving Exeter MMTs. Earnshill MMTs meaned for the period 1799–1804 were found to be higher than Exeter from March to November, the differences reaching up to 2.0–2.2 °C in June and July. They were slightly below Exeter MMT values from December to February. An additional consideration against the use of the Earnshill data here was that, as a result of a visit to Earnshill House, it became evident that, while the house lay in an open rural situation, the present owner was unable to give any details regarding the site (or sites) used, or details of instruments and times of observations, apart from the meagre information already available in the records themselves.

* A note written in volume I of the Weather Records of the Revd Thomas Heberden gives details of his places of residence, and states that he was Canon Residentiary of Exeter Cathedral from 1788 until his death in 1843. While no other details are given relating to the position where his observations were made, it can reasonably be inferred therefore that his residence was very near to the Cathedral and his observations of temperatures etc. were made at a location not very far from the position where the DEI installed their thermometers in 1817. The differences between individual observations suffice to suggest the sites were not identical but at least their heights above mean sea level were similar and their distance apart quite small.

Table 1. Monthly mean and yearly temperatures (°C) for Exeter, 1782–1839 and 1985–1988

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1782	—	—	—	—	—	—	—	—	—	—	—	5	—
1783	6	—	—	—	—	—	—	—	—	11	—	6	—
1784	1	(1)	—	—	—	—	—	—	—	—	—	—	—
1785	(7)	2	2	10	12	17	17	15	15	11	8	5	(10.1)
1786	7	6	3	11	11	17	16	17	—	—	—	—	—
1787	—	—	—	—	—	—	16	17	15	11	6	6	—
1788	—	—	—	—	—	—	15.9	16.5	14.4	10.8	6.3	0.0	—
1789	3.6	6.2	(2.1)	8.9	11.7	13.0	15.0	16.1	12.9	9.0	5.2	6.8	9.2
1790	5.7	7.2	6.9	(6.0)	11.5	14.1	15.1	16.2	13.1	11.2	7.1	6.4	10.0
1791	6.3	5.5	6.6	10.8	10.7	15.1	15.0	16.3	14.9	9.8	6.9	3.2	10.1
1792	5.2	6.0	6.6	10.5	10.8	14.0	15.4	17.2	12.6	9.6	8.2	6.9	10.3
1793	4.6	6.4	5.6	7.2	11.1	13.4	18.4	16.2	12.9	12.1	7.6	6.4	10.2
1794	2.4	[8.3]	8.6	10.8	11.4	16.0	18.6	15.4	12.9	10.9	8.7	5.4	(10.8)
1795	−1.9	3.4	5.4	8.9	11.9	12.9	14.3	16.2	16.4	[12.8]	5.7	(9.1)	(9.6)
1796	[8.6]	5.6	4.6	9.9	11.4	14.8	15.7	16.0	14.9	9.2	5.6	1.3	(9.8)
1797	4.9	5.2	5.3	7.5	11.1	(12.3)	15.4	15.2	13.0	8.7	7.7	6.6	9.4
1798	5.2	5.0	6.1	10.5	12.5	17.2	16.5	17.1	14.1	11.2	5.4	2.7	10.3
1799	3.7	5.1	4.4	6.0	10.5	14.8	15.9	14.9	12.9	8.7	7.3	1.5	8.8
1800	4.8	4.0	5.1	10.1	11.9	13.6	18.5	(18.7)	(15.9)	11.2	6.8	5.7	10.5
1801	6.6	5.3	7.9	8.8	11.8	15.3	16.9	18.5	(16.4)	12.2	6.8	4.7	10.9
1802	2.8	5.3	6.1	(10.8)	12.2	15.3	14.6	18.2	14.6	11.4	6.7	5.4	10.3
1803	2.3	4.7	7.1	9.1	10.9	14.2	(19.2)	(18.0)	13.0	10.7	6.3	6.5	10.2
1804	(8.1)	5.1	5.9	7.3	13.1	17.1	16.8	17.1	15.7	11.5	8.2	3.3	10.8
1805	2.9	5.0	6.6	8.0	10.5	13.3	16.7	17.4	15.7	9.5	7.0	5.4	9.8
1806	5.9	6.1	6.0	7.4	13.1	15.9	17.9	16.9	14.3	11.8	[9.2]	(9.1)	(11.1)
1807	4.3	6.1	3.6	8.3	12.8	13.7	17.7	18.0	13.0	12.6	4.7	4.3	9.9
1808	4.0	4.2	4.1	6.6	14.0	15.0	18.6	17.7	14.0	9.0	8.2	4.2	10.0
1809	4.6	7.8	6.6	5.8	12.8	14.6	16.8	15.7	14.1	11.3	5.6	5.5	10.1
1810	3.7	5.3	6.9	9.4	10.5	15.8	16.5	15.7	14.9	11.2	6.2	6.4	10.2
1811	1.8	6.6	8.1	9.4	13.2	14.8	17.4	16.3	14.9	13.4	8.4	5.3	10.8
1812	3.7	6.7	4.7	7.5	12.0	13.9	16.1	16.0	14.5	10.8	7.1	2.5	9.6
1813	3.2	6.0	7.4	8.3	12.1	14.0	15.4	16.8	13.7	10.2	6.5	4.1	9.8
1814	−0.7	3.2	3.5	10.0	10.3	13.3	16.5	16.1	14.3	8.8	6.5	6.5	9.0
1815	1.2	7.8	8.7	8.8	12.9	14.5	16.4	16.4	14.3	10.6	4.6	3.8	10.0
1816	3.4	3.8	4.6	7.4	10.4	12.5	12.9	13.5	12.9	10.7	5.0	4.0	8.4
1817	5.7	7.9	6.8	8.2	9.5	14.7	14.2	14.6	14.1	7.3	10.4	4.4	9.8
1818	5.6	4.3	6.2	8.2	12.4	17.5	18.9	16.7	13.9	13.1	11.2	4.4	11.0
1819	6.1	5.9	7.4	9.6	12.3	13.6	17.3	18.1	14.7	10.2	5.9	3.6	10.4
1820	1.2	3.7	5.3	9.9	11.8	14.5	16.2	15.9	13.1	9.5	6.3	5.3	9.4
1821	4.7	3.1	7.1	9.8	10.2	12.8	15.4	17.3	15.8	11.4	10.1	7.6	10.4
1822	5.8	7.0	9.1	9.1	13.6	17.7	16.2	15.9	13.7	11.5	9.2	2.8	11.0
1823	1.1	5.1	6.1	7.9	12.9	13.1	14.6	15.6	13.5	9.9	7.3	6.2	9.4
1824	4.6	6.1	5.8	7.7	11.3	13.8	16.7	16.5	14.9	10.7	9.2	6.9	10.3
1825	4.9	5.6	6.5	10.5	12.6	14.7	18.6	17.3	16.6	12.1	6.8	6.3	11.0
1826	3.1	7.8	7.1	10.2	12.6	18.1	18.9	18.0	15.3	12.8	6.1	7.7	11.5
1827	3.7	1.8	7.5	9.7	12.3	14.3	17.6	15.8	14.6	11.8	9.2	8.4	10.6
1828	6.8	6.6	7.9	9.2	12.9	15.8	16.6	15.3	15.4	11.2	9.3	9.2	11.3
1829	1.4	6.3	5.2	7.4	13.6	14.6	15.7	15.1	11.9	10.2	5.7	1.9	9.1
1830	0.2	3.0	8.5	9.6	12.4	13.4	16.6	14.9	12.5	11.5	8.2	3.2	9.5
1831	3.1	6.1	7.7	9.6	12.1	15.5	16.8	17.6	14.2	13.2	7.6	6.8	10.9
1832	4.6	4.2	6.4	8.4	11.7	14.8	16.6	16.3	13.3	10.6	7.5	6.5	10.1
1833	3.2	6.8	3.7	8.4	14.0	14.2	16.3	14.7	12.2	11.1	7.9	8.1	10.1
1834	8.1	6.2	7.8	8.5	13.5	14.6	16.7	16.3	14.5	11.3	6.5	6.1	10.8
1835	4.8	6.7	6.4	8.8	11.7	15.4	17.7	17.2	13.9	9.5	7.7	3.2	10.3
1836	5.1	3.3	6.5	7.6	11.4	15.0	16.3	16.2	12.6	9.2	6.7	5.3	9.6
1837	3.6	6.5	2.6	4.8	10.6	15.5	17.8	16.2	13.9	11.5	6.9	5.9	9.7
1838	0.3	2.2	6.4	7.2	11.7	14.2	16.3	16.6	13.6	11.2	6.2	5.4	9.3
1839	4.5	5.6	5.8	7.2	11.1	15.1	15.8	15.4	13.4	9.9	7.7	6.0	9.8
1985	1.4	4.3	5.7	9.1	11.6	13.9	16.6	15.3	14.5	11.6	5.3	8.1	9.8
1986	5.7	0.3	6.3	6.2	11.1	15.3	16.4	13.9	11.9	11.9	8.7	7.8	9.6
1987	2.1	5.2	5.7	10.0	11.1	13.8	16.6	16.7	14.9	10.9	7.9	7.1	10.2
1988	7.0	5.7	7.7	8.6	12.2	15.5	15.1	15.5	14.1	11.9	7.3	8.8	10.8

Brackets ( ) = value doubtful, [ ] = value derived (see text).

Italic figures are used for years 1782–1816 when HEB was the only station available for Exeter. For the years 1817–1839, HEB and DEI (and Shapter) values were available.

Returning to the original Heberden record, it begins with an interrupted series of monthly data made at Bridestowe, North Devon between December 1782 and October 1786, and this is followed by a few monthly observations made at Whimple, near Exeter until January 1788. In May 1788, Heberden began the series of MMTs at Exeter near the Cathedral, which continued without a break until 1843.

For the derivation of a reliable homogeneous series of MMTs for the location of Exeter from 1789 onwards, the Heberden record was virtually the only one available until 1817, the year when the DEI series was started —the Earnshill records for 1798–1804 have already been considered. Both records are nearly complete between 1817 and 1839, the period covered in this paper. Another record has also been published by Shapter (see Table III and references) covering the period 1824–53. However when a comparison was made between Shapter's figures and the DEI data, it became evident that Shapter had taken his data direct from the DEI data. The former's data were therefore not used in deriving the Exeter series presented here, except in some instances when DEI data were doubtful or not available, and in most of these cases the individual MMTs derived were then based upon Heberden and Shapter instead.

While deriving all the MMTs, values of the differences (HEB−DEI) were also noted and classified according as to whether they lay within the limits of 0.0 − 0.4, 0.5 − 0.9, or ⩾ 1.0 °C. In the end it was only found necessary to make use of this grouping when considering

Table II. Stations used for analysis of Exeter temperatures

Station	Latitude	Longitude	Height (feet)	Height (metres)	Period of observations
Exeter, Devon and Exeter Institution (DEI)	50° 43′N	03° 32′W	155	47	1817–43
Bridestowe, Devon	50° 41′N	04° 06′W	520	158	1782–86
Whimple, Devon	50° 46′N	03° 21′W	165	50	1787–88
Earnshill House, Somerset	51° 00′N	02° 52′W	66	20	1798–1804

Table III. Corrections used to reduce original observations made at fixed hours to their equivalent values of monthly mean temperature (MMT) related to $(T_{min} + T_{max})/2$ (°C)

Station	Fixed hours	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Exeter, Heberden record	0800 and 1400	−0.2	−0.1	−0.5	−0.9	−1.2	−1.2	−1.2	−1.1	−0.9	−0.6	−0.3	−0.3
Exeter, DEI record	0800, 1400 and 2200	−0.1	0.0	−0.1	−0.2	−0.3	−0.3	−0.1	−0.2	−0.2	−0.1	−0.1	−0.1
Shapter table	Daily max and min from 1824	0.1	−0.1	−0.2	−0.4	−0.9	−1.1	−0.9	−0.7	−0.4	−0.2	0.1	0.2
Bridestowe, early years of Hederden record	0800 and 1400	0.3	0.2	−0.5	−1.3	−2.0	−2.0	−1.7	−1.3	−1.1	−0.6	0.0	0.3

The above corrections include those for site effect (see correction C in Hay (1985)), fixed hourly values and for height a.m.s.l. In the case of Exeter DEI, correction C is not included here but was applied to the figures used in Table I before their inclusion in the table.

the reliability of a number of doubtful cases of MMTs, some when (HEB−DEI) ⩾ 1.0 °C, which were found through the period 1789–1839. In dealing with these months, the doubtful values as first derived were compared with the long period (LP) monthly extremes, highest or lowest, as appropriate, for Exeter, Oxford and Central England (CE). In most cases, doubtful values derived from (DEI+HEB)/2 arose because, when checked against the LP extremes, highest or lowest, for Exeter DEI as already derived for 1840–1984 in Hay (1985), these doubtful cases were found to be equal to or outside the LP limits. It remained to devise a stricter routine in this work, as follows. Firstly, all cases in which the MMT lay beyond the LP extremes and up to 1.1 °C (i.e. just inside the LP extremes) were noted. A decision on whether the high (or low) value of each doubtful MMT was correct (or nearly so) was then made possible in almost every doubtful case by applying this same procedure to the known MMTs for the same months for Oxford (from 1815 onwards) and for CE for the whole period from 1789. Where the DEI value of an MMT still remained doubtful, then the temperature anomalies (TAs) for DEI, HEB, Oxford and CE (with respect to the appropriate LP monthly averages) were derived and an inspection of their geographical distribution with respect to each other was sufficient to resolve the difficulty. For a 'hard core' of four cases 'derived MMTs' were found by making use of the data shown in Table IV. This table yields derived MMTs falling within the LP extreme MMT values in three cases, while it suggests February 1794 probably represents another extreme (mild) month. These derived values have therefore been included in Table I, as being the best available, to make it complete for the whole period.

3. Comparisons with Manley's Central England Series

Support for the accuracy of the figures in Table I using Manley's data for CE (1974) has been obtained as follows. Differences through 10-year periods 1810–19 ....1860–69 between monthly 10-yearly means of (CE−Exeter) were first extracted. This was done to ensure that no serious inhomogeneity existed between Exeter MMTs as derived for months for 1840 onwards in Hay (1985), and those for 1839 and earlier years as shown here in Table I. Any abrupt change in Exeter MMT through the years around 1840 should be shown by this comparison with the corresponding MMTs for CE. In fact the differences in MMTs for (CE−Exeter) between the means for 1830–39 and for 1840–49 amounted to +0.5 °C in winter (December, January, February) and −0.2 °C in summer (June, July, August) respectively. The largest differences for individual months were similarly +0.9 °C in December and −0.3 °C in July. (For the 30-year periods 1810–39 and 1840–69 the differences were similarly 0.0 °C in winter and −0.6 °C in summer.) Similarly the differences (CE−Exeter) over the 30-year (or 40-year) periods 1811–40, 1841–70, 1871–1900, 1901–40 and 1941–70 were respectively −1.3, −1.3, −1.2, −1.4 and −1.4 °C in winter, and −0.7, 0.0, −0.3, −0.4 and −0.3 °C respectively in summer.

The variances of the two sets of differences of annual mean temperatures (CE−Exeter) for the periods 1789–1839 and 1941–1973 were computed and found to be 0.0728 and 0.04 respectively, giving a variance ratio (F) of 1.82. Reference to the relevant tables show that for degrees of freedom 50 and 32 and assuming that, prior to calculating them, it was not known which period showed the greater variance, then the significance

Table IV. Monthly mean temperatures (°C) — derivation of doubtful cases

	Exeter Heberden initial reduced value	Exeter extremes 1840–1980	Exeter means 1841–1980	CE means 1851–1950	Differences (CE−Exeter) in months shown	Differences (CE−Exeter) for LP means	CE MMT for month shown	Derived* MMT for Heberden	† Col. 8 −Col. 2
	1	2	3	4	5	6	7	8	9
1794 Feb.	9.0	8.3	5.2	4.1	−1.8	−1.1	7.2	8.3	0.0
1795 Oct.	14.0	13.7	10.7	9.6	−2.3	−1.1	11.7	12.8	−0.9
1796 Jan.	9.2	9.0	5.0	3.7	−1.9	−1.3	7.3	8.6	−0.4
1806 Nov.	10.4	9.9	7.4	6.0	−2.6	−1.4	7.8	9.2	−0.7

* For each month (Derived Heberden) = (CE−Exeter) i.e. (col. 7−col. 6).

† Values in col. 9 show the differences in each case between 'Derived Heberden' and the long period (LP) extreme. Feb. 1794 probably represents an extreme (mild) month, the other three months falling up to approximately 1 °C below the appropriate extreme values.

level was low (around 10%) and hence it is probable these two variances are not significantly different. This result can be regarded as satisfactory, together with the fact that the overall mean differences (CE−Exeter) between mean annual temperatures were found to be −1.0 °C during 1789–1939 and −0.8 °C for 1941–1973 respectively.

The general conclusion drawn from the comparisons described above suggests that the MMTs, as derived here, for 1782–1839 for Exeter, while being virtually independent from CE, are in fact broadly in agreement with MMTs as given in Manley's long-period series. Besides providing a new 200 years MMT series for the Exeter area, these figures also afford a useful back-up for Manley's results through the period here considered.

Acknowledgement

Valuable assistance given by D. Griffith, Senior Meteorological Officer, Exeter Airport, in making available temperature records for the Airport from 1942 to date as needed, is gratefully acknowledged.

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Notes and news

American Society for Testing and Materials (ASTM) symposium on Mapping and Geographic Information Systems, San Francisco, California, 21–22 June 1990

This symposium is sponsored by the ASTM Standards Writing Committee D-18 on Soil and Rock. The Committee D-18 is one of 134 ASTM technical standards writing committees, and ASTM (organized in 1898) is one of the largest voluntary standards developments systems in the world.

The purpose of the symposium is to bring together an interdisciplinary, international group of engineers and scientists to:

(a) Provide a forum to exchange experiences related to the needs and methods for Geographic Information Systems (GIS), maps, and remote sensing, and the potential for standardization of some elements of each.

(b) Learn from both successful and unsuccessful case histories.

(c) Promote technology transfer between the various disciplines and countries represented.

(d) Provide an education resource for those attendees who may be considering using, for the first time, the three elements that make up an overall land information system.

More information is available from the symposium chairman:

Ivan Johnson
7474 Upham Court
Arvada
Colorado 80003, USA
Tel: 303-425-5610.

Reviews

Weather sensitivity and services in Scotland,

edited by S.J. Harrison and K. Smith. 180 mm × 257 mm, pp. viii+180, *illus*. Edinburgh, Scottish Academic Press, 1989. Price £25.00.

This book is the outcome of a conference which was jointly organized by the Meteorological Office and the Climatic Hazards Unit of the University of Stirling. It was held in February 1988 and was attended by about 150 delegates associated with a wide range of weather-sensitive activities.

The objectives of the conference, and therefore this volume, were to demonstrate the role of weather and climate information in the management of weather-sensitive activities and to encourage interaction between the providers and users of such information. This is a laudable aim and any small step in facilitating this is to be welcomed.

Four main areas are covered: advances in observing and forecasting the weather; transport; agriculture, water and wind resources; industrial applications. Some contributions expand on their topic at some length, while others are short and sometimes superficial. Indeed, individual contributions vary in length from 18 pages to little more than 3 pages. A contribution by Professor Keith Smith serves as a good introduction to the volume. He explores weather variability and its social and economic effects and, quite reasonably, argues that the drive towards greater efficiency leads to a greater vulnerability to weather extremes.

In the first of the four sections which follow, the papers by Collier and Golding give useful overviews of the topics: the use of radar and satellite data in forecasting; numerical weather prediction. Much of the material can be found in earlier papers by these authors, but these contributions are put together in a way which non-specialists will find palatable. It will be interesting to look back at the predictions, for numerical forecasting in the 1990s, made by Golding at the end of this article.

I found none of the articles in the section (on transport) particularly inspiring, but they serve the purpose of highlighting the needs of road and rail transport, and the attempts to cater for these needs by the Meteorological Office.

The third section contains three articles: one each on agriculture, water resource management and the wind-turbine industry. Callander points to the 'minimal' exploitation of weather services by the Scottish agricultural community, even more so since the demise of the Agricultural Meteorology Unit in Edinburgh in 1981. He holds out the hope that the provision of information from the eventual extension of the weather radar network (long a bone of contention with the broader meteorological community in Scotland) will provide real benefits to agriculture. The article by Sargent focuses on the expected benefits from radar in terms of flood forecasting, and Elliot and Barton bemoan the paucity of wind data appropriate for the wind-power industry.

The final section contains seven articles under the general title 'industrial applications'. Some of the contributions are very short and serve little purpose, but the enormous potential for better use of meteorological information is brought out — for instance, losses due to weather-related stoppages in the construction industry are estimated at £400m. The article by Steel on weather sensitivity in the gas industry is the longest, and in my opinion the best, contribution to this section. It presents demand-forecasting models used by the industry, expressing general satisfaction with presently available weather information.

This book will not have a large market, but forms a useful addition to a library alongside such texts as Maunders' *The uncertainty business*. It would be improved by the addition of even a short index.

K.J. Weston

A short course in cloud physics, third edition, by R.R. Rogers and M.K. Yau. 151 mm × 228 mm, pp. xiv+293, illus. Oxford, New York, Beijing, Frankfurt, São Paulo, Sydney, Tokyo, Toronto, Pergamon Press, 1989. Price £15.00, US$27.00 (paperback), £30.00, US$54.00 (hardback).

This book is the third edition of a book by the first author originally published in 1976. It is one of a series on Natural Philosophy which includes a few other titles of interest to meteorologists.

Lecture notes from a graduate course for physical meteorology students form the basis of the book, but it will also be suitable for undergraduates with a good knowledge of physics and mathematics. No previous knowledge of meteorology is assumed. Familiarity with differential equations is essential although the derivation of many equations is omitted. Prof. Rogers is experienced in the interpretation of cloud observations, especially the use of radar data, while this revised edition has also benefitted from the cloud modelling expertise of Dr Yau.

The book is intended to provide a basic understanding of cloud processes and it includes the necessary general meteorology to achieve this, for example, thermodynamics and stability. The treatment is brief but comprehensive. The treatment of most topics is not as deep as in the books by Pruppacher and Klett or Mason and, although therefore the book may not appeal to the cloud physics specialist, it is ideal for the more general meteorologist or for those who are concerned with the applications of cloud physics.

The first four chapters discuss the thermodynamics of dry and moist air, buoyancy and convection. They include a good description of thermodynamic diagrams and of the different instabilities in atmospheric flows. A new, and up to date, chapter on the observed properties of clouds begins a series of chapters which include most of the topics which come under the heading of cloud physics, cloud droplet and ice crystal growth, precipitation processes, severe storms and weather radar. Weather modification receives a rather cursory discussion which would have benefitted from more examples. Cloud electrification and lightning are not mentioned. The book ends with a chapter on numerical cloud-models which has been substantially rewritten and provides a clear discussion of the limitations of different types of model and of the scientific advances which have come about through the use of models, especially the dynamical interactions leading to the maintenance of severe storms.

Apart from the major changes mentioned above, the text has been revised in many places to include recent developments such as advances in the understanding of entrainment processes. It is a pity that SI units are not universally adopted in this edition; the application of empirical formulae often causes difficulties when different units are used.

The author has included in this edition, as in earlier editions, a number of examples for the student to work through. These are well thought out, reinforcing, and in several cases extending, the material. The answers, where provided, should be easily understood. Comprehensive and up-to-date references are provided and several of these are identified as providing fuller details in areas which are treated briefly. The book is well illustrated with carefully chosen and well reproduced diagrams; the use of colour for the radar images might have improved the attractiveness of the book but their absence does not affect the clarity of the argument.

The earlier editions of this book have been successful. The present edition is a significant improvement and is recommended to those who wish, or need, to know something of the complex processes which are too often dismissed by statements such as 'the air is forced to rise, as it does so it cools and water condenses to form rain'.

P.R. Jonas

Spacious skies, by R. Scorer and A. Verkaik. 222 mm × 288 mm, pp. 192, *illus.* Newton Abbot, London, David and Charles, 1989. Price £20.00.

Richard Scorer has long been regarded as a foremost authority on cloud physics, and uses cloud photography to illustrate his theories. This book could be looked upon as a supplement to his excellent *Clouds of the World*, published in 1972, by adding many well produced satellite pictures and comprehensive notes on their details. In addition, the many photographs of cumulus-type clouds by Arjen Verkaik greatly add to those used by Dr Scorer in his earlier work. Arjen Verkaik became fascinated as a boy by the ever-changing skies and from this began to collect many cloud photographs. This led to a desire to understand the physical processes at work and, encouraged by his wife, he delved even deeper into the subject. Fortunately, their common interest drew the two authors together in 1984 and resulted in the planning of this book.

The object of the book is to show how rewarding 'sky-watching' can be, and so help the reader to understand what clouds and their changes can tell us, using 'discerning eyes and tinted vision'. By photographing clouds and taking time-sequence series, the changes can be studied at leisure and the physical processes thus deduced.

The second and seventh chapters are devoted to satellite pictures. In chapter 2 there are many fine illustrations of the effect of land features on the overall cloud pattern. Many of the finer details could be overlooked had our attention not been drawn to them by Richard Scorer. The effects caused by Jan Mayen island are strikingly illustrated and he asserts that (para 3.1.a) 'It is undoubtedly the most interesting oceanic island in the World for the variety of patterns it generates'. Chapter 7 gives details of satellite orbits and the filters used to differentiate various cloud and dust or haze features. More striking satellite pictures show frontal cyclonic and anticyclonic cloud systems with comments, at times, almost poetical at the beauty so exhibited.

Chapter 3 discusses in a general way the convective processes, frontal clouds and variations in ALTO and ICE clouds. The illustrations are well chosen and adequate notes are given for each. Chapters 4–6 deal with cumulus-type clouds and related phenomena such as tornadoes etc. as seen by the camera of Arjen Verkaik. The wide experience of Richard Scorer can be detected in the text, and numerous explanatory diagrams are reproduced from his *Clouds of the World*. There are many sequence pictures to explain the thinking behind the deductions made. The discussion on cumulonimbus is interesting with its development from a single cell to multiple cells. The term 'dryline storm' is introduced and illustrated — a phenomenon not known in western Europe. The pictures in these three chapters, covering about half the book, and Haboob effects in chapter 13, are practically all taken in Canada and are the work of Arjen Verkaik.

A useful appendix is given on the physical nature of clouds and allied phenomena; the Index is comprehensive. There are few errors and the quality of the text and illustrations are good. Many of the pages are unnumbered, which hinders cross reference and the fifth picture referred to in para 6.30.e in the series does not appear.

As an experienced and enthusiastic cloud watcher and photographer myself, I can recommend this book as a must for all meteorological libraries, for students of cloud physics and to those dedicated cloud watchers who wish to delve more deeply into the subject.

R.K. Pilsbury

Books received

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

Weather radar and the water industry, by the British Hydrological Society (Wallingford, Oxfordshire, Institute of Hydrology, 1989) summarizes the proceedings of a seminar held at the Institute of Hydrology on 6 April 1989. It contains eight papers on the various aspects of the subject by authors from a cross-section of viewpoints.

Turning up the heat, by F. Pearce (London, Glasgow, Toronto, Sydney, Auckland, Paladin, 1989) is a wide-ranging survey of the pollutants that have caused concern about global warming. Ways of rethinking the approaches to the subject are presented.

Our drowning world, second edition, by A. Milne (Bridport, Dorset, Prism Press, 1989) contains explanations for the author's belief that nearly two thirds of the earth's surface will be flooded by polar ice-cap water — the result of human activity.

Earth's changing climate, by A. Milne (Bridport, Dorset, Prism Press, 1989) explores the importance of extra-terrestrial influences on the earth's weather patterns. It is a companion book to *Our drowning world*.

Atlas of the surface heat balance of the continents, by D. Henning (Berlin, Stuttgart, Gebröder Borntraeger, 1989) presents detailed analyses of mean multi-period values of many varied fluxes and parameters. A discussion of the three methods of data treatment used, an explanation of the main features of the maps, and tabulated area averages are included.

Satellite photograph — 23 November 1989 at 0824 UTC

Figs 1 and 2 illustrate the pattern of convective cloud near southern Britain as polar air flowed south and west over warm seas. Over the North Sea, tops of the convection probably approached 700 mb. However, further west the convection was limited by a marked subsidence inversion at 850 mb caused by an anticyclone which had recently developed near Ireland.

The NOAA-10 visible image (Fig. 1) indicates cellular cumulus cloud over the North Sea, but elsewhere the cloud top has a mostly stratiform appearance. Two cloud bands are noteworthy — a gradually widening band, within which a narrow line of cumulus tops (labelled A) is to be observed along the English Channel, and a similar but less well defined band (B) west of the Bristol Channel.

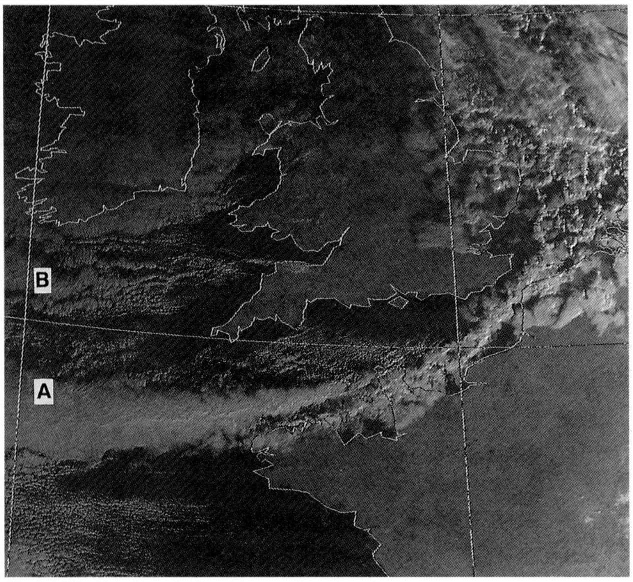

Figure 1. NOAA-10 visible image for 0824 UTC on 23 November 1989. The isobaric pattern at 1200 UTC is superimposed.

Sequences of Meteosat and NOAA images showed the bands persisted with little lateral movement for more than 2 days. During the subsequent long anticyclonic easterly period of weather, the English Channel band occurred on all but 2 of the next 18 days, although its position varied between the French and British coasts depending on the exact wind direction, and probably the strength of the land-breeze circulation. Further evidence of the persistence of the bands was obtained by calculating the mean brightness of sequences of Meteosat visible images that were 'normalized' (i.e. brightness corrected according to sun angle). The result for 23 November is shown in Fig. 2. Streamlines drawn directly from surface wind analyses derived from UK mesoscale-model data (Fig. 3) indicate marked convergence co-located with the cloud band in the English Channel, and weak convergence in the Bristol Channel. Due to the limited depth of the convection, precipitation beneath the bands was generally patchy and light. However, when instability is deep, convergence around the coast of southern Britain can lead to localized extreme accumulations of precipitation as described in Pike*, and another imminent issue.

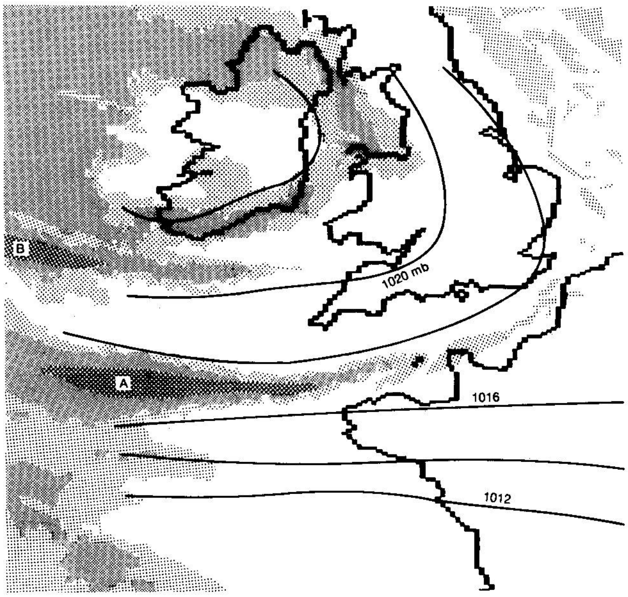

Figure 2. Average visible brightness during hours of strong daylight — 0930–1430 UTC inclusive — at intervals of 30 minutes.

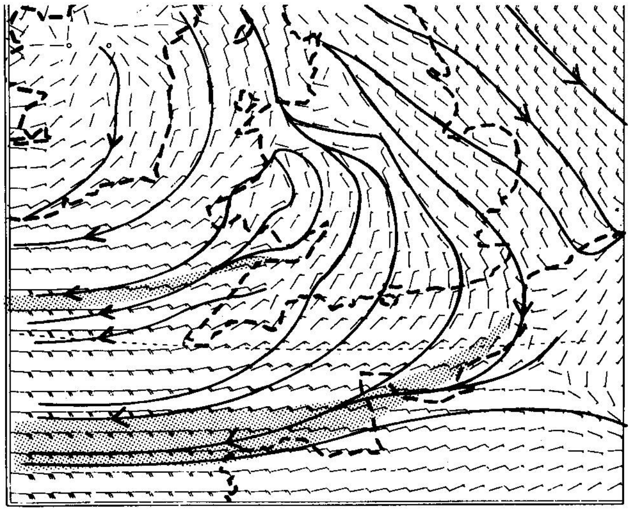

Figure 3. Streamlines of surface winds valid at 1200 UTC, drawn on a 12-hour forecast from the UK mesoscale model. The cloud bands associated with the convergence are shown hatched.

G.A. Monk

* Pike, W.S.; Persistent coastal convergence in a heavy snowfall event on the south-east coast of England. *Meteorol Mag*, **119**, 1990, 21–32.

GUIDE TO AUTHORS

Content

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

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

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

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

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS 1991: Part 1: 1976, and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

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Illustrations

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Sharp monochrome photographs on glossy paper are preferred; colour prints are acceptable but the use of colour is at the Editor's discretion.

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February 1990

Editor: B.R. May
Vol. 119
No. 1411

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ISBN 0 11 728662 1 ISSN 0026–1149

Printed in the United Kingdom for Her Majesty's Stationery Office
Dd. 0291241 C13 2/90 503 12521