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Real-time analysis of precipitation using satellites, ground-based radars, conventional observations and numerical model output

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Summary

In this paper we review methods of estimating precipitation using satellite data, which is a prime requirement of systems designed to aid the production of very-short-period weather forecasts or nowcasts. An attempt is made to assess and compare the accuracy of the various techniques in order to indicate the performance likely to be achieved by any procedure implemented in real time. The combination of several different types of data is likely to provide improvements in measurement accuracy. By way of illustration a real-time procedure currently being developed for operational use in the Meteorological Office is described. This procedure uses radar and conventional observations with satellite imagery and numerical model output. The need for quality control procedures, preferably based upon objective algorithms, is stressed, as no single source of data is capable of defining the precipitation field over large areas.

1. Introduction

The requirement for precipitation measurements arises in many aspects of both operational and research meteorology, climate monitoring, hydrology, and ecology. Collier, Szejwach and Testud (1988) discuss these requirements noting the differences between the needs of nowcasting (observation of the weather now and forecasts up to a few hours ahead) and those of regional and global numerical weather prediction models. In spite of these differences there is a consistency in space and time which ensures that measurements of precipitation made for nowcasting and short-period forecasting are also useful for larger-scale numerical modelling, although not providing the global coverage which is really needed. Hence, even for applications on these larger scales it may be more profitable to consider how best to measure precipitation for periods of less than one day rather than for longer time-scales.

In general this philosophy will be appropriate over data-rich areas of the world, but in other areas limitations imposed by a lack of data will mean that techniques to measure precipitation over sub-daily periods are inadequate. Over the tropical oceans, where there are no ground-based observations, we must rely on satellite-based systems, such as those proposed by Simpson *et al.* (1988), which will provide daily or monthly estimates.

Over Europe there are considerable amounts of data provided by a dense network of conventional observing stations, weather radars and the Meteosat satellite. Nowcasting systems are in place in some countries and plans are well advanced in many others. Mesoscale models are also nearing operational implementation. In addition, the nuclear accident at Chernobyl in 1986 highlighted the importance of wet deposition in determining the dispersion and distribution of radioactive nuclides. Hence the need for real-time estimates of precipitation over a wide area has become even more focused in Europe. Since observations over most of Europe are readily available via the WMO Global Telecommunication System, it is appropriate to assume that a combination of ground-based and satellite data offers the most likely means of providing estimates of precipitation which are of acceptable accuracy for these applications. We first consider possible methods of using satellite data.

2. Use of visible and infra-red data

Visible and infra-red data have been most commonly used to make estimates of rainfall and, to a lesser extent, snowfall. The thermal infra-red temperature as measured from a satellite is modified by the atmosphere. The radiation measured when looking down vertically is partly made up of reflected radiation from the surface in the clear-sky situation. If clouds are present then rapid changes in the observed radiant emission from a surface can occur.

Two types of technique for estimating rainfall have been developed, these being known as 'cloud indexing' and 'life-history' methods. (For comprehensive reviews see Barrett and Martin (1981) and Collier, Szejwach and Testud (1988).)

2.1 Cloud indexing method

Cloud indexing was the first technique developed for rainfall estimation. A rainfall coefficient or cloud index was evaluated from features of the satellite cloud-field defined by visible or infra-red images, for example brightness or texture. These indices were then related, via regression equations, to rain-gauge observations of rainfall (e.g. Turpeinen *et al.* 1987). These techniques are most successful for rainfall over periods of days or months, partly because satellite data from polar orbiting platforms are only available every 6 to 12 hours. Regression techniques are used with both polar orbiting and geostationary satellite data, but the procedure involves a high level of subjective interpretation by an analyst. In general these techniques only function well for convective cloud, as opposed to frontal cloud. Pattern recognition techniques using textural or radiance features with cloud models are also being assessed and show some promise (Wu *et al.* 1985, Adler and Negri 1988).

2.2 Life history method

Stout *et al.* (1979) were able to estimate the rainfall produced by convective clouds from the sum of the area of the clouds and the rate of change of that area, that is, volumetric rain rate for a particular cloud, $R_v = a_0 A_c + a_1(dA_c/dt)$ where A_c is the area of the cloud, dA_c/dt is the rate of change of cloud area, and a_0 and a_1 are empirical coefficients. This type of technique, known as a life-history procedure, requires satellite images at frequent time intervals which can only be provided by geostationary satellites.

Variants on the Stout *et al.* technique have been produced by Griffith *et al.* (1976, 1978), and Scofield and Oliver (1977a, 1977b). In the latter technique, precipitation in general is favoured by high cloud-brightness (low cloud-top temperature), and heavy rainfall in particular is favoured by low cloud-top temperatures and the growth and merging of clouds.

Improvements to deal more adequately with storm clouds having warm tops have been proposed by Scofield (1981, 1982). The addition of spectral and textural information from geostationary satellite images to the evolutionary data has been investigated by Martin and Howland (1986), and found to produce useful improvements in the tropics.

Negri and Adler (1981) found that thunderstorm-top ascent rates are correlated with maximum storm-radar reflectivities, and the minimum black-body temperature observed during the lifetime of a storm is correlated with the maximum volumetric storm rainfall. In general these techniques produce only acceptable estimates of convective rainfall. However, Negri *et al.* (1984) have concluded that these techniques are unnecessarily complicated for daily rainfall estimation. Recently Motell and Weare (1987) have proposed a simple regression technique for tropical rainfall, but this is very limited in its applicability. Doneaud *et al.* (1987) have proposed a simple procedure in which the area-time-integral of cloud areas over the lifetime of a storm is related to the total rain volume. Initial investigations are encouraging, although again the technique is likely to work well only for convective rainfall.

3. Use of multispectral data

The use of single images, or sequences of images of either visible or infra-red data, has been discussed in the previous section. However, procedures have not proved to be totally reliable as required for operational implementation. Improvements can be obtained by the combined use of data from several spectral bands as described, for example, by Liljas (1982).

Infra-red sensors on satellites provide information on temperature, and thus indirectly on the heights of the tops of clouds. On the other hand visible sensors provide information on the depth of clouds, their geometry and composition. Combination of this information enables recognition of high cloud-tops associated with deep clouds which are likely to produce significant rainfall. Early work on this type of technique revealed problems arising from registration errors between the visible and infra-red images, instrument calibration, time difference between images, and illumination geometry, which caused the results of the early work to be less encouraging than workers had expected. Lovejoy and Austin (1979a) demonstrated that these problems could be overcome.

Several investigations using models of convective processes aimed to tackle the problems from a physical, rather than a statistical, point of view (Gruber 1973, Wylie 1979). These techniques are able to define rain areas. However, the estimation of rainfall amounts is more problematical, and ground-truth data such as that provided by radar may be needed for calibration of the satellite data when making estimates of rainfall amounts or reliable estimates of rain area. Tsonis and Isaac (1985) have proposed a scheme which uses radar data to define areas of rain or no rain for calibration and subsequently uses the visible and infra-red satellite data only to delineate areas of rain; no quantitative estimates are produced.

The latest generation of satellites provide data with high spatial and cloud-top temperature resolution. Unfortunately these data are not adequate on their own to allow the automated analysis of different cloud types and the separation of these types into clouds producing precipitation and those which are not. In spite of the difficulties the UK FRONTIERS (Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite) system contains an operational implementation of the Lovejoy and Austin (1979a) technique using Meteosat infra-red and visible images together with data from the UK weather radar network. Because the coverage provided by the UK weather radar network is insufficient, even for a 3-hour advection forecast for areas within radar coverage, Meteosat imagery is used to infer probable areas of precipitation outside the area for which good radar data are available. This area depends upon rainfall type and is delineated by the Usable Data Boundary (UDB) (see Brown 1987). To maximize the reliability of the operational system, only rain or no-rain predictions are made at present.

The visible (VIS) and infra-red (IR) data are each divided into 16 classes and a table of 'probabilities' of rain for each class is produced by comparison with the radar data. Prior to correlation the forecaster can, if necessary, manually adjust the registration of the satellite imagery using any visible coastline. Three tables are constructed, visible alone, infra-red alone and visible plus infra-red, the last being a two-dimensional table. The technique using infra-red data alone is similar to that described by Heinemann *et al.* (1987). In order to apply the tables to the satellite data outside the UDB, it is necessary to select a critical probability which differentiates between rain and no rain. This is chosen dynamically, as the probability which predicts an areal extent of rain within the UDB which best matches the extent observed by radar.

The correlation technique often gives the best results using a two-dimensional diagram similar to that shown in Fig. 1, because this contains information on cloud thickness and cloud-top temperature. Visible data alone can be nearly as good, but infra-red data alone are often inferior, particularly in frontal cases, where they can lead to overestimation of the extent of the precipitation ahead of the warm front. However, the correlation method cannot work in certain situations, for example when there is insufficient radar data to form a reliable

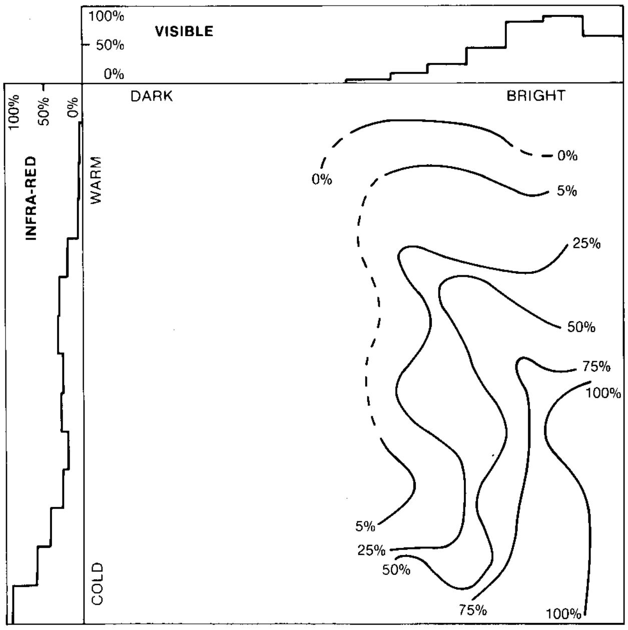

Figure 1. Visible (VIS) and infra-red (IR) rainfall correlation obtained by the FRONTIERS system from Meteosat data at 1130 GMT on 26 February 1987. The percentage chance of rain for any combination of VIS and IR is given. Histograms are also shown in which the percentage chance of rain using VIS only and IR only is given. Note that there is a wide spread of ranges of VIS brightness or IR temperature with greater than 50% chance of rain. This uncertainty is reduced by using both VIS and IR together.

correlation table because most of the precipitation is outside the UDB. Universal correlation tables can then be used, which have been constructed from past experience. If neither technique produces a satisfactory result, either the visible or infra-red imagery can be sliced so that a contiguous range of brightnesses or temperatures represents the rainfall field. If most of the precipitation lies outside the UDB the forecaster must judge the result using available synoptic observations and conceptual models of the distribution of precipitation within the prevailing synoptic archetype.

The final step of the satellite analysis allows the forecaster to modify the satellite-derived rainfall field and merge it with the radar field. Because of the lower reliability of the satellite estimate, rainfall can be added to or subtracted from it subjectively. The radar data are inviolate at this stage. Initially the combined rainfall field is displayed with the satellite estimate inserted beyond the maximum radar range of 210 km. This often leads to gaps between satellite and radar fields so that the forecaster is allowed to bring the satellite estimate up to the UDB wherever he choses. If unrealistic gaps still persist the forecaster may judiciously merge the satellite field with the radar field inside the UDB. This is justifiable because the UDB is calculated assuming a precipitation field of locally uniform depth, and so cannot perfectly describe the actual limit of radar coverage. Clearly the satellite field should not be used close to the radars where the probability of detection by radar is high.

Unfortunately the look-up tables are often rough when derived in real time, i.e. small and large VIS/IR counts are juxtaposed, and too many counts occur in the no-rain class. It is also found that, in the tables, areas with no data sometimes appear in the middle of areas with data. Such gaps may be filled by manual intervention or automatic interpolation, but it is often better to use a climatological look-up table providing suitably smoothed data. Bellon and Austin (1986) show how this technique may be used to estimate rainfall amounts for convective rainfall.They note that average rainfall rates of less than 0.5 mm h^{-1} that occur at VIS/IR pairs corresponding to high temperatures and low visible counts are mainly a result of improper radar-satellite matching. Such problems arise from uncertainties in the satellite navigation, time differences between the radar and satellite data, or from misalignment between the satellite view of the cloud tops and the level of the radar observations. The rainfall rates of these pairs are set to zero to avoid the generation of spurious areas of small or trace amounts of rainfall. This loss of rainfall of about 20% in the cases studied by Bellon and Austin was allowed for by them by multiplying the data in the look-up table by factor of 1.2. This is not done in the FRONTIERS system.

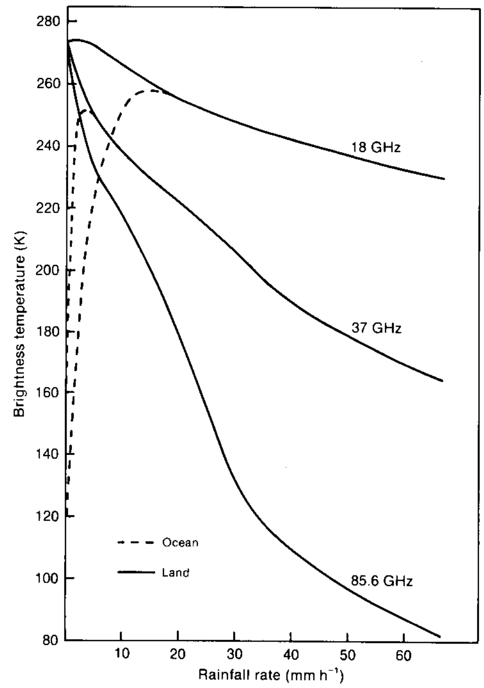

Figure 2. Brightness temperature–rainfall rate relationships at 18, 37 and 85.6 GHZ from the radiative transfer modelling of Wu and Weinman (1984). The vertical distribution of hydrometeors was based on averaged radar results and assumed ice precipitation above and liquid precipitation below the freezing level (from Spencer *et al.* (1988) after Wu and Weinman (1984)).

4. Passive microwave techniques

Passive microwave rainfall measurements are of two types depending upon the effect used to detect precipitation. These types are referred to as the absorption/emission (by raindrops) and scattering (by ice particles) methods. The absorption method (Wilheit *et al.* 1977) uses frequencies below about 20 GHz. It requires a cold background and is therefore applied over the sea, which appears cold by virtue of its low emissivity at these frequencies, and against which the precipitating cloud appears warm. Collier, Szejwach and Testud (1988) list the limitations and uncertainties associated with the absorption method.

The scattering method may be applied over land as well as over the ocean surface. The brightness temperature (the temperature of a black body that would emit the observed amount of radiation) of the precipitating cloud decreases with the number and size of scattering particles. The major scattering effect results from the presence of frozen hydrometeors at the tops of convective clouds (Wilheit *et al.* 1982). It is necessary to derive an indirect relationship between rainfall rate and the amount of ice using cloud models (Wilheit *et al.* 1982, Szejwach *et al.* 1986). This method uses frequencies above 60 GHz and, at present, is the only satellite-based technique for obtaining rainfall over land using passive microwave methods. Fig. 2 summarizes the relationships between rainfall rate and various passive microwave frequencies.

Much work is now being carried out to investigate the ability to measure precipitation of the Special Sensor Microwave Imager 88.5 GHz channels of the US Defense Meteorological Satellite Program, and Barrett *et al.* (1988) report early results which are very encouraging for convective rainfall. It remains to be seen to what extent mid-latitude frontal rainfall can be measured.

5. Active microwave techniques (radar)

Measurements of the strength of microwave energy, generated in a radar mounted on a satellite and reflected or scattered from the atmosphere or the Earth's surface, may be made on receipt back at the satellite antenna. The amount of back-scattered energy is related to the surface roughness, orientation, slope and the dielectric constant of the material of which the surface is composed. It also depends upon any rainfall intercepted by the radar beam, as short wavelengths are attenuated by heavy rainfall.

At present, active microwave systems are not being carried on civil satellites, but several satellite launches are planned which will carry radars. For example the Tropical Rainfall Measuring Mission (TRMM) (Simpson *et al.* 1988) includes the proposal to carry a 14 and 24 GHz active radar, together with microwave radiometers operating at 19, 37 and 90 GHz, and a visible/infra-red radiometer, at an altitude of about 300 km.

Although TRMM represents a major step forward in measuring precipitation from space, only part of the global requirement for precipitation data will be addressed. Collier, Szejwach and Testud (1988) summarize a number of combined active and passive microwave systems and assess their performance, cost and complexity. Unfortunately, as the accuracy increases so does the considerable cost and complexity.

6. Accuracy

Since several satellite systems will provide measurements of precipitation using parameters across a wide part of the electromagnetic spectrum, it is important to assess the relative merits and cost-effectiveness of each technique.

Evaluations of some techniques have been carried out (see, for example Johnstone *et al.* 1985), but Table I gives a summary of accuracy achieved, and likely to be achieved, across the whole electromagnetic spectrum from microwave to visible frequencies. Two points emerge from this table. Firstly, that most of the assessments of the accuracy of rainfall totals have been made as integrations over areas greater than 10^3 km^2. However, some techniques are capable of measurement over areas as small as 50 km^2, or over areas approaching global scales. Secondly, most of the studies have been concerned in the main with the measurement of convective rainfall rather than frontal rainfall. In addition, rainfall amount is not measured with uniform accuracy, and some techniques have to be fine-tuned to measure heavy rainfall.

A combination of the accuracy of rainfall measurements attained by ground-based radar techniques with the data shown in Table I is presented in Fig. 3. This figure indicates that ground-based radar and satellite techniques are complementary.

Bellon and Austin (1986) have concluded that, at present, satellite estimates of rainfall are better than rain-gauge estimates at locations where the nearest rain-gauge is further than 40 km. Therefore the implementation of such techniques is most useful in the data-sparse regions of the world. In those areas where numerous ground-based measurements are available the best method of measuring precipitation in real-time is likely to involve the blending of these measurements with those derived from satellites.

At present satellite-based techniques are unlikely to outperform ground-based radar within 100 km of radar sites. However, beyond this range satellite data will be useful, particularly in convective rainfall. Currently work is underway to use synoptic observations with

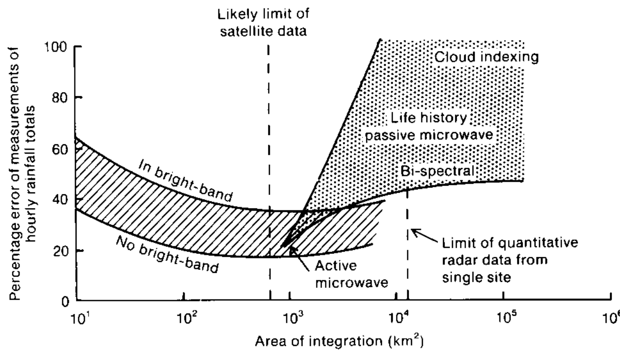

Figure 3. Illustrating the ranges of percentage error of measurements of hourly rainfall total presently attainable by ground-based radar (hatched area) and satellite techniques (stippled area), as functions of the area over which the measurements are assessed. The dashed lines show the upper limit of area over which quantitative radar data from a single radar is obtained, and the lower limit of areal coverage to which satellite data are likely to provide quantitative estimates of hourly rainfall (from Collier 1985).

Table I. Summary of the performance of satellite rainfall estimation techniques (from Collier (1985) partly based upon Lovejoy and Austin (1979b, 1980))

Technique	Area over which estimates are assessed (km^2)	Period of integration (*hours*)	Estimated or measured percentage error (%)	Sample references describing techniques (rainfall types)
Cloud indexing	10^5	24	122	Follansbee and Oliver (1975) Adler and Negri (1988) (convective/stratiform)
	10^4	½	41	
Life-history	10^4	1	85	Griffith *et al.* (1978) (convective) Wylie (1979) (convective) Stout *et al.* (1979) (convective)
	10^5	24	55	
	10^4	½	50	
	6×10^3	½	65	
Bi-spectral	10^5	½–2	49	Lovejoy and Austin (1979a, 1979b) (convective/frontal)
Passive	10^3	24	70	Lovejoy and Austin (1980) (convective/frontal) Wilheit *et al.* (1973) Spencer *et al.* (1983)
Active	10^3	12	20 (when combined with bi-spectral technique)	The accurary of this technique is unknown but Lovejoy (1981) suggests the figures given may be possible (see also Collier, Szejwach and Testud (1988)) Simpson *et al.* (1988) (convective)
	10^3	30×24 (monthly)	10	

satellite data for estimating rainfall (Anderson *et al.* 1986, Aschbacher 1987). In addition, consideration is being given to the use of numerical model output with remotely sensed information. One scheme being implemented operationally in the United Kingdom is outlined in the next section. All this work must be underpinned by comprehensive quality control in order to provide to users estimates of reliability, including its spatial variation.

7. Real-time precipitation analysis over Europe

In order to derive precipitation data over much of north-west Europe for input to the Nuclear Accident Modelling Exercise (NAME), nowcasting procedures, and ultimately, mesoscale models, an analysis package is being developed in the Meteorological Office.

The area covered by the analysis is that north of 20° N between 80° W and 40° E. Initially, work is concentrating over that portion of north-west Europe for which a radar composite image is generated hourly as part of the Commission of the European Communities COST-73 Project (Collier, Fair and Newsome 1988). Over this area precipitation data from the UK numerical forecast models, FRONTIERS and Meteosat are brought together with conventional observations. The many computer systems involved are connected via a local area network (Fig. 4) enabling the various data to be assembled, processed and dispatched in near real time.

The initial phase is nearing completion, and will become operational by the end of 1988. Fig. 5 shows an example of the coverage of data from FRONTIERS, COST-73, the mesoscale model and the fine-mesh model. These data have been combined to give the composite rainfall field in Fig. 6. Each data source will have an appropriate confidence factor attached to it, so that when the data are used in NAME (for example) the reliability of the final output may be estimated. The development of quality control procedures, preferably based on objective algorithms, will be an important task in the future. Investigation is underway to assess how best to compare and combine images with synoptic reports.

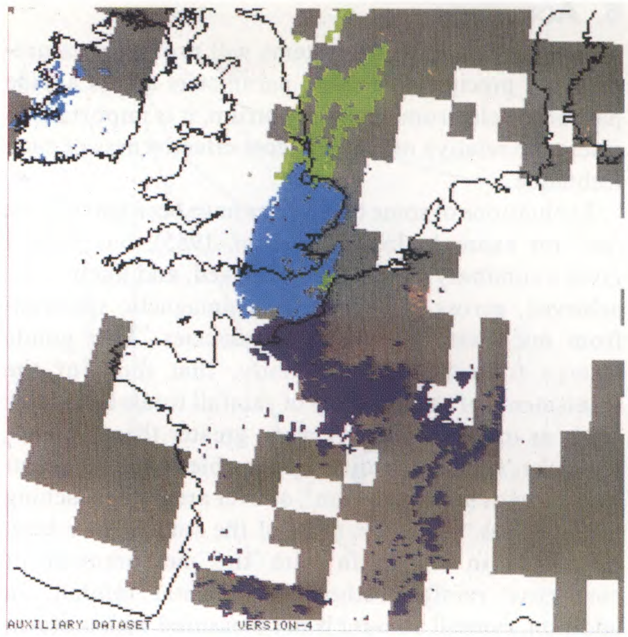

Figure 5. Illustration of the different data sets used to form a composite rainfall field over north-west Europe for 1500 GMT on 25 August 1987. The data sets used are FRONTIERS (blue), COST-73 (purple), mesoscale model (green) and fine-mesh model (brown). The limits of radar coverage and coastlines are shown.

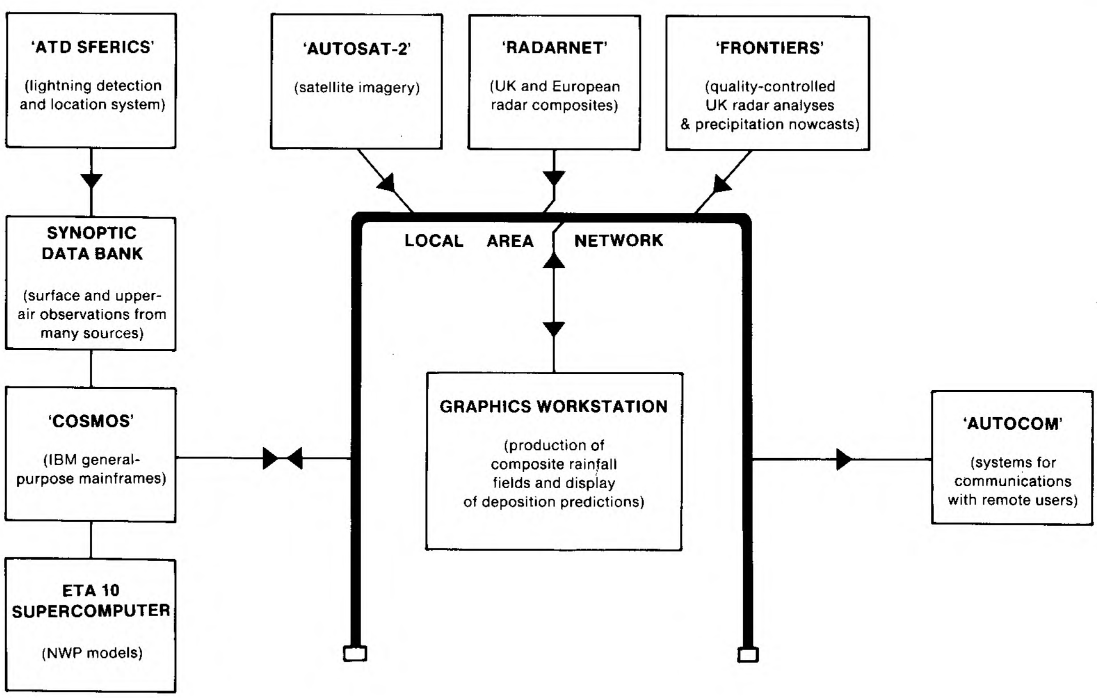

Figure 4. The interconnection of the graphics workstation for wide-area rainfall analysis and other computer systems at Bracknell.

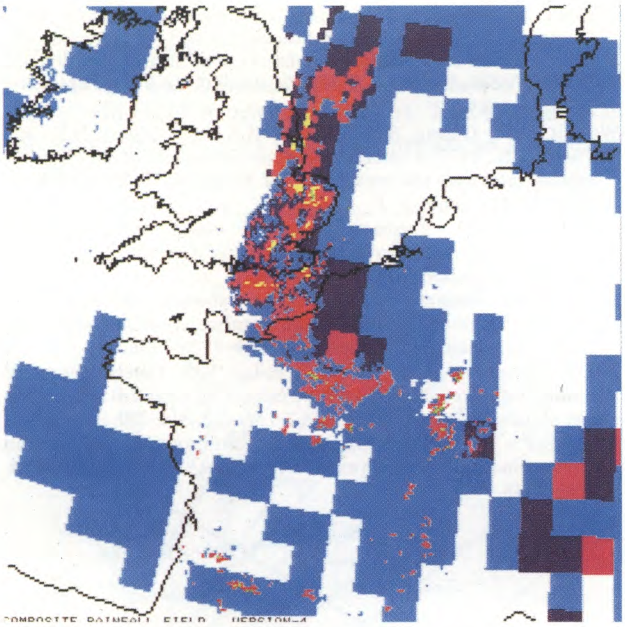

Figure 6. Composite rainfall field for 1500 GMT on 25 August 1987. The colours represent different rates of rainfall as follows: blue < 1 mm h^{-1}, purple 1–2 mm h^{-1}, pink 2–4 mm h^{-1}, red 4–8 mm h^{-1}, yellow 8–16 mm h^{-1}, green 16–32 mm h^{-1} and brown > 32 mm h^{-1}.

8. Conclusion

Europe is fortunate to have a variety of different meteorological data available in near real time, but other regions of the world could benefit from the data-combination approach to the analysis of precipitation. Global weather prediction models now provide products which are widely distributed. The combination of the numerical model data with satellite data and local observations, even if they are not as extensive as in Europe, will result in estimates of precipitation which are more reliable than using satellite data alone. This is one way of extending the use of existing ground-based weather radar installations such that their data benefit a much wider area than that defined by the limits of the radar coverage.

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An introductory review of fronts. Part II: A case-study

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Summary

This paper, on frontal meteorology, is one of a series of teaching papers on mesoscale meteorology developed at the Meteorological Office College. Part I described important dynamical aspects of both the formation and structure of frontal zones (Bennetts et al. *1988), and Part II illustrates the main features through a case-study of a cold front which crossed the United Kingdom on 13 January 1983.*

In Part I simple conceptual models were developed. Here, in Part II, those models are discussed in more detail with the help of a case-study of a cold front. The paper is not intended to be a comprehensive review.

1. Introduction

Over the past decade there has been a considerable number of theoretical and observational studies into the formation and structure of frontal zones. Much of this work has followed directly from the new mesoscale observational techniques that were developed in the late 1960s and 1970s, and from modern computers that permit numerical modelling to take place on a similar spatial resolution to that of the observational data.

The paper has been divided into two parts. Part I (Bennetts *et al.* 1988) discussed how frontal zones form, what determines their overall structure and the nature of sub-frontal-scale perturbations. In Part II, a case study is presented to illustrate many of the conceptual models that were developed in Part I. The case study is of an active cold front that crossed the United Kingdom on 13 January 1983.

2. The case-study

The synoptic situation used to illustrate the concepts developed in Part I (Bennetts *et al.* 1988) occurred on 13 January 1983. An active cold front moved south-eastwards across England and Wales during the early hours of the morning. The surface analysis for 0000 GMT is shown in Fig. 1. A small wave depression running north-eastwards along the front had delayed the movement of the front south-eastwards late on the 12th but by 0000 GMT on the 13th the wave had moved away into the North Sea.

Fig. 2 is a satellite photograph which shows the position of the frontal cloud at 0317 GMT (by which time the front was over central England), and shower clouds to the west of the United Kingdom which are associated with the cold upper trough. The frontal passage was marked by a very sharp wind veer (typically

120°), a large pressure kick and a substantial drop in temperature (about 8 °C in 15 minutes). The frontal passage was also accompanied by a short, sharp burst of heavy rain (cold-frontal squall line). This is evident in the radar data (Fig. 3) where it appears as a series of small line elements.

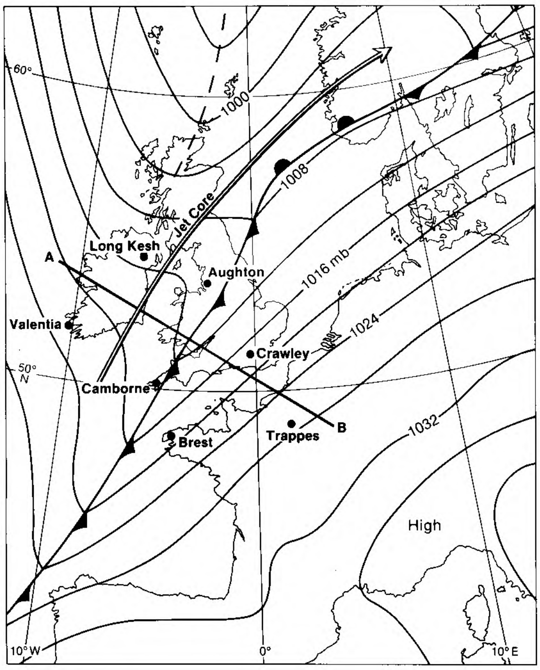

Figure 1. Surface analysis for 0000 GMT on 13 January 1983 showing the surface position of the cold front, the associated jet stream, and the line of the cross-section AB. The upper-air stations referred to later in the text are also shown.

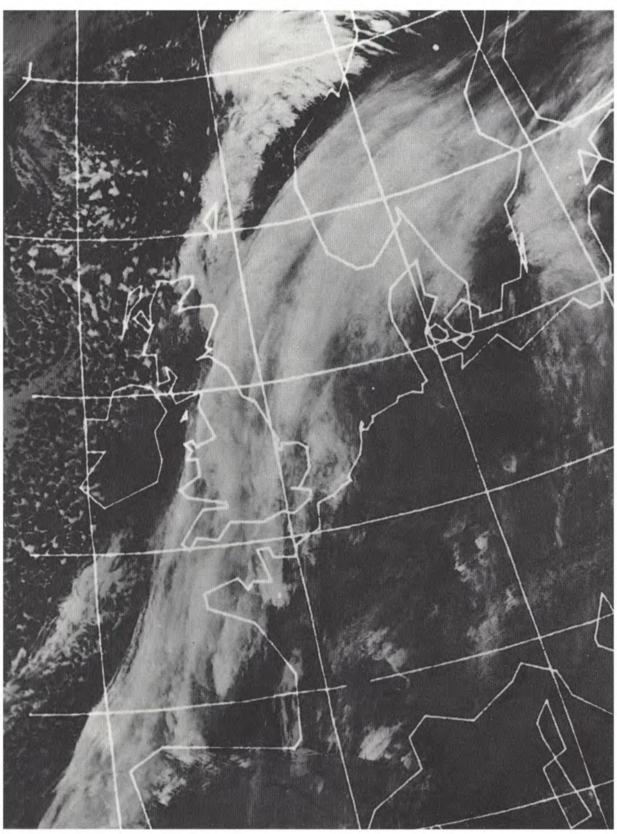

Figure 2. Satellite photograph taken at 0317 GMT on 13 January 1983. Photograph by courtesy of University of Dundee.

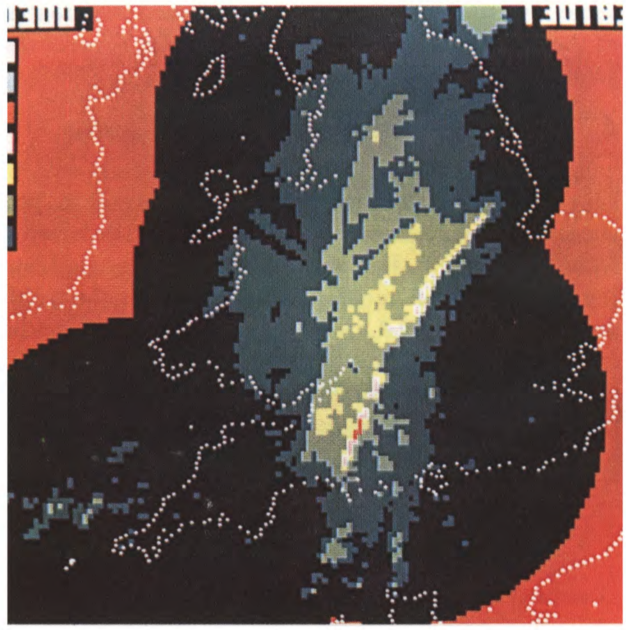

Figure 3. Radar network picture for 0300 GMT on 13 January 1983 showing rates of rainfall. Within the network area, areas of white, pink, red and light blue indicate heavy rain, yellow and green indicate moderate rain and dark blue indicates light rain.

3. General structure of the frontal zone

A cross-section along a line perpendicular to the cold front (300°–120°) was constructed using the 0000 GMT 13 January radiosonde ascents from Valentia, Long Kesh, Aughton, Camborne, Brest, Crawley and Trappes. The position of this cross-section relative to the front is shown by the line AB in Fig. 1. At this time the front was moving at 9 m s^{-1} along the line AB, which is taken to be the x-axis. The data are presented in the following diagrams — Fig. 4, wind component perpendicular and relative to the cold front, Fig. 5, wind component parallel to the cold front, and Fig. 6, cross-section of wet-bulb potential temperature and absolute momentum (M) surfaces. A general description of the main features will be given, followed by a comparison with the conceptual models developed in Part I.

In Fig. 6 the cold-frontal zone is delineated by the 4–7 °C θ_w surfaces (on the left of the diagram) and for convenience these surfaces are also outlined on Figs 4 and 5. Note the sharp nose to the frontal surface close to the ground. Also evident, bottom centre of Fig. 6, is a closed 10 °C θ_w contour which is nearly coincident with a velocity maximum of 28 m s^{-1} in Fig. 5. These two features identify a low-level jet (the conveyor belt) and, to help identification, the 10 °C θ_w contour is superimposed on Fig. 5.

In the top left-hand corner of Fig. 5 the upper-level jet stream, with a measured maximum speed of 59 m s^{-1}, can be readily identified. Note also that well ahead of the front, near the ground, bottom right of Fig. 4, the air is moving towards the front at 10 m s^{-1}. Although this looks rather unusual it will be recalled that the motion is relative to the frontal surface which is moving at 9 m s^{-1}. In fact, this air is moving at 1 m s^{-1} relative to the ground. In contrast, the air within the boundary layer some 100 km ahead of the front has a speed close to that of the front, and is moving at some 5–8 m s^{-1} over the ground.

4. Air motion within the frontal zone

Since ascending air within the frontal zone will, in general, be saturated, i.e. the air will conserve θ_w, the streamlines in the cross-frontal direction can be inferred from Figs 4 and 6. Just ahead of the surface cold front the low-level air is moving rapidly towards the front, and hence (constant θ_w) must rise up over the nose of the front. Note that to achieve this rapid acceleration of the air near the front requires there to be a nearby 'source', such as would be provided by the 'rearward sloping ascent' model, Fig. 7(a) (copied from Part I, Fig. 6(a)), in which some of the air from the warm conveyor belt leaks up over the cold front.

Behind the cold front the air also moves towards the front, except within the boundary layer. Such motion is consistent with the ideas shown in the conceptual model, Fig. 7(b) (copied from Part I, Fig. 7).

Turning now to some of the details of the conceptual models. In section 5 of Part I, a link was established between the difference in speed of the jet core just ahead of the cold front (see Fig. 5) from that of the surrounding air, and the scale over which the jet decayed on the warm (in Fig. 5, the right hand) side. The approach assumed that the low-level jet was in thermal

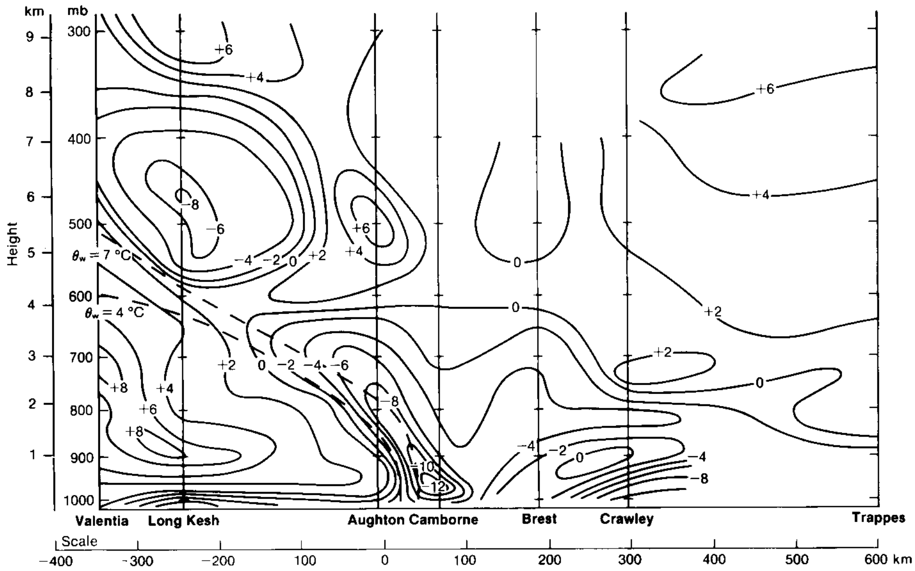

Figure 4. Cross-section along the line AB in Fig. 1 at 0000 GMT on 13 January 1983 showing the wind component in m s^{-1} perpendicular and relative to the front (which was moving west to east at 9 m s^{-1}). Positive values depict winds blowing west to east. The isotach labelled −12 m s^{-1} at 970 mb above Camborne indicates low-level air moving rapidly towards the front, as discussed in the text. The frontal zone is outlined by the θ_w values of 4 and 7 °C. Radiosonde ascents are indicated by the vertical lines.

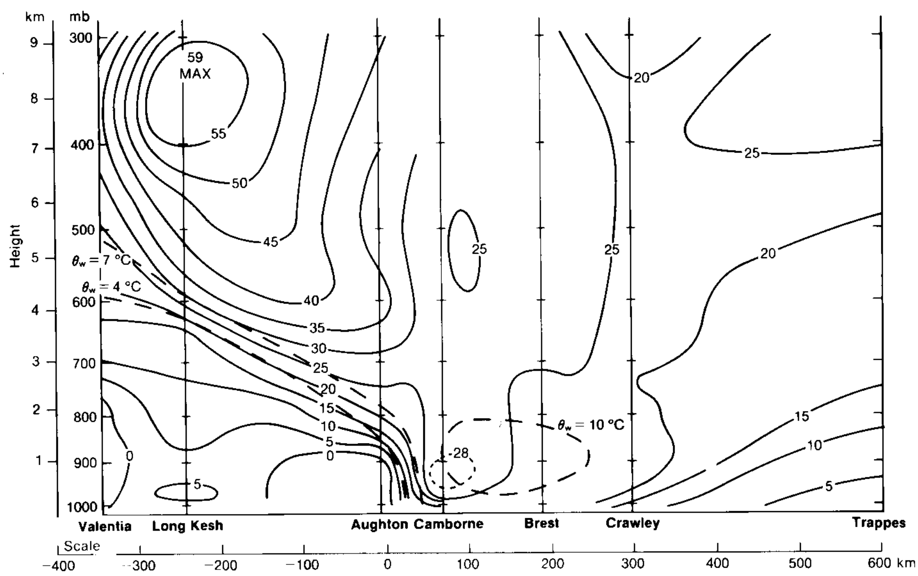

Figure 5. Cross-section along the line AB in Fig. 1 at 0000 GMT on 13 January 1983 showing the wind component in m s^{-1} parallel to the front. Positive values are winds blowing from the south-west, and into the paper. The upper-level jet appears above Long Kesh and the low-level jet is evident over Camborne. The frontal zone is outlined by the 4 and 7 °C θ_w values and the warm conveyor belt picked out by the 10 °C θ_w isotherm.

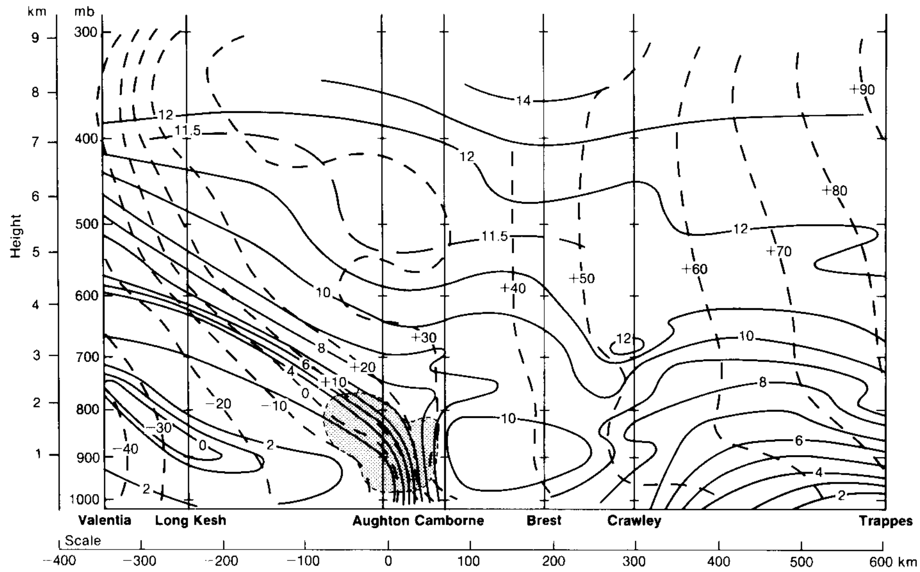

Figure 6. Cross-section along the line AB in Fig. 1 at 0000 GMT on 13 January 1983 showing θ_w surfaces (solid lines) (°C) and *M* surfaces (m s^{-1} — dashed lines). The stippled region within the frontal zone marks the area in which θ_w and *M* surfaces are parallel, and hence (see text) the area in which Conditional Symmetric Instabilities may be expected to develop.

wind balance. The validity of that assumption can now be investigated. Thermal wind balance is defined by the following equation (see Part I, section 2, equation (6));

$$\frac{\delta v}{\delta z} = \frac{g}{f\theta_0}\,\frac{\delta \theta}{\delta x}$$

where g=10 m s^{-2}, f=10^{-4} s^{-1}, θ_0=280 K and the constant $g/(f\theta_0)$ has an approximate value of 300 m s^{-1} K^{-1}. Although fields of potential temperature (θ) have not been shown in the paper, the data showed that θ changed by 7 K over a distance of 80 km in the vicinity of the jet. This calculation may be roughly checked by noting that, at a given level, $\delta\theta/\delta x$ is very nearly equal to $\delta\theta_w/\delta x$, and then referring to Fig. 6.

Fig. 5 shows the height of the jet to be about 1000 m and therefore the thermal wind equation predicts the jet-core speed to be

$$\delta z \times 300 \times 7/(8 \times 10^4) \approx 26\ \text{m s}^{-1}.$$

This is to be compared with an observed value of 28 m s^{-1}. The jet would appear to be in near-thermal-wind balance.

Return now to the relationship between the jet-core excess speed and the scale of the jet. In this case the jet core is some 3–5 m s^{-1} faster than the surrounding air and therefore the minimum distance over which the jet can decay is 30–50 km. This is in fair agreement with the scale found in Fig. 5, although the distance between the radiosonde ascents makes an accurate comparison impossible.

Overall, the case-study illustrates many of the features that were discussed in Part I namely:

(a) The ageostrophic cross-frontal circulation, modified by frictional effects (Fig. 7(b)).
(b) The presence of the warm conveyor belt (Fig. 7(a)).
(c) The presence of a low-level jet.
(d) The conceptual model in which warm air from the conveyor belt leaks up over the cold front (Fig. 7(a)).
(e) Thermal wind balance within the low-level jet.
(f) The asymmetry in the structure of the low-level jet.

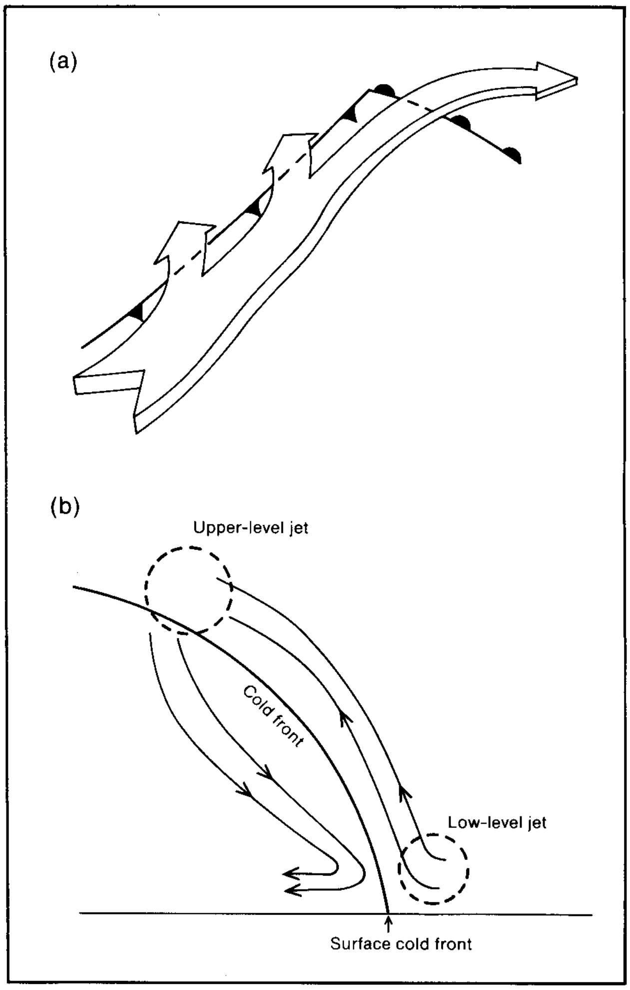

Figure 7. (a) The motion within the warm conveyor belt relative to the surface fronts (Fig. 6(a) of Part I). Depicted is the model showing rearward sloping ascent, and (b) cross-frontal ageostrophic motion when the effects of turbulent diffusion are included (Fig. 7 of Part I).

5. Absolute momentum surfaces

In section 6 of Part I the concept of absolute momentum (M) and its conservative nature within a frontal zone was introduced. In the present case-study, these surfaces are shown superimposed onto the wet-bulb potential temperature (θ_w) surfaces, Fig. 6. There is an arbitrary constant of integration in the calculation of the M surfaces and this has been chosen so that the M surface which is coincident with the surface cold front has a zero value.

Below about 700 mb, within the frontal zone (−100 to 0 km on the x-axis), the M and θ_w surfaces are nearly parallel (stippled region in Fig. 6). Thus a parcel of saturated air moving up the frontal surface would apparently have little difficulty in conserving both quantities. Further up the frontal zone, and away from the frontal zone, the two surfaces do cross. The zone well away from the front can be immediately dismissed since, in that region, there is no requirement for M to be conserved — see Part I, section 6. The two regions of interest, the stippled area and the area in the top left-hand corner of Fig. 6, require separate analysis.

The stippled region is the most difficult to analyse. It will be recalled from Part I, section 6 that whenever θ_w surfaces are steeper than M surfaces, energy is released spontaneously. Therefore whenever such a situation occurs, energy is transferred from the larger scale to the smaller scale instabilities, thereby restoring the atmosphere to a neutral state in which M and θ_w surfaces are again parallel. In consequence, regions in which θ_w surfaces are (to a significant degree) steeper than M surfaces are unlikely to occur, and will be exceptionally difficult to detect by anything other than the most thorough analysis. The implication therefore is that regions such as that stippled in Fig. 6, where M and θ_w surfaces are approximately parallel, are likely to contain Conditional Symmetric Instabilities (CSIs); either that or instabilities are about to develop.

Evidence of such instabilities should be sought in the rainfall patterns, and indeed Fig. 3 does exhibit irregularities, of the expected scale, in the appropriate region, between the surface front and Aughton.

The second region of interest, where M and θ_w surfaces cross, is in the upper part of the frontal surface (−100 to −400 km on the x-axis in Fig. 6). Here, however, M surfaces are steeper than θ_w surfaces and therefore (as shown in Fig. 10 of Part I) this is a region which is stable to CSIs. In partial confirmation of this, Fig. 3 shows a reasonably uniform area of rain to the western edge of the precipitation zone, although this cannot be taken as conclusive proof due to the poor resolution (because of the range and consequent height of the radar beam) of the data and the generally light precipitation in that area.

Thus, while the case-study does not prove the theory for rainband formation, it does exhibit many of the features that one would expect to find associated with CSIs. The analysis also illustrates that M surfaces can be drawn using synoptic-scale data, at least to an accuracy adequate for the identification of areas likely to exhibit sub-frontal-scale instabilities, and hence rainbands.

Acknowledgements

We would like to thank all the staff and students at the Meteorological Office College who have helped in the development of this work. We are also grateful to Dr R.W. Riddaway for the advice that he has given us during the writing of the paper.

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Direct use of satellite sounding radiances in numerical weather prediction

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Summary

Recent research on satellite sounding data and numerical analysis techniques has explored new ways of using the satellite data within numerical weather prediction (NWP) systems. It is now expected that greater benefit could be derived from these data if they were assimilated more directly into the NWP fields, rather than via independently retrieved profiles of temperature and humidity. The theory behind the new approach is outlined, and some aspects of the implementation of these ideas at the Meteorological Office are described.

1. Introduction

Atmospheric sounding radiometers on meteorological satellites do not measure temperature and humidity profiles; they measure the thermal radiation emitted to space at a number of spectral intervals, and these radiances may be used to derive profile information. At first sight this may seem to be a purely semantic point, but in fact it is an important distinction which must be understood if satellite soundings are to be used in numerical weather prediction (NWP) in an optimal manner.

Until recently satellite products have been used in NWP as though they were direct measurements of atmospheric profiles. The historical reason for this is clear, NWP analysis schemes have been designed and tuned to make full use of radiosonde data, and when satellite soundings first arrived they could be used most easily if they were processed to resemble radiosonde profiles. Indeed it is interesting to speculate how analysis methods would have developed if satellites had come first and radiosondes had been invented later. The characteristics of these two sources of information on atmospheric thermal structure are very different. Radiosonde data have high resolution in the vertical, but in the horizontal the observing system is absent over much of the world and, at its best, of lower resolution than current NWP models. Satellite sounders provide global coverage at high horizontal resolution, but their information concerning vertical structure is comparatively small because of the width of the weighting functions (see, for example, Smith *et al.* 1979, Eyre and Jerrett 1982). These characteristics should be recognized when trying to make the best use of the data.

The 'retrieval' or 'inversion' process, whereby satellite radiances are converted to atmospheric profiles, has some rather subtle properties and error characteristics (Eyre 1987). The problem is mathematically ill-posed — an infinite number of profiles are consistent with the radiance measurements, and additional constraints are required to choose between the possible profiles. This means that the retrieved profile will contain both observed information (from the radiances) and unobserved information imposed by the constraints. This leads to errors in the retrievals which are correlated in both the vertical and horizontal, and these characteristics have made the data difficult to use effectively in conventional NWP analysis schemes.

In addition to problems associated with the characteristics of satellite data, we must also be aware of the quality they must attain to be useful in NWP. In the European and North Atlantic areas, typical errors in a NWP background field (i.e. 6- or 12-hour forecast) of tropospheric temperature are about 2 K. Moreover, forecast errors are quite weakly correlated in the vertical, and satellite sounders' weighting functions are broad. When we put this information together quantitatively, we find that a typical forecast error translates into a much lower error in satellite-measured brightness temperature (equivalent black-body temperature) — about 1 K for a tropospheric temperature sounding channel. In other words, before the satellite passes over an area we know what it is going to measure to an accuracy of about 1 K. Hence, for the satellite measurements to be useful in NWP their errors must be very low, and this applies not only to the instrumental errors but also to the errors associated with the operations of calibration, processing and interpretation. Therefore it can be seen that the requirements of modern NWP models place very high demands on all aspects of the measurement and processing of the satellite data. This is certainly true for current sounding data from the TIROS Operational Vertical Sounder (TOVS) on the NOAA satellites (see Smith *et al.* 1979), but it will be equally true for the Advanced TOVS (ATOVS) instruments to be flown on the next generation of polar-orbiting satellites from about 1993 (Pick 1986). ATOVS will improve considerably over TOVS in terms of horizontal resolution, performance in cloudy conditions, sensitivity to humidity, cloud, precipitation, and other aspects. However, it will not improve significantly on vertical resolution in the troposphere, and the requirements for careful attention to all aspects of the data processing and interpretation will remain.

Conventional methods for using satellite data — through schemes for converting radiances to profile information, completely separate from NWP systems into which the profiles are to be assimilated — are being re-examined in the light of the problems discussed above. Attention is now focusing on how some of the problems may be removed or minimized if the radiance information is used more directly within the NWP system. The ideas involved are not specific to satellite data and may be applied to many types of 'indirect' observation, i.e. measurements of quantities not represented in the NWP models but related to those represented in some physical manner which is well understood (see Lorenc 1986). A useful analogy here concerns the use of wind observations in analysing the thermal field; in extra-tropical latitudes winds are indirect observations of the thermal field because they are related through geostrophic considerations. Similarly, measurements of radiance may be used when analysing the temperature field because the two are linked through the radiative transfer equation.

In the remainder of this paper, the theory underlying the direct use of radiances will be outlined and some practical aspects of the implementation of such a scheme discussed.

2. Theoretical considerations

The purpose of data assimilation in NWP is to find the best analysis of the atmospheric state for the subsequent forecast. It involves seeking the state which gives the best fit to the available observations and background information (to within their expected errors) and applying appropriate additional constraints concerned with dynamical or physical processes. Many analysis schemes may be considered conceptually as minimizing some 'cost' or 'penalty' function which measures the departure of the analysed state from the observations, the background and other information (see Lorenc 1986). For example, the cost function $J(\mathbf{x})$ for the NWP analysis field $\mathbf{x}$ could be represented as:

$$J(\mathbf{x}) = (\mathbf{x}-\mathbf{x}_b)^T.\ \mathbf{B}^{-1}.\ (\mathbf{x}-\mathbf{x}_b) + (\mathbf{y}\{\mathbf{x}\}-\mathbf{y}_o)^T.\ (\mathbf{O}+\mathbf{F})^{-1}.\ (\mathbf{y}\{\mathbf{x}\}-\mathbf{y}_o) + \text{other terms}, \qquad (1)$$

where $\mathbf{x}_b$ is the background field, $\mathbf{B}$ is its expected error covariance, $\mathbf{y}_o$ is the vector of observations, $\mathbf{O}$ is their expected error covariance, $\mathbf{y}\{\mathbf{x}\}$ is the 'forward model', an operator for interpolating from the model state $\mathbf{x}$ to the observation points, and $\mathbf{F}$ is the expected error covariance of the forward model.

The 'best' analysis is that which minimizes $J(\mathbf{x})$ in equation (1). The first term in this equation represents the closeness of fit of the analysis to the background field, the second term the fit to the observations, and 'other terms' any additional penalties from other dynamical or physical constraints. Here we are mainly concerned with the second term and in particular how it can represent satellite sounding observations.

There are of course many different analysis schemes but the differences between most of those used in practice in NWP may be shown to be different ways of approximating the solution to minimize equation (1). For example, if we ignore 'other terms', assume $\mathbf{B}$, $\mathbf{O}$ and $\mathbf{F}$ to be constant and the observations $\mathbf{y}_o$ to be linearly related to the model state $\mathbf{x}$, then the minimum value of $J(\mathbf{x})$ occurs when

$$\mathbf{x} = \mathbf{x}_b + \mathbf{B}.\mathbf{K}^T.\ (\mathbf{K}.\mathbf{B}.\mathbf{K}^T + \mathbf{O} + \mathbf{F})^{-1}.\ (\mathbf{y}_o - \mathbf{y}\{\mathbf{x}_b\}), \qquad (2)$$

where $\mathbf{K} = d\mathbf{y}\{\mathbf{x}\}/d\mathbf{x}$. This is familiar to NWP analysts as one form of the optimum interpolation equation. If $\mathbf{y}_o$ is taken to be a vector of satellite radiances, it is also familiar in the satellite sounding field as the minimum variance retrieval equation (Rodgers 1976). This illustrates that NWP analysis and satellite sounding inversion are similar mathematical problems and suggests that, in the context of NWP, we might consider them as one combined problem.

Returning to the second term of equation (1), if the observations are direct (i.e. of the same variable as represented by the NWP model) then the operator $\mathbf{y}\{...\}$ may be relatively simple, just representing an interpolation in time and space to the observation point. If the observations are indirect, then the operator $\mathbf{y}\{...\}$ is more complicated. In the case of satellite radiances it includes a radiative transfer calculation to find the radiances $\mathbf{y}\{\mathbf{x}\}$ which would be measured from an atmospheric state $\mathbf{x}$. In this case $\mathbf{O}$ represents the errors in the measured radiances and F the forward model error which includes expected error in the radiative transfer calculation. If, on the other hand, the radiances are first converted by a separate system to retrieved profiles, then these may be used as observations $\mathbf{y}_o$. This considerably simplifies the 'forward model' but leads to very complicated observational errors. They have strong correlations in the vertical and horizontal and also bias properties which are very difficult to handle. It is primarily the difficulty in representing correctly the true characteristics of satellite retrieval errors which inhibits their proper exploitation in NWP. Previously, satellite retrievals have been derived with too little attention as to how they will be used in NWP, and they have been applied without sufficient consideration of their true information content.

The radiances themselves have error characteristics which are easier to represent within the analysis formalism than those of retrieved profiles. Radiance measurements and calculations may contain significant biases which must be carefully monitored and allowed for, but this is a relatively straightforward problem and is comparable to that of dealing with the bias characteristics of radiosonde data. When analysing directly from radiances, the need for an 'inversion' or 'retrieval' operation is not removed but is transferred into the data assimilation system where, in principle, it may be handled better. In this way we can expect to improve the exploitation of the many strengths of satellite sounding data while making proper allowance for their weaknesses.

3. Implementation

In the theory presented above, if **x** represents the full three-dimensional NWP model state in all its variables, then the computation and minimization of the cost function represents a huge numerical problem. In future it may be practicable to attempt it, but at present certain approximations are necessary. The approach adopted in the scheme recently developed for operational use in the Meteorological Office (Lorenc *et al.* 1988) involves several, including splitting the vertical and horizontal aspects of the analysis: for each datum, a 'vertical analysis' first spreads the information at the observation's own horizontal location on to the vertical levels of the NWP model, then, at each level, the information is analysed to the model grid-points. This strategy is adopted for all data types, and for satellite sounding data it takes the following form. At each sounding location, first calculate the difference between the measured radiances and those calculated from the NWP model's background field (interpolated to the sounding location); then use these radiance increments to calculate increments to the model's temperature and humidity field at all levels. If the radiances (or brightness temperatures) are linearly related to the model parameters, then equation (2) gives the solution to this vertical analysis problem. In other words, it is the same as a conventional retrieval with the model background profile and its expected error covariance as constraints (rather than some climatological information or historical 'library' of profiles, as in many retrieval schemes). In the subsequent horizontal analysis, allowance should be made for the fact that the vertical analysis for each sounding has used the background information and will therefore contain errors which are correlated with the background and hence also with vertical analyses for adjacent soundings. A strategy for doing this has been proposed by Lorenc *et al.* (1986).

The Meteorological Office's Local Area Sounding System (LASS) for receiving and processing TOVS data from the European and North Atlantic areas has been described by Turner *et al.* (1985). In 1987 the retrieval stage was changed to use forecast information and thus resembles the 'vertical analysis' described above. Although this processing is still performed separately from the main NWP system, it is now done in such a way that it is mathematically equivalent to the direct assimilation of radiance data (provided that the retrieved profiles are subsequently assimilated in a compatible manner). Direct use of radiance data and 'forecast-background' retrievals may be thought of as the same theoretical approach; the difference between them is mainly a logistical one concerning whether the satellite data processing is completely integrated with the NWP system or (as at present) physically separated from it. In either case, the basic elements of the data processing involved are the same.

The process of assimilating radiance information is illustrated in Fig. 1. At the top we have measured radiances, calibrated and perhaps pre-processed in certain ways. At the bottom the NWP suite is represented by a continuous cycle of data assimilation and forecast processes. To assimilate radiance information, the background field is interpolated to the location of the radiance data and converted into radiances through an appropriate radiative transfer (or 'forward') calculation. These are compared with the measured radiances and the radiance increments converted back into the increments to variables of the NWP model through an 'inverse' operation and then interpolated to model grid-points. At present only the processes in the smaller dashed box are performed within the NWP data assimilation and the rest externally by LASS. In future it may be preferable, for reasons of computational economy and theoretical consistency, to perform all the operations in the larger

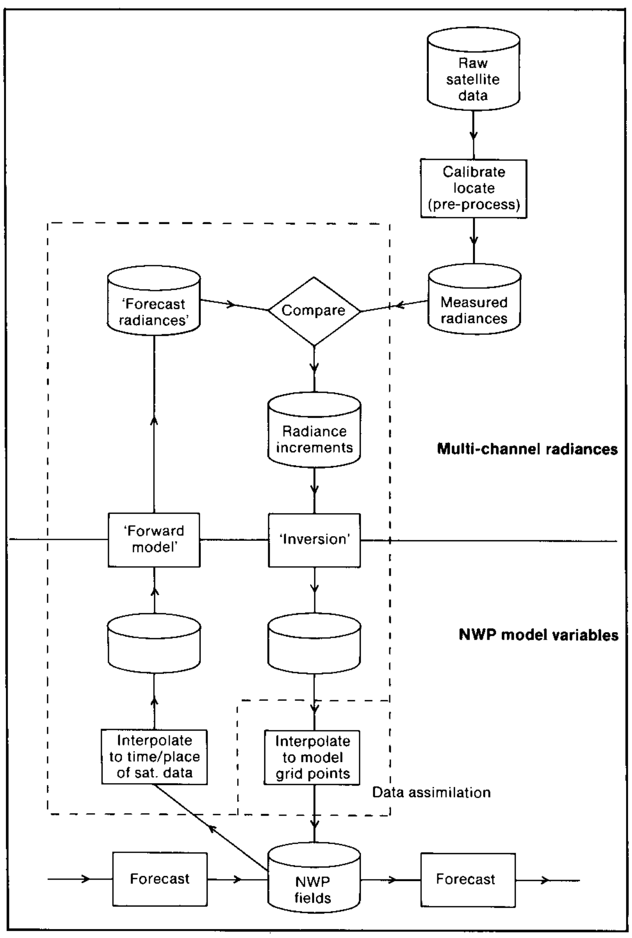

Figure 1. Illustration of the direct assimilation of radiances.

dashed box within the NWP suite. The NWP suite will then directly assimilate radiances physically as well as conceptually.

The present LASS performs an inversion based on equation (2) to convert cloud-cleared brightness temperatures to temperature and relative-humidity profiles, and it makes the assumption that they are linearly related. This is quite a reasonable assumption for the temperature inversion problem but not really satisfactory for humidity. It would be preferable to represent correctly the non-linear relations between observed radiances and atmospheric parameters. In the preprocessing stage of the present LASS scheme, the conversion of raw radiances to cloud-cleared brightness temperatures involves assumptions about the atmospheric profile and the cloud characteristics. The assumptions are inappropriate in some situations, causing errors and biases in the retrieved profiles. Knowledge of the atmospheric structure and clouds, from improved satellite instruments and forecast models, is improving, and so it may be advantageous to transfer the pre-processing step into the inversion problem. If we wish to invert the raw, potentially cloud-affected radiances, the problem becomes highly non-linear and we are forced to address it as such. Research is in progress on these aspects of the problem (Eyre 1989, Lorenc 1988).

4. Conclusions

It is now recognized that we should be seeking to use satellite radiances to give the best NWP analyses and subsequent forecasts, not to produce good retrievals for their own sake. This change of emphasis has led to increased activity on more direct ways to use radiance information in NWP.

The Meteorological Office is already processing TOVS data using a scheme involving forecast information which may be thought of conceptually as a direct assimilation of radiance information. Future developments are likely to address the closer physical integration between the satellite data processing and NWP suites, to improve the treatment of non-linear aspects of the problem and to explore the advantages of extending the current vertical (one-dimensional) analysis of radiances to a fully three- or four-dimensional approach to data assimilation. In these ways we hope to move from a situation whereby satellite soundings are treated as 'poor-quality radiosondes' to one in which they are exploited according to their true information content.

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Noctilucent clouds over western Europe during 1987

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Summary

The sightings of noctilucent cloud reported to the Aurora Section of the British Astronomical Association during 1987 are presented.

Table I summarizes the noctilucent cloud (NLC) reported to the Aurora Section of the British Astronomical Association during 1987. The times (UT) are of reported sightings, not necessarily the duration of a display. 'Negative' nights (Table II) are now based on the judgement of two or more experienced observers north of 54° N with clear or nearly clear sky conditions over the period of the night when NLC is likely to occur.

Despite a great deal of tropospheric cloud and bad weather over Britain and western Europe at the height of the NLC 'season', the large number of positive sightings on clear or partly clear nights suggests another year of high incidence of the phenomenon. Reports were received from 31 amateur observers widely distributed throughout Britain, 4 in Denmark and 1 in the Netherlands, 11 British meteorological stations including the weather ship *Cumulus* at *Lima* (57° N, 20° W) and 4 stations of the Royal Netherlands Meteorological Institute. The excellent Danish group co-ordinated from Bornholm by Mr Olesen has again submitted panoramic photographs and reports of a very high standard. Positive observations by the Finnish astronomers and of the observers in Alberta, Canada, are briefly listed in Table III. The former publish summaries in the periodical *Ursa Minor* of the URSA Astronomical Association (Laivanvarustajankatu 3, SF-00140, Helsinki 14). The 8 positive sightings from Canada are remarkable in that no less than 4 were coincident with aurora. As from the summer of 1988 an amateur North American NLC network will be operational and publishing data. Mr Mark Zalcik (# 2, 14225 82 Street, Edmonton, Alberta T5E 2V7) has kindly agreed to act as co-ordinator, and will be pleased to receive observations. Summaries will be exchanged between the networks.

Details of individual displays, and instructions for the observation of NLC, may be obtained from the author. All data are ultimately transferred to the Balfour Stewart Archive in the University of Aberdeen.

The author thanks all amateur and professional observers for their work, particularly Mr David Frydman who regularly puts in all-night watches from Helsinki and Wembley, near London, and supplies excellent photographs; also Dr M. Gadsden (Aberdeen), Mr R. Livesey (Director, BAA Aurora Section), Mr N. Bone (Director, Junior Astronomical Society, Aurora Section), Dr B. Zwart (Netherlands), Mr V. Mäkelä (Finland), Mr M. Zalcik and Mr J.Ø. Olesen, for useful advice and contributions.

Table I. Displays of noctilucent clouds over western Europe during 1987

Date — night of	Times UT	Notes
20/21 May	0010	NLC suspected very low in sky at Swansea.
30/31	2130–2145	NLC suspected at elev. 40° at Bracknell.
9/10 June	0120–0125	Faint NLC at Maastricht, elev. 4°.
11/12	0000–0330	Extensive but rather faint, all forms, observed over S. England, Wales and N. Ireland. Maximum elev. 65° at Witham, Essex, 0200; 60° at Basingstoke 0240.
12/13	2245–0115	Faint bands then veil and billows at Morpeth, max. elev. 13° at 0115.
15/16	2200–2320	NLC patches in tropospheric cloud gaps at Morpeth and Castleford, Yorks.
16/17	2300–0220	Thin veil over ⅜ of sky at Wick. Faint horizontal bands visible as far south as Yorkshire, best seen at Dumbarton.
17/18	2245–0230	Moderately bright and extensive display, all forms, described mainly as radiating bands from N horizon. Observed at 15 stations as far S as Bedford, and in N. Ireland. Max. elev. 50° at Morpeth 0200.
18/19	2300–0100	Faint veil and patchy bands, N. Ireland, Dundee (elev. 20°), Edinburgh.
19/20	2330–0215	Moderately bright veil and bands, N. Ireland and Isle of Man. Photographed by Mr McConnell at Lincoln (elev. 9°). Faint band at Rønne, Denmark.
22/23	2245–0150	Faint bands at Todmorden 2245, bands in S. Midlands from 0140, elev. 10° at Bedford.
25/26	2228–0130	Faint veil and bands in central Scotland, max. elev. 18° at St. Andrews 2350. Visible at Cambridge 2228–2245 to elev. 5°.
27/28	0045–0300	Bright bands and billows to 12° at *Lima*. Bright bands to elev. 11° at Copenhagen.
28/29 June	2315–0305	Bright billows at *Lima*, faint veil and bands at Wick, St. Andrews and Stirling.
29/30	0048	NLC trace suspected overhead at Kirkwall but no NLC in clear sky at Edinburgh and Morpeth.
1/2 July	2200–0307	Moderately bright veil, bands and billows observed at 14 stations as far S as Essex and Swansea. Photographed at Tayport but most of Scotland clouded over. Max. elevs 30° Tayport 0145, 21° Morpeth 2230, 35° Todmorden 0245, 10° Marham 0045.
2/3	2145–0240	NLC at 3 Netherlands stations. Bright bands and whirls at Kølvra and Vildbjerg, Denmark, max. elev. 18° at 2325.
4/5	2230–0244	Faint NLC in cloud gaps at Edinburgh 2230–2330. Veil, bands and billows seen by two London observers 0155–0244, elev. 16°, photographed by Mr Frydman.
5/6	0100–0215	Faint bands at Morpeth, elev. 7°, faint NLC at Stirling, visible only with binoculars.
6/7	2205–2220	Faint patches at Castleford, faint bands at Wisbech.
7/8	2255–0200	Faint bands and billows in Scotland, max. elev. 80° at Sumburgh 0200.
9/10	2335–0135	NLC in tropospheric cloud at Kirkwall 2335. Bands to elev. 6° at Eerbeek, Netherlands. Bands, billows and whirls from 0055 at Vildbjerg and Rønne, elev. 38° at Vildbjerg, 0135.
10/11	0210–0230	Bright billows at Maastricht, elev. 8°.
11/12	0130–0215	Faint bands at Edinburgh, max. elev. 10°.
14/15	2145–2225	Small, low and bright NLC: veil, bands and billows at Copenhagen and Vildbjerg.

Date — night of	Times UT	Notes
16/17 July	2200–2330	Faint to moderate bands in tropospheric cloud, central Scotland.
20/21	2115	Faint band at Alro, Denmark, elev. 20°.
23/24	2100–0027	Bright, extensive display observed at Helsinki by Mr Frydman. Faint veil over most of sky, veil and bands, whirl structure later, elev. 45° at 2147.
26/27	2040–2238	Moderate display, all forms, in tropospheric cloud at Helsinki.
27/28	2155–2304	Large faint NLC patches at Castleford, NLC in tropospheric cloud gaps at Wakefield and Basingstoke.
28/29	2200–2253	Faint veil and bands in cloud gaps, Morpeth and Helsinki. Aurora at Morpeth 0123–0131.
30/31 July	0205–0300	Faint, all forms, at Morpeth. Max. elev. 39° at 0300.
1/2 Aug	0145–0319	Faint bands and billows at Morpeth, to 7°.
2/3	2140–2321	Faint veil and bands at Helsinki, to 6°. Possible veil at Swansea 2140 but no NLC at 2200.
4/5	2256	Billows at Sumburgh, to 5°.
6/7	2134–2145	Swansea: suspect veil very low.
10/11	2200	Swansea: suspect NLC in cloud gaps.
18/19	2040–2220	Faint bands at Kirkwall.

Table II. Nights adjudged to have negative sightings of NLC (Finland excluded)

May 15/16, 18/19, 19/20, 31/June 1; June 1/2, 23/24, 24/25, 29/30, 30/July 1; July 8/9, 24/25.

Table III. Positive NLC sightings in Finland and Alberta, Canada

Finland:	May 26/27, 28/29; June 21/22, 23/24, 27/28, 28/29; July 2/3, 4/5, 7/8, 9/10, 11/12, 13/14, 23/24, 26/27, 28/29; Aug 2/3.
Alberta:	June 10/11*, 12/13*, 22/23, 24/25*; July 1/2, 17/18*, 19/20 (suspected), 26/27.

* Occasions when NLC was coincident with aurora.

Reviews

Acidification of freshwaters, by M. Cresser and A. Edwards. 178 mm × 253 mm, pp. viii+136, *illus.* Cambridge University Press, 1987. Price £19.50, US $34.50.

It is good to read a common-sense account of a subject that has been marked over the last 18 years and more by a lot of good scientific research but also by controversy, media distortion and, on a few occasions, by very angry exchanges. The debate is, of course, whether it is air pollution that is principally responsible for the acidification of freshwaters in northern Europe and North America, and the concomitant decline in fish populations and species which has been so evident in the last few decades, or whether these effects are due to other causes. Much hangs on the answer. To take but just one example, the cost of extracting a sizeable fraction of the sulphur dioxide from the emissions of the CEGB's fossil-fuel power stations would be as high as several billion pounds.

Almost inevitably such a well-balanced book does not conclude with a simple all-embracing answer supporting just one side of the argument. The issue is too involved for that. In so far as such a complex issue can be summarized, it proceeds as follows; acidifying air pollutants entering the atmospheric surface layer are often intercepted by vegetation which may alter the deposition rate and modify the ionic nature of water reaching the ground. According to the vertical and horizontal profiles of the soil and the amount of water involved, the pH of the water may be dramatically modified. On emerging into streams or into lakes the pH may again change as a result of changes in carbon dioxide content and by mixing. Even in the absence of air pollution the drainage water can be highly acidic. Both the vegetation and the soil character are subject to strong modification by man, both dependent on and independent of pollution.

Thus the nature of the freshwater depends on many factors; the level of air pollution, wet and dry deposition rates, the nature of the soil and its vertical and horizontal structure, the way water percolates through or over the soil into the streams, the effect of slopes and of vegetation, farming practices (in all its many facets, including the use of fertilizers and liming) and the way this has changed over the last 200 years, the role of forestation and deforestation, the way the ionic nature of the drainage water changes once it enters the streams and lakes, and how the fish and other freshwater dwellers react to this water of variable pH and its other mineral content. These and other factors are considered in some detail in the book in the light of the evidence from a host of experimental studies.

The authors conclude that recent acidification has to be viewed against the backdrop of a gradual but inevitable and natural acidifying development of all soils. This development can be delayed or accelerated by climatic changes or by man's activities. Thus each catchment must be considered individually. In some circumstances, acid rain may lower surface soil pH significantly over a few decades when the soil-plant-water ecosystem has become stressed by sulphate saturation of anion exchange sites within soil structure. However more generally there is no unequivocal evidence for soil acidification caused mainly by acid depositions from the atmosphere. Changes in land use as outlined above can equally produce rather rapid changes in drainage water pH, and these changes have happened very significantly over the last few hundred years (but particularly in the last few decades) and will continue in the future.

Thus the book, whilst not exonerating the air polluters, points to other major man-produced influences, all of which have to be viewed against many natural and sometimes more dominant processes.

This understandable book is well written and well produced, and is recommended to all working in this multi-discipline area.

F.B. Smith

Environmental meteorology, edited by K. Grefen and J. Löbel. 163 mm × 246 mm, pp. xi+661, *illus.* Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Price Dfl. 280.00, US $149.00, £84.00.

Conferences and symposia have definite positive uses. New ideas can be discussed and argued over with your peers, new acquaintances can be made, links can be made with other Institutions carrying out similar studies to your own, and so on. But one thing conferences are not generally good for is producing balanced informative textbooks on any subject, unless the meeting deliberately sets out to attract a few eminent speakers each of whom is burdened with presenting a well-balanced review, and which collectively are comprehensive and complementary. Alternatively, some giant in the subject may be persuaded to extract, from the whole panoply of papers presented, a logical and readable condensation. Of course any attendee at such a meeting wants to have copies of some papers which were particularly interesting and relevant to himself, but in this day and age, it is generally no great task for individual authors to come armed with a handful of quite professional-looking copies of his presentation produced on his Office PC, to hand out as required to other particularly interested participants.

As you may have guessed by now, I don't like most published Proceedings. This volume, almost entirely devoted to problems of air pollution, is no exception, although to be fair it does contain three review papers. The first by K. Höschele discusses the important problem of how to get representative meteorological data for various scales of time and space as part of a measuring programme for air pollution. The second review by Garland, Nicholson and Derwent of Harwell is an excellent summary of the problems associated with estimating the wet and dry deposition of trace substances from the atmosphere. The final review is by W. Kuttler who presents a splendid detailed review of the spatial and temporal character of the urban atmosphere and climate. These three papers on their own are worth anyone's shelf space. Otherwise my enthusiasm is definitely lukewarm. The volume contains (with unspoken apologies to the forests of the world) 661 pages of papers of variable quality: some are good, and many are interim reports of unfinished work or are specific to particular localities, few of which (if any) have been properly refereed.

F.B. Smith

Books received

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

The changing atmosphere, edited by F.S. Rowland and I.S.A. Isaksen (Chichester, New York, Brisbane, Toronto, Singapore, John Wiley and Sons, 1988. £39.95) contains papers from a Dahlem Workshop discussing the state of knowledge in many facets of the subject, with emphasis on changes in the trace gases and aerosol particles. Historic changes are included, and related to the results of human activity.

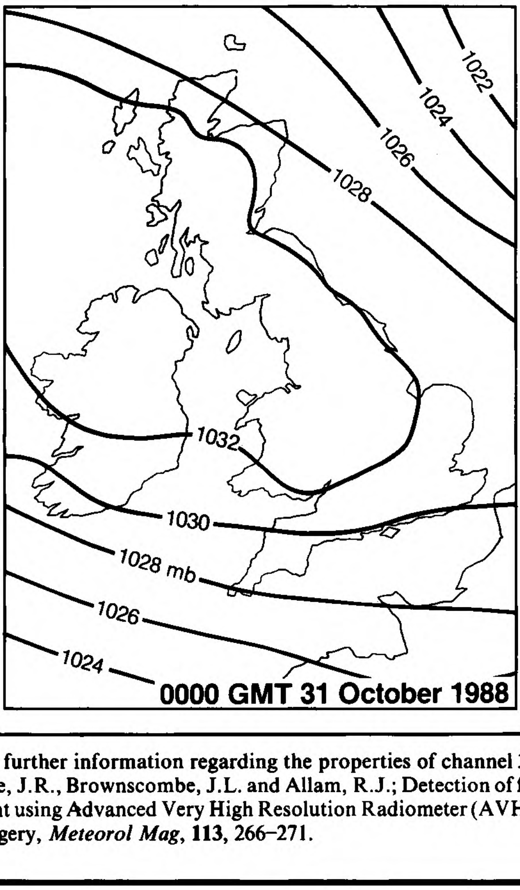
The climate of China, by M. Domrös and G. Peng (Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1988. DM 228.00) is a reference manual of the subject, especially in climatology and geography. There is a statistical section based on long-term averages, and the recent advances in research of the subject in China are included.

Long and short term variability of climates, edited by H. Wanner and U. Seigenthaler (Berlin, Heidelberg, New York, London, Paris, Tokyo, Springer-Verlag, 1988. DM 48.00) includes papers presented at a symposium held at Bern on 10–11 October 1986. It is volume 16 of the series Lecture Notes in Earth Sciences.

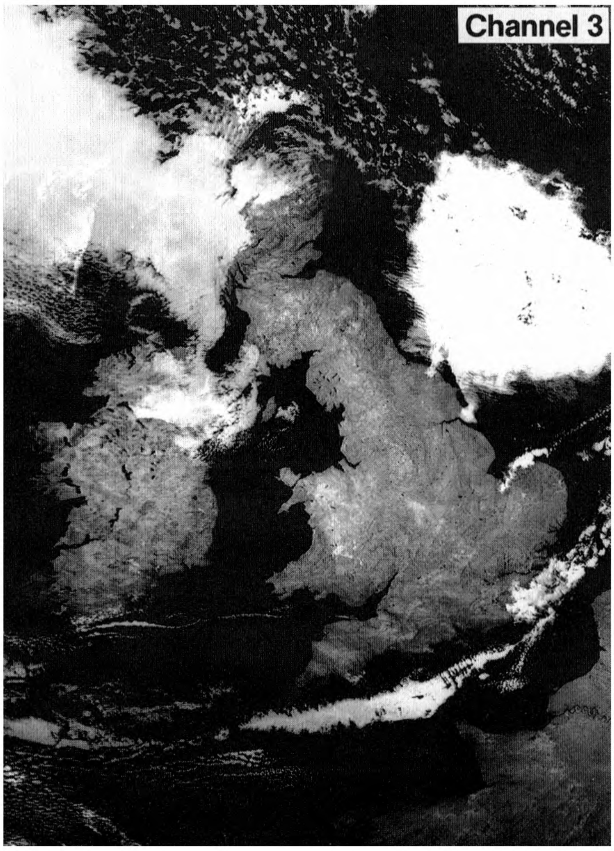
Satellite photographs — 31 October 1988 at 0206 GMT

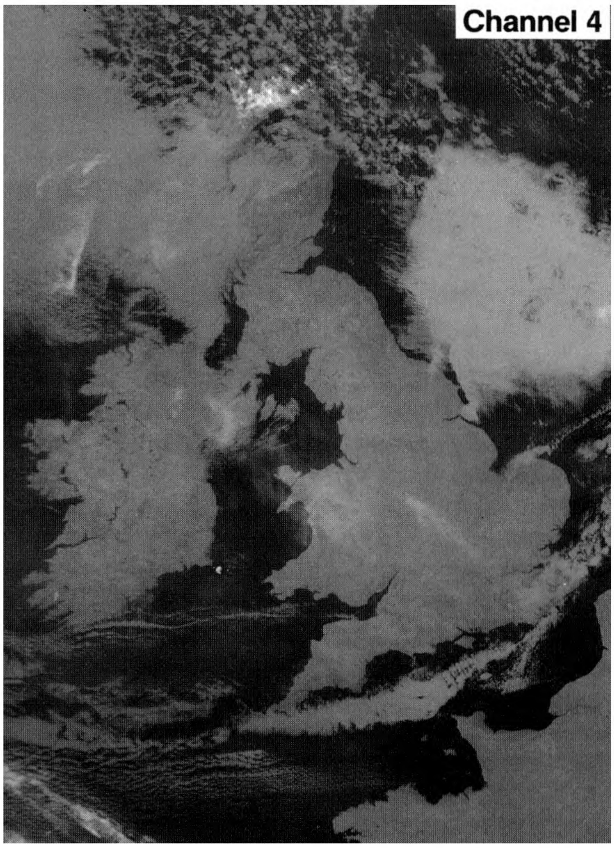
During the hours of darkness, NOAA satellites now routinely transmit data from infra-red channels 3 and 4 and, during daylight, visible channel 2 and infra-red channel 4,the change being made at local dawn and dusk as appropriate. Channel 3 pictures are similar to channel 4 except that in channel 3, warm clouds (or fogs) appear colder (whiter) and thin cirrus appears warmer (darker) than in corresponding channel 4 data*. Channel 3 information adds little to that of channel 4 at cirrus levels, since cirrus is seen clearly in channel 4. However, in cases where low cloud or fog-top temperatures are similar to those of the underlying surface, boundaries are indistinct in channel 4, but often clearly seen in channel 3, especially when images are displayed with high contrast across the range of temperatures in which low clouds occur.

In the pictures shown, with patches of low cloud present over the British Isles, the cloud and land surfaces are radiating at similar temperatures (channel 4 image) making it difficult to locate the inland penetration of cloud. However, in channel 3, the cloud areas are all whiter than the land, the high contrast magnifying this effect. In particular, the extent of cloud over central Scotland and Northern Ireland can be clearly seen. The channel 3 image also shows variations of surface temperature over the cloudless land. One drawback of the enhanced channel 3 data is that the inherent noise, which can be seen as vertical bands over and to the north of Ireland, is also enhanced.



* For further information regarding the properties of channel 3 see: Eyre, J.R., Brownscombe, J.L. and Allam, R.J.; Detection of fog at night using Advanced Very High Resolution Radiometer (AVHRR) imagery, *Meteorol Mag*, **113**, 266–271.





Photographs by courtesy of University of Dundee.

Meteorological Magazine

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Retirement of A. Gilchrist
Expert systems and weather forecasting
Air-mass thunderstorms at Athens
Sea temperature and prediction of monsoon
The spring of 1988
Seventh Meteosat Conference

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Meteorological Magazine

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Retirement of Mr A. Gilchrist

Mr Andrew Gilchrist retired in January 1989 from the position of Director of Research after a lifetime's career within the Meteorological Office. It began in 1951 when Mr Gilchrist joined the Office after taking a first class honours mathematics degree at the University of Glasgow. He very soon became involved in the Office's research programme, and his career has been in the research branches of the Office apart from the period 1957–63 during which he spent two years as a forecaster in the Central Forecasting Office, two years on secondment to the Nigerian meteorological department for research into tropical forecasting and two years as Scientific Assistant to Sir Graham Sutton the then Director-General. A comment from Sir Graham at that time identified Mr Gilchrist as the best Senior Scientific Officer who had occupied that post.

Mr Gilchrist has always taken a very pragmatic view of dynamical meteorology, and has not thought much of dynamical studies which have little impact on practical problems. The leadership which he has provided has done a great deal to keep the Meteorological Office in the forefront of dynamical meteorology. In particular he has played a key role in the development of numerical modelling within the Office.

One of his early research projects in the late 1950s was to investigate whether atmospheric motion could be usefully represented in terms of spherical harmonic functions. Most people would have considered the results of the research to be highly promising, but Mr Gilchrist was unenthusiastic (the work remained unpublished) because the technique, whilst mathematically viable, failed to map readily on to the observed behaviour of the atmosphere; the wave-like appearance of large-scale atmospheric flow should not be permitted to divert attention from the features which are most important (the influence of the continents and oceans, mountains, tropical convection, clouds and rainfall, fronts and individual depressions), and which do not readily fit into the spherical harmonic mould. Even after it was shown, several years later, that the computational expense could be greatly reduced by the use of fast Fourier transforms, he argued against the Office's jumping on the spectral modelling bandwagon because the technique obscured what was really going on and added nothing to the model's ability to represent the physics more accurately.

With George Corby, he was a founder member of the Dynamical Climatology Branch in 1963. Together, they led the development of the first Meteorological Office model of the general circulation, the 5-layer model, which was the basis of the present 11-layer model developed some years later. They designed finite-difference schemes possessing conservative properties and which avoided large truncation errors, especially those associated with the calculation of horizontal pressure gradients on the sigma coordinate system. He was particularly interested in the development of schemes for the representation of surface exchange and boundary-layer processes in the model. One of his personal projects was to develop a technique for representing the atmospheric boundary layer with an explicit top; it was a disappointment that numerical problems defeated attempts to introduce the scheme despite its well-founded physical basis.

Mr Gilchrist paid special attention to the need for models to display meteorologically realistic results; in a memorable presentation to the summer meeting of the Royal Meteorological Society in 1970, he demonstrated how a depression, which formed many days after the starting point of a 5-layer model run, showed many of the features observed in the life cycle of depressions, including frontal formation, occlusion and decay.

Mr Gilchrist took a full part in the task of writing computer code, though his rather personal programming style did not suit everybody — he could never understand why colleagues objected to his subroutines containing sequences of self-modifying assembler instructions.

His time as head of the Dynamical Climatology Branch ('amongst the happiest of my life') saw the expansion of the use of dynamical models for research into climate change. Indeed, the reputation of the Office now has in the field of research into the climatic impact of increasing atmospheric concentrations of carbon dioxide owes much to his foresight in encouraging the initiation of the work in the late 1970s. His contributions and incisive, critical observations on the subject have continued to be extremely valuable despite the diversions of higher administrative posts. He has written, lectured and given advice extensively on the development of general circulation models and their use for climate studies. Nevertheless, he has retained a realistic awareness of the limitations of the work to the extent of stating that 'all model results should carry a health warning'.

The 1970s also saw Mr Gilchrist's increasing interest in the effective use of atmospheric observations. He gave much encouragement to the use of data obtained in 1974 during the GATE experiment for developing convection parametrizations. He initiated work on Observing System Simulation Experiments for investigating the optimum design of the global observing system; his advocacy of observing-system experiments has continued to the present day with his chairmanship of the scientific steering group for OWSE-NA (Operational WWW Systems Evaluation for the North Atlantic). He was especially keen on encouraging the development of data assimilation schemes based on repeated correction of a forecasting model; he saw this as one of the most practical ways of coping with the increasing quantities of asynoptic data that would become available from satellites and other automatic instrumentation. An early version of such a scheme was used to produce analyses in near real time during the 1978/79 Global Weather Experiment, and a later version is now used for data analysis for the Office's operational numerical weather prediction system.

Soon after becoming Deputy Director, Dynamical Research, he was faced with the decision to stop the public issue of long-range weather forecasts and with increasing pressure to agree to the closure of the Synoptic Climatology Branch. His strong arguments against this and in favour of continuing both the routine preparation of monthly forecasts as a research exercise, and the use of past observations to investigate climate variability and change have borne fruit in the high international regard that is now held for the work of the branch. His advocacy of the use of numerical models for extended-range forecasting has enabled the Office to retain its place amongst the leaders in the subject.

From 1984 to 1986, Andrew Gilchrist was President of the Royal Meteorological Society, to which he gave strong scientific leadership — his Presidential address in 1985 on long-range forecasting is a masterpiece of well-judged exposition of a difficult and controversial subject.

In recent years, Andrew has played an increasing part in international programmes and committees. His thorough knowledge of dynamical meteorology, where he has few equals, and his lively and critical mind have ensured that his contributions at international meetings were always significant and appreciated. His membership (and chairmanship) of an international working group on numerical experimentation since 1982 has been particularly notable.

Andrew's contributions to the scientific literature have, by some standards, been sparse. Quality has always been of more importance to him than quantity. He has, however, contributed to the science and practice of meteorology not only through his writings but also through his style of leadership where the most dominant features have been his high standards and critical mind. Nothing weak or slipshod would pass his desk. No concession would be given to popularity — the points of view of others would be subjected to the most rigorous examination. This ruthless attention to quality has particularly paid off since 1985 during his period as Director of Research, when the idea of research and of its value have been increasingly under attack, and the provision of resources for research under threat.

As he retires, with his wife, back to his native Scotland, he will no doubt continue to follow, more remotely but just as critically as ever, the performance of the Office's products. We wish Andrew and Jean many years of happy retirement.

J.T. Houghton and P.W. White

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Expert systems and weather forecasting

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Summary

Expert systems are computer programs that perform high-level reasoning and judgemental processes within narrow specialist fields, rivalling the performance of human experts. They are being developed for weather forecasting applications in many countries and, at the Meteorological Office, Bracknell, pilot projects on nowcasting precipitation and forecasting thunderstorms using these systems have been started.

1. Introduction

Expert systems are a branch of artificial intelligence and a way of using computers to perform tasks normally requiring human judgement. They have been applied successfully in a variety of fields of significant importance and difficulty, including medical diagnosis, mineral prospecting, chemical analysis and configuring computer systems. Experiments are now under way in many parts of the world to apply expert systems to weather forecasting.

This paper explains what expert systems are and how they differ from conventional computer programs. It looks at the special demands weather forecasting makes on such systems and outlines the work which has started in the Meteorological Office to apply expert systems to short-period weather forecasting.

It has not been possible to do more here than touch on the main features of expert systems, with some inevitable over-simplifications. More comprehensive introductions to expert systems are to be found in Jackson (1986) and Hayes-Roth *et al.* (1982), and to artificial intelligence in general in Winston (1984). As with any specialism, expert systems work abounds with jargon. Some of the more common terms are introduced in this paper (where they appear first in italics) to show their meaning.

2. What is an 'Expert System'?

2.1 Definition

'An expert system is a computer program which, within some specified field, emulates the performance of a human expert.'

What do we mean when we describe someone as an 'expert'? We apply the term to someone who has developed a high level of skill in a particular area and from whom others seek advice; we should probably also expect certain specific characteristics as follows:

(a) The expert will have an extensive knowledge of his subject, and that subject will involve a significant level of difficulty.

(b) Some of the knowledge used will be in the form of *heuristics* (empirical rules-of-thumb) which the expert has gained through experience and which he may even use without recognizing explicitly. The use of heuristics is important — it enables the expert to pick out significant information from a mass of confusing material, and distinguishes his performance from that of a well-informed novice.

(c) The expert, though usually able to proceed quickly and efficiently to an outline solution, may have to resort to calculations or external references to fill in the details.

(d) The expert should be able to justify his conclusions and explain his reasoning, at least to the extent of indicating which pieces of evidence he considered important and how they were related.

(e) The enquirer is (usually) free to reject the expert's advice.

(f) The expert will sometimes be wrong.

These characteristics (including the last) are also found in expert systems.

The term 'expert' embodies the concept of 'reasoning': the selection, weighing and connection of appropriate ideas and evidence to arrive at useful conclusions. It is not simply the ability to perform a well-defined, repetitive task quickly and accurately. This is why conventional computer programs, though performing prodigious amounts of arithmetic or data manipulation, are not 'experts' any more than is a machine that, quickly and accurately, fills cans with baked beans.

The other important idea in our definition of an expert system is that of expertise being within a specific field or *domain*. An expert system is characterized by the knowledge it contains and that knowledge is specific to the narrow domain in which the system is designed to perform.

Human experts also operate within narrow specialisms outside which they may have no more than average capabilities — a neurologist will not necessarily be able to mend a television set. However, whereas a human expert has a wealth of general knowledge, enabling him to function in everyday life, present-day expert systems are profoundly ignorant outside their domains.

2.2 Structure

The structure of an expert system is illustrated in simplified form in Fig. 1. The two principal elements are the *knowledge base* and the *inference engine*. It is tempting to regard these as analogous to the database and application program in conventional computing, but there are important differences, as we shall see.

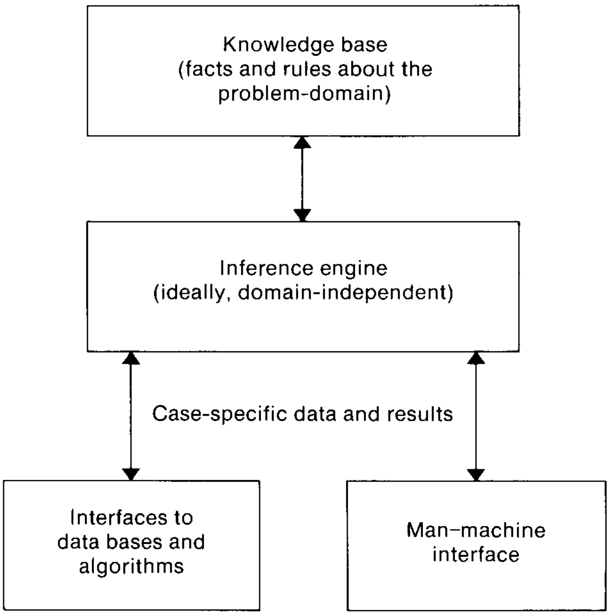

Figure 1. Main components of an expert system.

The most important part of any expert system, the part which ultimately sets a limit to the effectiveness of the system, is the knowledge base, and expert systems are often referred to as *Intelligent Knowledge-Based Systems (IKBS).* The knowledge base is an explicit representation of the available knowledge about the problem domain; much of this will be provided by human experts in the domain, though some may be derived automatically from collections of examples. It includes established facts and relations, rules-of-thumb and, sometimes, references to algorithms. It holds the relations which are believed to be true within that domain and which are used selectively, as they appear relevant, during the course of solving a problem.

Various formalisms exist for representing the knowledge. Perhaps the most easily understood is the use of *production rules* in the form of IF...THEN... relations. Note that these are not the procedural IF statements of programming languages like Fortran or BASIC (e.g. IF A=B THEN GOTO 100), but rather they assert that IF a condition is satisfied THEN a conclusion follows (e.g. IF it is a Bank Holiday THEN it will rain). Rules may take the form IF...AND...AND... ... THEN..., the left-hand side containing several conditions to be satisfied concurrently.

Rules can also express general relations which are applied to specific instances at execution time. A simple example might be a persistence forecasting rule — 'IF the weather today is X THEN the weather tomorrow will be X', where X is filled in or *instantiated* with the weather prevailing at run time.

A knowledge base may contain hundreds or even thousands of such rules. Each rule is self-contained; it does not direct the next step in the program and rules can appear in the knowledge base in any order. The programmer does not predefine the sequence in which the rules will be processed. The expert system functions by comparing the IF conditions in its knowledge base with what it is told about the problem it is tackling. When a match occurs, that rule *fires* and the THEN part is assumed to hold and is available for comparison with other IF conditions. The system repeatedly goes through its collection of rules and the evolving set of established conditions until a path to a final conclusion or *goal* is established (or shown not to exist). On the way it may ask for specific information that was not initially provided about the problem. It does this in a selective way which depends upon its line of 'reasoning' and the answers obtained to earlier questions.

The inference engine is the program that processes the knowledge base. In principle the inference engine may be completely independent of the problem domain. The domain is then defined entirely by the contents of the knowledge base, not by the details of the inference engine. From this has emerged the concept of an expert system *shell*, an inference engine plus an empty knowledge base, together with a knowledge-base editor and some input/output facilities, ready to be applied to any chosen domain. Many such shells are available for personal computers (PCs) at prices of a few hundred pounds, though more complex products at correspondingly higher prices are available for larger machines. Simple shells can be a cheap and relatively easy way of experimenting with expert systems, but they also have disadvantages compared with purpose-built expert systems. The formalism employed by a shell may be unsuited to the chosen application, and the facilities provided for entering data at run-time and for presenting results may be awkward and frustrating.

The inference engine contains mechanisms to control how it will process the knowledge base. Choices must be made about how to search for a path to a goal —whether to pursue one line of reasoning to its end before trying another (*depth-first search*), develop all available paths to the same depth before moving on (*breadth-first search*), or some combination of the two. Trying, without preference, every possible path until one works is usually too inefficient in large knowledge bases or where speed is important. Attempts may be made, at each step of the search, to calculate some measure of the closeness to a goal, and thus select the most promising path, but finding a reliable measure is often difficult. Heuristics gleaned from human domain-experts and built into the system may also be used to direct the search (essentially making intuitive leaps) and may appear in the knowledge base as *meta-rules* (rules about how the knowledge should be processed), supplementing rules about the problem domain itself.

Rules may be processed from left to right, by trying to satisfy the left-hand sides and proceeding by *forward chaining* to a conclusion. However, in some problems, particularly where there are few possible goals but a large range of initial conditions, it may be more efficient to use *backward chaining* — starting from a goal and seeking to establish the conditions that would lead to it.

Not all ideas can be conveniently expressed as production rules, and other formalisms are also used. *Frames* (Minsky 1975) are data structures which facilitate *inheritance* of properties within a class of objects. In such a representation 'cumulonimbus' might be a member of a 'convective clouds' class which in turn would be a member of the top-level class 'clouds'. A member automatically inherits the properties of higher levels in the structure except where it has specific values that distinguish it from other members. Some problems are best expressed as statements in formal logic, as implemented for example in the programming language Prolog (Clocksin and Mellish 1987). More than one formalism is sometimes used within a single expert system in order to express different aspects of the problem (e.g. Elio *et al.* 1987).

Nearly all practical systems also contain a 'Man–Machine Interface' (MMI) and many can connect to conventional databases and programs; real-time systems may incorporate interfaces to physical sensors. An important function of the MMI is to provide explanation facilities. In the face of a pronouncement from an expert system (particularly if the question or conclusion is unexpected) the user will often want reassurance in the form of an explanation of the reasoning involved, and facilities for this are provided via the MMI. Explanation facilities are widely regarded as an essential attribute of expert systems, even if implemented as no more than a trace of which rules fired during the reasoning process.

2.3 Differences between expert systems and conventional programs

Two important concepts in expert systems are (a) the use of *symbolic reasoning* and (b) *the separation of the knowledge base* (an explicit description of the problem domain) *from the inference engine* (the means of processing the information). From these concepts come most of the important practical characteristics of expert systems.

2.3.1 Symbolic reasoning

Expert systems manipulate representations of ideas, whereas conventional programs are usually concerned with numerical operations on items of data. Fig. 2 illustrates the difference. A surface analysis can be represented by arrays of numbers giving values of parameters, such as pressure and temperature, at regularly spaced grid-points. The same analysis can be represented as a pattern of meteorologically significant features — anticyclones, depressions, troughs, fronts, etc. Both views of the analysis are valid. Grid-point values are convenient for applying physical equations locally in a numerical model while the other, symbolic, representation enables the forecaster to summarize the situation very economically and to concentrate attention on regions of greatest interest.

Symbolic reasoning (considering the problem in terms of named conceptual features) does not preclude numerical processes, but uses them to fill in details within a broad picture or to answer specific questions thrown up by higher-level reasoning, such as 'Is that low

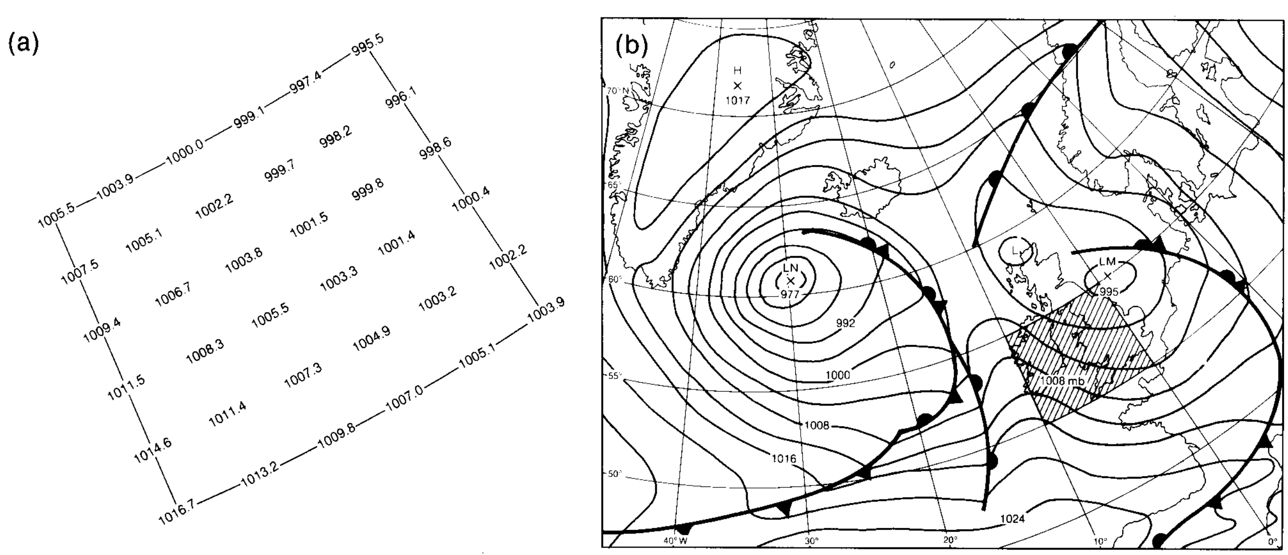

Figure 2. Different ways of representing a surface analysis, (a) as a regular array of parameter values suitable for numerical processing (mean-sea-level pressure (mb) shown here), and (b) in terms of meteorologically significant features, more convenient for a human forecaster or for symbolic reasoning in an expert system. The shaded area is the portion of the chart shown alternatively in (a).

still deepening?' or 'How fast is the pressure changing at Culdrose?' A meteorological expert system would access conventional routines, including pattern-recognition algorithms, to handle numerical operations and supply results which could then be reasoned about at the symbolic level.

2.3.2 Separation of the knowledge base and inference engine

In conventional programming we start with a user who wishes to do some job. This is the 'real world' problem. An analyst (who may also be the programmer and the user) examines what is wanted and constructs an idealized model of the problem. The programmer works out how this idealized problem might be solved and then writes a program, a series of step-by-step instructions for a computer to obey, to implement the chosen solution. The important point here is that the program describes the solution, not the original problem or even the idealized problem. It may well be possible to solve the problem in different ways and the corresponding programs, though ultimately doing the same job, might look completely different. Knowledge about the problem itself — how the user would describe it — does not appear explicitly. It was used by the programmer to translate from the problem to his solution and it is now therefore implicit in the structure of the program, inextricably mixed up with how the program operates.

In developing an expert system we start with the real-world problem as before. The analyst is now called a *knowledge engineer* and has the job of constructing the knowledge base from the user's understanding of the problem. Although some idealization must occur in any process like this, the object is to fill the knowledge base with a description of the problem domain as far as possible in the user's own terms and in a form that the user can understand. What is being produced is a description of the domain — a collection of facts, rules and assumptions which the user (the expert in that domain) uses in his work. There is no attempt to devise a solution and to program it as a set of sequential instructions. Programming the expert system for a particular domain consists of constructing as accurate and complete a description as possible in the knowledge base. The knowledge therefore remains explicit and accessible to the original user, and separate from the mechanisms directing the program's sequence of operations.

These structural and functional differences lead to the main strengths and weaknesses of expert systems compared with conventional programs:

(a) An expert system can often start to function and to produce useful results before the knowledge base is complete, and then evolve in a gradual way as further knowledge is added, just as a human expert continues to learn, and to refine his knowledge. By contrast, a conventional program represents a solution which is implemented complete, and it usually evolves in a series of large, discrete upgrades rather than by small increments.

(b) Because the knowledge base is a description of the problem area as far as possible in the user's own terms, the user is in a good position to understand it, check its correctness and propose modifications. In a conventional program, which relates to a solution rather than to the problem, the operation of the program may be obscure, not only to the user but to other programmers. The effort that goes into structuring and documenting programs is a recognition of this difficulty.

(c) The close correspondence between the problem and the knowledge base makes it easier to modify the expert system to reflect changes in the problem. With a conventional program such modifications are often difficult, because the program represents a solution, and the implications for that solution of even a small change in the problem may be considerable. Indeed, the particular problem-change may have been implicitly excluded as a possibility when the original solution was devised.

(d) Because an unavoidable step in conventional programming is to devise a solution to the problem, the program is not written unless a means of solution appears to exist. With an expert system, however, being able to describe the problem in the knowledge base does not guarantee that a solution to that problem can be found.

(e) The search strategies and inferencing mechanisms in an expert system are more difficult to optimize for speed and efficiency than the sequential instructions that form a conventional program.

3. Expert systems in weather forecasting

3.1 Requirements

Weather forecasting is a promising application for expert systems. In spite of advances in observing systems and numerical weather prediction (NWP) models, the production of forecasts, particularly short-period local forecasts of specific weather events, tailored to the needs of customers, depends to a large extent on the skill and experience of human forecasters. The forecaster must recognize and compensate for errors and biases in the numerical products, identify the sub-grid-scale phenomena that are likely to be present in different synoptic situations but not represented explicitly in the model, and also take account of local conditions, such as topography or a coastal location, which will modify larger-scale patterns. By storing and applying some of the forecaster's knowledge, expert systems should be able to act as useful advisory tools in forecast offices, continuously monitoring information about the weather situation and alerting the forecaster to the likelihood of severe or significant weather events.

Weather forecasting carries a combination of difficulties however, which must be overcome in any expert system designed to help the forecaster in real operational situations. The main challenges (discussed below) are pattern recognition problems, missing and conflicting data, and the need for convenience and speed.

Weather information comes from a variety of sources with widely different spatial and temporal characteristics. Only by recognizing and understanding the current weather pattern, fitting individual observations into coherent conceptual models (Browning 1986), can we reconcile apparently conflicting information and go on to predict the evolution of the pattern and consequent changes in local parameters like temperature and rainfall.

An important observational source, particularly for short-range forecasting, is remotely sensed imagery (Conway and Browning 1988). Much is often made of the difficulties of automatically recognizing patterns in images (e.g. McIntyre 1988) but in some cases the problem can be reduced to a search, made in the light of other evidence, for well-defined observational signatures associated with particular weather phenomena, as for example in the work by Campbell and Olsen (1987) on Doppler radar. The problem then becomes much less daunting than, say, the relatively unconstrained vision-analysis task involved in driving a car. One of the important functions of an expert system will be to use other meteorological knowledge and evidence to focus and constrain the pattern-recognition task, and avoid getting bogged down in huge amounts of low-level image-processing.

In most cases the observational data will be incomplete and contain errors and inconsistencies. This is a common feature of expert-system applications, and is normally tackled by assigning weights and probabilities to evidence and hypotheses. As humans we do not normally reason in numerical terms but prefer vaguer notions of things being 'probable' or 'likely', so the appropriate assignment of probabilities is one of the main difficulties of encoding human expertise in the form of rules. How best to deal with 'reasoning under uncertainty' is a subject of continuing research in the expert systems community (Mamdani *et al.* 1985).

A system which adds to the work-load of the forecaster and slows him down is no use in a forecasting office, however good its eventual pronouncements may be. This means that the amount of information entered manually must be minimized, and the sort of tedious dialogue via screen and keyboard, found in many simple, shell-based systems, must be avoided. The system must have direct access to current meteorological data so that it can work unattended as far as possible, reducing the need for manual data-entry and being ready to display results either when requested by the forecaster or when predetermined criteria are met. The expert system cannot 'look out of the window', so some input by the forecaster, either prompted or volunteered, may be unavoidable, but this must be kept to a minimum.

These are demanding but not impossible requirements and are found individually in many expert-system applications. Their combination here means that expert systems for weather forecasting have more in common with those for battlefield analysis (IKBS in Defence 1984) and industrial process-control (e.g. Paterson *et al.* 1985) than with those for administrative applications such as credit authorization and social security claims.

3.2 Progress in meteorological expert systems

Expert systems for weather forecasting are being developed in many parts of the world, and some of the work is already well advanced. The 1987 AIRIES conference (reported in Dyer and Moninger 1988) highlighted developments at various centres in North America. In a survey presented at the conference, these authors listed some 39 meteorological expert systems and related studies addressing a wide variety of forecasting and diagnostic tasks, including convective storms, precipitation, visibility, low cloud and wind. The systems were at various stages of development, from initial studies to real-time trials. Most activity was in the USA, but Canada, Europe and Australia were also represented. However, while giving a useful impression of the range of work being done, the survey did not claim to be exhaustive; other systems are being developed and applied elsewhere, for example in China, where they are being developed to forecast regional heavy rain (Dai *et al.* 1987).

An interesting development is the use of expert systems, not directly as forecasting tools, but to train student meteorologists. This off-line application avoids some of the more stringent demands of operational forecasting and may perhaps be accomplished using low-cost, PC-based shells (Reiss and Hofmann 1988).

The overall picture to emerge is one of vigorous activity and rapid growth, with many independent investigations exploring a diversity of ideas. It is too early to say which of the techniques now being tried will endure, but at least there is sufficient activity to allow useful comparison and cross-fertilization of ideas.

3.3 Developments in the Meteorological Office

In the Meteorological Office at Bracknell the emergence of expert systems for real applications instead of as mere research curiosities, and their possible use in meteorology, was examined by the author in the mid 1980s. Although the techniques appeared to hold promise, there was at that time little published work in the meteorological field and the available tools were mainly either cheap but simple PC-based products, such as shells for building consultation systems, or very expensive, specialized workstations. The affordable systems did not allow ready connection to machinable data or to software written in conventional languages. More immediate tasks precluded the diversion of much effort to investigating expert systems, but some experiments were done with cheap shells and artificial problems. These showed that the constraints imposed by such shells, in terms of the dialogue with the user and the internal representation of knowledge and uncertainty, would be quite unacceptable in even the simplest tasks in operational weather forecasting. The concepts embodied in expert systems were not invalidated, but these crude implementations fell well short of what was needed.

In August 1988, the Nowcasting and Satellite Applications Branch of the Meteorological Office was formed, bringing together existing research groups concerned with the processing, interpretation and use of remotely sensed images from satellites and weather radars. Experience of interactively processing remotely sensed imagery in near real time in the FRONTIERS project (Conway and Browning 1988) had by then shown the desirability of being able to transfer some of the higher-level judgemental tasks from the man to the machine. Meanwhile, the environment for developing expert systems had become more favourable — the availability of workstations and artificial intelligence software tools had improved, and the establishment of a data network linking together the Meteorological Office's main computers offered access to a full range of meteorological data. Accordingly, one of the tasks set for the new Branch was to investigate the application of expert systems to short-period forecasting and to do this by building and testing experimental systems for specific forecasting tasks.

Two pilot projects have been defined. One is the automation of the forecast stage in FRONTIERS, the other is thunderstorm forecasting.

In the FRONTIERS system (Conway 1987) image data from the UK weather radar network and from Meteosat are combined to produce analyses and nowcasts (forecasts for 3 hours or so ahead) of precipitation. The nowcasts are prepared by a forecaster who uses an interactive display system to view the recent movement of the rainfall pattern, identify separate clusters within the pattern and assign them velocities so that their movement can be extrapolated. Although this gives a somewhat crude representation of a complex evolving pattern it can often produce successful forecasts in the nowcast period, particularly for frontal rain.

The FRONTIERS forecaster works to a very demanding half-hourly cycle and, despite recent improvements in the efficiency of the software, in active weather situations he has difficulty in completing all his tasks on time. Planned extensions to the UK weather radar network will increase his work-load, so ways of lightening the burden by automating some of his tasks are needed.

The existing FRONTIERS forecast method is well-suited to an interactive system controlled by a forecaster, but automation allows other techniques to be considered. Thus a convenient way of automatically estimating the short-period movement of the rainfall pattern is to use trajectories derived from NWP model winds, in this case from the Office's mesoscale model (Golding 1987). This method offers a way of combining realistic, physically based trajectories with the better resolution and timeliness of the remotely sensed observations. One problem is to decide the heights of the 'steering winds' for different parts of the pattern (in which embedded convective cells may move with different speeds from the overall pattern) and to recognize those situations in which none of the winds corresponds to the movement of the rainfall pattern (e.g. because the rainfall is tied to topographic features or because the model output is wrong). Where the model wind fields are unsuitable it will be necessary to use other techniques to derive velocities, such as cross-correlation of successive rainfall fields (Austin and Bellon 1974); more than one method may be needed within a single case.

A multi-layer system is therefore envisaged (Fig. 3). The top levels are occupied by an expert system, which uses evidence from a variety of sources to make decisions about how the movement of the rainfall pattern is governed and, on the basis of these decisions, selectively accesses conventional programs in the lower levels to calculate trajectories, correlations, etc.

Thunderstorm forecasting is attractive as a pilot project because it is an important and non-trivial fore-

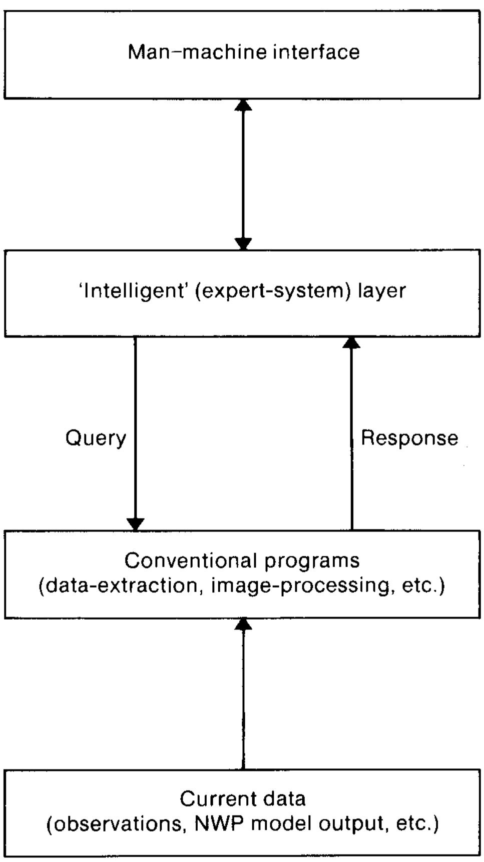

Figure 3. Hybrid structure for operational weather forecasting.

casting task, relevant observational coverage is good and, as a knowledge-engineering project, its problems complement those of automating the FRONTIERS forecast. Although some benefit may be obtainable from experience in North America of developing expert systems for convective storm forecasting (e.g. Elio *et al.* 1987), there are differences in the character of their storms, the local conditions and the observational sources. Thunderstorm activity encompasses a wide range of phenomena (lightning, hail, heavy rain, wind shear, turbulence, etc.) which do not necessarily all occur together and which are individually of importance to different customers. The first task is therefore to review these customer requirements and to limit the task to manageable size by focusing on particular aspects — this is currently under way.

The newly operational, high-resolution ATD (arrival time difference) Sferics system (Lee 1986), images from weather radars and satellites, and conventional surface and upper-air reports, together provide good areal and temporal coverage of ongoing thunderstorm activity and antecedent conditions. Together with forecasts produced by present methods they will form an archive of cases against which experimental systems can be tested during development. Further evaluation of performance must of course be done, preferably in real time, outside this 'training set'.

The experience and co-operation of practising forecasters will be essential in assembling and validating the knowledge base for this system, though other sources (the results of relevant research by groups in the Office and elsewhere) will also be important. The project will thus complement that on FRONTIERS by providing experience in the traditionally difficult process of eliciting and coding the knowledge of human experts (not only their formal knowledge and what they think they do, but also the short cuts and rules of thumb they use without even noticing). It is likely that the compilation of this knowledge will be a worthwhile exercise in its own right, and provide useful insights of practical value, quite apart from its role in developing an expert system. As with the FRONTIERS forecast project it is expected that a hybrid system will emerge, with an 'intelligent' upper layer controlling conventional routines to access and process observational data.

The aim of these projects is to provide experience in constructing expert systems for tasks of real practical value; they will teach us where the main difficulties lie, and demonstrate the strengths and weaknesses of this approach to automation. The first goal will be to show whether expert systems can be applied in these applications to produce successful forecasts when compared with traditional methods in the context of specific customer requirements. If so, work will be directed at making them satisfy the time-critical requirements of operational forecasters, as outlined in section 3.1, and examining other areas where the techniques might be applied.

4. Conclusion

Expert systems offer the prospect of using computers for tasks requiring reasoning (the selection, weighing, reconciliation and connection of evidence and ideas to draw conclusions) in contrast to their traditional 'number-crunching' role.

Weather forecasting, with its strong component of human skill and its basis in known physical laws, is an obvious application for expert systems, though the nature of the task poses some difficult problems and the requirements of operational forecasters will not be easy to satisfy. The development of expert systems in this field is the subject of intensive research by many groups around the world, and in the Meteorological Office two pilot expert-system projects in short-range forecasting have been started.

Expert systems are not an alternative to traditional computing methods but complement them, so that practical systems will be hybrids, with an expert system directing the use of numerical procedures, in the same way that the human being makes use of the calculating power of the computer in interactive systems like FRONTIERS.

Expert systems are certainly not magic ways of performing hitherto impossible tasks. If a task cannot, at least in principle, be done by a human being in ideal conditions (i.e. with access to all the relevant data sources and reference material, means of performing calculations, and no time constraints or distractions) then it cannot be done by an expert system either.

What an expert system can do, within its narrow domain of expertise, is to deliver consistent behaviour and performance. Its conclusions will not always be right, any more than a human expert will always be right, but it will not get tired, or have off-days or panics, or avoid boring or difficult calculations. It will not forget what it has been 'taught', and new knowledge can be added in the light of its mistakes so that it does better next time.

Considerable effort is being put into providing forecasters, at outstations as well as main forecasting centres, with a rich variety of observational data, including increasingly large quantities of remotely sensed images from radars and satellites, derived products and output from NWP models (Cluley and Hills 1988). There is a limit to the rate at which the forecaster can assimilate and use this torrent of information. Interactive computer-based display systems can make it easier to access and manipulate the data, but cannot remove the problem entirely if they rely on the human to do all the thinking. There is the danger that the forecaster, lacking the time to weigh, on each occasion, the relative importance of the full range of products available, will slip into the habit of using some familiar subset of them, so that items of only occasional importance will be ignored. We can alleviate this problem and make better use, both of the forecaster and of the wealth of data becoming available to him, if we can find ways of using machines to help with some of the higher-level judgemental tasks — scanning the data, forming initial conclusions and drawing the forecaster's attention to significant events.

Research into expert systems for weather forecasting is still at an early stage but is proceeding apace. There are many difficulties to be overcome and undoubtedly there will be many false starts, but success will provide a radically new way of using computers to aid the forecasting process.

Acknowledgements

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An investigation into the conditions in which air-mass thunderstorms occur at Athens

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Summary

An investigation was carried out into the conditions in which air-mass thunderstorms occur over the Athens region. Consideration is given to temperature and dew-point information from radiosonde ascents, and synoptic charts of the surface, 850 mb and 500 mb levels.

1. Introduction

The forecasting of thunderstorms for a city or relatively small region is a very difficult problem. This may be attributed to the fact that whereas a thunderstorm is a mesoscale phenomenon, synoptic-scale observations are used to forecast them. Summertime air-mass thunderstorms are a welcome relief to Athenians, although the associated heavy rainfall can sometimes be a problem.

The international meteorological literature contained little about thunderstorms until the publication of the remarkable study by Byers and Braham (1948). Since then a considerable number of studies concerning thunderstorms have been published and much has been learned. The improvement in meteorological instruments and the development of new observing methods have contributed to this. Also the development of mesoscale numerical models in conjunction with the increasing power of computers are hopeful signs that further progress can be made in the problem of thunderstorm forecasting. Meanwhile forecasters will have to try to improve forecasting techniques based on a more traditional approach.

A forecaster associates the occurrence of thunderstorms in a region with:

(a) the degree of instability,
(b) the amount of moisture available, and
(c) the presence of a trigger to release the instability.

Normally a thunderstorm occurs when, in a conditionally unstable atmosphere, a trigger forces boundary-layer air up to the level of free convection. However, in a relatively stable atmosphere it is possible for large-scale ascent (e.g. caused by strong convergence or considerable positive vorticity advection at 500 mb) to trigger thunderstorms. This suggests that it is useful to differentiate between air-mass (thermal) thunderstorms and dynamical thunderstorms.

Sometimes the term air-mass thunderstorm is not applied correctly — any thunderstorm which occurs during the afternoon and evening over land in the warm season is usually described as an air-mass thunderstorm. However, even though the surface pressure chart does not show a front and the pressure field is very slack, a dynamical trigger such as positive vorticity advection at 500 mb (often accompanied by cold advection which reduces the stability) could be responsible for the thunderstorms. Consequently, in order to consider just air-mass thunderstorms it is necessary to exclude occasions when there is positive vorticity advection towards the region.

Here, the air-mass thunderstorms which occur at Athens based on observations from Helliniko and Nea Philadelphia (located as in Fig. 1) will be considered.

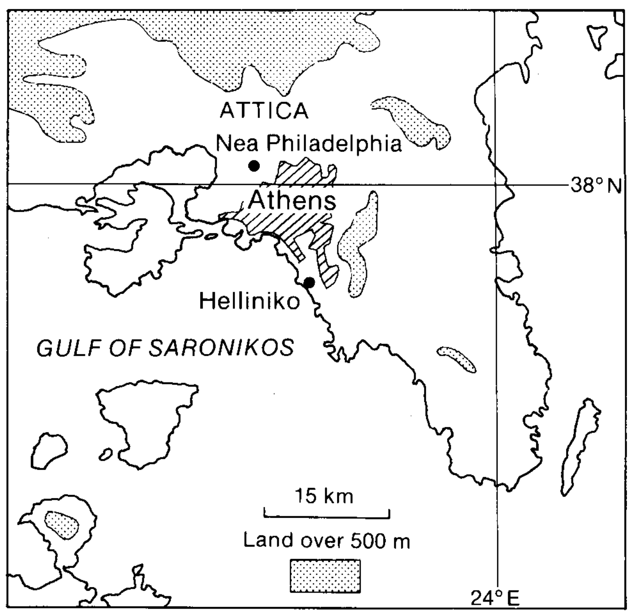

Figure 1. Map of the area under consideration, showing places mentioned in the text.

2. Air-mass thunderstorm days at Athens

According to WMO (1966) a thunderstorm occurs when one or more sudden electrical discharges are manifested by a flash of light and a rumbling sound. A thunderstorm may or may not be accompanied by precipitation. As far as observations are concerned, if thunder occurs without precipitation then a thunderstorm is occurring. However, if lightning is observed without thunder being heard at the station or without precipitation occurring then the event is not considered to be a thunderstorm.

The study described here was based upon days on which thunderstorms occurred in the vicinity of the Helliniko and Nea Philadelphia meteorological stations during the 6-year period 1970–75. These stations were chosen because Athens is located between them and less than 10 km from each (Nea Philadelphia to the north and Helliniko to the south close to the sea). For each station a thunderstorm day was taken to be a day for which at least in one synoptic observation (from the 8 every 24 hours) the present weather was reported as 17, 29 or 91–99, or the past weather was reported as 9. In the cases where the 0000 GMT observation had a past-weather report of 9 but no thunderstorms reported as present weather, the previous day was designated as a thunderstorm day. A thunderstorm day at Athens is taken to be one in which either of the meteorological stations has a thunderstorm day (Metaxas 1972).

After recording all the thunderstorm days at the two stations for May, June, July, August and September for 1970–75, the days in which air-mass thunderstorms occurred were identified. This was done by carefully examining the surface and 500 mb charts and excluding the occasions on which thunderstorms occurred due to:

(a) the passage of a front,

(b) strong cold advection at 500 mb, or

(c) positive vorticity advection at 500 mb.

Also, thunderstorms which occurred during the afternoon with total cloud more than 3 oktas during the morning were excluded. This criterion was imposed in order that any thunderstorms would be purely air-mass produced, and with half cover or more of cloud the insolation would be insufficient to be sure the thunderstorm was thermally produced. The remaining days were judged to be air-mass thunderstorm days — that is days for which the surface temperature exceeded the critical convective temperature and the thermal trigger released the instability and thunderstorms formed.

3. A statistical analysis of the air-mass thunderstorms

The number of air-mass thunderstorm days at Athens (based on the observations at Helliniko and Nea Philadelphia) for each month of the warm season in the 6-year period are given in Table I. Of the 30 days, 23 were thunderstorm days at both Helliniko and Nea Philadelphia, whereas on 4 occasions air-mass thunderstorms only occurred at Helliniko and on 3 occasions they only occurred at Nea Philadelphia. This behaviour was in contrast to what might have been expected (Metaxas 1972 and Mihalopoulos-Nistazaki 1978) but with synoptic experience suggests that this kind of thunderstorm starts over the continental parts of Attica and then develops towards the regions in the vicinity of the coasts of the Saronikos Gulf. It is of course possible that the centre of the released instability is indeed in the continental parts, but as the thunderstorm develops it is carried away by the northerly 700 mb winds which are usually light and so the electrical phenomena start quite far south near Helliniko. Consequently the thunder may not be heard near Nea Philadelphia due to heavy rain and thick cloud. This mainly occurs in winter (Metaxas 1972) but it is not impossible during the summer.

Table I. Number of air-mass thunderstorm days each month during the warm season (May–September) in Athens during the period 1970–75 based on observations from Helliniko and Nea Philadelphia

Year	May	June	July	Aug.	Sept.	Total
1970	0	3	1	0	1	5
1971	1	1	0	0	1	3
1972	1	1	4	1	0	7
1973	1	1	2	0	0	4
1974	0	0	0	1	1	2
1975	4	3	0	1	1	9
Total	7	9	7	3	4	30
Monthly mean	1.16	1.50	1.16	0.50	0.66	

Table I shows that June is the month with the highest number of air-mass thunderstorms. This is due to the large amount of solar radiation during the month and the higher frequency of light winds (the Etesians, the well-known north-easterlies, are more frequent in July and August).

The number of successive air-mass thunderstorm days at Athens is given in Table II. This shows that there are no cases with more than two successive thunderstorm days. Also the number of cases of successive thunderstorm days are so few that it can be concluded that the meteorological conditions which favour the occurrence of air-mass thunderstorms in Athens have a tendency not to persist.

Table II. Number of cases when an air-mass thunderstorm day during the warm season (May–September) in Athens during 1970–75 was not immediately followed by an air-mass thunderstorm day (column I) and the number of cases when air-mass thunderstorm days occurred on two successive days (column II).

Year	May		June		July		Aug.		Sept.		Total	
	I	II	I	II	I	II	I	II	I	II	I	II
1970	0	0	1	1	1	0	0	0	1	0	3	1
1971	1	0	1	0	0	0	0	0	1	0	3	0
1972	1	0	1	0	2	1	1	0	0	0	5	1
1973	1	0	1	0	2	0	0	0	0	0	4	0
1974	0	0	0	0	0	0	1	0	1	0	2	0
1975	2	1	1	1	0	0	2	0	0	0	5	2
Total	5	1	5	2	5	1	4	0	3	0	22	4

4. Conditions in which air-mass thunderstorms occur at Athens

4.1 Use of upper-air soundings

The meteorological parameters $T_{850}-T_{500}$ and $(T-T_d)_{850}+(T-T_d)_{700}$ can be computed from upper-air soundings (T and T_d denote the temperature and dew-point, and the subscript indicates the level in millibars). The first of these quantities provides a measure of the instability of the atmosphere whilst the second indicates the humidity in the lowest levels.

Fig. 2 show plots of $T_{850}-T_{500}$ against $(T-T_d)_{850}+(T-T_d)_{700}$ derived from the 0000 and 1200 GMT ascents at Helliniko for each air-mass thunderstorm day at Athens (each thunderstorm day has been labelled 1 to 30 but some ascents are missing). One immediate result which can be seen from the figure is that in all cases thunderstorms only occurred when $(T-T_d)_{850}+(T-T_d)_{700}$ is smaller than 22 °C and $T_{850}-T_{500}$ greater than 23 °C. This suggests that if the two quantities are outside these limits then the conditions are not at all favourable for the development of air-mass thunderstorms

The plots in Fig. 2 have been divided into three regions based on the characteristics of the thunderstorm days. Region A — severe thunderstorms of long duration with precipitation reported from both stations. Region B — thunderstorms of short duration with precipitation reported from at least one of the stations. Region C — thunderstorms without precipitation reported by either stations. Broadly the regions are determined by the amount of moisture in the lowest layers of the atmosphere.

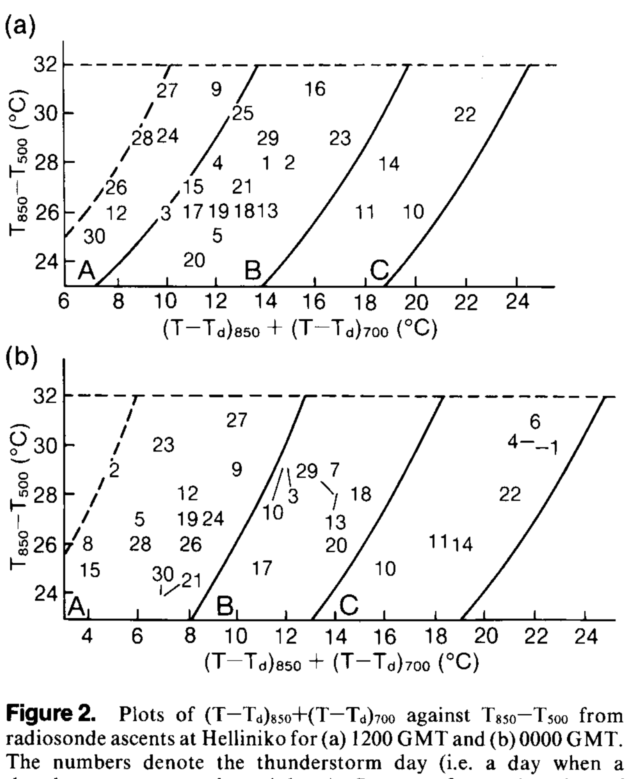

Figure 2. Plots of $(T-T_d)_{850}+(T-T_d)_{700}$ against $T_{850}-T_{500}$ from radiosonde ascents at Helliniko for (a) 1200 GMT and (b) 0000 GMT. The numbers denote the thunderstorm day (i.e. a day when a thunderstorm occurred at Athens). See text for explanation of symbols.

Comparing Figs 2(a) and 2(b) shows that the days in Region A at 1200 GMT (see Fig. 2(a)) are usually in the same region as 12 hours earlier (see Fig. 2(b)). The same applies for regions B and C. This suggests that the values of $T_{850}-T_{500}$ and $(T-T_d)_{850}+(T-T_d)_{700}$ for 0000 GMT can be used to forecast the likelihood and intensity of thunderstorms at Athens and the surrounding region. If these two quantities do not lie within the boundaries of the area in Fig. 2(b) then it is forecast that there is no likelihood of thunderstorms; if they do lie within the boundaries then it is forecast that thunderstorms may occur if the cloud conditions (and other surface synoptic features described in the next section) are suitable.

4.2 Use of synoptic charts

For the air-mass thunderstorm days at Athens the 850 and 500 mb mean charts were prepared for 0000 and 1200 GMT (0300 and 1500 local time) using data from the National Center for Atmospheric Research, Boulder, Colorado. The 500 mb chart is the traditional level at which the contour regime in the Balkans is related to the occurrence of air-mass thunderstorms at Athens. Consequently the difference between the mean height values and the normal values for the summer season (based on the normal monthly values published by the Deutscher Wetterdienst) were computed in order to detect centres of action.

Fig. 3 shows the mean 500 mb contour height and temperature at 0000 and 1200 GMT during the days characterized as air-mass thunderstorm days at Athens. Also shown are the anomaly of the contour height from the normal conditions in the warm season (it is the difficulty of maintaining these features that is responsible for there only being a few occasions on which air-mass thunderstorms occur on successive days). A feature of these charts are the low contour heights and cold air over Greece. Also the anomaly field shows that the contour heights are lower than normal for the summer over the whole of the Balkan region, the eastern Mediterranean and adjacent African coast, while in north-west and central Europe the contour heights are higher than normal. A statistical analysis of the anomaly shows that it is a very regular feature in cases where air-mass thunderstorms occur at Athens.

Fig. 3 also shows that the broad-scale flow associated with thunderstorms at Athens is a blocking anticyclone (Makrogiannis 1976 and Prezerakos 1978) which obstructs the regular eastward movement of the pressure systems. Note that the polar jet over the Atlantic splits and one of its branches passes over the Mediterranean resulting in a fall in the 500 mb heights whilst the subtropical jet retreats southwards. The blocking is a diffluent type and this suggests that the low and the accompanying cold air which occurs on a thunderstorm day comes from the west or north-west. So, for an air-mass thunderstorm to occur over Athens, it is reasonable to assume that a low at 500 mb and an

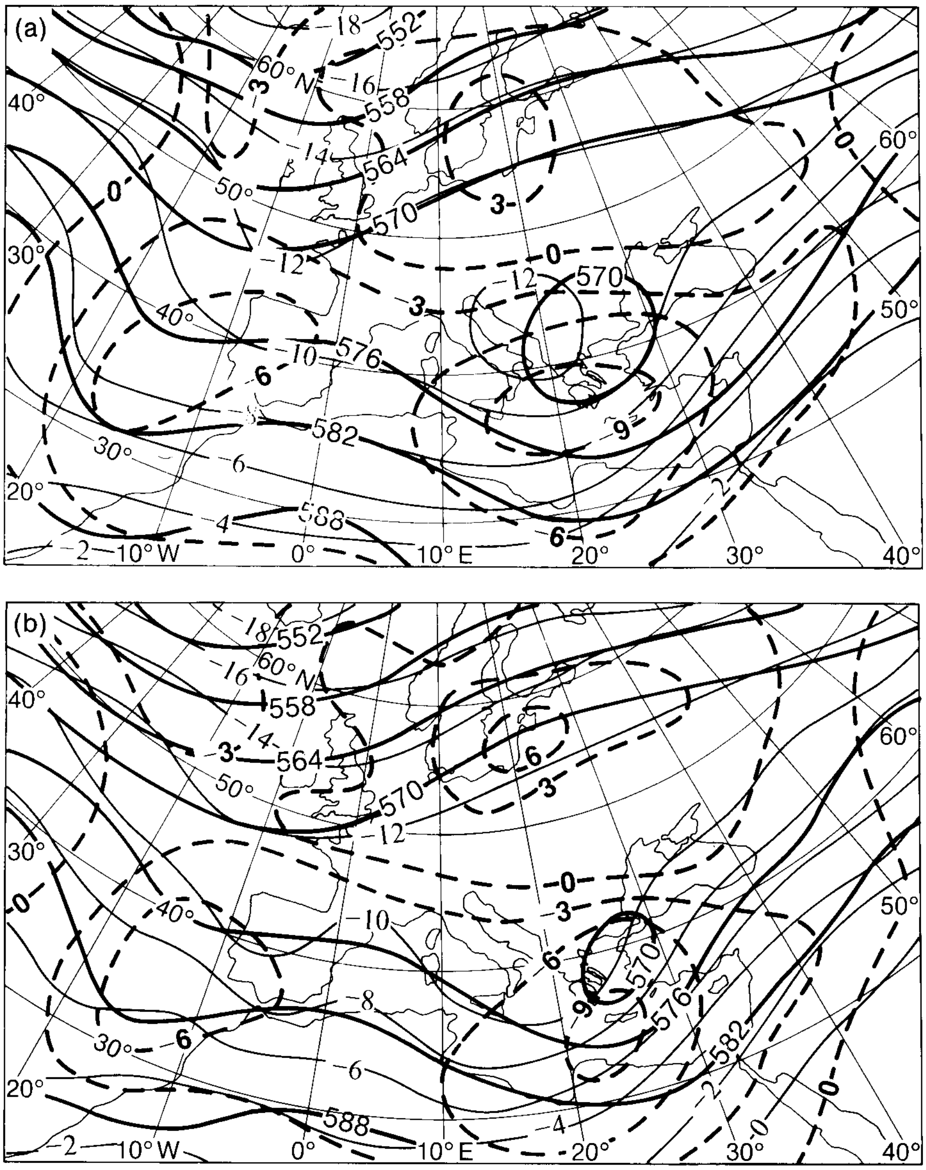

Figure 3. Mean 500 mb contours (dam, thick lines), isotherms (°C, thin lines) and height anomalies (dam, dashed lines) for the 30 air-mass thunderstorm days at Athens at (a) 0000 GMT and (b) 1200 GMT during the period 1970–75.

accompanying cold pool must occur in conjunction with the instability and moist lower troposphere.

At 850 mb the contour height and temperature for the air-mass thunderstorm days have low values in the Balkans and Greece, and high values in the European region north of the Balkans (see Fig. 4). Furthermore the spacing of the contours indicates that on air-mass thunderstorm occasions there are only light winds at 850 mb. This is consistent with the observed 850 mb winds, though there are occasions when the wind exceeded 15 kn (usually in the morning).

The mean-sea-level pressure chart for the air-mass thunderstorm days at Athens has a slack pressure gradient in the vicinity of the Balkans and Mediterranean. The associated calm conditions in the Athens region allows the surface heating to be sufficient to trigger the instability. This means that when the Etesian blows at Athens, thunderstorms are unlikely. Consequently the extension of the permanent thermal low over Cyprus towards Greece and/or the establishment of high pressure in the central Mediterranean, both of which are associated with the Etesian in Greece, are incompatible with air-mass thunderstorms at Athens.

4.3 A quick objective method

From the material presented in the previous two sections it appears that air-mass thunderstorms tend to occur at Athens if the following conditions are satisfied:

(a) In Fig. 2 the quantities $(T-T_d)_{850}+(T-T_d)_{700}$ and $T_{850}-T_{500}$ fall into the regions delineated.

(b) There is less than 4 oktas total cloud before noon.

(c) The 500 and 850 mb fields are similar to those given in Figs 3 and 4 with light winds at 850 mb and the surface.

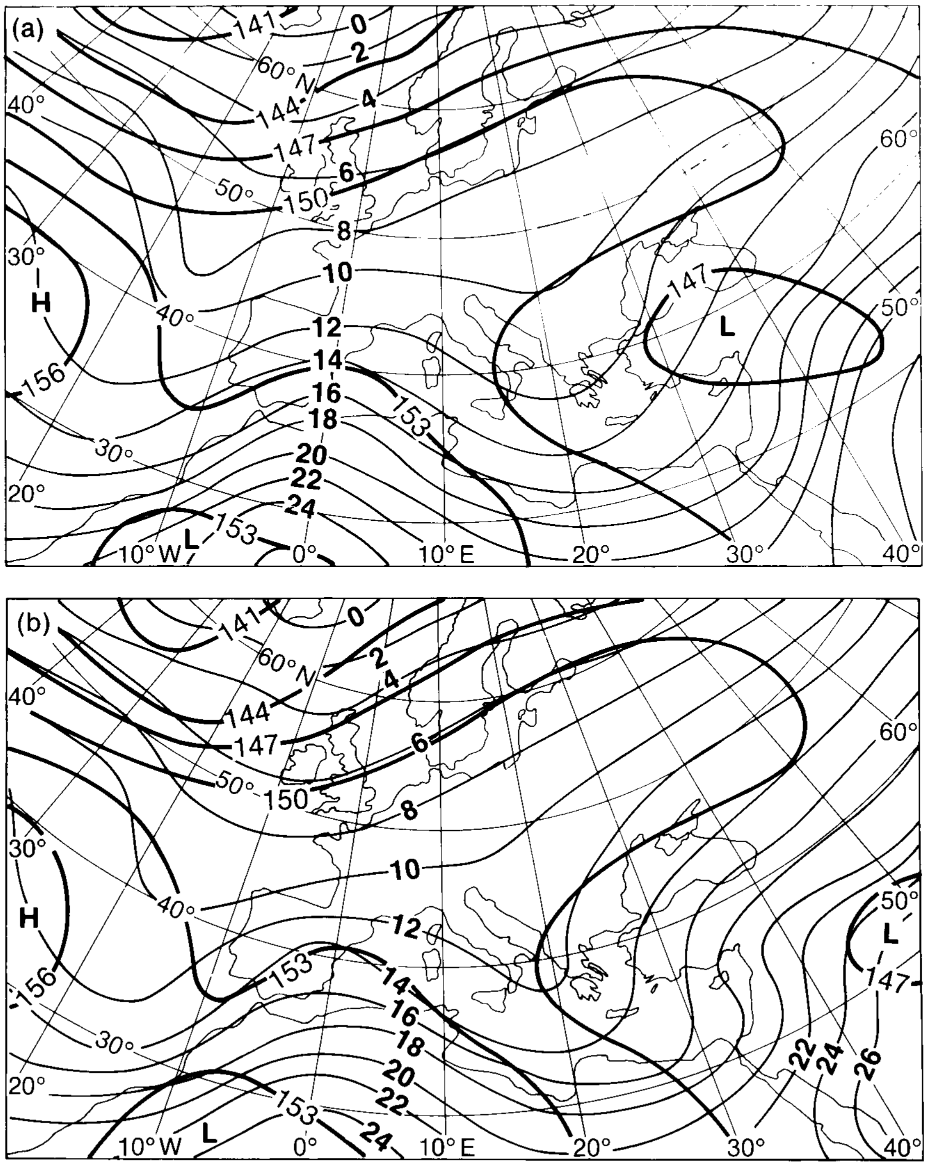

Figure 4. Mean 850 mb contours (dam, thick lines) and isotherms (°C, thin lines) for the 30 air-mass thunderstorm days at Athens at (a) 0000 GMT and (b) 1200 GMT during the period 1970–75.

This forecasting scheme was verified for May–September for the period 1980–82. For each day the humidity, $(T-T_d)_{850}+(T-T_d)_{700}$, and instability, $T_{850}-T_{500}$, parameters were estimated from both the 0000 and 1200 GMT ascents at Helliniko and the dates when these parameters fell within the areas A, B, or C in both Figs 2(a) and 2(b) are recorded. Twenty per cent of all cases were excluded as having more than 3 oktas cloud before noon. The similarity of the 0000 and 1200 GMT 850 and 500 mb charts with those in Figs 3 and 4 was then examined; this guarantees that the passage of a front, strong cold advection at 500 mb or positive vorticity advection at 500 mb did not occur in the afternoon. This eliminated a further 35 per cent of remaining occasions. Ninety-five per cent of the occasions left corresponded to observed air-mass thunderstorm days at Athens. It was not possible to identify any specific reasons for the failure in the residual 5 per cent of cases though more detailed studies may prove valuable.

5. Conclusions

The main conclusions resulting from this study are as follows:

(a) 59 days of thunderstorms (either air-mass or dynamical) occurred in Helliniko and 50 in Nea Philadelphia during the warm season (May–September) of the period 1970–75. From these it was deduced that during the period under consideration there were 30 air-mass thunderstorm days at Athens. Cases of three or more successive air-mass thunderstorm days at Athens were not detected during the 6-year period, and even the number of occasions of two successive days was extremely small.

(b) During the air-mass thunderstorm days at Athens $(T-T_d)_{850}+(T-T_d)_{700}$ is lower than 22 °C and $T_{850}-T_{500}$ is higher than 23 °C. In addition there are light winds at 850 mb and calm at the surface, and at 500 mb strong cold advection or positive vorticity advection do not occur in the afternoon.

(c) For air-mass thunderstorm days there is a 500 mb low in the vicinity of Greece centred to the east of Athens accompanied by a cold pool, and in northern Europe there is an anticyclone associated with a diffluent block. Also the 500 mb heights are much lower than normal with the subtropical jet stream displaced southwards so that the polar jet stream, which is to the north of the diffluent block, crosses Greece. At 850 mb the contour heights and temperatures are lower than usual.

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The effect of a sea surface temperature anomaly on a prediction of the onset of the south-west monsoon over India*

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Summary

At the time of the onset of the monsoon in June 1979 the sea surface temperatures in the eastern Arabian Sea were higher than usual. Experiments carried out with an atmospheric model show that a better prediction of the onset is obtained using the anomalously high temperatures rather than the climatological ones.

1. Introduction

The Global Weather Experiment (also known as the First GARP Global Experiment (FGGE)) carried out in 1979 has provided a wealth of data which have been used in numerous studies of the atmospheric circulation. Many research groups have investigated the ability of models to predict the onset of the south-west monsoon over India. These studies have met with varying degrees of success (Krishnamurti *et al.* 1983), but they are nearly all marked by an inability of the models to predict the formation of a tropical storm (also known as the onset vortex) over the Arabian Sea.

Seetaramayya and Master (1984) pointed out that the sea surface in the eastern Arabian Sea was warmer than normal at the time of the onset of the monsoon in 1979. They also suggested that the development of the tropical storm in this region was aided by the anomalously high surface temperatures. This hypothesis has been tested by making two predictions of the monsoon onset using an atmospheric model with and without the positive temperature anomaly. Here only a brief description of the predictions will be given; a full account of the results and a discussion of the mechanism of onset are given in Kershaw (1988).

2. Experimental details

Experiments were carried out with a global model of the atmosphere, developed by the Dynamical Climatology Branch of the Meteorological Office, which has a horizontal resolution of 2 degrees of latitude and 3 degrees of longitude, and is divided into 11 (unequally spaced) layers in the vertical. The model contains parametrizations of physical processes, including convection, radiation, large-scale precipitation and turbulent mixing in the boundary layer; a complete description may be found in Slingo (1985). The model is not normally used for numerical weather prediction; it is mainly used for the study of the general circulation and climate change.

Both the control and anomaly experiments started from the same atmospheric analysis — the FGGE analysis for 12 GMT on 11 June 1979 produced by the European Centre for Medium-range Weather Forecasts (ECMWF) using all the observations available for that time, collected during the Global Weather Experiment (Lorenc 1981). The analysis had to be horizontally and vertically interpolated from the ECMWF grid to that used in the 11-layer model. After the interpolation no initialization was carried out before running the model.

* An abridged version of a paper by Kershaw (1988) which appeared in the *Quarterly Journal of the Royal Meteorological Society.*

The sea surface temperatures were kept fixed throughout each 8-day prediction. In the control experiment the sea surface temperatures were simply the long-term average values for the appropriate time of year (Fig. 1(a)). The anomaly experiment used the same values as the control, except in the Arabian Sea where the temperatures are based on the analysis of Seetaramayya and Master (1984) (Fig. 1(b)). The difference between the temperatures used in the two experiments (the anomaly) is shown in Fig. 1(c)).

3. Discussion of the experiments

During the onset of the south-west monsoon the atmospheric circulation undergoes a considerable change; a westerly jet becomes established over the Arabian Sea in the lower troposphere and in the upper troposphere an easterly jet forms. At the same time the rainfall increases in south-west India and moves northwards along the west coast. In June 1979 these changes occurred more rapidly and somewhat later than is usual (Pearce and Mohanty 1984).

The developments in the lower troposphere over the Arabian Sea are illustrated by the sequence of 850 mb wind analyses in Fig. 2. At 12 GMT on 11 June the jet over the Arabian Sea had not yet fully developed and the strongest flow was near the Somali peninsula (Fig. 2(a)). By 12 GMT on 15 June (day 4) the Somali jet had strengthened and extended eastwards (Fig. 2(b)); the onset vortex had formed on its northern flank, close to

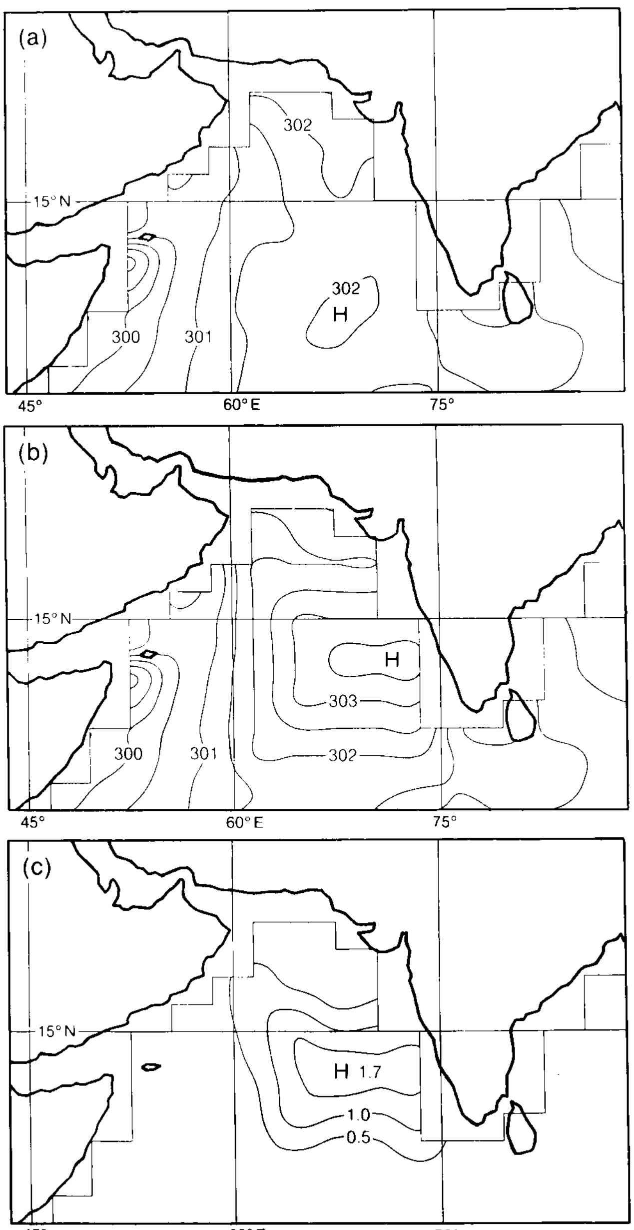

Figure 1. Sea surface temperatures (K) in the Arabian Sea for (a) the control forecast and (b) the anomaly forecast; (c) is the difference between (b) and (a).

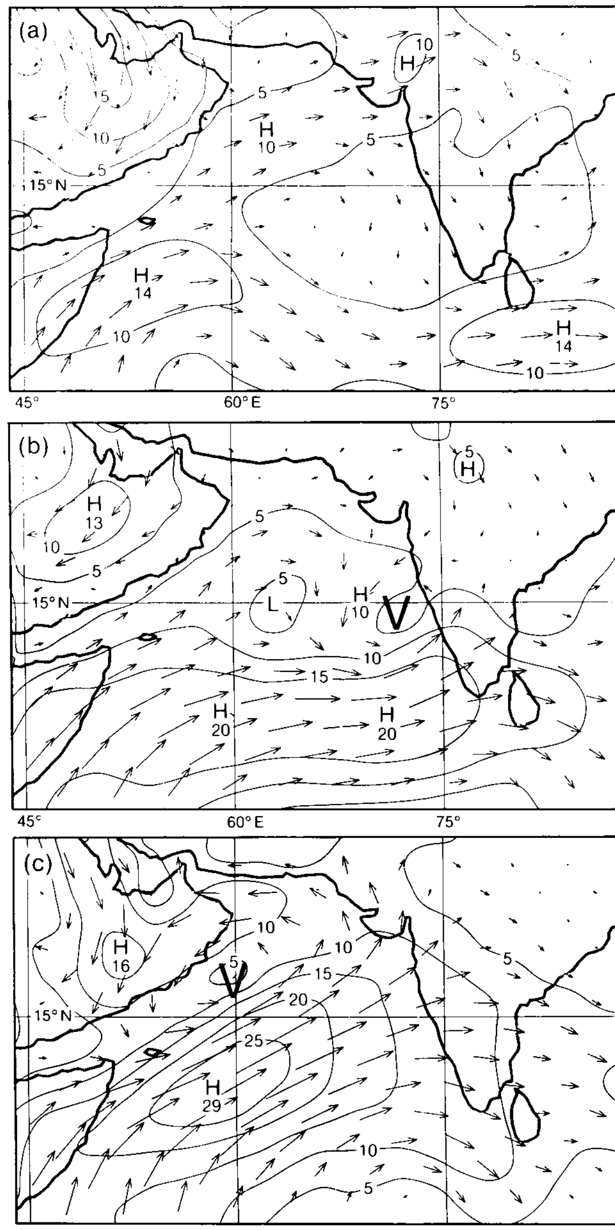

Figure 2. Wind vectors and isotachs (m s^{-1}) at 850 mb from the ECMWF FGGE analyses for (a) 12 GMT on 11 June 1979, (b) 12 GMT on 15 June 1979 (day 4) and (c) 12 GMT on 19 June 1979 (day 8). V marks the position of the vortex.

the Indian coast, and south-westerly winds were affecting southern India. The vortex strengthened and moved north and then west, so that by 12 GMT on 19 June (day 8) it was just a few degrees to the east of the Arabian coast (Fig. 2(c)). Meanwhile the jet strengthened and moved northwards, and strong westerly winds were affecting the entire west coast of India by 19 June.

In the control experiment the Somali jet did not move eastwards quickly enough or attain sufficient strength. By day 4 of the prediction (Fig. 3(a)) no vortex had formed on the north-eastern edge of the jet. During the next 4 days a weak vortex did form, but remained stationary, and the jet attained a maximum speed of only 24 m s^{-1} compared with the analysed speed of 29 m s^{-1} (Fig. 3(b)). Also the strong westerly winds had not moved northwards, so that by day 8 they were only affecting the southern part of India. Clearly the control prediction failed to capture the full intensity of the changes that occurred during the onset of the monsoon.

As shown in Fig. 4, the anomaly experiment produced a much better prediction of the changes. By day 4 (Fig. 4(a)) the low-level jet had extended further eastwards than in the control and the vortex had already formed, and during the next 4 days the vortex strengthened and moved north-westwards (Fig. 4(b)). By this time the jet had attained a maximum speed of 29 m s^{-1}, identical to the observed value, and the entire western coast of India was under the influence of the strong winds. The prediction was not perfect but, for an 8-day forecast, the quality was remarkably high. In particular, the forecast of the formation of the onset vortex was very good.

In the upper troposphere, both experiments predicted the strengthening of the easterly jet and the increase in the cross-equatorial flow, though neither experiment predicted the replacement of the weak westerlies by weak easterlies over northern India. However, the anomaly experiment was superior in that it predicted a stronger easterly jet which was more like that observed. The anomaly experiment also produced a more realistic forecast of precipitation over India than the control. Further information about the prediction of precipitation and the upper flow can be found in Kershaw (1988).

4. Conclusions

These results support the initial hypothesis that the sea surface temperature anomaly was instrumental in the development of the onset vortex, and there is evidence (not discussed here) that the main cause of this was the consequential enhancement of the release of latent heat over the Arabian Sea. Moreover, the use of realistic sea surface temperatures improved the prediction of other aspects of the onset of the monsoon. In particular, the strengthening of the Somali jet and the upper-level easterly jet, and the northward movement of the rainfall over India were all predicted more accurately in the anomaly experiment than in the control. This is a very good example of the beneficial

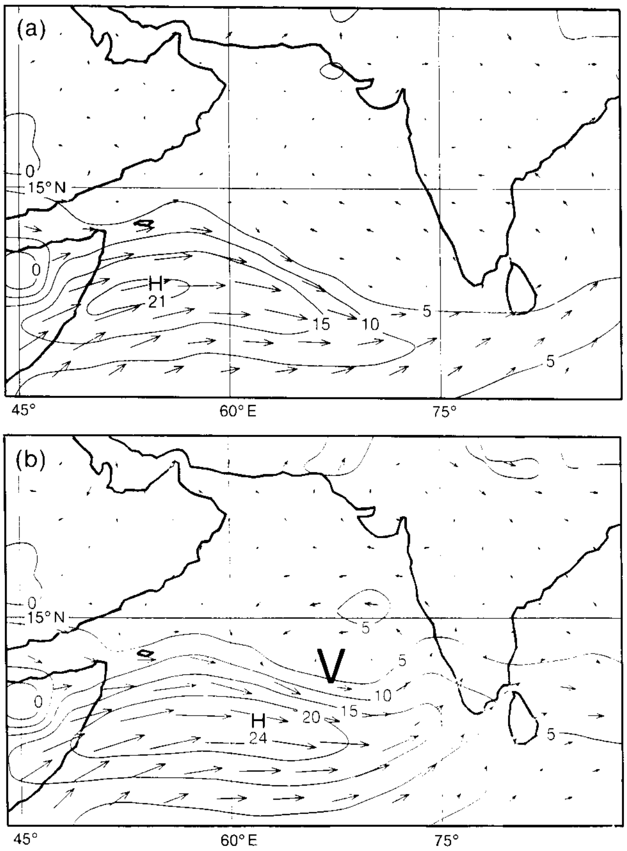

Figure 3. Wind vectors and isotachs (m s^{-1}) at 850 mb from the control forecast for (a) 12 GMT on 15 June 1979 (day 4) and (b) 12 GMT on 19 June 1979 (day 8). V marks the position of the vortex.

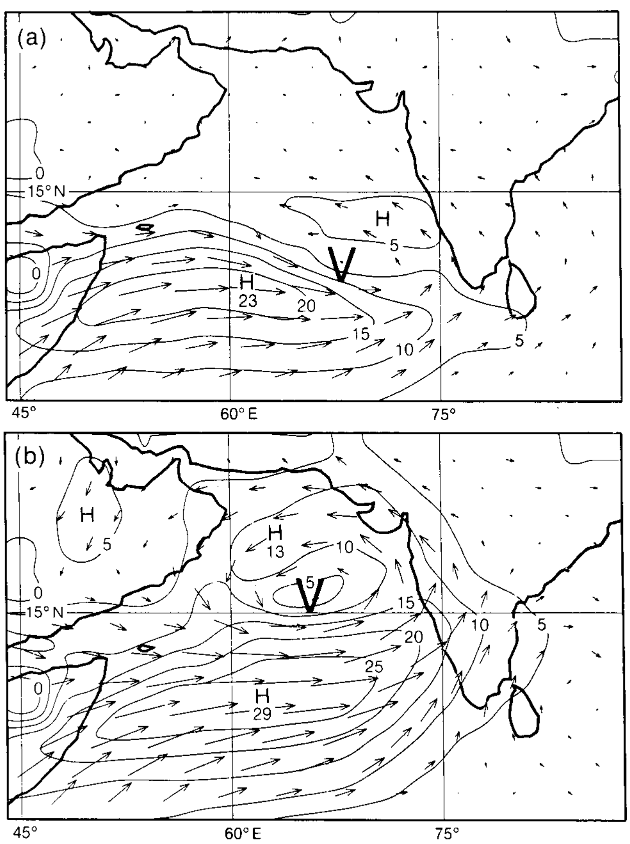

Figure 4. As Fig. 3 but for the anomaly experiment.

impact that the use of observed rather than climatological sea surface temperatures can have on numerical weather prediction in the tropics.

In the tropics a sea surface temperature anomaly will have more influence on the atmospheric circulation when the winds are strong over the anomaly. Therefore, because they develop near the low-level jet, monsoon disturbances are likely to be particularly sensitive to sea surface temperature anomalies. Also, the normal gradient of sea surface temperatures in the Arabian Sea will amplify the impact of an anomaly in the east because the prevailing low-level winds flow up the gradient from cooler to warmer seas. Thus it is likely that the onset of the monsoon in other years will be sensitive to such anomalies.

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551.506.1(41-4)

The spring of 1988 in the United Kingdom

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Summary

The spring of 1988 was generally rather wet, but mild in most areas and with average sunshine over the season.

1. The spring as a whole

Mean temperatures were a little above average in most parts of the United Kingdom, apart from some places in the north of Scotland and eastern England where temperatures were just below normal, ranging from 0.4 °C below normal in Shetland to 1.0 °C above normal in parts of south-east England. A very wet March and a showery May helped towards making the spring generally rather wet. Sunshine amounts were about average.

Information about the temperature, rainfall and sunshine during March–May 1988 is given in Fig. 1 and Table I.

2. The individual months

March. Mean monthly temperatures were above normal in all districts except northern Scotland, where they were generally below normal, and ranged from 0.7 °C below normal in northern Scotland to 1.3 °C above normal in parts of the Midlands. In Northern Ireland it was the mildest March since 1983. Monthly rainfall amounts were above normal in most parts of the United Kingdom, reaching about two and a half times the normal in some places in the Midlands and north-west, but slightly below normal in some parts of Northumberland. Silsoe, Bedfordshire reported the wettest March there since 1982, despite having 13 days with no measurable rain. Northern Ireland, where it was the wettest March since 1903, had around twice the normal rainfall for the month. It was a generally dull month with sunshine amounts not reaching even 70% of average on the south coast of England. However, coastal areas of north-eastern England and eastern Scotland, and Orkney and Shetland, had above average sunshine, and just over 130% was reached in the Fife Region of Scotland. At Oxford, where only 85 hours of sunshine was measured during the month, it was the second dullest March since records began and nearly 30 hours less than the long-term mean.

The month started with sleet and snow showers in many places and continued for the next few days with rain or showers, and some snow on the 4th. It remained unsettled with occasional rain or showers for most of the month. The 15th was a windy day in many places especially in the south. Brighter showery weather spread to all but the south-east of England during the 28th. There were further showers over Scotland and Northern Ireland during the closing days of the month, while in England and Wales there was a good deal of sunshine with a few scattered showers. On the 24th there were widespread reports of thunder from southern Scotland to East Anglia; lightning caused structual damage to property at Donington, approximately 13 km south-west of Kirton, Lincolnshire. Hail was reported frequently during the month, widespread at times.

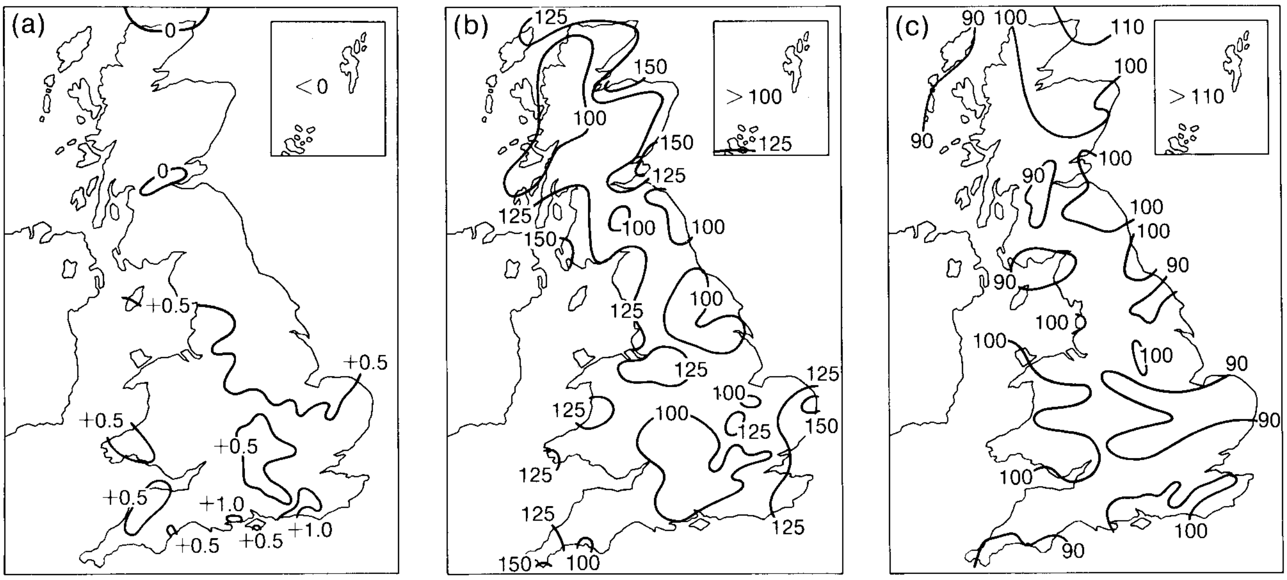

Figure 1. Values of (a) mean temperature difference, (b) rainfall percentage and (c) sunshine percentage for spring 1988 (March–May), relative to 1951–80 averages.

Table I. District values for the period March–May 1988, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+0.1	0	100	100
Eastern Scotland	+0.4	0	115	101
Eastern and north-east England	+0.4	+2	99	95
East Anglia	+0.6	+2	118	87
Midland counties	+0.5	+1	100	94
South-east and central southern England	+0.7	+1	98	95
Western Scotland	+0.3	+2	112	89
North-west England and North Wales	+0.6	+2	118	95
South-west England and South Wales	+0.6	+1	112	96
Northern Ireland	+0.6	0	103	89
Scotland	+0.2	+1	110	97
England and Wales	+0.6	+2	108	94

Highest maximum: 26.5 °C in the northern Scotland in May.
Lowest minimum: −10.2 °C in eastern Scotland in March.

April. Mean temperatures were above normal everywhere except for some east-facing coasts in the south and west and the far north of Scotland, where they were below normal, approaching 1 °C below normal in Shetland. Temperatures in Co. Antrim were just over 1 °C above normal. April was the fifth month in succession in which temperatures were above normal nearly everywhere. Monthly rainfall amounts were generally above normal north of a line from about Tyne and Wear to the Isle of Man except for a large part of western Scotland where it remained rather dry. South of the line it was generally rather dry apart from some places in central and south-eastern England and southernmost parts of Cornwall. Rainfall amounts ranged from nearly three times the normal at Arbroath, Tayside Region to less than 40% in Guernsey, Channel Islands. It was the driest April since 1984 in parts of Northern Ireland. Sheffield, Weston Park reported the lowest rainfall amount since 1981. Sunshine amounts were below the average generally, apart from the far north of Scotland, south-east England and South Wales where sunshine was near or just above average, ranging from 115% in East Kent to a rather dull 66% in the Isles of Scilly and the Southern Uplands of Scotland. Sheffield, Weston Park reported the dullest April since 1978.

The weather was changeable with warm and cold spells. There were reports of thunder in the Midlands, notably over Nottinghamshire and Derbyshire, on the 3rd and over a wide area on the 18th, with outbreaks in eastern and southern England from North Yorkshire to the Isle of Wight. Several places in Northern Ireland had thundery outbreaks on the 20th. Further thunder occurred on the 27th over much of central southern and south-west England. Hail was widespread in the north Midlands and in parts of southern England from Kent to Dorset on the 27th.

May. Mean monthly temperatures were above normal nearly everywhere, ranging from 0.3 °C below normal at Finningley, South Yorkshire to 1.5 °C above normal at Gatwick, West Sussex. Coventry (Bablake), Warwickshire reported the warmest May since 1970, the first without any frost in Coventry since 1970, while Hampstead, Greater London had the warmest May since 1976. Monthly rainfall totals were below normal in all districts except East Anglia, and south-west England and South Wales. A dry 52% of normal at Hurn, Dorset contrasted strongly with 128% of normal at Ilfracombe in the neighbouring county of Devon. The first 26 days of the month yielded just half the normal rainfall in the south-east, and across the United Kingdom it was the driest for 6 years. Monthly sunshine amounts were about normal in all areas, ranging from 93% in parts of East Anglia to 135% in eastern Scotland.

It was quite a warm month everywhere apart from the east coast where it was a little cloudier and cooler. The month was also rather showery with thundery outbreaks; warm, moist air from the Continent brought outbreaks of thundery rain to the south-east on the 8th, and some showers were reported in other areas. Generally dry conditions prevailed from the 13th, although some rain was reported at first in eastern Scotland and north-east England, and there were a few thundery showers in central southern England on the 15th. Scattered showers occurred on the 18th and 19th with thunder reported from southern counties of England and Wales on the 19th. The last three days were unsettled; however, much of southern and eastern Scotland escaped rain on the 30th and Wales and southern England soon became mainly dry on the 31st. A severe thunderstorm at Moel-y-Crio, Clwyd on the 1st just after 1300 GMT was accompanied by hailstones 15 mm in diameter that caused considerable damage to fruit trees and hedges in the vicinity; heavy rain caused some local flooding. Reports of coloured dust deposited on the 7th were received from places as far apart as North Yorkshire, Dyfed, Essex and the south coast.

Conference report

Seventh Meteosat Scientific Users' Conference, Madrid, Spain, 27–30 September 1988

The 7th Meteosat Scientific Users' Conference was held in Madrid from 27–30 September 1988. It was jointly organized by the Instituto Nacional de Meteorologia (INM) and Eumetsat. Both organizations are to be complimented for their contributions to a most interesting and rewarding meeting. INM, the local Spanish hosts, made all attendees feel most welcome. The meeting was conducted in English, despite the large contingents from Spain and France and the paucity of native English speakers.

The proceedings were divided into sessions as follows:

(a) Present and future systems — this included a description of aspects of the current system and the forthcoming Meteosat Operational Programme (MOP), and papers on Meteosat Second Generation (MSG). Three papers in this section were of particular interest.

- De Waard (European Space Operations Centre) presented a keynote address on changes that will occur when the MOP series becomes available from April 1989.
- Bonneyfoy (European Space Technical Centre) presented a keynote address on MSG, summarizing the current requirements for instruments. This includes an eight-channel imager with a spatial resolution of 2 km (oversampled by 1.5), a sounder with both infra-red and microwave channels and numerous scientific instruments. However, technology places limitations on these requirements; characteristics of instruments resulting from the compromise between what is needed and what is feasible were presented.
- Bizzari (Italian Meteorological Service) continued the theme with a paper on the spatial resolution of the MSG imager. He showed that the detection of objects of a certain size by an imager was dependent upon the difference between the temperature (or brightness) of the object and that of its background. Plans to extend the function of the imager to provide information on temperature profiles through the judicious selection of spectral channels were also discussed.

(b) Cloud and radiation — one paper of interest was by Borger of The Netherlands and described work in classifying clouds using knowledge-based methods. Another was one by Geneviève Sèze (LMD/Centre National de la Recherche Scientifique) on the spatial and temporal variability of radiance values. Differences between the radiances of pixels as a function of distance were interpreted in terms of scale invariance. Extensions of this type of study to smaller spatial scales, for example using Landsat or SPOT data, could assist in the interpretation of measurements of surface temperature at the coarser scales.

(c) Systems for research and operational environments — this session gave the opportunity for the developers of systems to show off the features of their wares. The main aim seemed to be to produce a cheap receiver and image processor for use by the emerging nations. Systems included one from the University of Bristol that specialized in the detection of precipitation, and one from the University of Bradford that used software from the University of Reading's Department of Meteorology.
(d) Radiation — the temporal resolution of Meteosat has been exploited to gain knowledge of global radiation for use in studies of the radiation budget.
(e) Surface and climate — a large number of papers was presented on these topics. Many were concerned with extracting information about regional variations of surface characteristics, including soil moisture and albedo. Flitcroft (University of Reading) gave an interesting paper on the relationships between point measurements of precipitation and areal averages. The consequences for the Sahel region were discussed.
(f) Precipitation — this session also had a large number of papers, more than half of which described applications to measuring rainfall in Africa. Some of the problems of such applications were discussed by Dugdale (University of Reading); he is forced to use stream-flow measurements combined with a catchment model to derive rainfall in an area devoid of conventional data! Collier's (Meteorological Office, Bracknell) keynote address on the measurement of precipitation from space was delivered by Richard Allam. The paper by Isabelle Jobard again alluded to the variations of precipitation in space and time.
(g) Atmospheric dynamics — Debois' keynote paper reviewed progress in determining winds from the apparent motion of clouds. Anke Eriksson described preliminary results of a new method of extracting wind vectors from water vapour images. The usual slick films sent to the conference by Zick (Free University of Berlin) showed it is possible to give a 'paper' without actually being present in person.
(h) Operational meteorology — this rather mixed session featured presentations from two members of the Nowcasting and Satellite Applications Branch of the Meteorological Office; Geoff Monk on the imagery associated with the October 1987 storm, and Richard Allam on sea-fog monitoring. Interesting papers on forecasting in Spain were also presented, including a case-study in which more than 800 mm of rain (exceeding the annual average) fell on a narrow coastal strip of eastern Spain in 24 hours. A movie loop revealed that a mesoscale convective system remained anchored to topographical features in the area, despite the obvious marked upper flow relative to it.

Four themes seemed to run through the meeting. The first was the extensive use of Meteosat imagery in the monitoring and forecasting of rainfall in arid regions of Africa. The second was the encouraging sign of appropriate research being performed by the African nations themselves, rather than by European countries. The third was the scientific interest in problems associated with the variations of the properties of objects and images at different spatial scales. The fourth was the universal enthusiasm with which scientific work with Meteosat data is conducted, and the optimistic view of future applications with both the MOP and MSG systems.

R.J. Allam

Notes and news

The European Geophysical Society

1. General Information

The European Geophysical Society (EGS) was founded in 1971 to promote both disciplinary and interdisciplinary co-operation among scientists in Europe and throughout the world concerned with the full range of geophysical studies. According to the broad divisions of geophysics, the activities of the Society are organized into three main sections:

Section I — Solid Earth and planets
Section II — Hydrospheres and atmospheres
Section III — Upper atmospheres, ionospheres, magnetospheres and external geophysics.

To promote its aims the EGS organizes annual scientific General Assemblies at different venues in Europe normally held in spring during the second, full working week before Easter; publishes a *Newsletter* to keep members informed about its activities; runs the journal *Annales Geophysicae* (for Sections II and III) and jointly with the American Geophysical Union the journal *Tectonics*, and participates in the running of the *Geophysical Journal* (for Section I) of the Royal Astronomical Society; and co-sponsors appropriate scientific meetings, summer schools, or workshops organized by other bodies.

Membership of the EGS is open to all scientists as individuals or as societies, institutes, laboratories or groups. Members are entitled to subscribe to the EGS journals at greatly reduced concession rates, and to attend the General Assemblies at a reduced registration fee.

2. The 1989 General Assembly

The 14th General Assembly of the EGS is to be held in Barcelona, Spain from 13–17 March 1989.

Many of the topics being discussed in symposia, workshops, open and joint sessions are of interest to meteorologists and climatologists. The following are of particular relevance:

Symposia on: atmospheric and oceanic boundary layers, hydrological and desertification processes at land surfaces, mesoscale precipitation (measurement, modelling and forecasting), prediction, predictability and low frequency variability of the atmosphere, mediterranean weather systems.

Workshops on: the atmospheric boundary layer over non-homogeneous terrain, innovative numerical techniques in atmospheric modelling, Arctic polar ozone.

Joint sessions on: forecasting extreme hazardous events, and stratospheric ozone depletion.

Open session on meteorology and climatology not dealt with elsewhere.

The EGS makes Travel Awards for young scientists (less than 30 years old) to attend the Assemblies to present papers. Although the application deadline for these awards (and attendance generally) at this year's Assembly is now passed it should be noted that the 15th General Assembly is to be held in Copenhagen from 23–27 April 1990. The EGS is currently seeking ideas for topics for the symposia and workshops and names of potential conveners for this next Assembly.

3. Further Information

For further information or to make suggestions and proposals for the forthcoming Assembly contact:

The EGS Office
Max-Planck-Str. 1
Postfach 49
D-3411 Katlenburg-Lindau
Federal Republic of Germany

METARC launched

The first edition of Parts 1 and 2 of the Meteorological Office Archive Catalogue (METARC) has recently been published.

The Meteorological Office has an obligation under the Public Records Acts to produce a catalogue of holdings in the Archives and a limited hand-compiled edition was produced in 1975. In 1984 a feasibility study was made for a computer-based version which indicated that it would be a long job but a start on its compilation was made in early 1986. The Office's Systems Development Branch first produced a 'user-friendly' program for the Archive staff to input to the mainframe computer the details of all main holdings. In 1986 the observation registers for approximately 900 stations in England, Wales and overseas held in the Archives were being moved, sorted, counted and re-shelved and so it was decided that these would be the first to be catalogued. This has taken over two years and has resulted in METARC Part 1 — observation registers from England and Wales, and Part 2, for overseas stations (mainly ex-colonial or wartime airfields).

In this context daily registers of observations usually made at 1-, 3- or 6-hour intervals, should not be confused with registers of once daily observations made by the daily climatological stations.

In both parts the form number of the register is given which usually indicates whether the observations are in SYNOP, AERO or SYRED form, along with the period and times of the observations and remarks about missing data. In Part 1 the entries are arranged in alphabetical order of (pre-1974) county name and then station name with National Grid Reference. In Part 2 the entries are in alphabetical order by continent or ocean and then country or island, and the details are the same as in Part 1 except that the latitude and longitude are given.

METARC may not contain details for more recent registers as these are kept at observing stations (for 25 years for official meteorological offices and 2 years for Auxiliary ones) before being deposited in Archives.

It is hoped to produce further METARC catalogues of observation registers from stations in Scotland and Northern Ireland currently held in the Archives at the Meteorological Offices in Edinburgh and Belfast. Meanwhile progress is being made in the cataloguing of the climatological observations held at Bracknell from approximately 5000 stations, some of which go back to the mid 1850s.

Copies of the METARC Parts 1 and 2 are available on application to the Meteorological Offices and all of the catalogued registers are available for inspection in the Office's Archives at Eastern Road, Bracknell during normal working hours.

Books received

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

Precipitation, by G. Sumner (Chichester, New York, Brisbane, Toronto, Singapore, John Wiley and Sons, 1988. £45.00) brings together the meteorology, climatology and hydrology of the subject. It provides a link betweeen the subjects of geography, meteorology, hydrology and engineering without assuming knowledge of complex mathematics and physics.

Satellite photograph — 4 December 1988

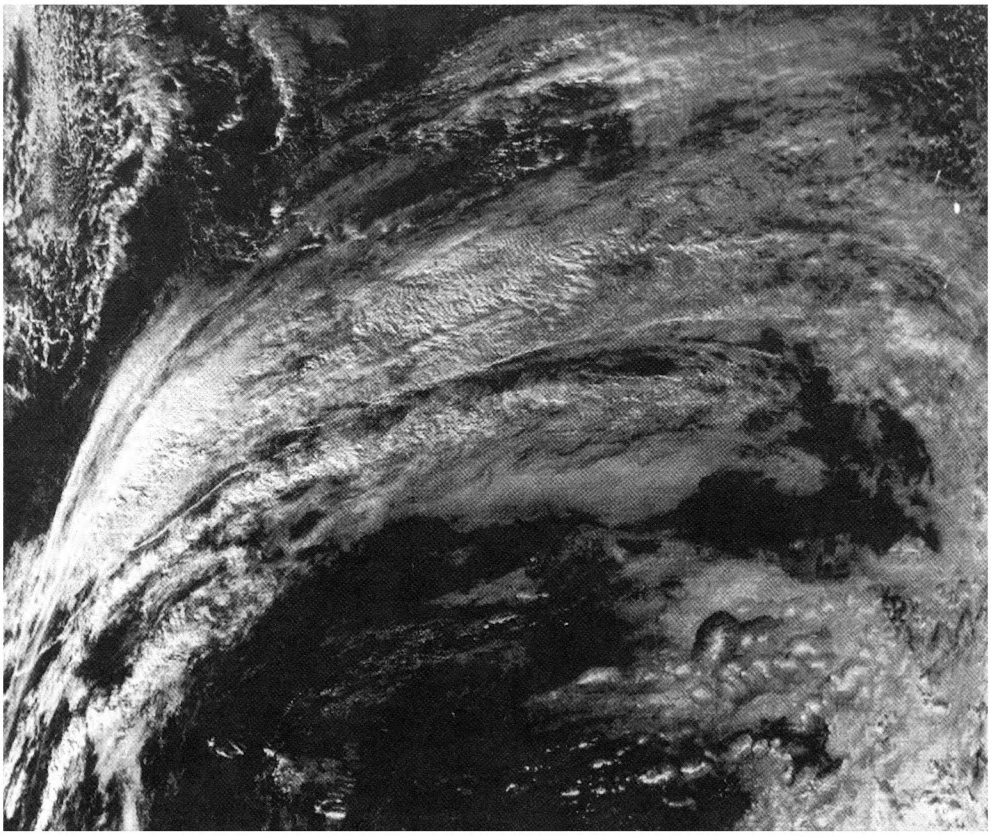

Figure 1. NOAA-11 visible picture for 1445 GMT on 4 December 1988.

This NOAA-11 visible picture illustrates a remarkable cold front in that its surface position can be located by a 'rope' of low cloud over a distance of some 1800 km (see Figs 1 and 2). Just ahead of the cold front (in the warm sector), there is a band of instability and considerable stratocumulus cloud.

Of particular interest is the structure of the cold-frontal zone as implied by the image shown and the corresponding infra-red image. Immediately poleward of the surface front, the broad band of thick cloud is mostly at middle and upper levels, suggestive of a region of slantwise ascent, probably commencing at the surface front (as shown schematically in Fig. 3). Such direct evidence of a classical 'ana' front is not often seen in the eastern Atlantic. More often, the leading portion of the middle or upper cloud 'overhangs' the relatively shallow cloud at the surface front obscuring its position in satellite imagery. Ana (surface) fronts on radar are often marked by line convection. This front was no exception, with radar observations indicating line convection in the English Channel when the front reached the UK weather radar network some 18 hours later.

The portion of the cold front in the western half of the picture lay beneath a very marked jet-entrance region with wind speeds increasing from 60 to 170 kn over only 600 km. The jet stream lay close to and parallel to the poleward edge of the frontal cloudiness. Classical cold fronts are usually located near to and downstream of marked jet-entrance regions and/or confluent troughs.

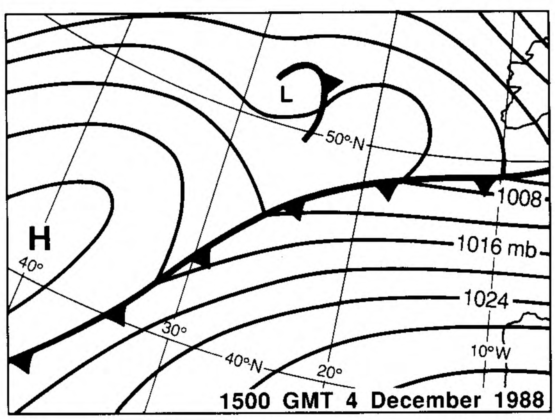

Figure 2. Synoptic chart, interpolated from 1200 GMT data, so as to correspond to the time of the image.

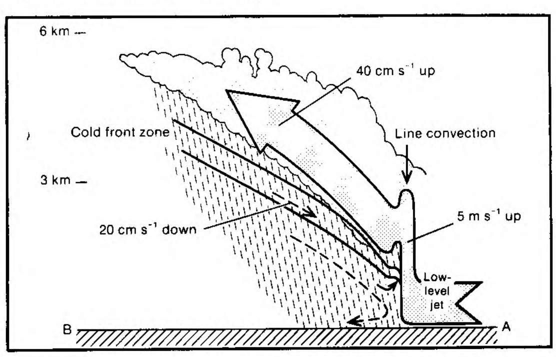

Figure 3. Idealized cross-section across a classical anafront (from Browning, K.A.; Conceptual models of precipitation systems. *Meteorol Mag*, **114**, 1988, 293–319).

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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The Meteorological Magazine

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Periodic variations in extreme rainfalls
Unusual pressure fall over Shetland
Radar observations of an ash plume
Forecasting for Antarctic Ozone Experiment
Sea-breezes over Sriharikota

HMSO

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Periodic variations in extreme hourly rainfalls in the United Kingdom

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Summary

Extreme 1-hour rainfalls observed in the United Kingdom during the period 1881 to 1986 are shown to have roughly sine-wave variations with approximate periods of 7, 11, 20 and 50 years and amplitudes of 7%, 10%, 5% and 7%. The 11-year period variation and solar activity, as measured by sunspot number, have maxima and minima which are closely synchronized.

1. Introduction

This article concerns the behaviour of annual maximum 1-hour rainfalls observed at many locations in the United Kingdom during the period 1881 to 1986. The results were obtained from an analysis of these rainfalls during a comparison of their frequencies of occurrence over a long period against the frequencies recommended in the Flood Studies Report, Volume II (NERC 1975) which were based on observations over a shorter period, from 1951 to 1970. The investigation was prompted by an intriguing graph in the Flood Studies Report which showed evidence for a small, but clear periodic variation in annual maximum rainfalls for 2-hour durations in the 20-year interval.

2. The data processing

The observations used here are annual maximum rainfalls for 1-hour duration collected from all known sources and which are available in the Meteorological Office data archives. They total 4532 values with a wide range of record lengths up to 94 years, from 234 stations distributed over the whole of the United Kingdom but mainly in southern and central England.

A variation of annual maximum rainfalls which has, at a particular time, the same phase over the whole of a region can easily be hidden by the large random variations of these maxima from one year to the next observed at a particular location. A synchronous variation like this can be isolated by dividing the sequence of maxima at each station by their mean value and then, for each year, finding the median, D, of these normalized maxima from a representative selection of stations. For a region covering the whole of the United Kingdom, i.e. using all available stations' data, the D values for 1-hour rainfalls have been calculated for each year from 1881 to 1986.

3. Results

The spectrum of D (Fig. 1) shows the amplitude of components as a function of frequency at intervals of 0.01 cycles year^{-1}, along with their period in years. D has four main components with periods estimated to be within the ranges 6.9 to 7.4, 10.5 to 11.8, 18.2 to 22.2 and 40.0 to 66.7 years, defined by the 0.01 cycles year^{-1} frequency bands in Fig. 1, with corresponding amplitudes in the ratio 3:4:2:3. From the analysis described in the following sections we show that the periods are close to 7.2, 10.8, 20.0 and 50.0 years but, for simplicity, we refer to the 7-, 11-, 20- and 50-year period waves.

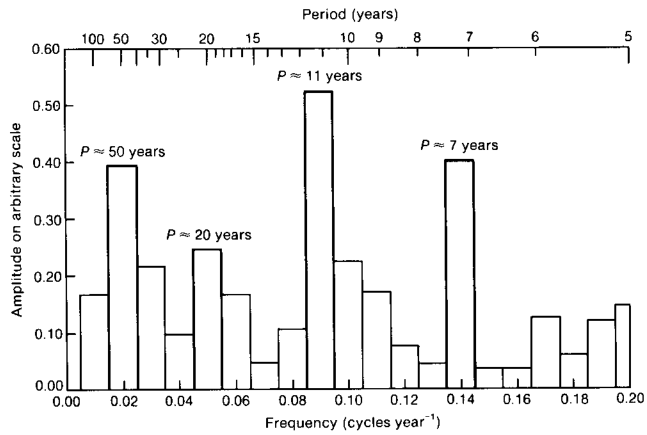

Figure 1. Frequency spectrum of D, the median normalized annual maximum 1-hour rainfall for the United Kingdom from 1881 to 1986, showing spectral components at a resolution of 0.01 cycles year^{-1}. The largest components have periods close to 7, 11, 20 and 50 years.

To remove obscuring short-period variations in D, running means over three years, D_3, have been calculated, where the means are ascribed to the middle year. D_3 is plotted against year in Fig. 2 which shows the combined effect of the four components producing near-regular episodes of maxima and minima superimposed on a longer period background variation. The numbers of normalized annual maxima contributing to the D values for each year are indicated at the top of Fig. 2 at five-year intervals.

The spectrum reveals only the periods of components but not their waveform or when their maxima and minima occur. To isolate waveforms, sliding means over selected durations can be used to suppress some components and not others. A sliding mean of duration p applied to a sine wave of period P and unit amplitude is a sine wave of amplitude $f = \sin(\pi.p/P)/(p/P)$. If f is positive the sliding-mean wave is in phase with the original wave and 180° out of phase if f is negative. If p is an exact multiple of P then $f = 0$. Although these results are true for sine waves they also hold adequately for waveforms which are approximately like sine waves in shape.

3.1 50-year period wave

This is isolated by taking running means of D over 21 years (D_{21}), which is nearly an exact multiple of 7.2, 10.8 and 20.0 years, for which f has values of +0.03, −0.03 and −0.04, so almost completely eliminating the contribution of these components. The waveform is shown by D_{21} in Fig. 3(a). It has maxima in about 1893 and 1940 and a minimum in 1915 which are consistent with a period near 50.0 years. Allowing for the reduction by smoothing over 21 years ($f = 0.73$) the mean amplitude over the whole 87-year interval is estimated to be about 7%, decreasing after 1930 to near zero from 1960 onwards.

3.2 20-year period wave

This is isolated by taking means of D over 9 years (D_9) which reduces considerably the amplitude of the 7- and 11-year period components, by factors $f = -0.18$ and +0.19, but reduces the 20- and 50-year components by smaller amounts, with $f = 0.70$ and 0.95. D_9 is plotted in Fig. 3(a) in which the 20-year wave is seen to modulate the 50-year wave; taking the ratio D_9/D_{21} removes the 50-year variation and leaves the 20-year wave as in Fig. 3(b). This wave has maxima in about 1895, 1914, 1934 and 1954, very close to a 20.0-year period. The maximum in 1970 is a partially remaining one of a shorter period component. The minima of the 20-year wave are at more irregular intervals, in 1909, 1922 and

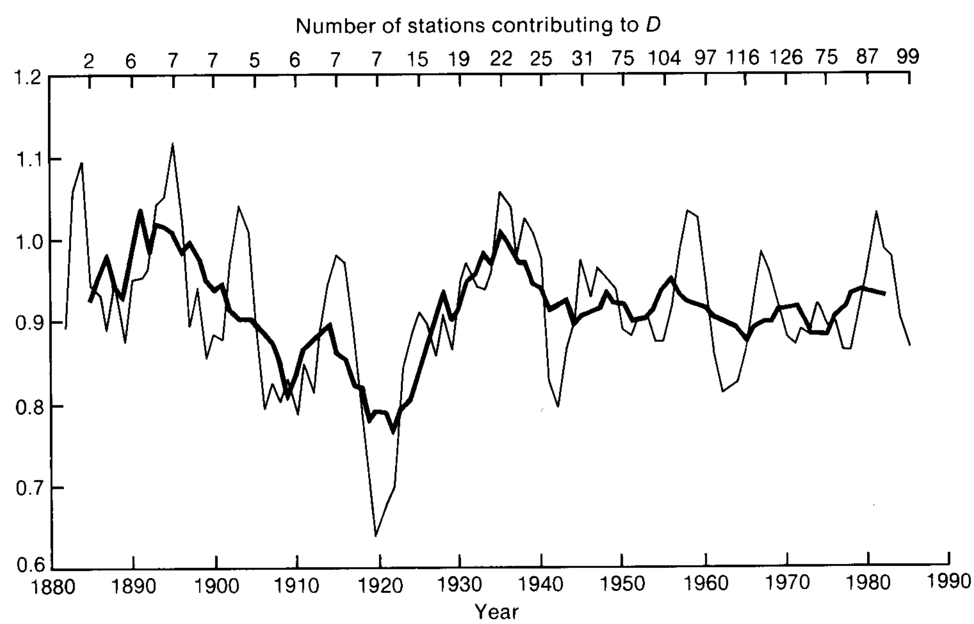

Figure 2. Running means of D over (a) 3 years (D_3) showing the combined contribution of the 7-, 11-, 20- and 50-year components (thin line), and (b) 9 years (D_9) showing the contribution of the 20- and 50-year components only (bold line). The number of stations from which the D values for each year are calculated are shown along the top of the figure.

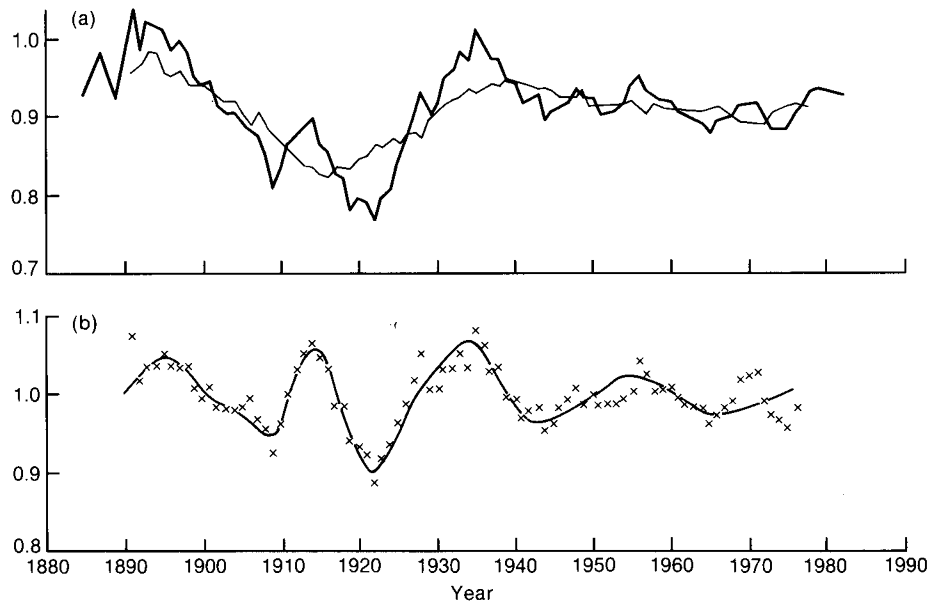

Figure 3. (a) Running means of D over 9 years (D_9) showing the contribution of the 20- and 50-year components only (bold line), and 21 years (D_{21}) showing the contribution of the 50-year component only (thin line), and (b) D_9/D_{21} reproducing the waveform of the 20-year wave alone.

1943. The mean amplitude over the whole interval is about 5%, after correction for a smoothing factor $f = 0.70$, increasing up to about 1920 and decreasing afterwards.

3.3 11-year period wave

It is not possible to isolate the 11-year wave using this process so an alternative method is used. D_3, in Fig. 2, contains all the four components at nearly full amplitude while in D_9, also shown in Fig. 2, the amplitude of the 7- and 11-year waves are considerably reduced by the factors given in section 3.2. The ratio D_3/D_9, plotted in Fig. 4 with a smooth curve estimated by eye, shows clearly the combined 7- and 11-year waves almost completely free of the influence of the 20- and 50-year waves.

In this combined waveform the maxima are separated by alternate longer and shorter intervals of approximately 13 and 9 years and the successive minima are narrower and deeper, and broader and shallower. The pattern of their combination repeats with little change over 104 years which suggests that the individual periods must be close to a fixed simple ratio, in this case 2:3, in order to preserve the phase relationship. These features can be reproduced, as shown in Fig. 5, by the expression $1.0 \times (\sin(360° \times n/10.8)) + 0.6 \times (\sin(360° \times n/7.2) + 45°)$, where n is in years, representing the addition of sine waves with periods of 7.2 and 10.8 years, which are

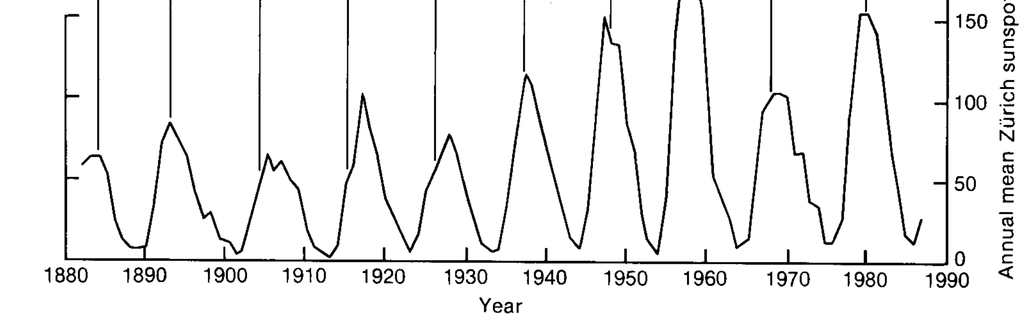

Figure 4. Upper trace, D_3/D_9 (D_3, D_9 as in Fig. 2), showing the combined waveform of the 7- and 11-year waves. Lower trace, the annual mean Zürich sunspot number. The upper vertical lines mark the years of maxima of the combined waveform; the lower vertical lines the estimated years of the maxima of the 11-year wave only.

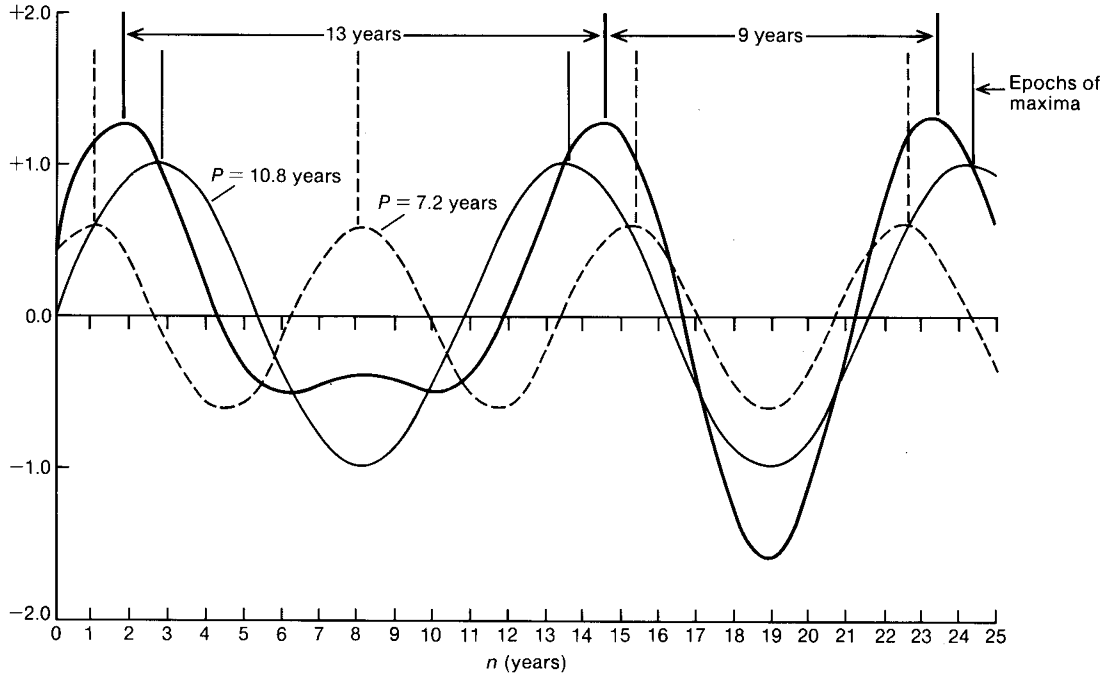

Figure 5. Synthesis of a combined 7- and 11-year waveform (bold line) from the addition of a 7-year sine wave (dashed line) and an 11-year sine wave (thin line) from the expression $1.0 \times \sin(360° \times n/10.8) + 0.6 \times \sin((360° \times n/7.2) + 45°)$, with n in years. The vertical lines show the approximate epochs of the maxima in the three waveforms.

in the exact 2:3 ratio. These two periods are within the ranges quoted in section 3. The factor 0.6 arises because the amplitudes of the waves are in the ratio 0.75, from Fig. 1, further modified by smoothing over 3 years (f for 7.2 years = 0.74, f for 10.8 years = 0.88, and $0.75 \times 0.74/0.88 \approx 0.6$). Fig. 5 shows that although the 7-year wave is relatively large the particular phase relationship of the two components is such that the combined wave still has only two prominent maxima in an interval of 21.6 years, i.e. 2×10.8 years, as observed.

The maxima of the 11-year wave occur one year before and after the maxima of the combined wave, from Fig. 5, and, from Fig. 4, they occur in years given approximately by the expression $1883 + (N \times 10.8)$ where N is the number of periods elapsed. In the same way the minima occur in the years $1888 + (N \times 10.8)$. The mean amplitude of this wave is estimated to be about 10% with possibly a small decrease since 1920.

3.4 7-year period wave

The curves in Fig. 5 indicate that the maxima of the 7-year wave are midway between, and one year before and after, the maxima of the combined 7- and 11-year waves. From this property, from Fig. 4, the years of the maxima and minima of the 7-year wave are given approximately by the expressions $1881 + (N \times 7.2)$ and $1884 + (N \times 7.2)$. The amplitude of this wave is about 7%.

4. Applicability of the results

To check the reality of these variations D values were calculated from one half of the original number of stations by taking the alternate ones from their arrangement in order of station number. Although this shortens the total record length, the frequency spectrum still shows components with periods very close to those reported above but with slightly different amplitudes.

These periodic variations of D can be detected even before 1920 when there were only 9 stations contributing observations (no more than 7 in any year). These stations are widely distributed over the United Kingdom, at Falmouth (Cornwall), Kew Observatory and Camden Square (London), Skipton (West Yorkshire), Eskdalemuir (southern Scotland), Aberdeen (eastern Scotland), Ben Nevis and Fort William (western Scotland) and Armagh (Northern Ireland). The widespread distribution of these stations suggests that the variations are synchronous over most of the United Kingdom. The number of stations increased rapidly after about 1930 and so it is expected that the D values are consequently less liable to error after that time.

During the data extraction it was noticed that, except for stations in the extreme west of England and Wales, and north-west Scotland, the annual maximum amounts occurred most frequently (> 80% of occasions) during the summer months from April to September within events whose short durations from 1 to 3 hours suggests that they were intense convective rainfalls. There were too few stations to establish whether these variations also occur in extreme amounts from frontal rainfall.

It seems implausible that the variations described here are experienced by only the annual maxima and not, for instance, the second, third, etc. largest rainfalls in each year which may not be much smaller than the maxima, and so it is likely that they are present in all large 1-hour duration rainfalls.

5. Related observations

Median normalized 2-hour rainfall amounts from 22 unspecified stations in south-east England from the Flood Studies Report have been used to give the D_3 values from 1952 to 1969 in Fig. 6. They are in good agreement in amplitude with the values, also in Fig. 6, for 1-hour rainfalls, the corresponding maxima and minima differing in epoch by one year or less.

Lightning is often associated with extreme short duration convective rainfalls, and its occurrence in Britain has been studied by Stringfellow (1974). Running means over 5 years of his annual lightning incidence index, the number of flashes per unit area per year, are also shown in Fig. 6. They are highly correlated with D_3 for 1-hour rainfalls over the whole period from 1933 to 1971.

6. Origin of the variations

The dominant component of period 10.8 years, with maxima repeating strongly throughout the 104-year record as in Fig. 4, suggests a connection with solar activity. One measure of this activity is the Zürich sunspot number which has a dominant frequency component with $P = 11.1$ years (Herman and Goldberg 1978).

The annual mean Zürich sunspot number, Z, is plotted in Fig. 4. There is a clear correspondence even between the combined 7- and 11-year waves (D_3/D_9) and Z, extending over ten maxima. The lower vertical lines in Fig. 4 are estimated epochs of the maxima of the 11-year wave alone; for six out of the ten maxima the epochs for Z and this wave agree within one year, bearing in mind the limitation in time resolution imposed by using annual maxima for rainfalls and annual means for sunspot numbers. For the remainder the maximum difference is two years, occurring at times when the background variation is changing most rapidly.

The size of the maxima in D_3/D_9 do not show the gradual increase from 1880 to 1960 of the maxima of Z in its original units. If the 3-year running mean of Z is expressed relative to the 9-year running mean, analogous to D_3/D_9, then this does have the same appearance as D_3/D_9 with a nearly constant amplitude. The running mean of Z over 9 years represents well the background variation implied in Fig. 4 which has a period of about 180 years (Herman and Goldberg 1978) but a variation of this period cannot be resolved in the frequency spectrum of D because it is too long compared with the record length. It must be stressed that Z is only an indicator of activity displayed by many solar phenomena such as the emission of charged particles and electromagnetic radiation, and the strength of magnetic fields.

Currie (1988) reports variations with period 10.6 years and variable amplitude in monthly rainfalls over the last 100 years for many stations in the north-east United States. There are prominent maxima in the years 1881, 1892, 1905, 1916, 1927, 1937, 1948, 1958, 1968 and 1979 agreeing well with those estimated for the 11-year wave from Fig. 4. Currie (1987) also finds a strong variation of period 10.8 years in the level of the Nile summer flood during the interval 1690 to 1962, presumably related to rainfall in the African highlands. He attributes both of these variations, which have periods within the ranges quoted in section 3 to the 11-year period of solar activity; Stringfellow (1974) also suggests that the variation of lightning incidence index in Fig. 6 has the same origin.

The spectrum in Fig. 1 also shows small amplitude variations with periods from 5.0 to 6.0 years, i.e. about one half of the solar activity cycle period. The spectrum of Z also has a small component with period 5.5 years and some meteorological phenomena show variations with this period (Herman and Goldberg 1978).

Atmospheric luni-solar tides governed by the 18.6-year period of revolution of the moon's orbit with respect to the ecliptic have been suggested by Currie (1988) as the origin of a variation of period of 19.2 years and amplitude 5% in the north-east United States monthly rainfall records and a period of 19.8 years in the level of the Nile summer flood (Currie 1987). These both show maxima near 1916, 1936 and 1955 in good agreement with the maxima of the 20-year wave in Fig. 3. Again these observed periods are well within the ranges given in section 3.

A search of the literature has failed to reveal any description of a 7-year period variation in atmospheric phenomena. Its apparent close relationship of period to

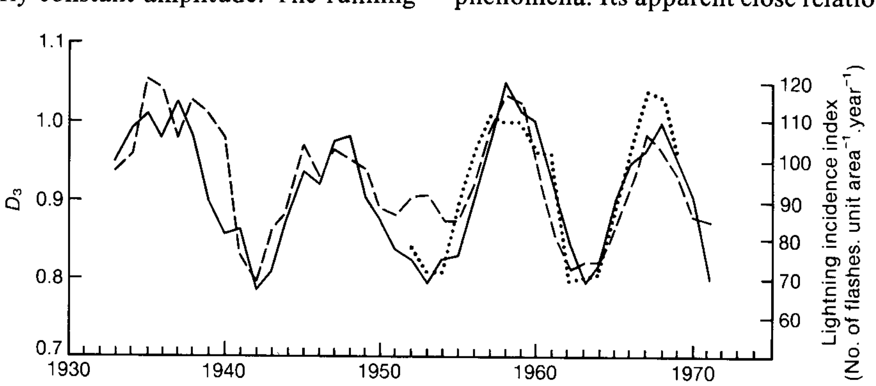

Figure 6. Comparison of D_3 for 1-hour (dashed line) and 2-hour (dotted line) rainfalls and the lightning incidence index (continuous line).

the 11-year variation suggests that the two waves have some common factor. For instance it has a period about one third of the double solar activity cycle of close to 22 years, which has been observed in such phenomena as the magnetic polarity of bipolar sunspot groups, geomagnetic activity and the intensity of cosmic rays (Herman and Goldberg 1978).

The 50-year period of the remaining variation suggests a climatic effect, of unknown cause, and again no evidence of observations of other phenomena with the same period have been found.

7. Conclusions

Annual maximum 1-hour duration rainfalls observed during the interval 1881 to 1986 over the whole of the United Kingdom appear to have four main components, approximately sine wave in shape, with periods of about 7, 11, 20 and 50 years and mean amplitudes of 7%, 10%, 5% and 7%. The two longer period components have decreased considerably in size since about 1935 and are now nearly undetectable, but the two shorter period components have decreased in size only slightly. These variations are believed to affect most large convective rainfalls and to be synchronous over the United Kingdom.

The maxima of the 11-year period wave have repeated strongly throughout the interval covered by the observations, and are closely synchronized with the maxima of the solar activity cycle.

The next prominent maximum of extreme rainfalls should occur in 1990, one year ahead of the next sunspot maximum which is expected to be in 1991, from Fig. 4. The prediction of the epoch of maximum sunspot activity is always uncertain though and it should be noted that judging from the large initial rate of increase since 1986, the next maximum of *Z* could occur as early as late 1989 (Gribbin 1988).

Apart from the intrinsic interest of these results they have practical relevance. Large one-hour rainfalls are important in causing flood events in some urban catchments with a response time of about this duration. For instance, for 1-hour duration rainfalls in locations in southern England there is an average interval (the 'return period') of 20 years between exceedances of 27 mm. If this is the threshold amount required to produce a flood in a particular catchment then for rainfall amounts increased by 10% (comparable to the magnitudes of the variations described here) the return period decreases to 17 years, and increases to 31 years for a 10% decrease in rainfall amount. These changes in return period can have important consequences for the design of flood control structures and the risk of their failure.

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An investigation into an unusual pressure fall over Shetland

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Summary

On 8 January 1988 a short-lived sudden fall of atmospheric pressure was observed over the whole of Shetland. Descriptions of the event and of an investigation to establish its cause are given.

1. Introduction

Sudden large falls of surface pressure, not obviously associated with the passage of fronts or troughs, are relatively rare. One such event on 25 January 1977 over south-eastern England has been described by Harvey and Warren (1978) who concluded that the pressure changes were caused by an atmospheric gravity wave, rather like the ripple formed when a small stone is tossed into a pool. In that example the wave travelled east-north-eastwards for several hundred kilometres with a speed of 32 m s^{-1}.

A similar event occurred on Friday 8 January 1988, the first indication being a sudden fall of pressure and change of wind direction and speed observed at 0650 GMT at Lerwick Observatory. Barogram and wind records, where available, were then requested from all observing stations in Shetland and Table I records the data extracted. In most places the fall exceeded 4 mb within a few minutes.

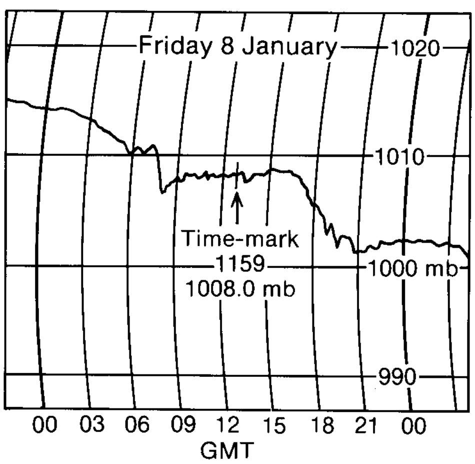

Figure 1. Diagrammatic representation of a portion of the barograph trace from Sella Ness meteorological office (60° 27′N 01° 16′W) for the period of interest. Note that the trace is running about 1 hour ahead of time.

Table I. Pressure and wind changes over Shetland

Station	Mean wind change (deg./kn)		Pressure change (mb)	Time (GMT)
	From	*To*		
Fair Isle	180/28	150/23	−4.2	0640
Sumburgh	170/28	140/25	−3.9	0650
Lerwick	190/26	170/23	−3.5	0650
Sella Ness	180/26	140/16	−4.3	0650
Collafirth Hill	No record available		−4.4	0650
Muckle Flugga	No record available		−4.2	0650

Immediately afterwards the pressure started to rise. At the same time the surface wind backed about 20 degrees but then returned to its original direction during the following hour. No other significant changes took place at the time.

The wind speed generally decreased at the time of wind shift but rose again immediately after to about its previous level. This effect was most marked at Sella Ness. All barogram traces were remarkably similar, showing a small rise followed by an almost instantaneous fall, followed by a significant rise. The barogram and anemogram from Sella Ness are shown in Fig. 1 and Fig. 2, respectively, to illustrate the event. The apparently smaller fall of pressure at Lerwick

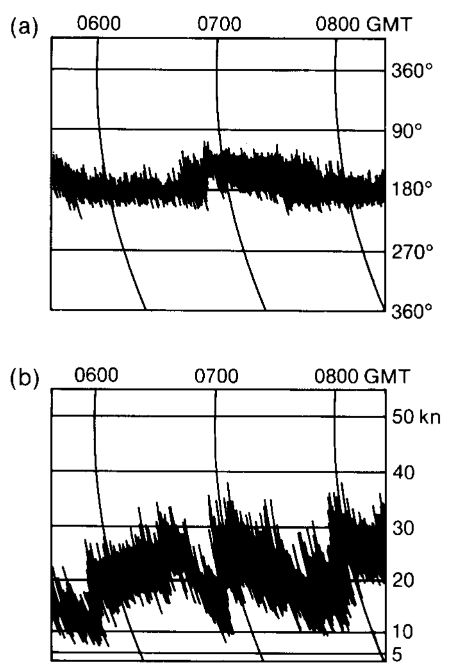

Figure 2. Diagrammatic representation of (a) wind direction, and (b) wind speed traces from Sella Ness for the period of interest on 8 January 1988.

may have been due to the use of a marine barograph with greater damping.

Mr Wheeler, the auxiliary observer on Fair Isle, noticed the event as it was happening and was able to read pressures (both converted to mean sea level) at 0650 GMT (1009.6 mb) and 0658 GMT (1007.2 mb), a drop of 2.4 mb in 8 minutes.

2. Synoptic situation

At 0001 GMT on the morning of 8 January, a strong, broad south-westerly jet was propagating north-eastwards across the Atlantic towards the north of Scotland. At the same time, the surface analysis showed a deep depression to the south of Iceland, an old,occluded front moving north-east across Iceland and Faeroe, and a second occlusion from the centre of the low, running south to a triple point at 56° N, 12.5° W. A ridge of high pressure over the eastern United Kingdom was rapidly declining and moving away quickly into the North Sea.

By 0600 GMT (Fig. 3) a strengthening south-south-westerly airflow was becoming established over Shetland with the centre of the depression over south-west Iceland and the associated, occluded front running south-east, just to the west of Faeroe, to the triple point at 57.5° N, 6° W. The midnight Lerwick ascent showed strong, warm advection from the surface to 500 mb (Fig. 4). At this time the low-level air mass over Shetland was unstable compared with the sea temperature of 9 °C, but topped by an inversion at 800 mb and a second just below 750 mb. Further to the west, the midnight Stornoway ascent (not shown) showed an inversion at 950 mb with the air mass conditionally unstable from about 900 mb to 600 mb. However, the ascent steadily 'dried out' from 950 mb up to 600 mb.

The occlusion appeared to pass through Lerwick from the west just before midday with a small rise in temperature and dew-point but no noticeable change in

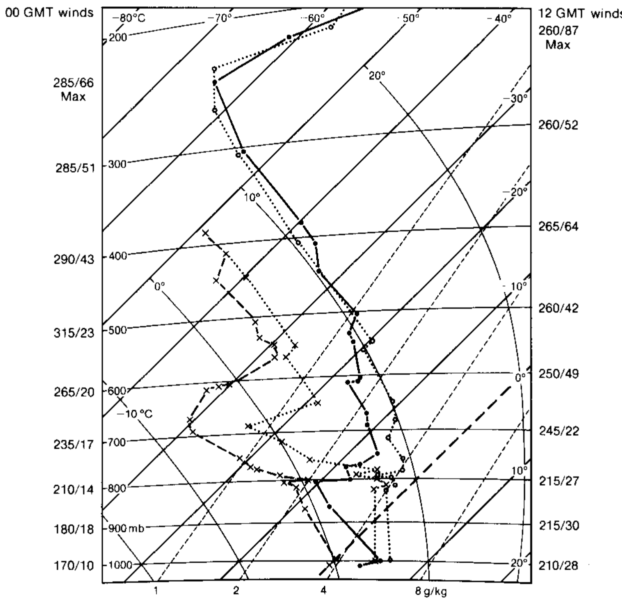

Figure 4. Radiosonde ascents made at Lerwick on 8 January 1988; the solid and dashed lines show the 0000 GMT ascent, and the dotted lines show the 1200 GMT ascent. The direction (deg.) and speed (kn) of the wind are shown.

wind speed and direction. It is therefore reasonable to assume that the Lerwick midday ascent, launched at 1115 GMT, was representative of the air mass just ahead of the occlusion at low level.

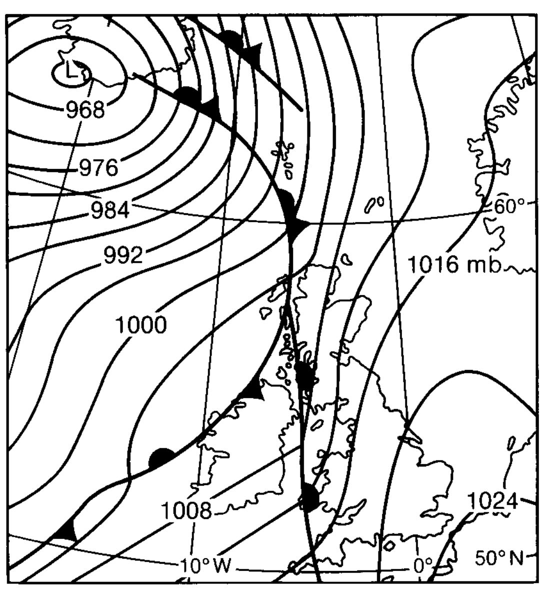

Figure 3. Surface synoptic situation for 0600 GMT on 8 January 1988.

3. Further observations and discussion

It was decided to examine barograms from stations to the west of Shetland, as far south as 57° N, and also from Faeroe, Norway and the North Sea oil installations. The results are summarized in Table II.

Table II. Pressure changes at stations other than in Shetland

Station	Pressure change (mb)	Time (GMT)
St. Kilda	−1.0	0100
Benbecula	−1.5	0310
Stornoway	−1.8	0340
Butt of Lewis	−2.2	0345
Neist Point	−4.0	0400
Diabaig	−1.5	0430
Cape Wrath	−3.5	0445
Wick	−3.0	0555
Kirkwall	−3.0	0600
Dalcross	−3.8	0600
Aviemore	−0.7	0630
Vagar (Faeroes)	−1.5	0630
Lossiemouth	−1.2	0655
Kinnaird Head	−1.0	0810
Thistle Alpha	−3.5	0900 *
Pacesetter 4	−4.0	0900 *
Hellisøy (Norwegian lighthouse)	−1.3	1200
Bergen	−1.0	1220
Utsira (Norwegian lighthouse)	−0.7	1340

* Approximate time as no time-marks etc. on barogram.

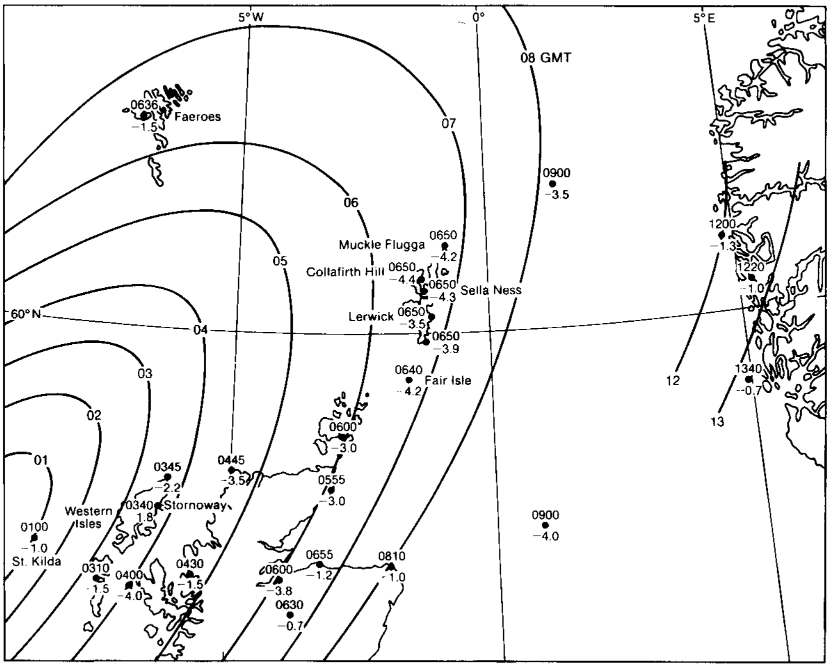

Figure 5. Isochrones of the arrival of the pressure fall, with spot positions of time (GMT) and fall (mb). Some of the places mentioned in the text are marked.

These data, together with the Shetland reports, were plotted and isochrones drawn as shown in Fig. 5.

One of the striking things about this event is the extraordinary similarity of most of the barogram traces examined, and also the strong resemblance to the trace from the event over south-east England in 1977.

Two possibilities for the origin of this event have been considered. Firstly, that it might have been induced by the strengthening south-south-westerly airflow over the Scottish mountains, but this was soon discounted by its appearance at St. Kilda and the Western Isles. However, it is suspected that the mountains may have played a part in increasing or decreasing the amplitude and rate of movement as the wave moved eastwards.

The second possibility was that the gravity wave was initiated by the frontal system advancing from the west, i.e. at the boundary between air masses of different density. This would agree reasonably well with the St. Kilda report at 0100 GMT — although some way ahead of the surface position of the front.

The pressure falls at Stornoway and the Butt of Lewis, appeared to coincide with the frontal passage as there was a veer of wind of 20 degrees and a significant rise in dew-point. At Kirkwall and Wick there were no changes to indicate the passage of a surface front; and in the case of Shetland, the front did not pass through until between 1100 and 1200 GMT, long after the gravity wave.

From examination of the surface pressure charts of the Central Forecasting Office, Bracknell, the triple point moved east-north-east at an average speed of about 20 m s^{-1} between 0000 and 1200 GMT. An examination of the isochrones in Fig. 5 shows that the average speed of movement of the onset of the sudden pressure fall was about 26 m s^{-1} to the north-east, along a line from St. Kilda to Muckle Flugga. This figure for the rate of movement must be considered unreliable due to the lack of information to the north-west of Scotland. Also, its rate of travel would appear to have been erratic and less than the frontal speed at times — leading to the front catching up at Stornoway and the Butt of Lewis.

It would therefore seem possible that the gravity wave was initiated at, or near, the frontal surface as it intersected the sea: it then propagated and amplified ahead of the front in the stable air under the inversion at 800 mb, evident on the 1200 GMT Lerwick ascent.

4. Conclusion

It is suggested that a gravity wave was initiated at, or close to, the frontal surface, possibly at the triple point, and that it propagated north-east and amplified in the stable air below 800 mb, the rate of propagation being generally considerably greater than the frontal speed. Over the more mountainous areas of northern Scotland there is evidence to suggest that the gravity wave lost some of its identity due to topographical effects. It is also possible that some of the largest pressure falls went unrecorded over the sea to the north-west of Scotland.

Acknowledgements

I wish to thank the many individuals who have helped by supplying advice and much of the basic data.

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Radar observations of the ash plume from a large fire

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Summary

A large Army warehouse at Donnington, Shropshire caught fire on 25 April 1988. The plume of ash from the fire was observed by the weather radar situated at Clee Hill. The radar measurements show the evolution of the plume and its subsequent dispersal.

1. Introduction

On 25 April 1988 a fierce fire broke out in a hangar at an Army store at Donnington in Shropshire (National Grid Reference SJ710130). Press reports indicated that the fire caused damage valued at or about £100 M and it resulted in asbestos and ash being distributed over an area of more than 100 km^2 of the surrounding countryside. The incident received national publicity which highlighted public concern over the spread of asbestos.

The fire produced a cloud of smoke and ash, which rose to an altitude of over 2000 m. Radar echoes from the ash cloud were picked up by the Clee Hill weather radar and appeared in the 5 km resolution national weather radar composite. Information from a number of higher elevation scans and some data with 2 km resolution are recorded on site for off-line analysis; these data were used to study the evolution of the cloud in greater detail.

2. Radar data collection

The Clee Hill weather radar operates at C-band (5.6 cm wavelength) and has a beam width of 1.0°. Every 5 minutes the radar performs a series of 4 PPI* scans in sequence at elevation angles of 2.5°, 1.5°, 0.9° and 0.0°. Fig. 1 shows a vertical section through the radar beams over Shropshire. Above Donnington, which is 37 km north-west of Clee Hill, the centres of the beams are at 2230 m, 1580 m, 1200 m and 615 m above sea level. The beam has a circular cross-section which at this range is 650 m wide between the one-way full-width half-power points.

Data are collected in polar co-ordinates with a resolution of 187 m in range by 1.0° in azimuth, and corrections are made to allow for range effects, ground clutter and attenuation. The relative strengths of the reflected and transmitted radar waves are a measure of the radar reflectivity factor which is converted to an equivalent rainfall rate. Finally the data are mapped from polar co-ordinates on to Cartesian grids of 2 km and 5 km resolution. Grid data with 5 km resolution from all four elevation scans are archived on magnetic tape together with 2 km resolution data from the 0.0° scan. Real-time estimates of surface rainfall are transmitted to local users at 5-minute intervals and to the central radar networking computer, RADARNET, every 15 minutes.

For the present analysis the recorded rainfall rates were converted back to radar reflectivity factors (Z). The analysed data are shown in dBZ where dBZ= $10.0 \log_{10}(Z)$. During the Donnington fire the observed dBZ values ranged from the minimum detectable of 3 dBZ up to a maximum of 38 dBZ.

* PPI or Plan Position indicator is a circular picture produced by scanning a radar beam through 360° in azimuth at a low elevation angle.

3. Synoptic situation

Fig. 2 shows the synoptic situation at 1200 GMT on 25 April 1988. High pressure over southern England was giving way as a weak trough approached from the north-west. At Shawbury (17 km west-north-west of Donnington) the 10-minute average 10-metre wind varied in direction between 050° and 115° during the period of the radar observations, the mean wind being 095° / 3.0 m s^{-1}. The 1200 GMT Aughton radiosonde sounding showed a weak inversion at 903 m. Immediately above the

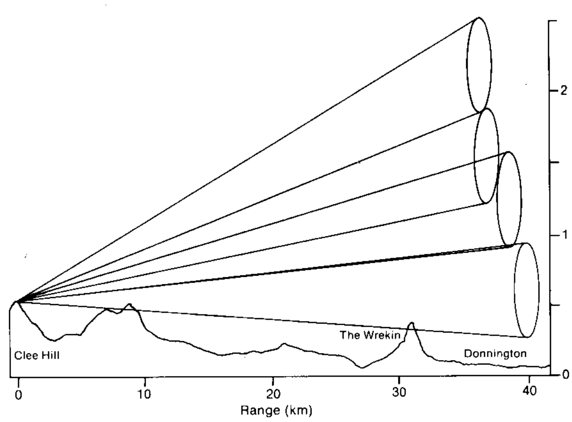

Figure 1. A vertical cross-section through the Clee Hill radar beams over Shropshire. The radar performs PPI scans at elevation angles of 2.5°, 1.5°, 0.9° and 0.2°. Above Donnington (70 m AMSL) the centres of the beams are at 2160 m, 1510 m, 1130 m and 545 m above ground level, and the beam is 650 m wide.

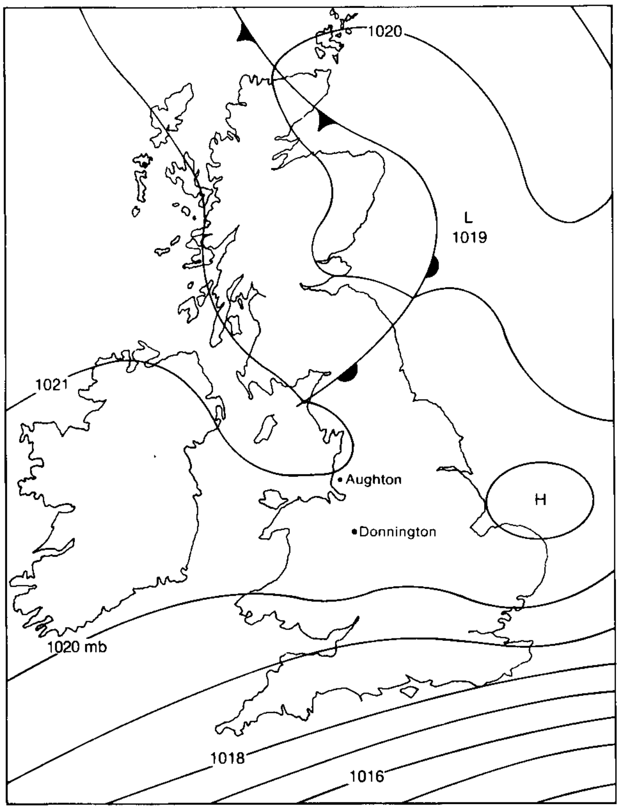

Figure 2. Synoptic situation at 1200 GMT on 25 April 1988. Isobars are at 1 mb intervals. The locations of Donnington and Aughton are shown.

inversion the wind was 095° / 5.7 m s^{-1} and at 2169 m it was 080° / 5.2 m s^{-1}. Above this height the wind backed steadily to 320° / 6.2 m s^{-1} at 4300 m. All the air in the lowest 3 km was sufficiently dry such that lifting to 3 km height would not cause saturation.

4. The radar observations

Fig. 3 shows the sequence of observations made over Shropshire by the 0.0° elevation scan at intervals of 5 minutes. This sequence clearly shows the development of the plume, its motion and subsequent dispersion. The radar measurements provide a definite indication of the plume's presence in a given square but the absence of a measurable signal can either mean that the plume was absent or that its concentration was too low to be detected.

The fire started at about 1440 GMT and the sequence shows the plume expanding and spreading steadily westwards. Press reports indicated that by 1520 GMT the fire was at its most intense and between 1525 and 1545 GMT the strongest radar returns where observed. At approximately 1630 GMT the fire was brought under control and the generation of the ash cloud effectively ceased. The plume then 'broke away' from Donnington and the last observations were made at 1725 GMT near Shrewsbury.

Radar returns from the ash cloud were first detected at 1448 GMT within the 1.5° scan, having risen to this height (1580 m AMSL) since the previous 0.0° scan which was performed some 2.5 minutes earlier. This implies that the cloud must have initially risen at a rate of greater than 6.4 m s^{-1}.

On only two occasions (1531 and 1535 GMT) were returns observed in the 2.5° scan (2230 m AMSL), so it would appear that the bulk of the material in the plume was contained below 2000 m.

The 1535 GMT scan shows ash 15 km downwind of Donnington in a direction of 260°; this means that it must have moved with a mean speed of 5.3 m s^{-1} over the 47 minutes since the first observations were made. The plume's velocity could also be estimated by tracking individual features as in Fig. 4 which shows the average intensity of the radar return as a function of distance west of Donnington, at 5-minute intervals. Using Figs 3 and 4, peaks in the intensity patterns near Shrewsbury at 1625 and 1655 GMT could be traced backwards to give mean velocities of 075° / 4.8 m s^{-1} and 080° / 5.6 m s^{-1} respectively. These values can be compared with the 1028 m and 2169 m winds at Aughton which were 095° / 5.7 m s^{-1} and 080° / 5.2 m s^{-1}.

Fig. 5 shows the average intensity of the radar return observed over the whole period. Of some interest is the spread of the plume transverse to the mean wind direction. Examination of the 1525 GMT scan in Fig. 3 shows that the plume has spread over a sector of at least 45°.

5. Discussion

Radar returns as large as 38 dBZ were observed during the Donnington fire. If raindrops were the target this would imply a rainfall rate of around 10 mm h^{-1}, but the air was too dry for precipitation to have been generated.

Sufficiently sensitive weather radars are able to obtain measurements from 'clear-air'. These returns may be attributable to birds, insects or man-made chaff* but generally they are from gradients of refractive index (caused by gradients of temperature and humidity in the atmosphere) occurring on a scale comparable with half the radar wavelength (James 1980). Such returns are commonly observed by sensitive 10 cm wavelength radars in the boundary layer and in particular allow the observation of forced convection associated with stubble burning. Viscous damping however means that such returns are generally too small to be detected by conventional 5 cm weather radars. During the Donnington fire temperature gradients much larger than those occurring in the free atmosphere would have been generated so that it is possible that returns from 'refractive index homogeneities' may have contributed to the radar signal close to Donnington.

Press (*Shropshire Star*) and television coverage reported asbestos and ash particles several centimetres across scattered over the nearby countryside and indeed

* Chaff is a cloud of narrow strips of metalized foil normally launched by rocket or dropped by aircraft.

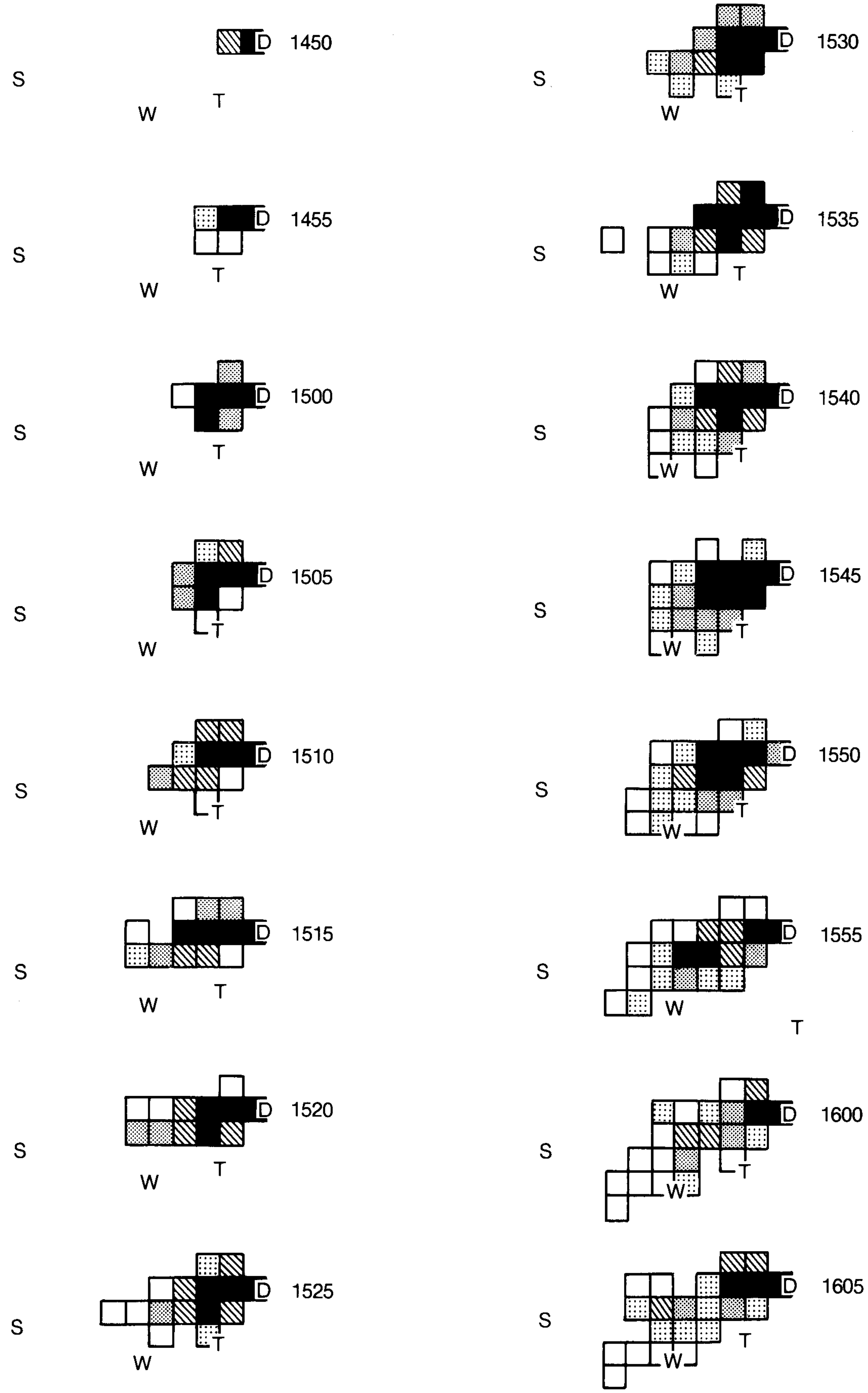

Figure 3. A sequence of radar observations made by the 0.0° scan at 5-minute intervals from 1450 to 1715 GMT. The locations of Donnington, Telford, The Wrekin and Shrewsbury are indicated by the letters D, T, W and S respectively. The radar observations on the 2 km mesh grid are shaded to indicate the strength of the return as shown in the key.

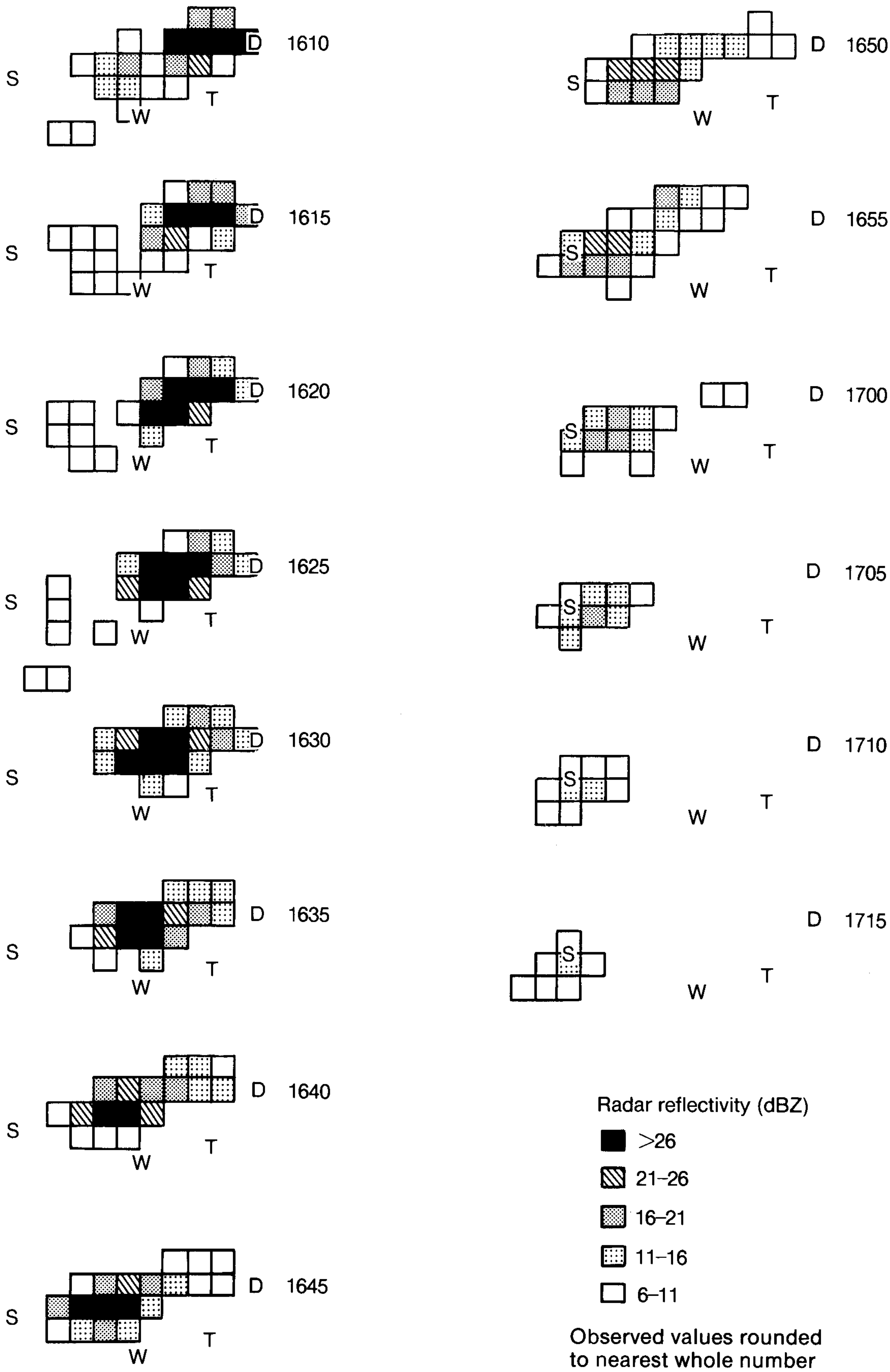

Figure 3 continued.

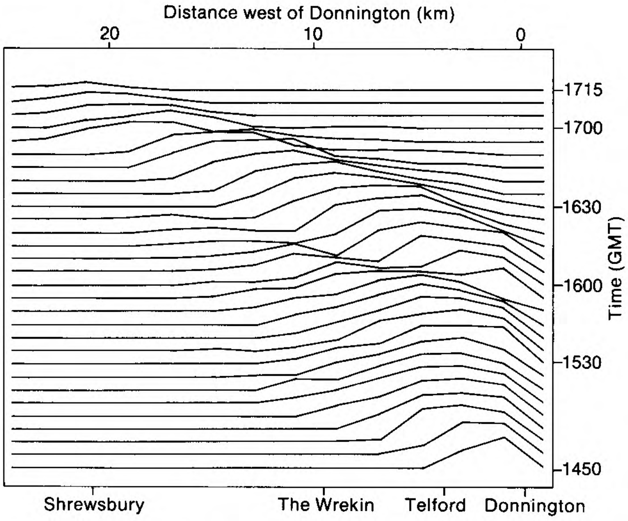

Figure 4. The intensity on an arbitrary scale of the radar return at 5-minute intervals averaged over all squares in the north-south direction as a function of distance west of Donnington.

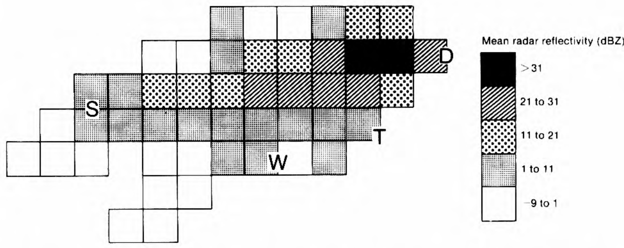

Figure 5. Average radar reflectivity observed over the period 1450 to 1715 GMT. For scale see key. This scale was chosen so that if the minimum detectable signal was registered in a 2 km square in a single 5-minute period then it would also appear on this figure. Each step on the scale corresponds to an increase in the mean radar reflectivity by a factor of 10.

such particles reached Shrewsbury which is more than 20 km from the source of the fire. The ash cloud over Shrewsbury was sufficiently dense that, for a period during the afternoon, the automatic street lights came on. Although asbestos and ash are relatively poor radar reflectors the large quantity of this material carried by the strong updraughts associated with the intense fire allowed it to produce an easily detectable return signal.

The fire occurred under relatively light wind conditions and the plume spread a considerable distance transverse to the mean wind direction. Such a spread highlights the problems which face forecasters attempting to predict the path of material following an event of this type in light wind conditions.

On this occasion the dispersal of a pollutant could be observed by the weather radar network. In general most pollutants — chemical, biological or nuclear — cannot be observed by weather radars. In principle, however, chaff could be introduced into the region where a release occurs then the subsequent dispersion could be directly tracked by radar.

Reference

James, P.K., 1980: A review of radar observations of the troposphere in clear air conditions. *Radio Sci*, **15**, 151–175.

A note on forecasting for the Airborne Antarctic Ozone Experiment

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Summary

An account is given of forecasting for the Airborne Antarctic Ozone Experiment, and some simple comparisons are made between reported and forecast high-level winds over Antarctica.

1. Introduction

Ozone (triatomic oxygen) is a vital constituent of the earth's atmosphere. Although it is present in concentrations of only a few parts per million, ozone is able to absorb solar radiation at wavelengths shorter than about 310 nm. It therefore acts as a shield for the earth's biosphere and protects it from harmful ultraviolet radiation. Photochemical processes caused by solar radiation occur high in the atmosphere and reach a maximum at levels around 20 km, both to produce and destroy ozone. Ozone is initially formed when oxygen molecules dissociate into atoms, which then recombine with other oxygen molecules. Destruction of ozone occurs mainly as the result of catalytic reactions involving other gases. Some of these gases are unfortunately the breakdown products of man-made source gases.

International concern over the possible impact on the ozone layer by man-made source gases such as chlorofluorocarbons (CFCs) was first aroused in the late 1970s when research showed dramatic reductions in ozone concentrations during the Antarctic spring (Farman *et al.* 1985). This led to the signing in September 1987 of the Montreal Protocol. This agreement was signed by virtually all the CFC-producing nations, and commits them to a significant reduction in CFC output over the next few years.

Two basic but different theories have been advanced by atmospheric scientists to explain the observed reduction in the Antarctic ozone concentrations. These are:

(a) that large-scale circulation changes introduce air with low ozone concentrations such as might come, for example, from tropospheric sources, into the Antarctic stratosphere, or

(b) that the changes in the ozone concentrations are linked to changes in source gas concentrations, specifically compounds containing chlorine and nitrogen.

It was to investigate this so called 'ozone hole' that specially instrumented aircraft of the United States National Aeronautics and Space Administration (NASA) were tasked with making detailed measurements of elements considered vital to the explanation of why the sudden drop in ozone concentration at the end of the austral winter should occur.

2. Meteorological support

The Meteorological Office was involved in two important aspects. One was concerned with the theoretical science side of the experiment and involved the Atmospheric Chemistry Group at Bracknell. The other involved the flight forecasting problems and concerned the two forecasters who were deployed to Punta Arenas in southern Chile. A dedicated network of communication links between the USA, the United Kingdom and Chile was set up by Research and Data Systems Corporation under contract to the project management to provide the flow of data to and from the project staff at Punta Arenas. In particular, dedicated links were set up between the Regional Telecommunications Hub in Bracknell and Punta Arenas, and between the European Centre for Medium-range Weather Forecasts (ECMWF) and Punta Arenas. In the event of a breakdown on one of these links, Bracknell was also linked to ECMWF.

Host nation support was provided by the National Meteorological Service of Chile while the communication links to the United Kingdom allowed the numerical weather prediction (NWP) model products to be received from Bracknell, and also from ECMWF, in real time. The Meteorological Office coarse-mesh model products were provided twice daily for up to 72 hours ahead and fine-mesh model products once a day for up to 36 hours ahead. These products covered fields of surface pressure at mean sea level, and winds and temperatures at standard levels up to flight level (FL) 780 (78 000 ft). They were used operationally as the basis for flight documentation as well as for planning purposes. Like the products from the Meteorological Office, those from ECMWF were provided to cover standard levels up to FL780 but the forecasts were extended up to 240 hours ahead. These ECMWF data were used primarily for determining 'weather windows' so that development of the plans for successive aircraft missions could proceed well ahead of the event.

The Atmospheric Chemistry Group provided routinely, charts of isopleths of isentropic potential vorticity (IPV) for different temperatures based on data from the Meteorological Office coarse-mesh model. These IPV data permitted a parcel of air sampled by a high-flying aircraft to be followed theoretically (i.e. assuming no mixing etc.) around the polar vortex, and to be considered for re-examination many days later by a further flight, weather permitting. Ozone measurements by satellite were also made available in real time at Punta Arenas through communication links to the USA, and added an important dimension to the scientific aspect of flight planning not experienced previously by the mission forecasters.

In addition the Chilean forecasting office in Punta Arenas provided routinely, plotted surface-weather charts and cloud pictures; the latter could be interpreted by colour-slicing techniques made available by the Chileans. The Chilean meteorologists also provided airfield forecasts and some upper-air data from Antarctica required by the project staff. Not least, a NASA radio station set up at Punta Arenas by the project management was in frequent contact with the US base at Palmer Station in Antarctica, which provided upper-air soundings in support of the project at a location close to a number of the aircraft flight paths.

3. Requirements for aircraft operations

NASA deployed two research aircraft to Punta Arenas during August and September 1987, a DC-8 and a modified version of the U-2 known as the ER-2. The ER-2 operated at altitudes up to 18.5 km and as far south as 72° S. The limit of 72° S placed on the ER-2 was primarily for safety reasons. The DC-8 operated at altitudes up to 11 km and made several flights to or near the South Pole.

The requirements of the two research aircraft for meteorological support were quite varied. Both required detailed forecasts of upper winds and temperatures at the planned operating levels which between them varied between FL240 and FL700. For take-off and landing the ER-2 required the surface wind speed to be no more than 25 kn with a cross-wind component no greater than 12 kn. Cloud-base criteria were not very restrictive, the only requirement being that the cloud base should be 200 feet or more above ground level, with visibility not less than 1500 m. In flight, forecasts of areas where clear air turbulence (CAT) might be encountered were required and, in addition, up-to-date forecasts for the planned diversion airfield of Puerto Montt. This airfield is located some 800 miles to the north of Punta Arenas. Finally, ambient temperatures below −85 °C were of significance since it was believed that these could cause crystallization of various lubricants used in the aircraft control mechanisms.

The requirements of the DC-8 were more flexible when it came to take-off and landing. Surface winds were preferred to be less than 34 kn with a cross-wind component no greater than about 23 kn. Cloud base should be over 500 ft above ground level and visibility more than 800 m. In flight, forecasts were required for the diversion airfield of Rio Gallegos in southern Argentina, in case of encounters with areas of CAT, and for ambient temperatures below −76 °C. Temperatures lower than this could have caused waxing of the aircraft fuel. Forecasts of areas free from dense cirrus cloud were also required. The forecasters had not expected extensive areas of cirrus cloud at high altitudes in the Antarctic stratosphere near the Pole but they were features of some of the flights, even on occasions extending up to the ER-2 flight levels and sometimes thick enough to obscure the sun. This led to a requirement for the forecasters to predict areas where dense cirrus was likely. Flight plans were then made to avoid such areas of cirrus since many of the onboard spectroscopic instruments required either a clear view of the sun or clear-column conditions above the aircraft in order to obtain good quality data.

4. Results

An example of a forecast surface pressure chart issued for a DC-8 flight on 2 September 1987 is shown in Fig. 1 with the associated coarse-mesh forecast of FL340 winds and temperatures in Fig. 2. The actual track of the aircraft is shown in Fig. 3 and the winds and temperatures encountered in flight in Fig. 4. Whenever possible the actual winds and temperatures encountered during flight were relayed back to the NASA radio station set up at Punta Arenas, from where they were relayed rapidly to Bracknell and ECMWF for inclusion in the next computer run, while the Chilean meteorologists forwarded the data to the Global Telecommunication System, for world-wide use. Owing to the vagaries of Antarctic radio reception, one such report was inaudible in Punta Arenas but was received by a station in Boulder, Colorado. This report was subsequently relayed back to Punta Arenas and in this roundabout way eventually to Bracknell.

The example in Fig. 4 provides a good illustration of the complexity of the upper-wind fields which were sometimes experienced over Antarctica. The model provided rather dubious guidance on this occasion. The west or west-north-westerly winds of around 50 kn between Tierra del Fuego and the Palmer Peninsula were well forecast, as was the position of a trough near the peninsula and a corresponding ridge over the Weddell Sea.

The model wind speeds were much too low on the south side of the trough though, and also too smoothed out. The aircraft encountered wind speeds of 60–80 kn from the north-east in an area where the model

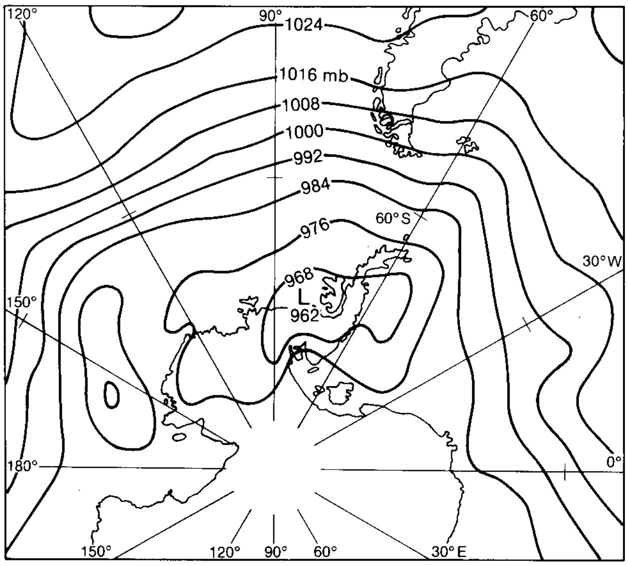

Figure 1. Forecast surface chart valid for 1800 GMT on 2 September 1987 issued for a flight by the DC-8 aircraft.

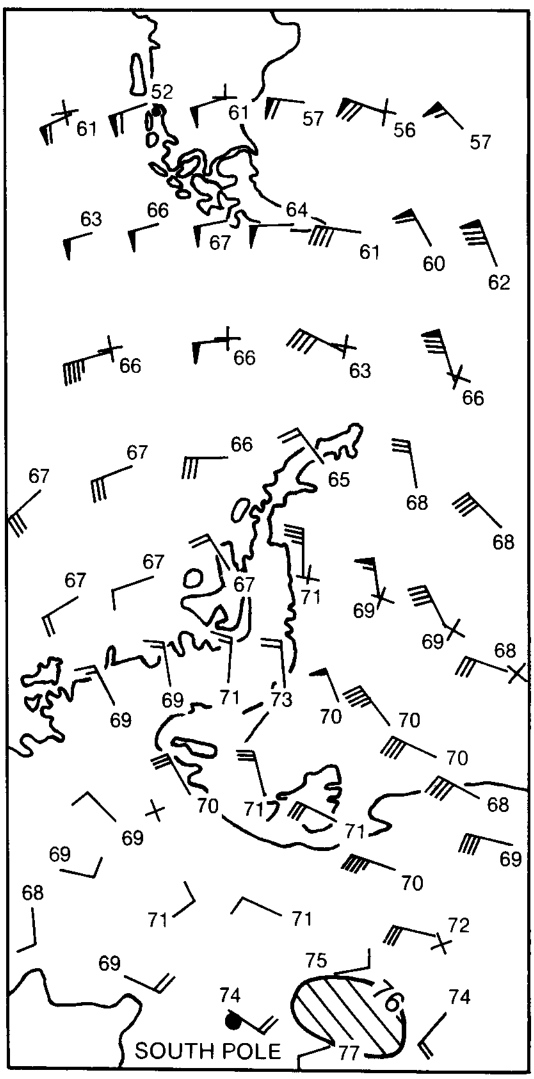

Figure 2. Coarse-mesh forecast chart for FL340 valid for 1800 GMT on 2 September 1987 issued in conjunction with the surface chart shown in Fig. 1. All temperatures shown (°C) are negative. The hatched area depicts an area of forecast temperature below −76 °C.

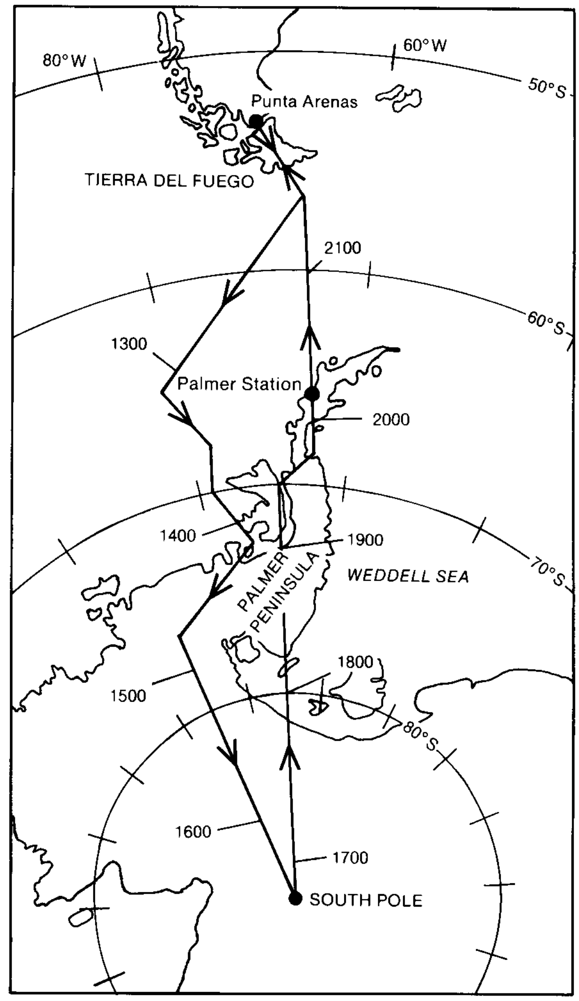

Figure 3. Flight track of the DC-8 aircraft on 2 September 1987 with times shown in GMT.

predicted a northerly wind of 15 kn. West-north-westerly winds of up to 83 kn quite close to the Pole were also a surprising feature of this flight and were not predicted by the model. The forecasters came to realize early in the project that an element of modification was required in forecast winds for the DC-8 which were frequently underestimated by the NWP products. On occasions this modification was to a significant extent and this was true particularly in relation to upper ridges, which were frequently predicted to have insufficient amplitude and wind strength over central Antarctica. The modification was based on interpreting all of the data to hand as well as partly a result of experience and of other flights, and was carried out by drawing modified isotachs on the documentation issued and providing charts of forecast jet-stream locations and strengths.

The forecasting of areas of high cirrus relied heavily on satellite information provided by the local Chilean forecasting office. This information was analysed and interpreted in conjunction with the Meteorological Office NWP products. It was found that the 150 mb forecast products were particularly useful in identifying likely regions of cirrus development penetrating the area over the Antarctic plateau. This was especially true when the forecasters successfully modified and extended the southerly range of high-amplitude upper ridges over Antarctica, since this permitted the DC-8 to be tasked to fly around the areas of thick cirrus and give the onboard spectroscopic instruments a clear view of the sun or clear-column conditions. Fig. 5 illustrates the track that the DC-8 was required to fly on a particular day so that it could operate in the right place and at the right time and avoid the cirrus.

Model performance at the higher levels flown by the ER-2 was surprisingly good, and examples are shown in

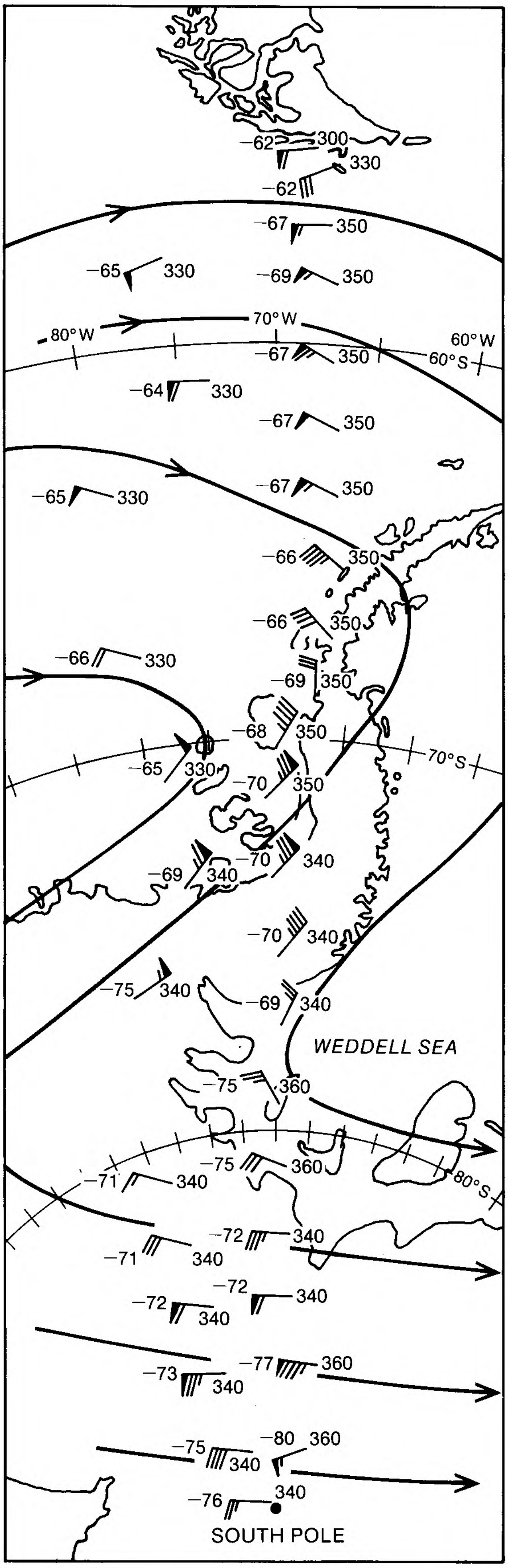

Figure 4. Actual winds and temperatures (°C) at stated flight levels, and inferred wind pattern (bold lines), encountered by the DC-8 aircraft during the flight on 2 September 1987.

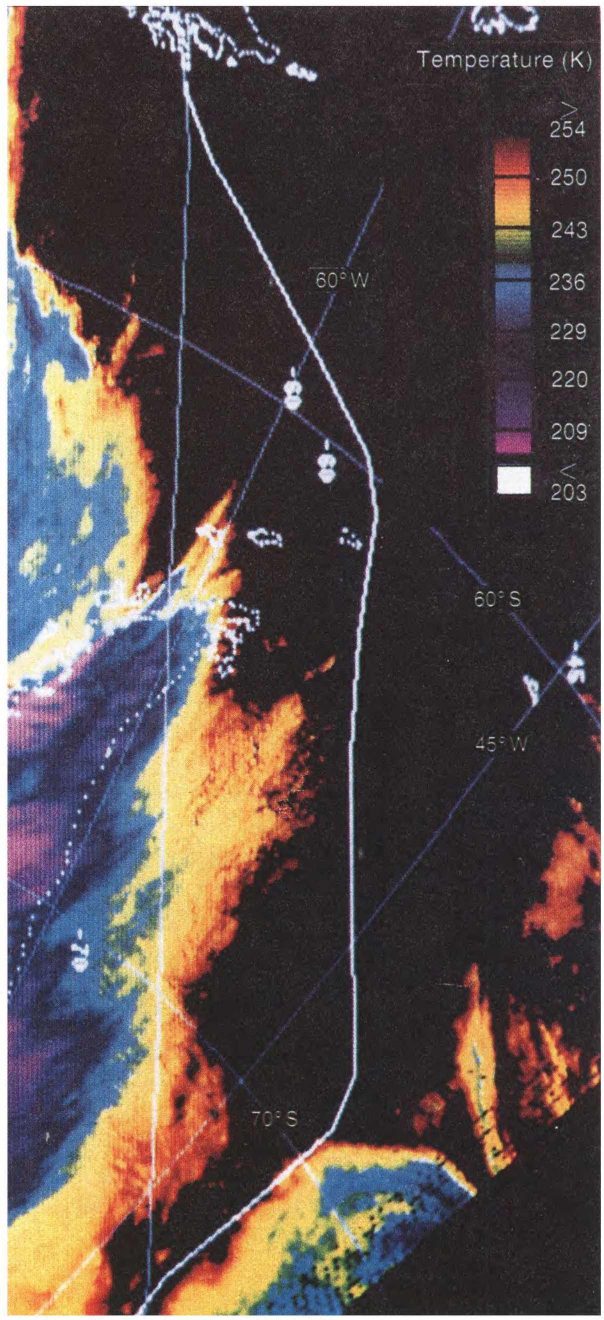

Figure 5. Cloud-temperature colour-slice showing the flight path of the DC-8 aircraft on 5 September 1987 which was successfully planned to fly to the east of the coldest cloud over the Palmer Peninsula and west of the cold cloud at the bottom right of the picture.

Table I. Winds and temperatures measured by the ER-2 aircraft compared with model forecast winds. Data from the aircraft are related to a validity time of 1800 GMT ± 3 hours.

	Forecast winds			Actual winds reported		
Position	FL	Wind (deg./kn)	Temp. (°C)	FL	Wind (deg./kn)	Temp. (°C)
17 August 1987						
56° S, 68° W	610	250/75	−70	610	245/76	−71
58° S, 66° W	610	250/80	−72	610	240/76	−74
60° S, 63° W	610	250/80	−75	590	245/68	−76
62° S, 63° W	610	250/80	−76	610	240/81	−76
64° S, 65° W	610	250/80	−79	610	245/100	−80
66° S, 68° W	610	260/75	−80	630	250/80	−84
28 August 1987						
57° S, 67° W	610	300/100	−63	560	300/82	−64
61° S, 70° W	610	310/95	−69	580	300/82	−70
64° S, 72° W	610	320/80	−74	600	304/75	−75
67° S, 75° W	610	330/75	−76	620	304/69	−77
70° S, 78° W	610	330/55	−78	630	307/63	−80
72° S, 80° W	610	330/55	−78	640	307/58	−81
9 September 1987						
55° S, 68° W	610	280/90	−73	610	272/86	−66
57° S, 67° W	610	290/90	−74	610	279/83	−69
60° S, 63° W	680	290/90	−76	660	283/94	−76
62° S, 64° W	680	280/75	−77	660	289/62	−74
63° S, 64° W	680	280/70	−78	660	284/60	−76
65° S, 64° W	680	280/55	−79	660	295/64	−80
67° S, 65° W	680	280/50	−79	660	280/50	−78
68° S, 65° W	680	310/35	−80	660	301/44	−79

Table I. Here the predicted values from the coarse-mesh model forecast issued to the pilot before take-off, are compared with the actual winds measured by aircraft sensors at various points along the flight track. Data for three flights are shown; those on the 17 August, 28 August and 9 September. These examples were chosen because on these flights the aircraft stayed near a flight level for which a forecast chart was available. Only the outbound leg is considered in each example since there was little variation on the return leg. Ignoring the difference in height between a standard flight level and that actually flown, it can be seen that there are a few occasions when spot differences between forecast winds and temperatures and aircraft reports are quite large. However, the most important point to emerge from a comparison is that the examples show that for each flight there is a mean vector difference of around only 10 kn and a mean temperature difference of around ±2 °C. This was most encouraging for the aircrew who came to expect a high standard as a routine.

5. Conclusions

At the outset of the project, it was expected that the notoriously windy weather at Punta Arenas and the environmentally severe problems of flying over Antarctica would severely restrict aircraft operations. In the event, twelve ER-2 flights were completed successfully which together with thirteen DC-8 flights provided a wealth of scientific data. Throughout the experiment the NWP products provided good guidance for the forecasters, especially at the high levels flown by the ER-2, and in part contributed significantly to the success of the experiment.

Acknowledgements

It is a pleasure to acknowledge the encouragement in particular of the aircraft pilots, the project scientist Dr A. Tuck of the Aeronomy Laboratory, NOAA, the project leader Dr R. Watson of NASA Headquarters, and Dr E. Condon the project manager, without which the forecasters would have found the task even more daunting. The ER-2 flight data were made available by K. Roland Chan of the NASA Ames Research Center, California. The Chilean forecasters and staff at Punta Arenas airfield provided a good deal of data which assisted the project forecasters' contribution to the experiment.

Reference

Farman J.C., Gardiner, B.G. and Shanklin, J.D., 1985: Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction. *Nature*, **315**, 207–210.

Sea-breeze features over Sriharikota, India

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Summary

Using temperature, humidity and wind records since 1977 at the Sriharikota observatory, the occasions of occurrence of sea-breezes have been identified and their characteristics over the island have been studied. There are some differences in sea-breeze characteristics over Madras (70 km to the south) and Sriharikota Island. An attempt has been made to predict the sea-breeze occurrence over the island using the temperature and surface wind observations at 1000 hrs local time as parameters.

1. Introduction

Sea-breezes over the coasts are due to thermally driven mesoscale atmospheric circulation, for which differential heating is the essential requisite. A direct thermally driven circulation such as the sea-breeze occurs more frequently and with more regularity in the tropics than in middle and high latitudes. Since a moist air mass moves over the land during a sea-breeze, a change in temperature and humidity takes place and the wind direction is from the sea to the land. Thus, the sea-breeze moves as a front and can also be detected by radar under favourable radio propagation conditions.

The study of air motion in either mesoscale or any other scale of circulation forms an integral part of meteorology. Sea-breeze occurrence is an important event in environmental monitoring and aviation meteorology although it is a purely local phenomenon. Many climatological studies of sea-breezes have been attempted in India (Narayanan 1967, Dekate 1968, Ramakrishnan and Jambunathan 1958, Ramanadham and Subbaramayya 1965, Ramanathan 1931, Ramadoss 1931 and Roy 1941) and more general studies have been made elsewhere (Arakawa and Utsugi 1937, Brittain 1978, Hatcher and Sawyer 1947, Leopold 1949 and Marshall 1950)

Sriharikota (13.7° N, 80.2° E) is a rocket launching centre of the Indian Space Research Organization located as shown in Fig. 1. Many rocket launching operations and programme stages are dependent on the environmental conditions and hence for planning the operations efficiently a full investigation of sea-breeze fronts over the island was essential.

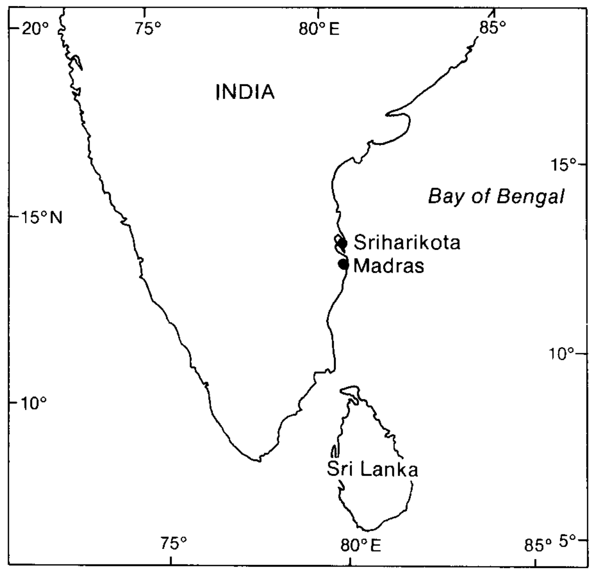

Figure 1. Location of Sriharikota and other locations mentioned in the text.

2. Data and methodology

Autographic weather records are available for the Sriharikota observatory since 1975. The temperature, humidity and anemograph charts of 1977–86 were scrutinized and the occasions of sea-breeze occurrence were identified by abrupt changes in these parameters. Some earlier sea-breeze reports (Venkataraman and Prakash Rao 1977, Prakash Rao 1985) were available for a few years but they were based on changes in relative humidity alone. First a statistical survey of sea-breezes was made. Later the characteristics of sea-breezes were derived in relation to the changes they bring about in meteorological parameters. The vertical extent of sea-breezes was also estimated from the pilot-balloon ascents which were made twice daily, one between 05 and 06 GMT and one between 09 and 11 GMT. The pilot-balloon wind data were available for the five years up to 1986. Occasions when sea-breezes set in after 06 GMT but well before the afternoon pilot-balloon ascent were considered and, from a comparison of the wind fields, an estimate of the vertical extent of sea-breeze fronts was attempted. Finally the probability of sea-breeze occurrence as a function of the morning wind and temperature data was investigated so as to develop forecasting methods for sea-breezes.

3. Results and discussion

3.1 Occurrence and detection

The number of occasions of a sea-breeze (1351 in total) were studied and their monthly frequency is shown in Fig. 2. The first point to note is a maximum in the summer months of April and May. This is to be expected as the phenomenon is basically due to differential heating. Even during winter sea-breezes are detectable, although in limited numbers.

The occasions were sub-divided into the percentages in which they were detected by temperature and humidity change together, temperature change alone or humidity change alone, and these are shown in Table I. It can be seen that in the summer (April and May) and south-west monsoon (June to September) months, in only about 4 out of 5 occasions can the sea-breeze front be detected using both parameters. During November and the winter months, relative humidity alone is able to reveal the occurrence of the sea-breeze on most occasions. In February and December both humidity and temperature charts need to be monitored in order to detect the occurrence of a sea-breeze.

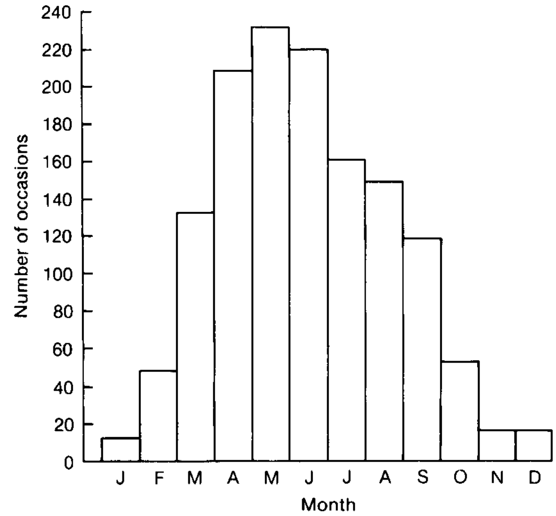

Figure 2. Monthly frequency of sea-breezes at Sriharikota, from the 1351 occasions studied in this paper.

3.2 Time of occurrence

Table II presents the distribution by time of sea-breeze arrival and Fig. 3 shows the average time of occurrence. Whilst the forenoon (1000–1200 hrs Indian Standard Time (IST)) is the more usual time of occurrence in April and May, as the south-west monsoon sets in and progresses in July and August, the time shifts to the mid-afternoon. For winter months the times begin in the late afternoon and advance again to near-noon in March. There is a temporary advance in time in September from 1515 to 1415 hours IST.

3.3 Fall of temperature

One of the advantages of the sea-breeze is the greater human comfort it brings about by lowering the temperature. There is a rapid fall in temperature taking less than 15 minutes between the fairly constant temperatures before and after the sea-breeze onset, and this can be determined accurately from thermograph records. The average and maximum falls found during the period February to October are shown in Table III. The maximum fall of temperature can be as high as 7.8 °C, but on average the fall is only about 3 °C in summer. The average fall in temperature shows a maximum in June. This differs from the tendency at Madras which has its maximum in mid-July (Rao 1955). The mean fall of temperature at Madras shows a wide seasonal variation from 1.1 °C in April to 4.6 °C in July. In comparison the range at Sriharikota is from 1.8 °C in February to 3.5 °C in June. The reason for the seasonal differences at Madras may perhaps be its urban nature, which is not the case at Sriharikota.

Table I. Percentage frequency of sea-breeze occurrence at Sriharikota, detected using different parameters

Detected by	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Humidity and temperature	0	27	59	72	81	83	83	77	79	36	12	—
Temperature alone	0	19	2	1	2	4	2	5	1	9	6	23
Humidity alone	100	54	39	26	18	13	15	18	20	55	82	77

Table II. Monthly distribution by time of the arrival of the sea-breeze at Sriharikota

Time (IST)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1000–1159	0	10	55	123	111	23	8	2	18	8	0	1
1200–1359	4	31	64	78	84	62	36	40	40	16	1	3
1400–1559	2	6	10	4	20	59	58	36	27	15	8	3
1600 onwards	5	0	3	2	16	66	58	70	33	15	8	9

Table III. Average and maximum falls in temperature (°C) at the onset of the sea-breeze at Sriharikota

	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
Average fall	1.8	2.1	2.7	3.3	3.5	3.1	3.0	2.5	2.3
Maximum fall	3.8	5.0	7.2	7.8	7.7	6.5	6.0	6.5	3.8

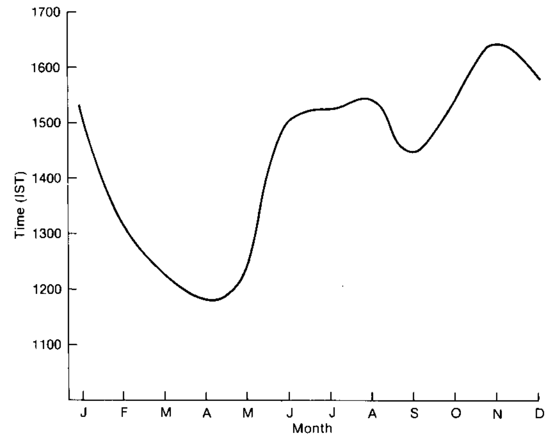

Figure 3. Average time (IST) of arrival of the sea-breeze at Sriharikota.

Table IV gives the average fall of temperature with the onset of a sea-breeze occurring in the specified time periods, i.e. forenoon, early afternoon, late afternoon, evening, and later. It can be seen that the fall in temperature at all times of occurrence over Sriharikota is a little less than that over Madras. However, the diurnal trend is exactly the same at both locations.

3.4 Winds

With the setting in of the sea-breeze the easterly component in the wind direction is dominant because of the influence of the large area of the Bay of Bengal to the east. While in about 66% of occasions a wind speed increase was noticed, a reduction occurred in the remaining occasions. If the westerly component was strong, the easterly sea-breeze component has to overcome the westerlies dynamically and perhaps this might be the reason for the reduction in wind speed, as the magnitude of the wind was considered irrespective of the direction. Of the total number of wind increases recorded with the sea-breeze front, on about 21% of occasions the speed increased by 3 m s^{-1} or more and on 55% of occasions the speed increased by 2 m s^{-1} or more.

Table IV. Average fall in temperature (°C) at the onset of the sea-breeze at Sriharikota and Madras, occurring within specific time periods

Time (IST)	Sriharikota	Madras*
1000–1159	2.2	2.6
1200–1359	2.9	3.0
1400–1559	3.3	3.7
1600–1759	3.5	4.7
1800 onwards	3.2	3.5

* From Rao (1955)

3.5 Vertical extent of the sea-breeze front

Upper-air wind profiles from pilot-balloon ascents could be constructed for most of the sea-breeze occasions during 1985 and 1986 and for a number of occasions in the early 1980s. The analysis showed that the depth of the atmosphere within which the sea-breeze could be detected (by changes in wind direction with height) over Sriharikota was never less than 100 m. The maximum observed depth of the sea-breeze front was 750 m (once in June and once in August). The greatest average depth of the sea-breeze occurs in May and is of the order of 400 m. It may be relevant that the highest insolation over Sriharikota occurs during May as suggested by the higher daily maximum temperatures.

Table V emphasizes the main salient points regarding the vertical extent of sea-breeze fronts during the summer and south-west monsoon months.

3.6 Forecast criterion

The temperature and surface wind at 1000 IST were noted and their correlation with the sea-breeze occurrence was investigated. Although the 0300 GMT (0830 IST) observation is the standard time for the morning synoptic observation in India, due to logistic constraints 1000 IST is the morning main observation hour for the Sriharikota launching range. The probabilities of the sea-breeze occurring within specified limits of ambient temperature are shown in Table VI. It is clear that if the temperature is greater than 31 °C at 1000 IST then, during the months of April to July, there is a good chance (≧72%) of a sea-breeze occurring on that particular day. Similarly from Table VII, which relates the probability of occurrence with surface wind speeds at 1000 IST, a wind speed of 6 m s^{-1} or more suggests a high probability (≧75%) of sea-breeze occurrence during the day, particularly during the months March to June. The two criteria put together will be helpful in forecasting the incidence of a sea-breeze on any particular day.

4. Conclusions

The average time of sea-breeze onset at Sriharikota is before noon for the summer months (April and May) which changes steadily to the afternoon in subsequent

Table V. Vertical extent of the sea-breeze at Sriharikota

	Apr.	May	June	July	Aug.	Sept.
Mean depth of sea-breeze (m)	270	400	330	320	340	290
Maximum depth of sea-breeze (m)	550	650	750	650	750	450
Percentage of occasions when sea-breeze front exceeds 400 m in depth	8	40	11	20	16	11

Table VI. Percentage probability of sea-breeze occurrence at Sriharikota in relation to the ambient temperature at 1000 IST

Temperature (°C)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
26–31	5	20	38	44	25	46	36	36	27	17	5	4
31–36	—	—	81	73	73	77	72	67	50	20	0	—
36–41	—	—	—	100	95	97	—	—	—	—	—	—

Table VII. Percentage probability of sea-breeze occurrence at Sriharikota in relation to the surface wind speed at 1000 IST

Wind speed ($m\ s^{-1}$)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0–2	4	4	12	45	67	61	32	33	15	15	2	2
2–4	1	7	20	31	58	60	50	47	27	13	9	7
4–6	8	33	51	76	82	78	67	55	53	24	4	7
6–8	0	45	75	95	91	82	63	68	61	19	2	3
8 and above	0	0	0	100	83	75	67	50	50	0	7	6

months. The fall of temperature with the sea-breeze front can be as high as 7.8 °C with an average value of 3 °C. On only 4 out of 5 occasions do both temperature and humidity change with the arrival of the sea-breeze. A temperature of 31 °C or more with a wind speed of 6 m s^{-1} or more at 1000 IST suggests a high probability of sea-breeze occurring on that day. Sea-breezes can be discernible up to a height of about 750 m over Sriharikota.

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UK weather radar picture — 14 January 1989 at 0100 GMT

The United Kingdom weather radar network is now in its tenth year of operation. Fig. 1 shows one of the best examples of the banded nature of precipitation at cold fronts observed since the networks' inception. On this occasion the surface front is marked by line convection elements that extend across the whole network area. The line convection, of the order of 5 km in width (one pixel), is seen at the leading edge of the general area of rain. On the surface chart (Fig. 2), the cold front has been drawn slightly 'stepped' so as to fit the position suggested by radar data. This position is supported by surface observations, a number of which also indicated a temperature drop of 3 to 4 °C, a marked pressure kick and gusts of around 35 kn during frontal passage.

Almost all line convection events occur at 'classical' rearward-sloping cold fronts. The upper-air wind field shown in Fig. 3 is typical of that associated with a classical front with the front lying downstream of a marked jet-entrance region forward of a confluent trough.

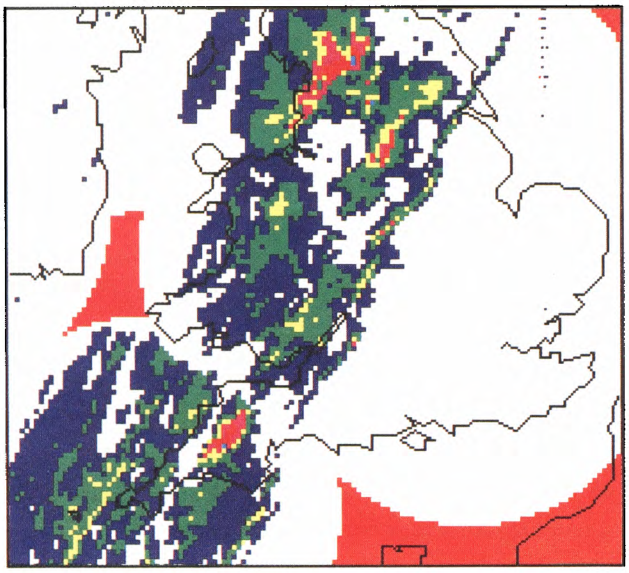

Figure 1. Radar network picture at 0100 GMT 14 January 1989. Rainfall intensities: white 0–⅛ mm h^{-1}, dark blue ⅛–1 mm h^{-1}, green 1–4 mm h^{-1}, yellow 4–8 mm h^{-1}, magenta 8–16 mm h^{-1}, red 16–32 mm h^{-1} and cyan > 32 mm h^{-1}.

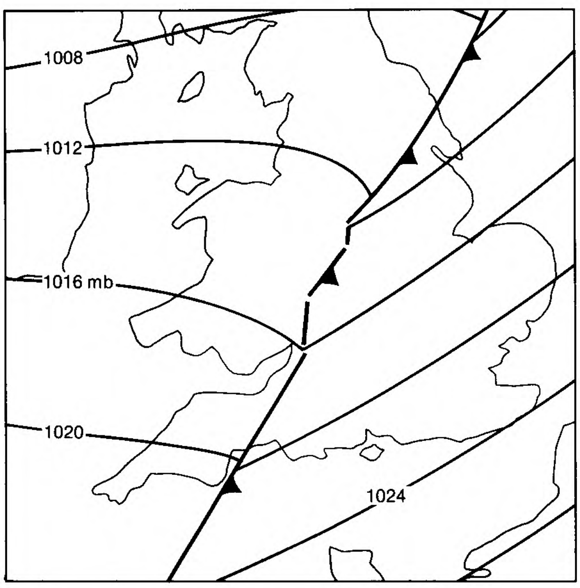

Figure 2. Surface analysis at 0100 GMT 14 January 1989.

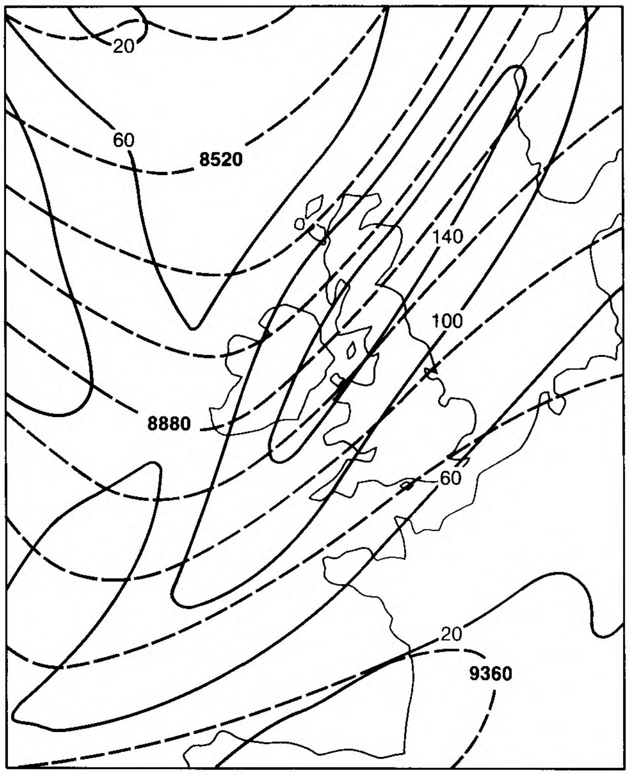

Figure 3. Fine-mesh model-analysed 300 mb isotachs (solid line, contour interval 40 kn) and contours (dashed line, interval 120 m) at 0000 GMT 14 January 1989.

Meteorological Magazine

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Forecasting a small-scale synoptic event
Orographic precipitation

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The forecasting of sea fog*

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Météorologie Nationale/Centre de Météorologie Marine

Summary

This article contains a discussion of the various methods of sea fog forecasting, introducing expert systems to the problem. A practical example from the North Sea is also presented.

1. Introduction

Fog at sea represents a significant hazard to navigation in many parts of the world and has contributed directly to a substantial number of marine safety incidents, including the loss of many lives (Tremant 1987a). At the same time, the forecasting of fog at sea presents substantial difficulties to National Meteorological Services providing forecasts to the maritime community, in view of the general lack of data from ocean areas coupled with the requirement for a close understanding of both the meteorological processes leading to fog formation, advection and dissipation and also the microphysics of the fog itself.

In this article, the navigational aspects of sea fog (Tremant 1987a), and the classification, distribution and physical properties of sea fog, which have been well described by Binhua (1985), are not considered. Only the meteorological forecast methods are presented here.

2. Difficulties in fog forecasting

Like clouds, fog results from the condensation of water vapour in the air, following the effect of various thermodynamic mechanisms. For a given temperature there exists a maximum value (said to be saturated) of the concentration of water vapour; with concentrations greater than this value (i.e. following either a cooling of the air or the presence of additional vapour) there is condensation. However the qualitative difference that the appearance of fog produces, corresponds to a very small quantitative difference in water droplet concentration. Thus the saturated concentration in proximity to the surface varies, in general between 5 and 10 g m^{-3} of air, according to the temperature but it only needs an additional supply of the order of 0.1 g m^{-3}, i.e. less than 2%, to create relatively dense condensation.

It is, in large part, for this reason that the numerical methods of weather forecasting, despite their recent progress, are not able at present to correctly forecast fog (as they also fail to forecast visibility in a satisfactory manner). At first, therefore, we are reduced to exploiting the fact that it is known that fog is more likely to appear in certain meteorological situations and to make qualitative forecasts. This is the present situation — at the moment there is no objective method of fog forecasting, either at sea or on land.

Since sea fogs are weather phenomena occurring in the lower atmosphere under the influence of the sea, their formation is related to both the ocean and the atmosphere. In particular, the interaction between the properties of shallow sea and those of the lower atmosphere, both near the air–sea interface, are the dominant effects on the formation, continuation and dissipation of sea fogs. From the view point of the mechanism of sea fog generation, the air–sea interaction is on a small scale, but sometimes we have to consider

* An abridged version of a report in French by Tremant (1987a).

the generation from the larger-scale point of view in certain areas with sea fogs.

3. Methods of sea fog forecasting

At present the following five methods for sea fog forecasting are used:

(a) synoptic method,
(b) statistical methods,
(c) numerical models,
(d) instrumental methods, and
(e) forecasting with expert systems.

3.1 Synoptic method

The synoptic method for sea fog prediction has been, and is still being, employed by coastal meteorological stations. To make this prediction, we must have a good forecast of:

(a) wind speed and direction,
(b) air, dew-point and sea surface temperatures, and
(c) the type of fog likely to occur.

Moreover, for coastal fog we must take into account the topography of the location.

3.2 Statistical methods

There is a way of making progress without waiting for the development of numerical forecasting models to reach a state (which could take a long time) in which explicit forecasts of fog for visibility purposes can be made. This method consists of making the hypothesis that there is a link between the presence of fog and certain other meteorological quantities; without trying to understand this link, we try empirically to establish correlations, and on this basis build a method of forecasting.

Despite its indirect nature, this way of working has already proved its effectiveness several times, whether it is a question of forecasting phenomena which are not explicitly taken into consideration by the numerical models, or to adapt these models to a finer spatial resolution. Obviously the chances of success depend on the number of physical reasons for the meteorological quantities in which we are interested (the predictors) to be linked to the quantities we wish to forecast (the predictands), in this case the presence of fog.

3.2.1. The linear parametric discrimination

The linear parametric discrimination is the statistical method most often used for the study of meteorological phenomena.

Fog has been studied in the North Sea (Tremant 1985) and more precisely on Frigg Field (60° N, 02° E). We have used 3-hourly ship observations transmitted over the GTS (Global Telecommunication System). With the help of the results from statistical programs, a very simple method to forecast sea fog was developed:

Condition 1: Air, sea surface and dew-point temperatures are very close (less than 1 °C difference between all three).

Condition 2: Wind direction must be from between 150° and 200°.

Condition 3: Atmospheric pressure must be higher than 1010 mb.

Condition 4: During this study on fog it was possible to deduce that in a 'showers area', that is to say behind a cold front when the shower regime is well established, there is **never** any fog.

When conditions 1, 2 and 3 are satisfied, fog is forecast. When either condition 2 or 3, is not satisfied, then fog is possible as long as condition 1 is met. If condition 4 is the case, there cannot be fog. Condition 4 has priority over all previous conditions. Fig. 1 shows the variation of the temperatures, which are involved in condition 1 along with periods during which conditions 2, 3 and 4 are satisfied, for a specimen duration of 30 days in May 1981 at Frigg Field. There is a close relationship between fog being forecast as probable or possible, and it being observed.

Results obtained by this method of forecasting have been very encouraging — 65% of good forecasts of fog, but the ratio between false alerts and good forecasts was nearly two.

3.2.2 Multiple linear regression

Quinn (1978) has established a set of multiple linear regression equations which describe the distribution of marine fog over a large sea area of the North Pacific Ocean (30–60° N). The predictand is identified as a probabilistic fog parameter whose value is determined from unique combinations of reported present and past weather, visibility and low cloud type or just weather and visibility elements. Thirty-eight model output and climatological predictor parameters are interpolated to each observation point and used in conjunction with the predictand in the development of the regression parameters in each equation, and these are combined with the fog frequency climatological parameter to form an interactive parameter, and a new set of regression equations is derived.

Karl (1978) has described the development and application of a program to forecast important air–ocean parameters using the methods of model output statistics. The focus of this operationally orientated study is to forecast atmospheric marine horizontal visibility using a discrete analysis of observed visibility and the NOGAPS (Navy Operational Global Atmospheric Prediction System) model output parameters. Three strategies (two based on maximum probability and one based on natural regression) are compared to two multiple linear regression methods. The primary data covers from the North American coast and then eastward to about 37.5° W. Both the dependent and independent data were derived from the same basic set. New or unfamiliar concepts, in addition to the primary methodology, include the statistical division of the North Atlantic Ocean into physically homogeneous

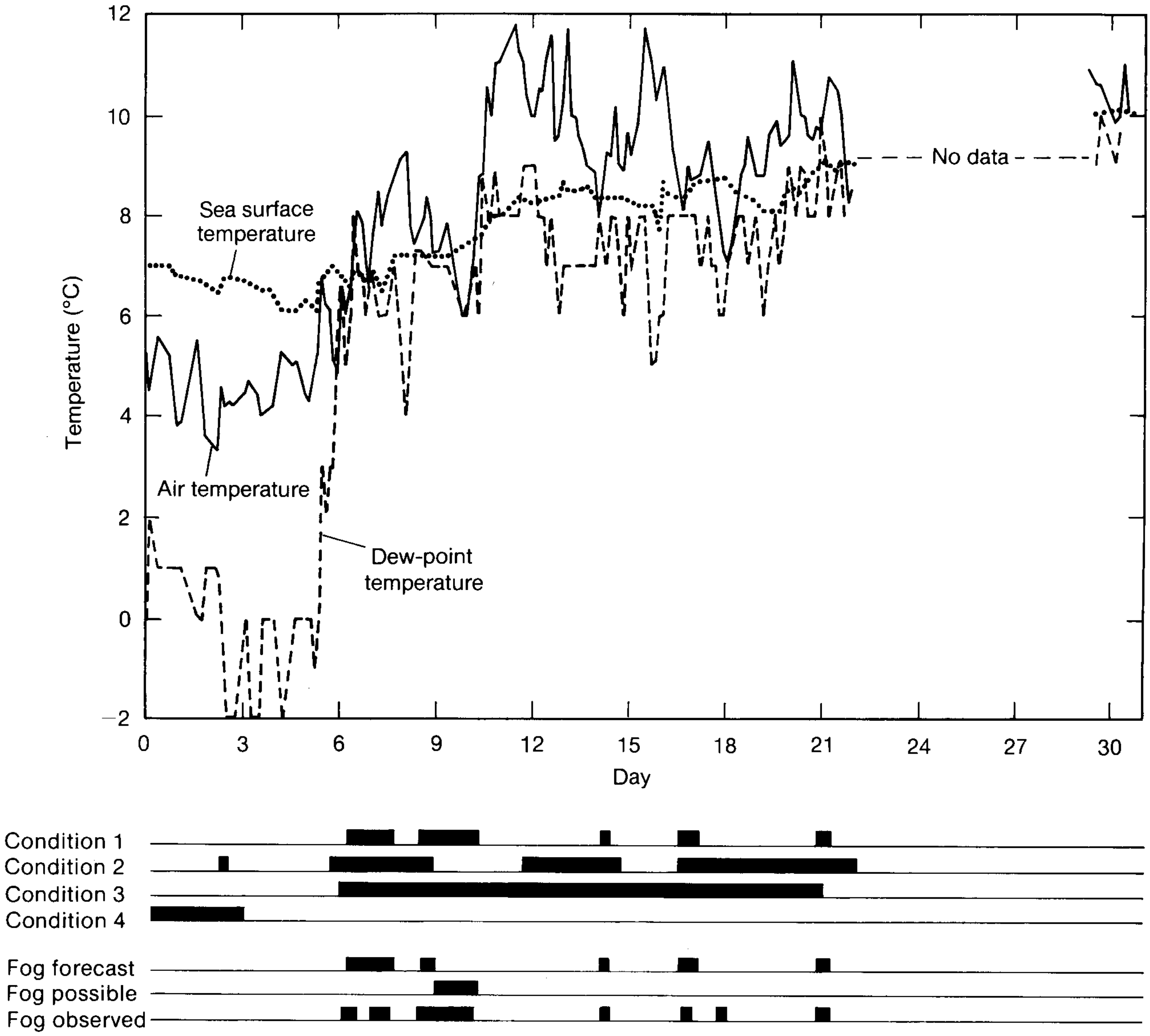

Figure 1. Temperatures recorded on Frigg Field (North Sea) during May 1981; see text for explanation of conditions.

areas, two new threshold models for the application of linear regression equations, linear regression based upon a 'decision tree' concept, functional dependence of predictors and class errors.

The following recommendations are offered for future research:

(a) Investigate the problem of determining the optimum number of equally populated predictor intervals.

(b) Investigate the use of potential predictability in determining the selection of predictors.

(c) Search for better predictors which are particularly suited to visibility prediction.

(d) Investigate other ocean areas and seasons to determine whether the physically homogeneous area scheme is consistent and viable. Develop prediction tables and other aids specifically tailored to region and season.

3.2.3 Other statistical methods used

An algorithm that minimizes the number of errors in linear separation of sets of two different classes has been developed by Polyakov *et al.* (1978). A new method is given by Polkhov and Terziev (1981) for forecasting evaporation fogs on the basis of asynchronous relationships between the thermodynamic state of the atmosphere and the dichotomic variable which takes the value (absence) or (presence) for a given meteorological phenomenon. Quadratic discriminant analysis is used to reveal the relationships.

3.3 Numerical models

Fog formation can result from different causes (radiation, advection, etc.) and it is very difficult to express the role and relative importance of the various processes involved in the formation, development and dispersal of fog. Moreover, a knowledge of the number of droplets of different sizes in a fog is essential to the understanding of many of the physical processes. In all numerical models, the parameter liquid water content is used, which varies quickly spatially and is very difficult to parametrize.

There is no numerical model which forecasts all the types of fog, but different models are used for the different types of fog. Only numerical models of maritime fog are considered here.

From a model elaborated by Fisher and Caplan (1963), Feit (1972) has built a new numerical model which simulates fog in a maritime environment. In this study, some of the features important to the formation and maintenance of sea fog were evaluated. Some experiments point out:

(a) The importance of taking into account the changes of sea surface temperature gradient along the expected air trajectory — a relative minor change in the gradient may mean a difference between fog and no fog.

(b) The effect an irregular sea surface temperature gradient may have on fog formation — the existence of a warm pocket of water along the air trajectory enhanced the formation of fog in quantity, space and time.

The author states that the further development of the model should concentrate upon the effects of radiation and stability on wind shear. Both of these factors are of prime importance in determining the flux of heat into the sea.

Barker (1977) has described a two-dimensional boundary-layer model. Radiational heat loss along with the transport of static energy, moisture and momentum are treated. Cloud droplet distributions are parameterized using a gamma distribution from which radiative properties and droplet fall velocities are computed. Turbulent exchange coefficients are calculated using the Monin-Obukhov theory of similarity which accounts for variations in atmospheric stability. Although the boundary-layer depth depends only on turbulent intensity during stable atmospheric conditions, its growth during unstable conditions is determined from the intensity of the capping inversion and the amount of turbulence generated at the surface.

Several experiments are presented which demonstrate the effects of various meteorological parameters on the formation and duration of stratus and fog. Energy-budget analyses show the importance of each of the physical processes being modelled. Although not a new idea, radiative transfer processes are shown to be extremely important in the transfer of heat from the boundary layer and in the process of fog formation. Fog formation location is highly sensitive to the moisture content upstream, whereas changes in wind speed have much less effect in the spatial variability of fog location. Numerical experiments with other processes such as downward radiation from the atmosphere, haze and cloud-droplet population are described and shown to have smaller effects.

A paper by Pilié *et al.* (1979) summarizes the results of a study on the formation of marine fog along the California coast. On the basis of observations and analyses, physical models have been formulated for the formation and persistence of at least four different types of marine fog which occur off the west coast:

(a) Areas of fog triggered by instability and mixing over warm water.

(b) Fog developed as a result of lowering stratus cloud.

(c) Fog associated with low-level mesoscale convergence.

(d) Coastal radiation fog advected to sea by nocturnal land breezes.

In addition, it has been found that the triggering of embryonic fogs and further downwind development produces a synoptic-scale fog-stratus system, and is responsible for redevelopment of the unstable marine boundary layer. A major problem in explaining the formation of fog over the ocean is the question of how the air reaches saturation.

Telford and Chai (1984) discuss two aspects of convection over oceans and the following conclusions are derived from theoretical considerations:

(a) The air layer over the sea will usually convect even when the water surface is 10 °C or more colder than the initial air temperature.

(b) An inversion at the level of stratus cloud tops is created by the stratus, and is not a necessary pre-existing condition. Such inversions persist after subsidence evaporates the cloud.

(c) Radiational heat exchange does not play an essential role in stratus formation or maintenance, and can either heat or cool the cloud.

(d) Dry air convection does not erode inversions at the top of the convecting layer.

(e) Fogs are most likely to form at sea where the water is coolest and need no radiation effects to initiate cooling or a boost from patches of warmer water, to begin convection.

(f) Both stratus cloud growth, and the evaporation of clouds by cloud-top entrainment, readjust the vertical structure of the air to leave a constant wet-bulb potential temperature with height.

These conclusions are supported by, firstly, a convective model which has been developed and which shows that vapour-driven convection over the ocean will proceed with zero or negative heat fluxes, at rates which saturate the lowest layer of the atmosphere in a few hours to altitudes of many tens of metres. Secondly, the availability of condensed moisture at the top of the surface layer cools the warmer entrained overlying dry air parcels so that when they descend they are no warmer than the sea surface temperature, and this induces downward moving plumes. This occurs if the wet-bulb potential temperature of the overlying air is less than the sea surface temperature, even if it is 10 °C or more warmer than the dry-bulb temperature.

Musson-Genon (1987) has developed a one-dimensional boundary-layer model to simulate a fog event. This model described the condensation processes at sub-grid-scale, the gravitational settling of fog droplets and their interactions with solar and thermal radiation, as well as the turbulent transport associated with turbulent kinetic energy.

The different parametrizations used are rather simple, aimed at operational forecasting. The model seems to be able to describe the mechanisms occurring in fog evolution from its appearance to its disappearance. The data set is one of the most complete ever published, but as yet it is difficult to validate the different parametrizations. Nevertheless, the importance of turbulent transport is emphasized. The sensitivity of the model to thermal cooling, the gravitational settling velocity and the initial data are described together with the usefulness of sub-grid-scale parametrization. In this work emphasis has been placed on the quantitative comparison between computed and observed evolutions.

3.4 Instrumental methods

3.4.1 Lidar

A method of determining the predictors of the formation and dissipation of radiation fogs by means of lidars is presented by Tyabotov and Tikhonov (1982) and the possibilities of its practical use are evaluated. It is shown experimentally that the ratio of the scattering coefficients at wavelengths 1.06 and 0.53 micrometres and the degree of polarization of the lidar radiation backscattered by atmospheric aerosol, are observed to differ during formation and dissipation of fog. Such a difference in the indicated parameters occurs as a consequence of a change in the size and shape of the particles during condensation of water vapour or as a result of evaporation of droplets, and also upon a change in the optical density of the medium.

3.4.2 Satellite images

For some years satellite images have been used routinely in operational weather forecasting as a means of detecting the positions and development of cloud systems and for analysing their characteristics. Systems have been developed which present the image on a display screen and which have sufficient interactive capability to allow enhancement of each image through changes to the grey-scale contrast, magnification, etc. Also, increasing use is envisaged for colour display systems to extend further the amount of information which can be conveyed with a single image.

Detection of fog during the daytime is relatively straightforward using conventional visible and infra-red images. Areas of fog are characteristically bright in the visible image since, in common with most other types of cloud, they strongly reflect solar radiation at visible wavelengths. In contrast to other forms of cloud, however, fog and low stratus appear relatively warm on infra-red images since their temperature is close to that of the underlying land or sea surface. It is because of the latter characteristic that detection of fog on satellite images is difficult at night when visible images are not available. The thermal contrast between the fog top and the surface is usually very small, and, even where this is measurable, it is often difficult to distinguish changes in temperature caused by the presence of fog from spatial variations in surface temperature.

Eyre *et al.* (1984) have studied a method of detecting fog at night using a combination of infra-red images at different wavelengths. The variation of emissivity with infra-red wavelength exhibited by fog is used to distinguish it from land or sea surfaces at similar temperature. An interactive image display system has been used to provide a false-colour representation of a combination of the Advanced Very High Resolution Radiometer (AVHRR) images at 11 and 3.7 micrometres in such a way as to highlight areas of fog and low stratus cloud.

In their paper, Eyre *et al.* have demonstrated the detection of fog and low stratus at night using channels 3 and 4 of the AVHRR imagery. This technique is expected to have considerable potential for application in operational weather forecasting. In addition this work provides an example of one particular application of full resolution digital AVHRR data and illustrates the wealth of information which can be extracted from the images with suitable processing and interactive display techniques.

3.5 Forecasting with expert systems

Investigation into the use of artificial intelligence began in 1956. At the beginning, researchers sought to produce general programs which could solve any problem. Many difficulties arose and researchers turned their attention towards expert systems doing more specialized work.

3.5.1 'Ideal' characteristics of an expert system

Modularity of knowledge: Information from experts in the subject is programmed in a non-structured fashion.

Modification of rules: Rules initially supplied by experts can be easily modified or suppressed, and new ones inserted.

Simplicity of operation of the system: The quality of the man–machine interface is very important. An unqualified person should have no problem in using the system.

Quality of the system: Uncertain information and approximate estimations must be able to be handled. The result must be given as quickly as possible and the number of questions presented to the operator must be as small as possible.

3.5.2 Structure of an expert system

An expert system generally comprises:

A language for expressing expert knowledge: This should be as close as possible to everyday language.
Knowledge base: All the 'production rules' and facts necessary for the correct operation of the system should be included in the knowledge base.
Pattern directed inference system (PDIS): The active element of the system is a program which exploits knowledge stocked in the base, interprets it and works out a final diagnosis.
Complementary functions: These are dialogues with the operator about explanations and the 'path' of reasoning which help correct errors.

3.5.3 Why an expert system?

Compared with a traditional program the advantages are numerous (Tremant 1987b):

(a) Production rules are introduced without a prearranged pattern whilst in traditional programs the representation of knowledge is intimately connected to the sequence of instructions,
(b) the same PDIS can be used to activate several knowledge bases in very different domains. For traditional programs, one program is necessary per domain,
(c) the control of knowledge is completely independent of the knowledge itself in an expert system: in traditional programs this control is set in the structure of the program,
(d) adding new rules poses no problem for an expert system; in traditional programs it is sometimes practically impossible,
(e) production rules for expert systems are easily understood by the operator, which simplifies his work.

The use of expert systems in meteorology is described in greater detail by Conway (1989).

3.5.4 Example of an expert system used to forecast fog

A statistical study showed that it would be very difficult to build a physico-statistical model of fog forecasting at sea. On the other hand, a pre-operational trial proved that the subjective forecast was not too bad. So an expert system was developed to help fog forecasting on Frigg Field in the North Sea (60° N, 02° E). This system was named '4F' (Fog Forecasting on Frigg Field) (Tremant and Roland 1988) and the object of '4F' is to forecast fog for a maximum period of 24 hours using information sent by 'SHIP' messages on the GTS and the detailed analysis maps produced by the various European Weather Centres.

We use the PDIS 'M1' which operates with an IBM/PC compatible computer. The rules are written in PROLOG.

Principle of reasoning followed by the system

It is very important to note that '4F' system was intended for advection fog forecasting on Frigg Field (more than 90% of fog on Frigg Field is advection fog). This system does not forecast radiation fog on Frigg Field but it does take the evolution of such fog into account.

As far as advection fog is concerned, the logistics consists of following its movements in the North Atlantic Ocean. It is also necessary to check that meteorological conditions will not bring about its disappearance in the next 24 hours. It was also checked that there were no 'exceptional' meteorological conditions, and the extent of fog was determined with the help of meteorological data coming from around Frigg Field.

Definitions of areas of study

The most likely movements of perturbations forming off the coast of Newfoundland were considered in order to define three areas of study.

Firstly there was Frigg Field, the subject of the study.

The second area considered, called a sub-synoptic area is defined by the latitudes, 65° and 50° N, and the longitudes, 10° W and 10° E. This area is situated around Frigg Field. The fact that it extends to the north of the English Channel enables any depressions coming from the south to be taken into account, a phenomenon which happens especially in winter.

Finally an interesting area is defined which is called the synoptic area because it allows a picture of almost the whole of the North Atlantic Ocean. It covers from 45° to 70° N and 10° to 45° W. It is in this area that the movements of perturbations were followed.

Reasoning with uncertainty

The expert knowledge being represented includes a factor of uncertainty which has been taken into account in the representation adopted. For this we use a measure of confidence in the forecast and work with four values of certainty. Fog can be 'improbable', 'possible', 'probable' or 'certain' according to specified conditions attached to temperature, atmospheric pressure, and wind speed and direction.

Results obtained

To test our expert system, observations from meteorological charts from previous years were used. These enabled us to be free from mistakes made by the operator. When the system asks the operator for a forecast, the real value taken from the chart is used. Only the reasoning principle was tested, so eventual errors of forecasting are totally attributable to the system. The first results of the '4F' system were very encouraging, as shown in the contingency table below. This expert system was then used in 'real time' for 4 months and seemed to work correctly. However, it is illusory to think that it is possible to forecast all the fogs and it is necessary to remember that, in certain cases, it is as difficult to forecast 'no fog' as it is to forecast 'fog'.

		OBSERVATIONS	
		No fog	Fog
F O R E C A S T S	No fog	correct forecast of no fog 110	non-detection 1
	Fog	false alert 3	correct forecast of fog 9

4. General conclusion

Many numerical models of fog forecasting (generally on land but also over sea) have been actually studied, but a better knowledge of the droplet spectrum, liquid water content and exchanges due to turbulent transport, seems to be necessary to obtain good forecasts of fog.

With statistical models, another problem is encountered — the lack of data over the oceans.

The information which can be extracted from the satellite images is expected to have considerable potential in fog forecasting.

Hence it is recommended that:

'Automatic visibility recorders are installed on ocean-going military and civilian passenger/cargo ships. This will place visibility observations on a more objective basis and lead to improved methods of forecasting visibility, as well as verifying such forecasts'.

Expert systems seem to be the ideal tool to forecast fogs, and more especially coastal fogs. It is very easy, for instance, to introduce rules which take into account the topography of the location for which the fog forecast is prepared.

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Improved values of 1-hour M5 rainfalls for the United Kingdom

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Summary

Previously existing data sets of annual maximum 1-hour duration rainfalls at locations in the United Kingdom have been enlarged with additional observations. This has enabled improved station values of the exceedance rainfall amount with a 5-year return period to be calculated and values for additional stations to be obtained; these are compared with presently used values dating from the early 1970s. The values for south-east England appear to show the influence of summer storms moving north-westwards from France.

1. Introduction

In 1975 the Flood Studies Report (NERC 1975) was published. The report, referred to as FSR, contains recommended values for the rainfall amount which has a specified average interval (return period) between exceedances, as a function of duration and location in the United Kingdom. These exceedance amounts are denoted by the abbreviation used in the FSR — 'duration M return period' values — where the return period is in years. The analysis of data leading to these results was carried out in the Meteorological Office and the methods used are described in the FSR. The data were observations of annual maximum rainfalls for a variety of durations extracted from original autographic records, manuscript tabulations and computer data sets of observations from daily-read storage rain-gauges and tilting-siphon recording rain-gauges, made at many stations in the United Kingdom. For sub-daily durations observations from just over 100 stations were available mainly covering the period from 1950, not long after many new Meteorological Office observing stations opened, to 1970 when the FSR data analysis started.

Because of the wide separation of these sub-daily stations it was not possible to produce an adequately detailed map of 1-hour (or 60-minute) M5 rainfall by simply contouring to station values (the small distinction between 60-minute and 1-hour duration rainfalls, unimportant at present, is explained later). Instead a method was used in which the few observed values of 1-hour M5 rainfall were related by regression equations to two parameters assumed to be associated with the size of extreme short duration rainfalls; these were the average number of days per year with thunder reported, and a complicated function of the occurrence of high humidities. The equations enabled an apparently more detailed map of 1-hour M5 rainfall over the United Kingdom to be produced. It was not stated in the FSR how well the regression equations fitted the data so that it is not possible to judge just how much of the detail in the map is correct; it is demonstrated later that the map does not appear to reproduce all the original FSR station values.

The FSR contains a copy of this map for occasional use but the map has also been digitized so that a spatially interpolated 1-hour M5 rainfall for a specified location can be extracted rapidly by computer. These values, produced by the 'ITED' computer program (Keers and Wescott 1977) are still used frequently by the Meteorological Office Advisory Services Branch after 11 years to answer enquiries in a wide range of applications.

In 1987 a further analysis of 1-hour annual maximum rainfalls was started. More data than were available in the early 1970s have been accumulated by extending station records forward to 1986 and backwards to the start of the observations, and data from additional stations have been found. This has enabled improved values of exceedance amounts to be obtained for a range of return periods but in this paper a description is given of results for 5-year return period values only. These are of particular relevance since they are frequently used by hydrologists and engineers in the design of drainage structures for urban catchments which are often sensitive to flooding from intense rainfalls of about 1 hour's duration. The aim of the work is to investigate whether there is any evidence which would suggest that the FSR recommendations require amendment or can be improved.

2. Estimation of 1-hour M5 rainfalls

In the FSR it is stated that the geometric mean of the annual maxima for a station in the upper half of their arrangement in ascending order of magnitude is an accurate estimate of the exceedance amount for a return period T which is approximately 5 years (strictly 4.45 years). The estimate for a T of exactly 5 years, M5, can be obtained by adding a small correction $+0.11\ \alpha$ where α is the slope of exceedance amount plotted against y, the reduced variate $= -\ln[\ln\{T/(T-1)\}]$. The exceedance amounts for other return periods, required to estimate α, are given by further functions of the ordered annual maxima as specified in the FSR. Typically α is $+5.0$ mm and so the correction is approximately 0.6 mm or 3% to 6% of M5 which varies from about 20 mm in southern England to 10 mm in north-west Scotland.

This method is used in the work described here and in the FSR to estimate the 1-hour M5 rainfalls except that in the FSR it was not stated explicitly how the correction was made.

The standard error of the M5 estimate is given by s.e. $= 1.8 \times \alpha \times n^{-1/2}$ where n is the number of annual maxima used. The standard error decreases with n, i.e. the longer the record the more accurate the estimate is likely to be.

A detailed record of rainfall at a station can be analysed to produce annual maxima of either 60-minute rainfalls which can start at any time or, more usually nowadays, 1-hour rainfalls which are constrained to start on GMT hours. A 60-minute period can be located freely to contain the absolute largest rainfall in such a period during a year. This amount is as large or larger than the annual maximum for 60-minute periods which start on GMT hours because these periods cannot be located freely. As a consequence 60-minute M5 values are larger on average than 1-hour M5 values, by a factor of 1.15 as quoted in the FSR. Therefore, where necessary, 60-minute M5 values are multiplied by 0.87 to give corresponding estimates for 1-hour M5 rainfalls. All results in this paper are for 1-hour duration.

3. Sources of data

The following sources of annual maximum rainfalls are used here.

(a) The original values in manuscript for 112 stations, mainly for the period 1951–70 and extracted in the Meteorological Office for the preparation of the FSR. The maxima were for 60-minute rainfalls from 33 stations and 1-hour rainfalls from the remaining stations.

(b) Further tabulations of hourly rainfalls stored in the Meteorological Office's data archives at Bracknell, Edinburgh and Belfast have been scrutinized to extend many of the records in section 3(a) backwards to the start of observations and forward to 1979. Annual maxima have also been extracted for additional stations whose tabulations were not available at the time of the FSR analysis. Since 1980, hourly totals have been transferred routinely to computer data sets and the annual maxima have been extracted from these.

A computer data set of all these annual maxima has been created with provision for updating. It is believed that this now contains most of the reliable 1-hour or 60-minute annual maximum rainfalls available from sources within the Meteorological Office Archives. Some stations have values missing for occasional years but if these are randomly distributed through the length of records this does not result in bias errors in the M5 values. In this work, record length is the number, n, of the annual maxima in a station's record. For some stations only recently commencing observations the record lengths are short but their maxima have been included in the data set in anticipation of their continued operation giving data for future use.

Fig. 1 shows the number of stations with the indicated record length as used in the FSR, and in this work. The number of annual maxima are 2284 and 4532 and the number of stations 112 and 234 respectively, about doubled in both cases. The data from new stations are mainly confined to England and Northern Ireland while the addition to Scottish and Welsh data is mostly in increased record lengths. Unfortunately the addition of new data does little to improve the lack of observations from high altitude stations, Ben Nevis (National Grid

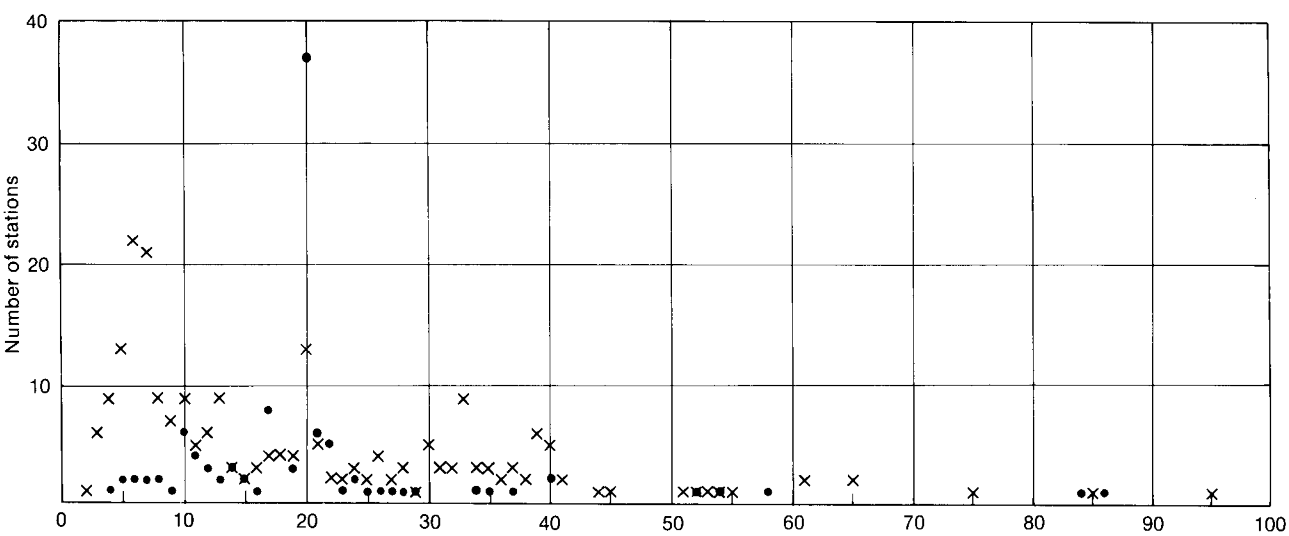

Figure 1. Statistics of station record lengths used in the FSR (dots) and in this paper (crosses), showing the numbers of stations having the specified number of annual maximum 1-hour (or 60-minute) rainfalls in their record.

Reference NN 167713) at 1343 m still being the only station with an altitude greater than 400 m. The stations are distributed over the whole of the United Kingdom but concentrated in south-east England as shown in Fig. 2 in which those with record lengths of 20 years or greater, i.e. at least four times the return period, are shown by the larger dots.

4. Variation of extreme 1-hour rainfalls and M5 values with time

In the FSR, 1-hour M5 values were presented as being generally applicable to a period of few decades up to 1970 without any consideration of whether there were changes during that period in the 'climate' of extreme rainfalls. This was mainly because record lengths for sub-daily rainfalls were inadequate. The extended data set of annual maximum 1-hour rainfalls now available has enabled an investigation of changes in the size of extreme rainfalls and 1-hour M5 values to be made.

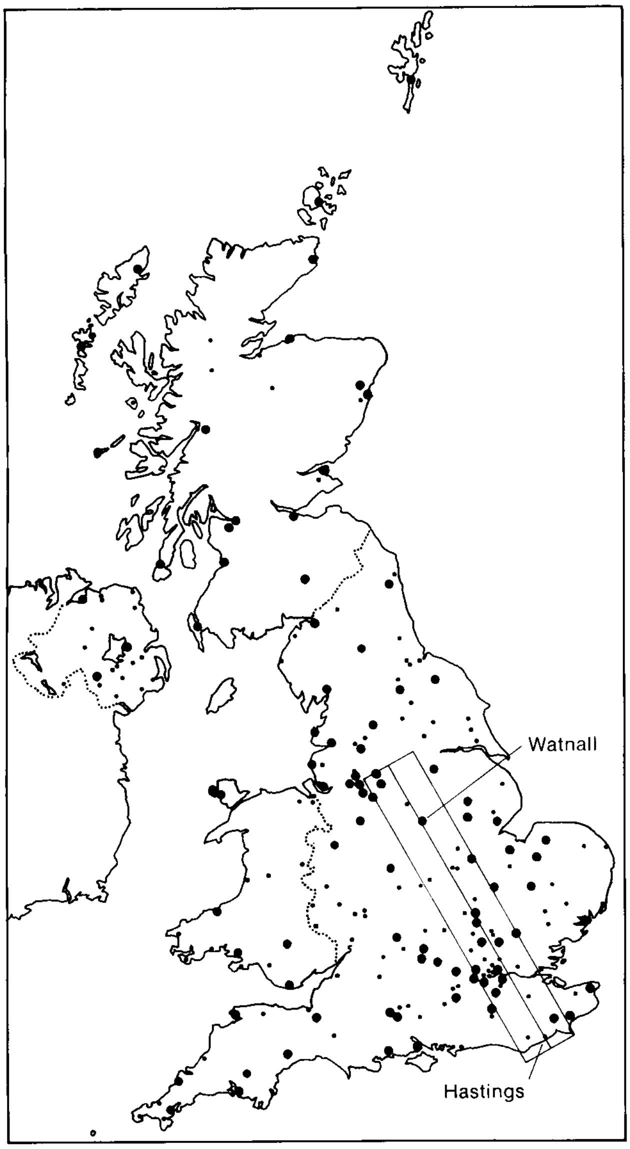

Figure 2. Location of stations whose annual maximum rainfalls have been used in this study. The larger dots indicate those stations with record lengths of 20 years or more. The rectangle, of width 60 km, along a line from Hastings (East Sussex) to Watnall (Nottinghamshire), contains the stations whose 1-hour M5 rainfalls are plotted in Fig. 4.

May and Hitch (1989) have demonstrated that over the period from 1881 to 1986 these annual maximum rainfalls contain roughly sine-wave variations of period 7, 11, 20 and 50 years with amplitudes of 7%, 10%, 5% and 7%. They have also suggested that these variations occur synchronously over most of the United Kingdom (but at any specific station they are hidden by the larger natural random year-to-year variation of annual maxima) and affect all large rainfalls, not only the maxima.

Since about 1940 the amplitude of the 20- and 50-year period waves have reduced almost to extinction, but the 7- and 11-year period waves have maintained their size over the whole of the 106-year interval. The latter waves appear to be related to the 11-year periodicity of solar activity but their combination has maxima at alternate intervals of 9 and 13 years, instead of 11 years. On the basis of past behaviour, the next maxima of rainfalls are expected to occur in 1990 and 2003, and minima in 1996 and 2007, with magnitudes of about 10% greater and 10% less than the overall average since 1940.

In effect M5 values have a variability which is influenced by this periodicity of extreme rainfalls in both magnitude and phase. Depending upon the length and epoch of a record, an M5 value may contain some influence of the 7-, 11-, 20- or 50-year period variation. In this work all M5 values were corrected to equivalent values appropriate to the period since 1940 though of course they are still inaccurate to some extent because of the finite record lengths used. All of these corrections were smaller than ±4% and most were zero.

5. The 1-hour M5 values which are compared

The following values are investigated:

(a) the original 'FSR' values, which were derived in the preparation of the FSR as described in section 2 (apart from the unknown correction) using the data described in section 3(a),

(b) values generated using the 'ITED' program which was based on the FSR data, and

(c) 'MH' (May-Hitch) values, along with their standard errors calculated from the longer records from more stations described in section 3(b) using the methods described in section 2.

6. Results of comparisons of 1-hour M5 values

6.1 MH and FSR values

6.1.1 With identical maxima

This comparison is made to determine the component of (MH−FSR) differences arising from the way the small correction described in section 2 is applied; it is made for the sample of 38 stations (well distributed over the United Kingdom) for which the MH and FSR M5 values are calculated using the identical sequence of annual maxima. The small interquartile range, 0.2 mm, confirms that the differences are nearly constant with a median value of +0.4 mm, which is very small compared with other differences described later and with the range of M5 over the United Kingdom.

In effect, the methods used to calculate the MH and FSR values give nearly identical results.

6.1.2 Approximately doubling the record length

It is useful to investigate changes in M5 values arising from changes in record length. There are 37 stations used to calculate the FSR values with original record lengths which have been approximately doubled prior to calculating the MH values, typically from about 19 to 38 years. The M5 values are either increased or decreased by increasing the record length, which results in an increased interquartile range of (MH−FSR) of 1.5 mm with a median value of +0.6 mm, of which 0.2 mm and +0.4 mm respectively can be attributed to the (MH−FSR) differences described in the previous section. This suggests that the balance of 1.3 mm in the range and +0.2 mm in the median is the increase resulting from doubling of record length, and again these are small compared with the range of M5 values. This size of increase of record length is unlikely to change the broad-scale picture of the variations of M5 over the United Kingdom. It does not mean though that it is pointless continuing making measurements to increase record lengths and hence accuracy; the consequent improvement in accuracy of the M5 values enables interesting and significant smaller-scale detail to be resolved as demonstrated in the next section.

6.2 MH and ITED values

The main purpose of the work described in this paper is to compare the new MH values with the established ITED values.

Fig. 3 is a map of contours of the percentage difference between MH and ITED values defined by {(MH−ITED)/MH} × 100%. The station values are not shown for reasons of clarity. The positions of the contours in Fig. 3 were estimated by eye taking into account the standard error of each MH value and giving a greater weight to the values with small error; they are drawn over some sea areas only as a visual guide. In Scotland (especially), Wales and the south-west region the stations are still widely separated in spite of the increased numbers and this leads to an inevitable lack of detail in the contoured fields in these areas. In Northern Ireland there is more implied complexity of the field but it is based mainly on station records of less than fifteen years' duration (only three stations have longer records — Armagh, Aldergrove and Ballykelly with $n = 85$, 61 and 24 years). The densest congregation of stations is in the London and Manchester areas.

Over the United Kingdom as a whole the percentage difference ranges from about −30% (MH less than ITED) to +20%. At first sight there appears to be no reason for the particular shape or position of the contours — for instance they are not obviously related to large-scale areas of high ground which is the case for other aspects of rainfall such as the annual average. However, the denser observations in south-east England depict an interesting pattern of alternate elongated areas of positive and negative differences roughly transverse to a line drawn from Hastings to Watnall and beyond, as indicated in Fig. 2. This undulating pattern could be caused by similar variations in the MH or the ITED

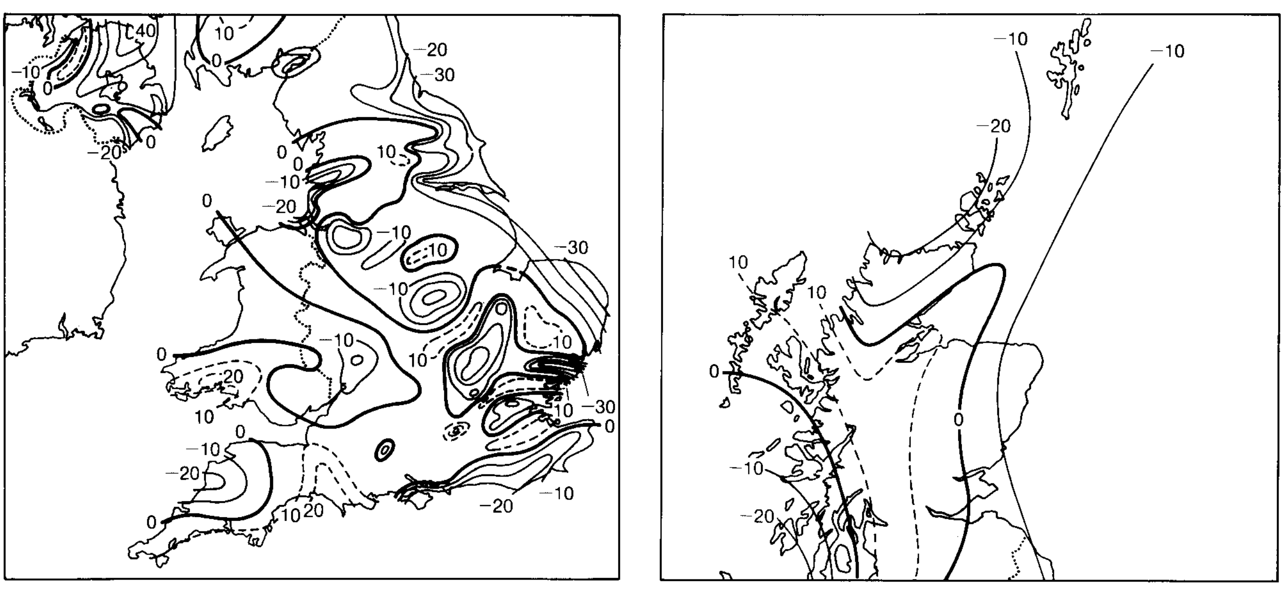

Figure 3. Isopleths of {(MH−ITED)/MH} × 100%, where MH values are 1-hour rainfalls described in this article and ITED values are based on the digitized version of the FSR map. Isopleths are at 10% intervals, with positive values being dashed and negative being full lines; the zero isopleths are the bold lines. See text for explanation of terms. The diagram is split for convenience.

values, or both. In Fig. 4(b) are plotted the MH values of 1-hour M5 with their standard error bars for all stations within 30 km either side of the Hastings–Watnall line against their distance along the line north-westwards from an arbitrary reference point off the coast as shown in Fig. 2. These values show a clear undulation whereas the ITED values for the same stations, as shown in Fig. 4(a) show hardly any variation at all. For comparison the smaller number of original FSR values are shown in both Figs 4(a) and 4(b). They agree well with the MH values (with the exception of one station) which is to be expected from the results of the previous comparisons. The FSR values plotted in Fig. 4(a) suggest the presence of the undulation as is also the case in the FSR map, but not with the clarity of the MH values. In Fig. 4(a) the ITED values do not even reproduce the small amount of structure implied by the FSR values but are a very smoothed version of them. This departure between FSR and ITED co-located values is extensive over the United Kingdom — for a widespread sample of 88 stations the difference (FSR−ITED) has an interquartile range of 2.0 mm and a median of −0.6 mm. These values increase to 3.7 mm and −0.9 mm for (MH−ITED) differences for 48 stations which were not used in the construction of the FSR map; taking into account the (MH−FSR) contribution, the equivalent (FSR−ITED) differences for these independent stations have a range and median of about 3.5 mm and −1.3 mm. These results suggest that the ITED values depict only the large-scale features of the variation of 1-hour M5 values over the United Kingdom, probably not as much as is implied by even the original FSR station values, and they do not even reproduce those very closely, although their standard errors are about 2.5 mm on average.

Although some of the MH values have large standard errors the overall consistency with which they show the undulation in Figs 3 and 4(b) gives confidence in its reality.

The Hastings–Watnall line is of interest because it cuts across successive areas of high ground — the Sussex Weald, North Downs, Chiltern Hills, Northamptonshire Weald and finally the Peak District, as shown schematically in Fig. 4(c). The spatial wavelength of the undulations in 1-hour M5 rainfall is close to that of the underlying ground height. It is not possible to say whether the maxima of 1-hour M5 of about 20 mm and the minima of about 14 mm, are more closely co-located with the maxima, minima or intermediate slopes of the ground profile. Certainly a strong possibility is that the maxima of 1-hour M5 are co-located with the south-east facing ground slopes as indicated by the lines in Fig. 4, and the undulating pattern in Fig. 3 gives the impression of spreading from the south coast. This suggests that we are seeing the effects of heavy rainfalls produced by orographic uplifting associated with summer thunderstorms which are observed to develop over the French mainland, cross the English Channel perhaps favouring

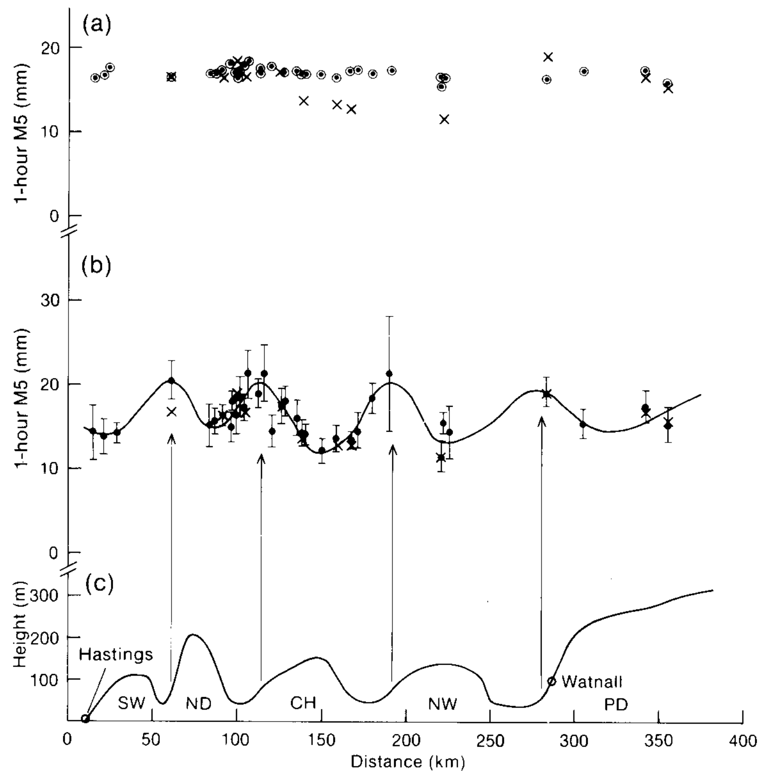

Figure 4. Variation in (a) ITED (dots) and FSR (crosses), (b) MH (dots with standard error bars) and FSR (crosses) station values of 1-hour M5 rainfall as a function of distance along the Hastings–Watnall line (terms as in Fig. 3), from all stations in the rectangle in Fig. 2, and (c) is a schematic cross-section of ground height along the Hastings–Watnall line, where SW = Sussex Weald, ND = North Downs, CH = Chiltern Hills, NW = Northamptonshire Weald and PD = Peak District.

the narrowest crossing and then travelling north-westwards well into the Midlands; this behaviour is well known to forecasters but is not well documented. It should be noted that, according to Prichard (1976), the major thunderstorm regions in the United Kingdom are the Pennine Hills, particularly around the Peak District and the east Midlands especially from Nottingham to the western suburbs of London, an area roughly coinciding with the rectangle in Fig. 2.

7. Variation of occurrence of annual maximum rainfalls during the year

During the extraction of the annual maximum rainfalls the month in which they occurred was noted and for each station an index, I, was calculated which is the percentage of years in which the maxima fell in the 'summer' months April–September. An index of 100% indicates all maxima occurring in summer and 50% means that they are distributed more evenly throughout the year. Fig. 5 shows a map of I based on stations with record lengths of 20 or more years. Apart from areas of south-west England and Wales, and north-west Scotland, with $I \approx 60$–70%, the maximum rainfalls show a strong tendency towards summer occurrence with $I \approx 90$–100% particularly in the area from south-east England through the Midlands to the Manchester area. Again in the south-east the undulating pattern in evident as in Fig. 3, though the position of its features are not obviously related to those of M5.

Figure 5. Isopleths of I, the percentage of years in which the annual maximum 1-hour rainfall occurs in the 'summer' months April–September.

8. Conclusions

The new results reported here with their greater accuracy indicate that 1-hour M5 rainfall in south-east England (at least) has a more complicated structure than is indicated by the map in the FSR and its digitized version used in the ITED computer program. The FSR map probably oversmooths the original FSR station values on which it was based presumably because of the particular way in which climatological data were used to improve the map through regression techniques.

The larger number of station values of 1-hour M5 rainfall now available allows a more detailed map for south-east England to be drawn directly without the use of supplementary data. In this area the spatial variation of M5 appears to be related to high ground in a way which depends upon the local meteorology of summer storms. This suggests that it may be difficult to devise general regression schemes for interpolation between station values over the whole of the United Kingdom using conventional climatological or topographical data as in the FSR. It is not known whether the availability of more station values in other parts of the United Kingdom would reveal a more complicated structure of 1-hour M5 rainfall determined by their local storm meteorology. It seems that there may be a role here for radar observations of rain with their dense coverage in time and space for determining the local meteorology of the occurrence of extreme falls in different areas, which could then be used to infer small-scale structure within the accurate M5 values from gauge observations.

Acknowledgement

The authors wish to acknowledge the assistance of the staff of the Meteorological Offices in Edinburgh and Belfast for supplying annual maximum rainfalls for stations in Scotland and Northern Ireland, and also of the staff of the Meteorological Technical Archives, Bracknell, in tracing tabulations of hourly rainfalls.

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Local forecasting of a small-scale synoptic event over the Isle of Man on 18 November 1986

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Summary

The rainfall distribution and low-level winds associated with a warm front wave which passed over the south and east of the Isle of Man on 18 November 1986 are analysed, illustrating some of the problems associated with forecasting for an island smaller than the grid size of a fine-mesh numerical model (Meteorological Office 1986 version).

1. Introduction

A warm front wave moved eastwards across the Irish Sea during the evening of 18 November 1986, passing over the south and east of the Isle of Man, producing heavy rainfall and local flooding. Flooding is not common on this rugged island, but was particularly severe in and near the village of Laxey, which lies at the seaward conjunction of two deep river valleys on the eastern side of the island (Fig. 1).

The climatological rainfall distribution over the island virtually follows the orographic contours, with over 125% more rainfall on the highest ground than on the north and south coastal extremities. However on this occasion the rainfall distribution was markedly different (Fig. 2), with most of the rain falling on the south-eastern slopes of the south-west to north-east ridge of high ground which forms the 'backbone' of the

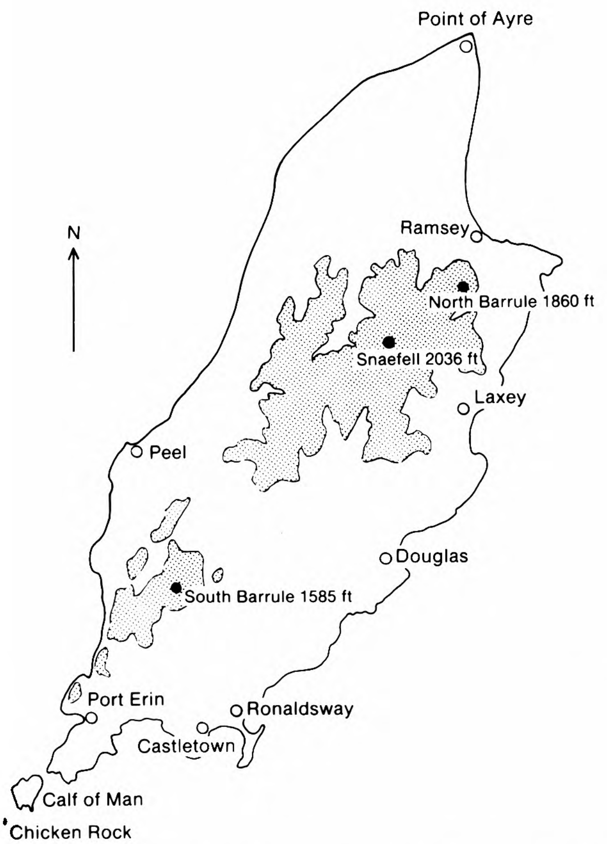

Figure 1. Map of the Isle of Man (situated in the Irish Sea) showing location of places mentioned in the text. The stippled area denotes land above 750 feet.

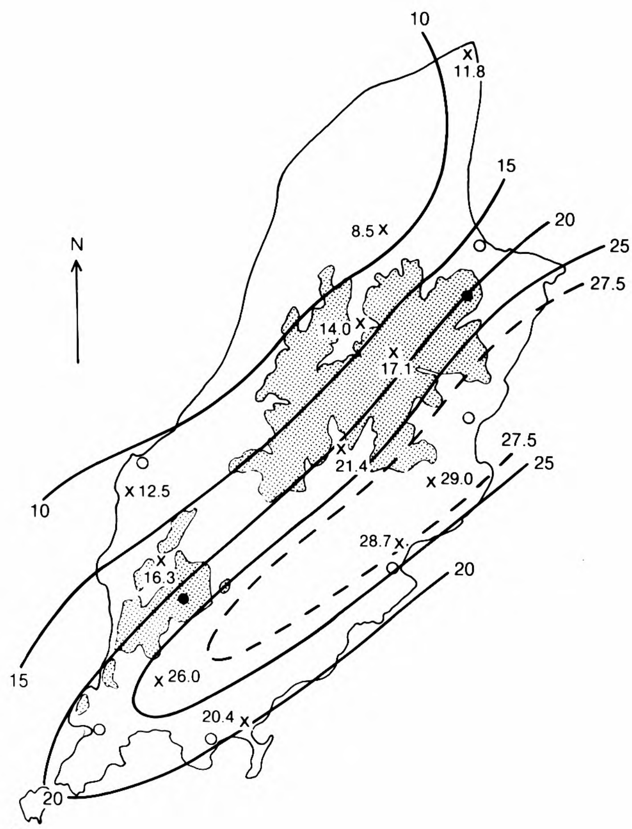

Figure 2. Contours of rainfall (mm) over the Isle of Man between 0900 GMT on 18 November and 0900 GMT on 19 November 1986. Crosses with small figures show location of rain-gauges and measured amounts (mm). High ground stippled as in Fig. 1.

* Mr McGain died during the preparation of this article, which was completed by Dr A. Hisscott of the same department.

island. The highest daily totals (0900 GMT on 18 November to 0900 GMT on 19 November) approached 30 mm (most of which fell between 1800 and 2200 GMT) and occurred in the Douglas-Laxey area.

Ronaldsway is a forecasting office with aviation and public service commitments. Forecasters rely heavily on surface synoptic charts and numerical model forecast products broadcast from Bracknell by landline facsimile. This event illustrated some particular difficulties in forecasting for an island which is smaller than the grid length of the fine-mesh model (Meteorological Office 1986 version) and not explicitly represented in the model topography. The teleprinter broadcast of radar rainfall information from the UK weather radar network proved useful, but satellite images (received locally from Meteosat using Feedback WSR 513/5 equipment) were of little value in this instance because the whole weather system was shielded by a thick cirrus layer.

2. Synoptic details

Fig. 3 shows the path of the centre of low pressure associated with the warm front wave from the west coast of Ireland at 1800 GMT on 18 November 1986 across the Irish Sea and northern England to reach the North Sea by 0200 GMT on 19 November. The central pressure slowly filled during that time from 989 mb to 990 mb as it passed close to Ronaldsway at 2200 GMT, then to 992 mb by the time it reached the North Sea. The leading edge of the warm air at the surface is also indicated at 2-hour intervals. The warm air progressed

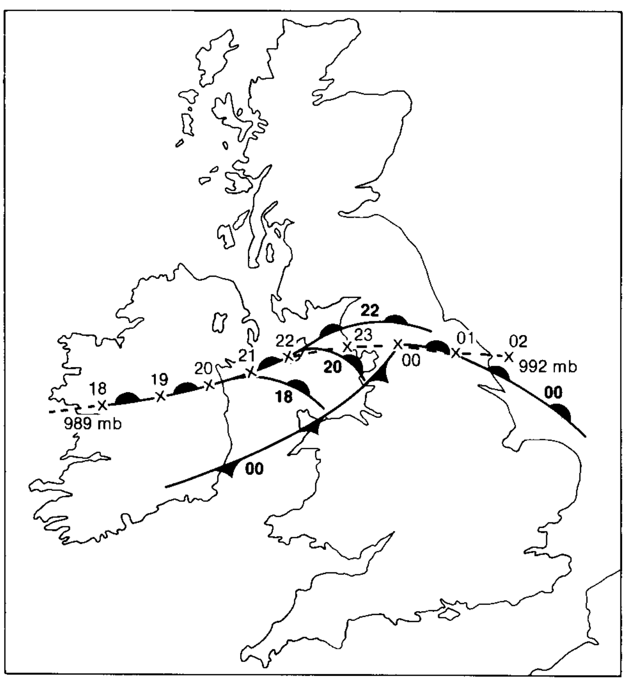

Figure 3. Track of low pressure centre as it crossed the British Isles. Crosses show position of centre from 1800 GMT on 18 November to 0200 GMT on 19 November 1986 with values of central pressure at those times. Also indicated are the positions of the surface warm front at 2-hour intervals (times shown in bold) and the surface cold front at 0000 GMT on 19 November 1986.

north-eastwards from southern Ireland at 1800 GMT up the east side of the Isle of Man during the evening to reach its most northerly extent (Ramsey–Cumbria) by 2200 GMT. It appears that the surface front became quasi-stationary over the east side of the Isle of Man, with the transition from a northward moving warm front to a south-eastward push of cold air occurring probably near Laxey (perhaps influenced by the orographic uplift and convergence provided by the island).

An accurate location of the warm front was provided by an executive turbo-prop aircraft equipped with instrumentation to display instantaneous wind speed and direction, on approach to runway '09' at Ronaldsway. At 1900 GMT the pilot reported a wind of 220° 54 kn at 1000 ft over Chicken Rock (in the warm air) and flew through the front to reach Ronaldsway some 14 km east-north-east at 1907 GMT where the surface wind was 080° 12 kn. The pilot reported 'significant low-level wind shear on approach'!

The warm air reached Snaefell, the highest peak on the island at 2036 ft, at around 2000 GMT when the surface wind changed from easterly at 30 kn to south-westerly at 12 kn by 2015 GMT. The surface front did not reach as far north as Point of Ayre, where the surface wind remained between east and north-east throughout the evening and the dew-point did not rise above 8 °C (compared with 10 °C characteristic of the warm air). Subjective reports of surface wind suggest that the low centre passed north of Ronaldsway but south-east of the ridge of high ground at South Barrule (1585 ft). The largest rainfall accumulations occurred along the surface front as it lay over the eastern flank of the Isle of Man. The largest recorded total, near Laxey, was probably due to the front becoming quasi-stationary here as the cold air began to push south-eastwards. Onshore low-level winds may have also contributed through orographic enhancement.

3. Local forecasts

Ronaldsway is a small forecasting office. Most forecasts are based on surface chart analysis (assisted by satellite and radar information) and the fine-mesh and coarse-mesh numerical products broadcast from Bracknell. The fine-mesh data are normally particularly useful. The mean-sea-level pressure fields assist in estimating surface winds at the airfield and over the northern Irish Sea. The 850 mb wet-bulb potential temperature (θ_w) fields, in conjunction with sea surface temperatures measured daily at Port Erin by the Marine Biological Station, are useful in predicting low cloud and coastal fog. The 6-hour accumulated rainfall totals at the closest fine-mesh grid-point (east of the island, highlighted in Fig. 4) are usually a helpful guide to precipitation amounts and intensity expected over the island.

The T+24 hr fine-mesh forecast frames for 0000 GMT on 19 November 1986 (based on analysis of data from the previous midnight) are shown in Fig. 4(a).

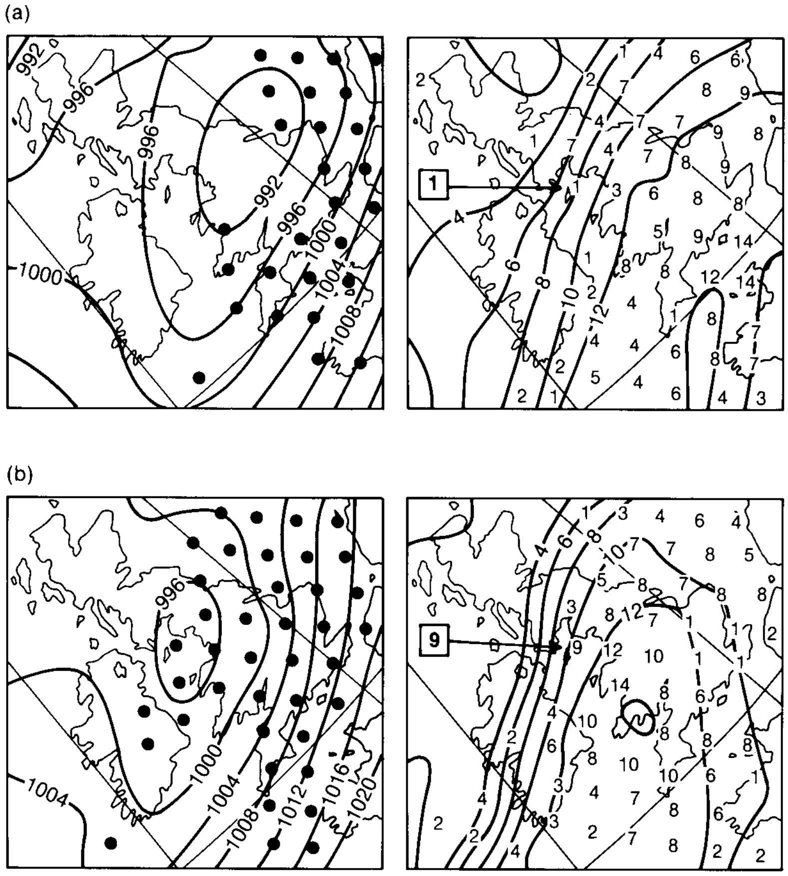

Figure 4. Fine-mesh model forecasts of mean-sea-level pressure (mb) and instantaneous rainfall (dots show 0.5–4.0 mm h^{-1}) on the left, and 850 mb θ_w contours (°C) and 6-hour (to verification time) accumulated rainfall totals (mm) on the right, for (a) 24-hour forecast, and (b) 12-hour forecast, both verifying at 0000 GMT 19 November 1986. The highlighted rainfall accumulation forecast is for the grid point nearest to the Isle of Man.

Similar forecast frames for the same time but a T+12 hr forecast from midday data on 18 November are shown in Fig. 4(b). The pressure pattern for both forecasts is quite good, with a low centre crossing the Irish Sea during the evening, although the timing of the earlier forecast proved to be too fast and that of the later forecast too slow, and the warm-sector winds were significantly stronger in the latter. The 850 mb θ_w pattern of the T+24 hr forecast showed a θ_w gradient across southern Ireland, North Wales and northern England, whereas the later T+12 hr forecast showed a much tighter band of θ_w gradient further north across the Isle of Man which correlated well with the observed frontal behaviour.

The earlier forecast predicted a midday to midnight 12 hr rainfall accumulation of 3 mm at the grid point closest to the island. Morning forecasts issued from Ronaldsway, based on this information, did not mention heavy rain explicitly. The later fine-mesh forecast predicted 13 mm at this point during the same period, and afternoon forecasts disseminated by Ronaldsway mentioned periods of heavy rain, and a warning was issued to the local authority (based on a criterion of 10 mm accumulation). Both numerical forecast runs predicted the largest rainfall accumulations further south in the warm sector, away from the front.

4. Discussion

Analysis of observations from around the Isle of Man on the evening of 18 November 1986 showed that the heaviest rainfall occurred close to the surface front and that there was significant wind shear associated with this synoptic feature. Neither of these phenomena could be easily inferred from the available fine-mesh numerical forecast products. Although the large-scale advice from the model is basically very good, forecasters must beware of the model tendency to average out quantities over the scale of one or two grid lengths, shifting the emphasis away from the air-mass discontinuity whereas in the real atmosphere many of the interesting features arise from the dynamics of the discontinuity. In this case, curving of the isobars to fit smoothly between grid points detracts from the detail of the observed wind shear. The occurrence of almost 30 mm of rainfall on one side of the island and less than 10 mm on the other is not far from the model prediction of 13 mm averaged over the area represented by one grid square. However, the model output would not lead forecasters to expect the heaviest rainfall along the surface front. Although most research today is done in terms of numerical models there is still a need for detailed synoptic analysis of interesting weather features.

Mechanisms of orographic precipitation*

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Summary

The mechanisms which are thought to produce orographic rainfall in various climate zones of the world are discussed.

1. Introduction

The effect of mountains on the hydrological cycle is most clearly seen on maps showing the correspondence between patterns of precipitation amount and terrain height. Examples are shown in Figs 1 and 2. This correspondence has been known in some geographical areas, and suspected in others, for many years, yet scientific research on the problem has proceeded slowly. The current understanding of orographic precipitation is reviewed in this article. More general discussions of the subject are given by Bonacina (1945), Browning (1978, 1980) and Smith (1979).

Orographic precipitation enhancement occurs in a wide variety of latitudes, climates and weather conditions, near terrain of differing size and shape. It appears almost certain that the enhancement mechanisms vary from region to region. Four basic mechanisms have so far been identified: smooth forced ascent, the Bergeron seeder-feeder cloud mechanism, diurnally forced convection and triggered convection by forced ascent or blocking.

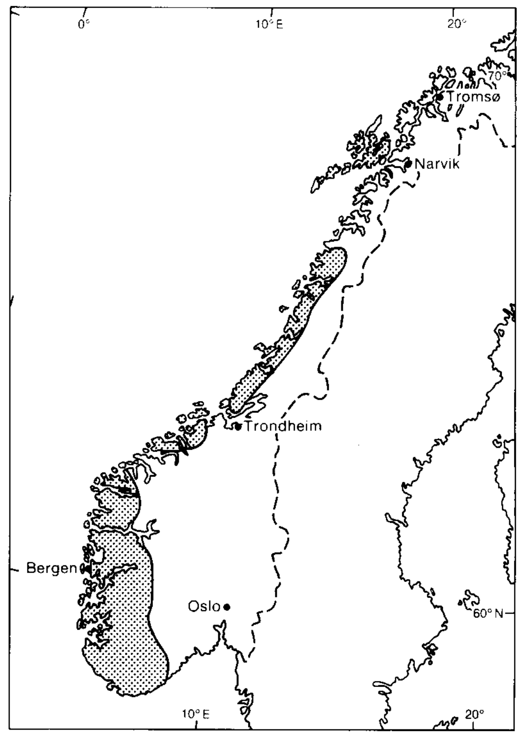

Figure 1. Mean annual precipitation in Norway during the period 1931–60 showing the enhancement near west-facing mountains. The stippled area receives more than 125 cm, while the annual global average precipitation is 88 cm.

2. Smooth forced ascent

A common aspect of orographic precipitation is that the enhancement occurs on the upwind side of a mountain range. In some climates this relationship is so reliable that the precipitation pattern around a mountain range can be used as a crude indicator of regional wind direction. In a recent study, Fjørtoft (personal communication) suggests that the rainfall at three stations in Norway can be used to classify the northern hemisphere circulation features into distinct flow types. Each distinct circulation type brings upslope conditions to the different stations in Norway. Such a correlation is remarkable considering that no details of the precipitation process (synoptic, mesoscale, or cloud physical) are considered.

The most often heard explanation for such observations is that smooth terrain-forced ascent will cool the air adiabatically, producing condensation and perhaps precipitation (Fig. 3(a)). Although this is the textbook

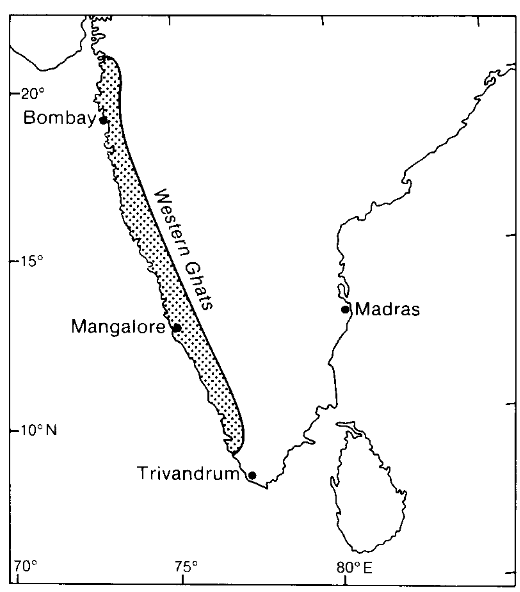

Figure 2. As Fig. 1 but for the Indian south-west monsoon season.

* Based on a paper presented at the 1986 ECMWF Seminar, 'Observations, theory and modelling of orographic effects', ECMWF, Reading, United Kingdom, 15–19 September 1986.

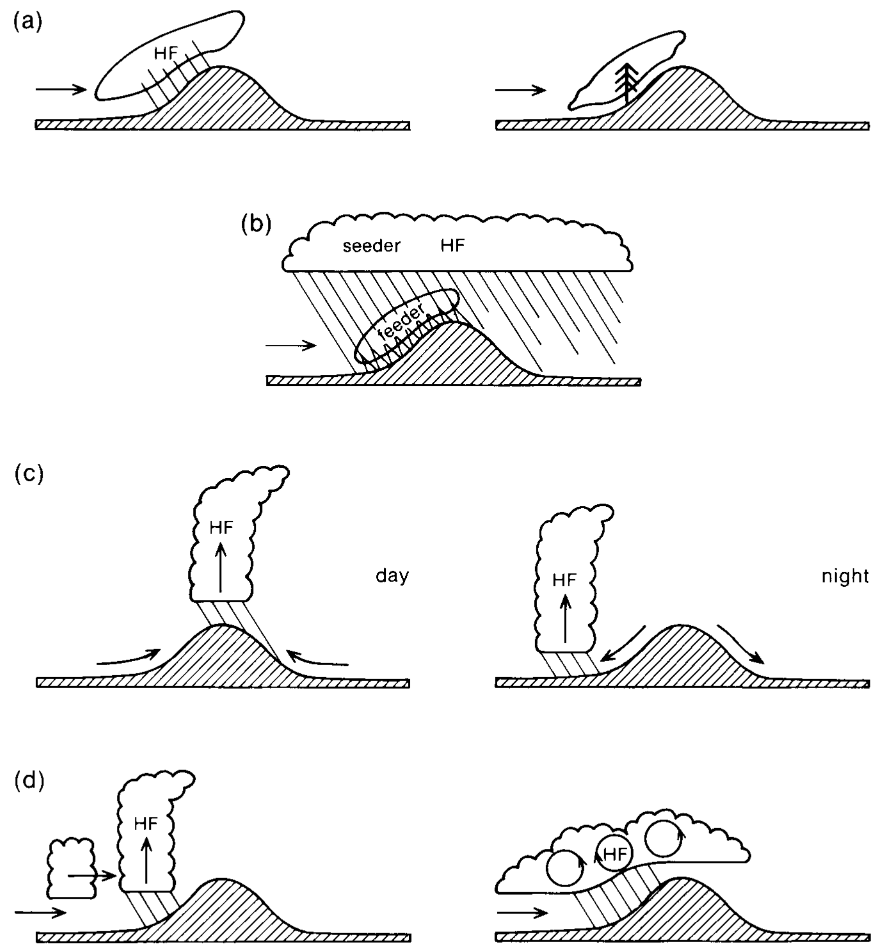

Figure 3. Four idealized mechanisms for orographic rain, (a) smooth forced ascent with hydrometeor formation or scavenging by foliage, (b) seeder-feeder, (c) diurnal convection and (d) triggering penetrative or shallow convection. The region of hydrometeor formation (HF) is shown.

explanation for orographic rain, it has a serious weakness. As pointed out by Bergeron (1960), if the mountain width and the wind speed are moderate, there is not sufficient time for hydrometeor formation; both the collision-coalescence mechanism and the ice-phase mechanism take time to work. Furthermore, supercooled water, which is needed for the ice-phase mechanism, may not be present in the low-level air forced up by terrain. As research on these problems has advanced over the last 20 years, it has become more and more possible that the 'textbook' mechanism may not be found anywhere on earth! Of course it is still a convenient way for beginning to teach students about the thermodynamics relating ascent and condensation.

One recently proposed location for the application of the smooth forced ascent model is the island of Hawaii. Data from the Hawaiian Warm Rain Project in 1985 suggest that very rapid hydrometeor formation is possible in ascending air upwind of the island (Cooper, personal communication). Perhaps salt crystals in the maritime air mass act as giant cloud condensation nucleii and accelerate the collision-coalescence process. We must await a complete analysis of that data to rehabilitate the forced ascent model.

A modified version of smooth forced ascent is known to occur. Low-level cloud droplets generated by forced ascent can be directly removed from the air by impact on tree foliage. The resulting precipitation is called 'tree-drip'. This can be a primary mechanism of precipitation on windward slopes in the subtropical high pressure belt where the descending branch of the Hadley cell discourages cloud formation. The Canary Islands (latitude 28° N) experience this phenomena as does the coastal range of Queensland, Australia (near latitude 25° S).

Rejection of the smooth forced ascent mechanism implies that other factors are needed to explain orographic rain. This agrees with a most important observation; orographic precipitation, i.e. heavy rain on the windward slopes, is almost always accompanied by weaker precipitation over a larger region. Thus high terrain seems to enhance precipitation but not act as its sole cause.

3. The Bergeron seeder-feeder cloud mechanism

The difficulty in the rapid production of hydrometeors in low-level orographically lifted air was addressed by

Bergeron's suggestion of a two-cloud system of orographic precipitation enhancement. An upper 'seeder' cloud is presumed to be precipitating with no influence from the terrain (Fig. 3(b)). This cloud is associated with ascent in a regional synoptic-scale disturbance. Its mid-troposphere position (and temperature) allows an ice-phase formation of hydrometeors. The precipitation from the regional seeder cloud is partly evaporated on the way to the earth's surface. This decreases the rainfall rate at the surface and serves to moisten the low-level air. When this air is locally lifted by the terrain, it reaches saturation quickly and a dense low-level cloud or fog is formed, i.e. the feeder cloud. The falling hydrometeors collect cloud droplets from this 'feeder cloud' and grow in size. Great droplet enlargement may lead to drop-splitting and multiplication. Even on small hills (height ≈ 100 m) significant rainfall enhancement may result.

The pure seeder-feeder mechanism is an idealization. In practice, the two clouds may be combined into one. Furthermore, the seeder cloud may be influenced by the terrain. A further description of the seeder-feeder mechanism can be found in papers by Bergeron (1960), Browning *et al.* (1974, 1975), Storebø (1976), Bader and Roach (1977), Passarelli and Boehme (1983) and Carruthers and Choularton (1983).

4. Diurnally forced convection

One of the most regular and predictable types of orographic rain occurs in warm season conditions over high mountains. The daily heating of the hillsides generates warm upslope winds which continue rising after reaching the mountain ridge-top and trigger deep convection (Fig. 3(c)). These clouds produce precipitation in the afternoon over the peaks or downwind if there is cloud drift. This behaviour is shown clearly in satellite movie-loops and is part of the daily cycle for people who work or live in the high mountain areas during the summer. The precipitation patterns on islands and mountainous coastlines throughout the tropics are dominated by this mechanism.

At night the thermally forced winds reverse, and low-level convergence may trigger convection some distance away from the mountains. On mountainous tropical islands this may produce a statistical night-time precipitation maximum near the coast or offshore. East of the Rocky Mountains, thunderstorms may build over the Great Plains at night.

Further discussion on the subject of diurnally forced convection over mountains is found in papers by Liu and Orville (1969), Kuo and Orville (1973), Astling (1984) and Banta (1984).

5. Triggered convection by forced ascent or blocking

In an attempt to understand how terrain can influence precipitation so strongly, it is often supposed that forced lifting can trigger some sort of instability which will then produce additional condensation and hydrometeor formation (Fig. 3(d)). Three possibilities have been mentioned:

(a) blocking and upstream lifting triggering deep penetrative convection, e.g. Smith and Lin (1983), Grossman and Durran (1984) and Smith (1985),

(b) blocking and upstream lifting triggering conditional instability in stratiform layers (e.g. Lee 1984), and

(c) blocking and differential advection causing fronts to overturn, triggering conditional instability in stratiform layers (e.g. Smith 1982).

These suggested mechanisms are rather difficult to verify for at least two reasons. First, if the environment is close to instability, there are likely to be disturbances and precipitation already in the area. This makes it difficult to isolate the effect of the mountain. Second, in interpreting surface rainfall amounts, the effect of low-level feeder cloud enhancement must be subtracted out. The question then is whether the seeder cloud is influenced by the terrain. Observationally this is best studied by direct aircraft measurements (Marwitz 1974, 1980) or radar (Browning *et al.* 1974).

As an example of these problems, consider the Western Ghats (Fig. 2) on the west coast of India. The undisputed facts are these:

(a) during the south-west monsoon, the rainfall is much greater on the coast and the windward slopes than east of the mountains, and

(b) the rainfall is associated with deep convection.

One could postulate that an upstream blocking effect of the mountains could trigger convection in the approaching south-westerly air current, but verification of this idea is difficult as the statistics and synoptic meteorology of cloud clusters in the Arabian Sea are poorly understood, and the upstream effect of the Ghats is difficult to estimate.

An alternative solution to the Western Ghats problem is pictured in Fig. 4. Naturally occurring convection over the sea and the coastline during disturbed or unstable conditions will be cut off at the mountain ridge due to an air-mass modification effect. Low-level air will be scavenged of its water by drops falling from a seeder cloud above. As the air descends beyond the mountain crest it is dry and cannot restore its water vapour by evaporation from the sea. Without the low-level moisture, convective precipitation is suppressed.

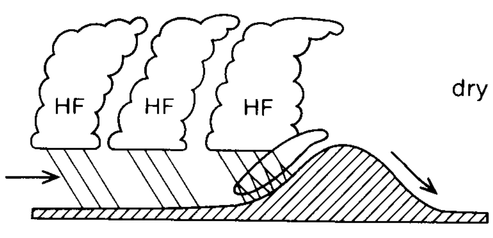

Figure 4. Orographic control of precipitation by an air-mass modification effect. The region of hydrometeor formation (HF) is shown.

6. Climate type and orographic rain

The relative importance of the mechanisms mentioned above is not known. The possibility of finding these mechanisms in each climate zone might be roughly as follows:

Tropics/monsoon	
Diurnal convection	certain
Upstream triggering of convection	possible
Orographic air-mass transformation	possible
Seeder-feeder	likely
Subtropics	
Smooth forced ascent	possible
Tree-drip	certain
Mid latitudes	
Seeder-feeder	certain
Upstream triggering of stratiform convection (winter)	possible
Diurnal convection (summer)	certain

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Notes and news

Monthly and annual totals of rainfall 1985, and 1986, for the United Kingdom

These volumes are, in effect, the 126th and 127th in a series containing tabulations of rainfalls for UK stations, and commentaries on rainfall, which first appeared in 1860.

Dr G.J. Symons produced the first volume of *British Rainfall* for the organization of the same name as a hard-cover book of small-page format (127 mm × 203 mm) containing yearly total rainfall data for about 500 stations in the United Kingdom (then including all Ireland) for 1860. By 1884 the volume had expanded to include monthly totals for 233 stations and yearly totals for 2000 stations plus articles of interest to rainfall observers. In 1919 the functions of the British Rainfall Organization were taken over by the Meteorological Office which produced the last volume in this page size in 1960 by which time it contained monthly and yearly totals for 414 and 6000 stations respectively. In 1961 the page size was enlarged to 203 mm × 305 mm and the contents were standardized for the next few years to include tabulated rainfall totals, wet and dry spells and evaporation, and maps of annual total. In 1969 the volume appeared only in paper-back form with only the general table of monthly and annual rainfall.

The latest changes starting with the 1985 edition involve content and printing style. The contents are now:

(a) Explanatory section.
(b) Description of the rainfall station numbering system.
(c) A summary of rainfall for the whole year plus details of extreme falls.
(d) Maps of annual rainfall totals (amount, and percentage of the 1941–70 average).
(e) Maps of monthly rainfall as a percentage of the 1941–70 average and summaries of features of the rainfalls in the month.
(f) Monthly, seasonal and annual areal rainfalls for various regions of the United Kingdom.
(g) Tables of monthly and annual totals for about 4500 stations (currently), and the largest daily total for approximately 65% of this number, which form the bulk of the volume.

The opportunity has also been taken to use a more legible type-face than that used previously which makes all parts of the text easier to read. This is particularly true of the comprehensive tabulations of monthly and annual totals which, by necessity, have to be printed small to avoid producing a volume which is too bulky. The cover, too, has been redesigned to incorporate the Meteorological Office's commercial logo and drawings of suitable 'watery' themes.

To the keen student of rainfall in the United Kingdom this volume, like its predecesors, contains the expected wealth of detail, but now more attractively presented. The maps of monthly rainfall and the accompanying commentaries are particularly useful additions.

The 5th IAMAP Scientific Assembly, Reading, 31 July to 11 August 1989

1. History of IAMAP

In 1919 the International Union of Geodesy and Geophysics (IUGG) was formed, embodying a Meteorological Section which brought together already-existing bodies (such as the International Radiation Commission) formerly part of the International Meteorological Organization. The Meteorology Section of IUGG became the International Association of Meteorology in 1930 but in 1957 it took over interests in Atmospheric Physics as well, resulting in the International Association of Meteorology and Atmospheric Physics (IAMAP) as it exists today.

The World Meteorological Organization (WMO) assumed responsibility for operational matters leaving the non-governmental IAMAP to represent the interest of researchers from universities and laboratories (but not exclusively).

2. IAMAP/WMO relationships

IAMAP profits from the guaranteed continuity provided by WMO in matters of observing systems and their improvement, the maintenance of data archives and the development of atmospheric circulation and climate models. On the other hand WMO benefits through the intellectual stimulation and research activities initiated by IAMAP which are further developed jointly. IAMAP can also coordinate on an international basis university research which is outside the influence of WMO.

3. IAMAP structure

Ten Commissions within IAMAP, which coordinate scientific work and organize topical symposia, have the following areas of scientific interest.

- Atmospheric chemistry and global pollution
- Atmospheric electricity
- Climate
- Cloud physics
- Dynamic meteorology
- Meteorology of the upper atmosphere
- Ozone
- Planetary atmospheres and their evolution
- Polar meteorology
- Radiation

In addition the IAMAP Executive and Secretariat give guidance to the Commissions and organize major meetings such as the Scientific Assemblies, held every four years, usually in collaboration with other IUGG Associations.

4. Fifth Scientific Assembly

The Fifth IAMAP Scientific Assembly is to be held at the University of Reading from 31 July to 11 August 1989.

This Assembly will have four components: invited overview lectures, four major symposia, thirteen topical symposia and a variety of workshops.

The *overview lectures* are to be given by speakers chosen by the Presidents of the Royal Meteorological Society and IAMAP.

The four *major symposia*, each lasting 4 to 5 days, deal with The Global Weather Experiment — 10 years later, middle atmosphere sciences, global energy and water fluxes, and atmospheric trace constituents and climate/global change.

The *topical symposia*, each lasting from one to three days, are concerned with — aerosol and cloud effects on climate, atmospheric transparency, boundary-layer parametrization and larger-scale models, influences of polar regions on global climate, Martian meteorology, mesoscale analysis and forecasting incorporating now-casting, mesoscale processes in extra tropical cyclones, meteorological and chemical aspects of tropospheric air quality, noctilucent clouds, non-linear dynamics and atmospheric flow, remote sensing in polar regions, remote sensing of trace constituents, and the Earth's radiation budget.

Finally one- or two-day *workshops*, with limited participation, on the following topics are planned — global data sets, International Satellite Land Surface Climatology Project, interpretation of satellite and radar imagery, needs and opportunities for observational studies and numerical prediction models of mesoscale weather systems, and noctilucent clouds.

In the second week of the Assembly a commerical exhibition, METEX '89, will be held for exhibitors to demonstrate their products.

Staff from many establishments in the United Kingdom with an interest in meteorology and atmospheric physics — the Universities of Reading, Oxford, Cambridge and Southampton, the Institute of Hydrology, Natural Environment Research Council, European Centre for Medium-range Weather Forecasts, British Antarctic Survey and the Meteorological Office — are involved in organizing the meetings and in making local arrangements for the many delegates who are expected to attend.

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Reviews

The climate of China, by M. Domrös and G. Peng. 169 mm × 248 mm, pp. xiii+361, *illus*. Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1988. Price DM 228.00.

The authors of this book have set themselves the substantial task of providing a full account of the climate of China for the international community. Therefore, after a summary of the data available and an interesting sketch of existing work on the subject, they briefly review China's geography. For readers unfamiliar with China, this chapter would have benefited from the inclusion of regional topographical maps with names of towns, rivers, etc. to clarify the many geographical statements later in the book.

The chapter on the basic atmospheric circulation contains much useful background information for the geographer and climatologist. The description of the atmospheric circulation features associated with the *mei-yu* (plum) rains is of particular interest.

Having established the geographical and broad-scale dynamical controls on China's climate the authors proceed to present the behaviour of individual climatic elements, of which temperature and precipitation occupy the longest chapters. Much that is of interest emerges, such as the summary of the evidence for the 'Little Ice Age' (*c*. AD 1450–1850) and other historical climatic fluctuations, the analysis of precipitation as a function of elevation, and the studies of mountain and valley breezes. There are, however, some shortcomings of interpretation. The greater lapse-rate between Garze and Nagqu (p. 116) is likely to be because Nagqu is in a frost-hollow, as suggested by its greater diurnal ranges (see Appendix). Chengdu's small diurnal range (p. 121) results from its cloudiness (see Appendix). The authors could have commented on why percentage cloud and percentage sunshine regularly exceed 100 as evidenced by the data in the Appendix. In Tables 7.4 and 7.5 they could have represented valley breezes better using afternoon data. In Chapter 9, the diurnal range in the tropics should have been described as greater relative to the annual range, not in absolute terms.

The final two chapters are on the climate classification and division of China, and on China's climate zones, and are useful background material for the geographer and climatologist, and, no doubt, for agriculturalists, economists and ecologists too. The concluding Appendix of climatological statistics gives quantitative support to the entire text, though its introductory table could have been clarified by providing units (e.g. centimetres for snow depth) and by full definitions of the parameters (e.g. snow depth is the maximum, not the average, according to the main text). Also, the monthly 'average' temperatures do not equal the mean of the daily maxima and minima — it would be useful for their interpretation to know how they were calculated. The station numbering system is very helpful.

Unfortunately the text is often difficult to read, or inconcise, and is occasionally confusing. Ideally, the book should have been independently language-edited. Examples of the need for this are the use of 'passates' on page 28 for trade-winds, the expression 'meager climatic importance of temperature variability' on page 122, the confused final paragraph of Section 5.3.1, the use of 'exposition' for 'exposure' on page 191, and the ambiguous title to Figure 7.3. There are also some printing errors and numerical inconsistencies involving, for example, the criteria for the dryness index on page 196 and resulting in confusion between the text and Figures 5.21 and 5.22 as to which periods were dry and wet.

As a general reference and for background study, this book is to be recommended. For precision and scientific incisiveness, a subsequent edition would be welcomed. This could also take advantage of new types of information now available on China's climate such as radiosonde profiles and satellite imagery. In the meantime, the book is a welcome sign of growing international co-operation in climatology.

D.E. Parker

Multiprocessing in meteorological models, edited by G.-R. Hoffmann and D.F. Snelling. 170 mm × 247 mm, pp. xvi+438, *illus.* Berlin, Heidelberg, New York, London, Paris, Tokyo, Springer-Verlag, 1988. Price DM 118.00.

This book collects together the papers presented at two workshops held at the European Centre for Medium-range Weather Forecasts (ECMWF) in 1984 and 1986 on the subject of parallel processing in meteorological models. There are 26 papers from contributors who are experts in the fields of numerical modelling and computer science. The topics covered are wide ranging and include descriptions of parallel computers and their applications, parallel algorithms and programming languages, multi-tasking aids, user experience and thoughts on the future direction of numerical weather prediction. The book also contains summaries of the open sessions at each of the workshops which discuss the programming and computer requirements for meteorological modelling in the future.

As stated in the cover notes, the time-critical nature of numerical weather prediction has ensured that the major weather forecasting centres have always had access to the most powerful computers available. Since the current level of technology (and eventually the speed of light) limits the speed of a single processor, parallel computations have become necessary in order to achieve large increases in performance. The current generation of supercomputers, such as those manufactured by Cray, generally contain a small number of very powerful vector processors which may be used in parallel. Experience with these types of computers forms the subject matter of the majority of the papers in the book. The trend towards massively parallel architectures is also recognized and is discussed in several of the papers.

One of the fundamental questions discussed at the workshops is how to compare the performance of parallel computers of differing architectures in a meaningful fashion. Several of the papers consider ways of measuring the intrinsic vector and multi-tasking performance of parallel processing computers, either by the use of simple measures based on specific combinations of instructions, or by the use of benchmark programs constructed from numerical weather prediction models. Both of these methods have their drawbacks; simple performance measures can sometimes be misleading when used to predict the performance of a large program, while the effort required to optimize a large meteorological model for a particular computer is usually so great that true comparisons are difficult to obtain. Nevertheless, despite these caveats, these papers do provide a useful insight into the performance potential and limitations of a range of computer designs.

The design of efficient algorithms for parallel systems along with techniques for maximizing multi-tasking performance are examined by many of the authors. A variety of practical tools for analysing the overheads incurred and the degree of parallelism achieved when writing multi-tasked code are also presented.

Some of the most interesting papers are those which report hands-on experience of multi-tasking large meteorological models. Perhaps it is a sign of recent history, that all of these are for Cray computers. The two papers documenting the ECMWF experience in multi-tasking their spectral model on Cray X-MP computers are quite illuminating. ECMWF was the first centre to multi-task its operational model and these papers chart their experience and the refinements made to their multi-tasking strategy over the period of the workshops. There are also contributions from other centres on the plans for multi-tasking their models, which provide a wider perspective on possible ways of multi-tasking operational codes.

In general, this collection of articles is well produced and illustrated. Unfortunately, a few of the papers, written by authors for whom English is not their first language, contain inappropriate words or phrases which make certain passages difficult to read and this detracts from the overall quality of the product. Because of the rapidly evolving nature of the subject, some of the computer systems referred to in the book are no longer manufactured and indeed some have never reached the market place. It is therefore regrettable that it was not possible to publish these articles closer to the dates of the workshops. Nevertheless, the book contains a wealth of interesting and useful information which is highly relevant to users of today's supercomputers, providing a rare insight into the use of parallel processing in time-critical applications.

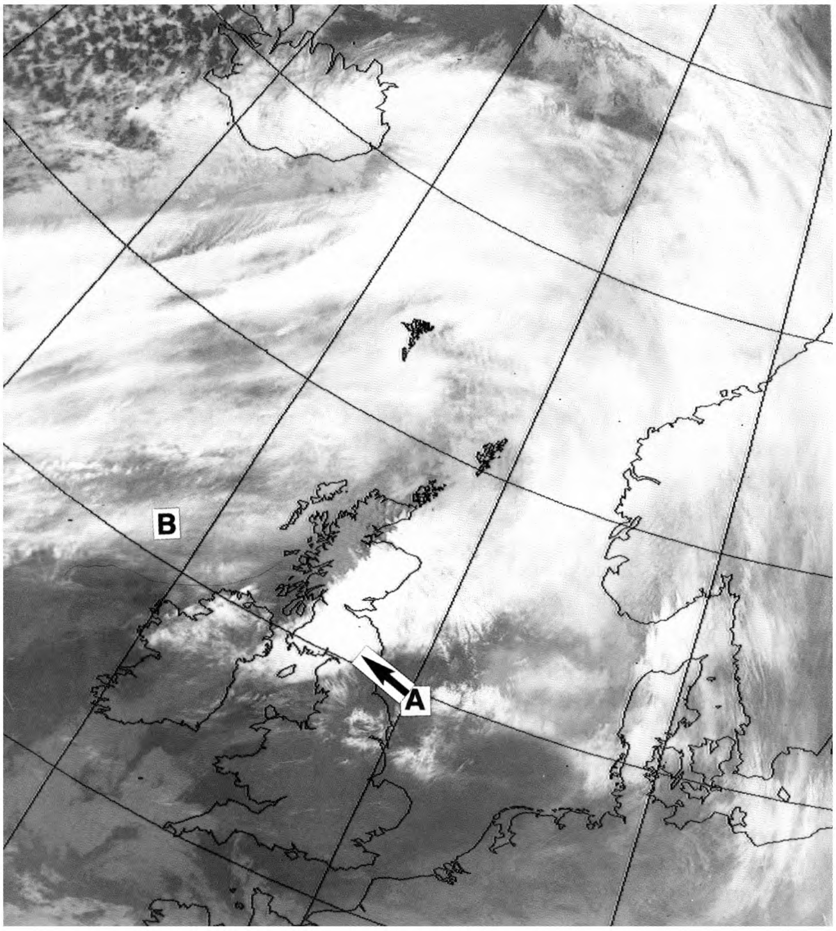
I expect that those people actively involved with multi-tasking meteorological models will find the papers in this book most useful. The contents also form a valuable introduction for someone new to the field. However, the main interest in the book may come from outside the meteorological community, from those areas of engineering and science which are only now thinking about using large parallel computers for the first time.

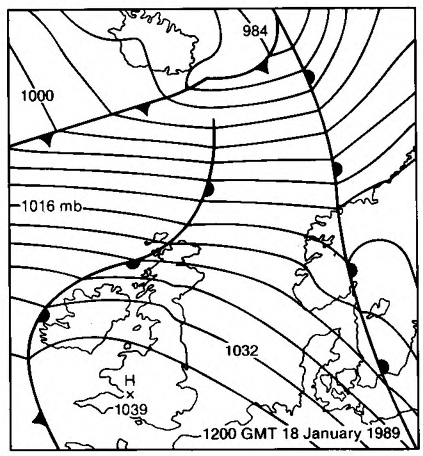
A. Dickinson

Books received

Atmospheric tidal and planetary waves, by H. Volland (Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Dfl.210.00, US$99.00, £59.00) is for workers in meteorology, middle atmosphere and space physics, and deals with global-scale dynamical processes within the whole depth of the atmosphere. The concept of the separation of atmospheric flow into eigenmodes on the sphere is used extensively in the analysis of observed global fields. Forcing functions are identified and equations governing the vertical and meridional structure are derived.

Satellite photograph — 18 January 1989 at 1217 GMT





Photograph by courtesy of University of Dundee.

An anticyclone was centred over southern England with a broad south-westerly flow over the northern part of the British Isles. An extensive area of orographic cirrus cloud, labelled A, was situated over the northern part of the British Isles. This was the subject of a study using the Hercules aircraft of the Meteorological Research flight. Visual observation from the aircraft showed that the cloud extended from an altitude of 24 000 ft to approximately 40 000 ft (above the altitude of contrails formed by commercial air traffic).

Upwind, time-lapse picture sequences showed that cirrus, labelled B, was dissipating due to descending motion produced by the orographic flow (Fig. 1). Ahead of the leading edge of the orographic cirrus, lee-wave motions with a wavelength of around 12 km were clearly visible in the altostratus layer. The leading edge was itself marked by stacks of individual lenticular clouds. Further downwind, these spread into layers which eventually merged. The Hercules made a number of runs alongwind into the cirrus edge at about 57° 30′N to observe the formation and growth of cloud particles at different temperatures.

The nature of the cirrus remained largely unchanged between 0830 GMT when it was first noted during the pre-flight briefing and about 1500 GMT when the aircraft left the area. Traces of it were still visible at 0200 GMT on the following day.

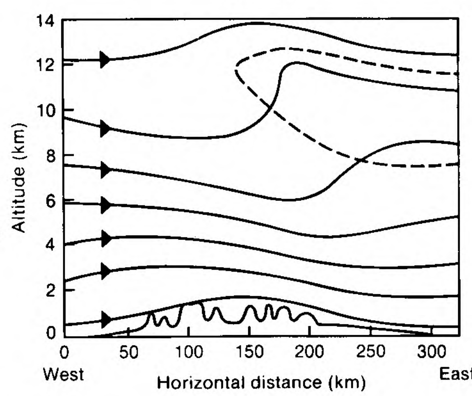


Figure 1. Schematic cross-section showing streamlines of the airflow over northern Scotland. Smaller scale lee-wave motions are not shown (after Reid, S.J., Long-wave orographic clouds seen from satellites. *Weather*, **30**, 1975, 117–123). The region contained by the dashed line shows the location of the orographic cirrus.

Meteorological Magazine

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

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May 1989

UK road ice prediction system
Assessing incidence of fog
Journeys to the North Pole
The summer of 1988
Climatological data processing

HMSO

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The
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A preliminary performance and benefit analysis of the UK national road ice prediction system

J.E. Thornes
University of Birmingham

Summary

The ice prediction system is described, and assessments of performance are analysed. The practical benefits in two areas of the United Kingdom are discussed quantitatively, based on winter indices.

1. Introduction

Since the winter of 1986/87 several local authorities in the United Kingdom with responsibilities for road maintenance have made use of computer-generated forecasts of overnight road surface temperatures which may lead to icy conditions. These forecasts are made by the Meteorological Office Weather Centres and disseminated through the 'Open Road' service provided by the Office using software developed by Thermal Mapping International (TMI) which is based at University of Birmingham.

The variation of the temperature of a road surface with time is determined by emitted and absorbed radiation, the turbulent transfer of heat to the overlying air and conduction through the road-bed material (Rayer 1987). Starting from an estimated or measured road surface temperature at 12 GMT the forecast variation of the meteorological elements air temperature, humidity, wind, cloud amount and type, and rainfall, which are involved in the heat budget processes, lead to an estimate of the subsequent variation of surface temperature and a prediction of the occurrence or not of frost and ice. The forecasts can be updated when necessary by monitoring actual measurements of road surface temperatures from sensors at roadside 'outstations' (some of which also provide continuous measurements of the meteorological variables). These forecasts are made for a few widely spaced locations at which there are outstations, but interpolation to a dense network of roads can be made by using the results of thermal mapping surveys. These surveys, made by infra-red detectors in vehicles driven at night, indicate the extent to which different sections of roads cool in different weather conditions.

Local highway authorities use these forecasts to make decisions whether or not to grit or salt roads. Potentially, much directly accountable money can be saved by accurate forecasts of overnight road conditions simply from the cost of materials, labour and administration used in salting or gritting roads. Probably much more non-accountable money can be saved by the reduction in injury, damage and disruption to traffic resulting from reduced numbers of road accidents.

In the following sections of this paper the performance of some aspects of ice prediction systems are described along with indications of the cost savings and benefits to be expected.

2. The scale of operations in the United Kingdom

By the start of the winter of 1988/89 the thermal mapping of more than 21 500 km of roads in 45 highway authority areas had been undertaken in the United Kingdom. More than 320 road weather outstations had been installed in 30 counties or regions and more than 50 counties or regions were taking the Open Road service. Altogether more than £5 million has already been invested in road weather systems in the United Kingdom compared with the cost of about £100 million for maintenance during an average winter.

These figures bear a very favourable comparison with those for, say, North America (USA and Canada) with 500 km of thermal mapping and 110 outstations, or the main snow- and ice-affected countries of the world (including the United Kingdom) with 34 000 km of mapping and 1700 outstations altogether. For North America snow and ice control is estimated to cost £1200 million per winter, and for the northern hemisphere as a whole the figure is about £2000 million with £20 million (i.e. one per cent of the annual maintenance bill) being spent on road weather systems in the last 5 years.

At present, in the United Kingdom, each highway authority is responsible for its own involvement in ice prediction systems, and there are already signs of regional systems developing such as in Wales (Perry *et al.* 1986). A computer bureau has been installed in Manchester Weather Centre to serve all 14 district and motorway authorities in the counties of Greater Manchester and Merseyside; so far the Boroughs of Stockport, Bolton and Oldham have joined the system. A new bureau is being installed in Leeds Weather Centre potentially to serve the equivalent of 4 counties. The computer bureau at the University of Birmingham is also serving as the central processor for Suffolk, West Midlands motorways, Warwickshire motorways, Staffordshire and Berkshire.

The 14 Meteorological Office Weather Centres around the United Kingdom are ideal hubs for regional systems. It is from these Weather Centres that forecasters provide the crucial human input to the ice prediction models; this consists of forecasts for each 3-hour period of air temperature, humidity, wind, precipitation and cloud. Facilities exist to monitor the performance of the systems and models at the larger Offices at Glasgow, Leeds, Cardiff and London, and at the University of Birmingham Ice Prediction Centre run by TMI.

As the use of ice prediction systems has now become firmly established within highway authorities it is appropriate to review their effectiveness in practice. Forecast thermal maps and ice prediction curves look pretty on the computer screen but how are they used operationally? How long does it take the average highway engineer to learn how to use such information effectively? How can an ice prediction system aid management as well as day-to-day operations? How cost effective is the system? These are the types of question that have been asked, and information is now available to try and answer some of them.

3. The performance of ice prediction systems

The Birmingham Ice Prediction Centre run by TMI is also able to produce statistical summaries which help to assess the benefits to be gained by the system (described in the next section). The following is a sample of results from the monitoring of the system performance.

3.1 Reliability of data supply

A typical county ice prediction system with eight outstations operational from 1 November to 31 March will collect data for about 160 days, or 30 720 hours ($8 \times 160 \times 24$). In Cheshire, in the winter of 1987/88 a total of 677 hours of data were lost out of a possible total of 29 184, or 2.3%, due to power and computer failures and defective data lines. It is suggested that the target should be at least 98% data availability.

3.2 Assessment of forecast success

Using input data based on the forecaster's judgement of the expected weather conditions, an ice prediction computer model is run for forecast sites in defined climatic zones within each county/region. The accuracy of these forecasts is assessed which provides feedback to forecasters about how well the road surface temperature and wetness is modelled. For example Fig. 1 shows the accuracy of the forecasts of minimum road surface temperature for the winter 1987/88 for the Ray Hall outstation in the West Midlands. Two forecast variations of road surface temperature are issued, one of which is based on the best estimate of the likely weather conditons (the 'realistic' one) and the other on the worst conditions which could happen, say, rain followed by clearing skies, which is the 'pessimistic' forecast. Fig. 1 shows that the mean error in the minimum road surface temperature for realistic forecasts was −0.3 °C (forecast−true) and −3.4 °C for pessimistic forecasts, for a sample of 113 nights.

An analysis of correct/incorrect forecasts can also be made in terms of the four possible combinations of frost/no frost forecast and frost/no frost occurring. A frost in this context is road surface temperature falling below zero. The potential consequences of the two types of erroneous forecast are different:

Type 1 error: No frost forecast/frost occurs — potential for accidents.
Type 2 error: Frost forecast/no frost occurs — potential for wasting salt etc.

Fig. 2 shows that for the 113 nights the realistic forecast was correct on 87.6% of occasions but this reduces to 66.4% for pessimistic forecasts. For realistic forecasts, both Type 1 and 2 errors occur equally on 6.2% of occasions, but for pessimistic forecasts errors of Type 2 occur on 33.6% of occasions. The percentage of nights on which one or other of the two forecasts was correct is 93.8% with no Type 1 errors.

3.3 Results of surveys of microclimate and thermal mapping

The average minimum air and road temperatures during the winter have been analysed to identify the coldest and warmest sites under differing weather

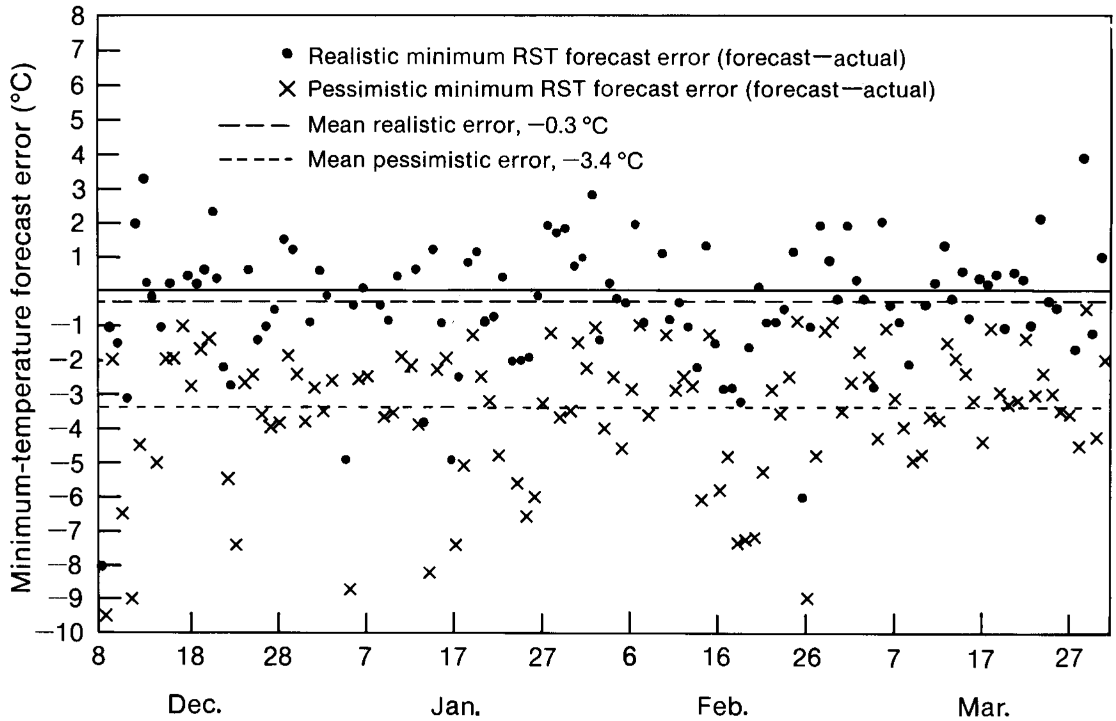

Figure 1. Minimum road surface temperature (RST) forecast accuracy at Ray Hall, West Midlands during the winter of 1987/88 (see text for explanation of terms).

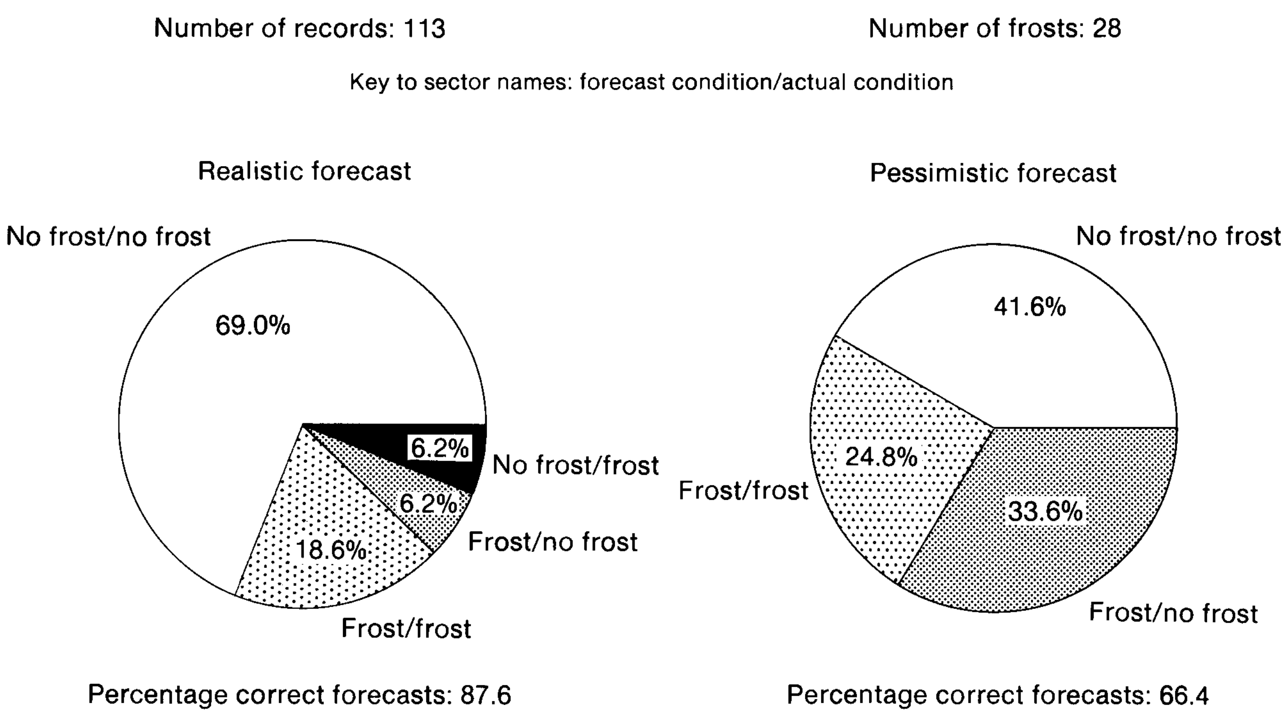

Figure 2. Forecast accuracy displayed in sectors, data as in Fig. 1.

conditions. Fig. 3 shows the average minimum air temperatures at 12 sites in the Hereford and Worcester area at different altitudes for nights with three different weather conditions. These are 'extreme' nights with clear skies and little wind, 'damped' nights with overcast skies, moderate winds and possibly precipitation, and 'intermediate' nights in between. On extreme nights, air temperature increases with elevation by approximately 2 °C in 1500 feet, on average, while on damped nights the temperature decreases with elevation by about 3 °C in 1500 feet. On intermediate nights the temperature again decreases, by about 2 °C in 1500 feet increase in altitude; in the United Kingdom approximately 70% of winter nights fall into the intermediate class.

The significance of these types of night is that they require three corresponding thermal maps of the detailed road network in a region for use in interpolating between the forecast temperature changes for the small number of outstation sites. The forecaster chooses the appropriate map according to the weather conditions indicated by the observations from the outstations and the progression of forecast temperatures.

3.4 Comparisons of model performance

Two models for forecasting road surface temperatures have been used in the 'Open Road' service, which have been developed at Birmingham University (TMI model I, see Thornes 1985, Parmenter and Thornes 1987) and by the Meteorological Office (Rayer 1987). A further model, TMI model II is still under development.

Table I gives results of comparisons of these models where actual measurements of the meteorological variables have been used, rather than forecast variables whose impact of errors would need to be assessed in a separate comparison. The results are based on data for 50 nights (unless otherwise specified) at Coleshill on the M42 during the 1987/88 winter.

Table I. Comparative errors in performance of three ice prediction models (see text for explanation of terms)

Model	TMI I		TMI II		Meteorological Office	
	Mean	r.m.s.	Mean	r.m.s.	Mean	r.m.s.
Comparison						
A	1.15	0.45	0.85	0.33	0.88	0.26
B			0.11	1.49	0.21	1.54
C	1.09	0.79	0.29	0.80	−0.25	0.86
D			−0.54	1.45	−0.16	1.43
E	1.60					

All errors are in the sense (predicted−observed)

A is the r.m.s. error of temperature for 24 values from predictions made at 12 GMT for each hour from 13 GMT to 12 GMT the next day (°C)
B is for maximum road surface temperature (°C)
C is for minimum road surface temperature (°C)
D is the timing of the zero temperature (hours)
E is the same for A but for 114 nights and includes errors of forecasts of meteorological variables.

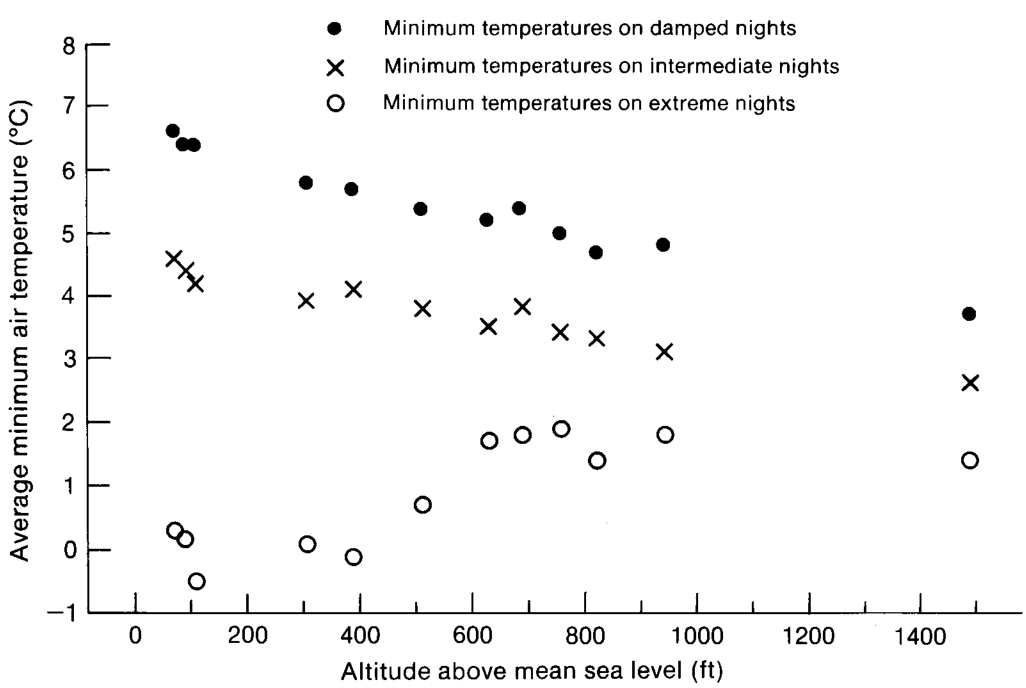

Figure 3. Average minimum air temperatures at 12 sites in the Hereford and Worcester area in winter at different altitudes and weather conditions (see text for explanation of terms).

4. Benefits of the use of ice prediction systems

4.1 Winter indices

In the course of its operations the Birmingham Ice Prediction Service developed two winter indices to study:

(a) The variation of expenditure on winter maintenance from year to year (temporal winter index (TWI)), and

(b) The variation of expenditure across a county or region in a particular winter (spatial winter index (SWI)).

4.1.1 Temporal winter index

This is based on Hulme's index (Hulme 1982) used to assess the severity of a winter (1 November–31 March).

The TWI uses three variables:

(a) Mean maximum air temperature (T, °C) in units of degree Celsius,

(b) Number of days with snow lying at 09 GMT (S), and

(c) Number of nights with a ground frost (F)

such that

$$\text{TWI} = (10 \times T) - (18.5 \times S)^{\frac{1}{n}} - F$$

where n = 3 in the United Kingdom (but less in areas with more snow).

For example, in Fig. 4 is shown the yearly variation of TWI at Manchester (Ringway) relative to the mean for 30 years so that cold winters now have a negative index (anomaly) and warm winters a positive index.

The lowest and highest TWIs for Manchester are −55 (winter 1962/63) and +38 (winter 1973/74) but the winter of 1987/88 was the first to have a positive TWI since 1982/83. For planning purposes based on the 30-year sample it can be seen that most winters in this area will have a TWI in the range −25 to +25 (20 out of 30) but for 1 in 3 winters the index will be outside this range. There have been 5 winters with a TWI of −25 or less, so there is a 1 in 6 chance of a winter being this cold.

These figures for Manchester are typical of the area covered by the highway authorities served by Manchester Weather Centre. TWI values have been calculated for the locality of each weather centre.

4.1.2 Spatial winter index

Not only do winters vary from year to year but the severity of road conditions will vary across a region due to the geography of an area and the road construction and traffic. For instance Cheshire County has relatively warm motorways like the M6 running north/south at a modest elevation but also lesser roads climbing up into the Pennines. As an example consider the night minimum temperatures during the winter 1987/88 for the Cat and Fiddle outstation at 1686 feet (514 m) compared with those for Hassall Green on the M6, at 259 feet (79 m). The two sites are only 50 km apart but the Cat and Fiddle had 65 nights on which the road temperature fell below 0 °C whereas Hassall Green had only 28 nights.

An SWI can be defined in terms of a count of the relative number of wet and dry frosts. A dry frost occurs when the road surface temperature falls below 0 °C but the road remains dry. A wet frost occurs under the same

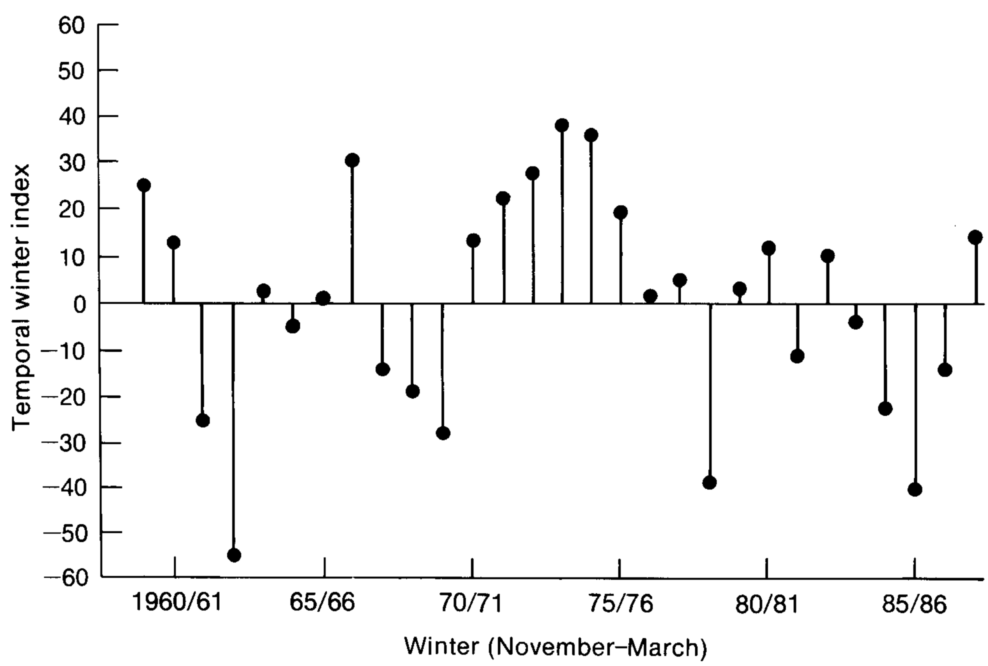

Figure 4. Values of temporal winter index (TWI) at Manchester (Ringway) for the winters shown, commencing in November. See text for explanation of TWI.

conditions of temperature but there is moisture present on the road which may be rain, snow, hoar frost or be caused by the hygroscopic nature of salt on the road. The Cat and Fiddle and Hassall Green outstations represent the extremes among the 8 sensors in the Cheshire County area — the Cat and Fiddle had 6 dry and 59 wet frosts and Hassall Green 15 dry and 11 wet frosts.

This SWI can be related directly to the maximum number of salting runs that should have been necessary in the vicinity of an outstation sensor site. In snow conditions or with showers about, multiple salting runs may have been necessary but the index gives a good guide to possible nights with under- or over-salting.

Also it is necessary to know how representative of the road network the sensor sites are, over a region, and this requires extensive thermal mapping. Again taking Cheshire with its 8 outstations as an example, this area has three operational divisions — East, West and Motorways — and it is possible to devise an average SWI for each division.

4.2 Analysis of salt usage in two areas

4.2.1 Cheshire

The TWI for six winters has been compared with salt usage figures supplied by Cheshire County Council. The index is calculated for Manchester and has to be assumed to be representative of the whole of Cheshire; also the usages are for the whole county and probably no more accurate than ±1000 tonnes. In Fig. 5 the winter usages are plotted against the TWI showing the expected inverse relationship. Cheshire County Council installed their ice prediction system at the start of the 1986/87 winter but there was no obvious reduction in salt usage in that winter (possibly the start of a learning process?). From a linear regression applied to the five points for the winters 1982/83 to 1986/87 in Fig. 5, the predicted usage for the winter 1987/88 is 16 100 tonnes compared with the actual usage of 13 050 tonnes; this 20% reduction is attributable to the use of the ice prediction service. Further monitoring of salt usage in Cheshire for another 3 years is planned, so that firm conclusions can be drawn about savings.

4.2.2 Hereford and Worcester

Ponting (1984) has produced a detailed examination of salt usage by Hereford and Worcester County Council. He showed that during the winter of 1983/84, forecasts of wet frosts were successful on only 57% of occasions resulting in a wastage of approximately 30% in salt usage. During 1987 the Council installed an ice prediction system and an identical study was carried out on salt usage during the winter 1987/88, as for the earlier winter (not dissimilar in weather), representing a useful 'before and after ice prediction' comparison. Preliminary analysis shows that the success rate of accurate wet frost forecasts increased to 91% and salt wastage reduced to 15%. Over the last 10 years this Council has used an average of 18 620 tonnes of salt each winter; the cost of salt is about £20 per tonne so that the reduction of wastage to 15% represents an average winter saving of £56 000 just for salt. Reduced labour costs, wear and

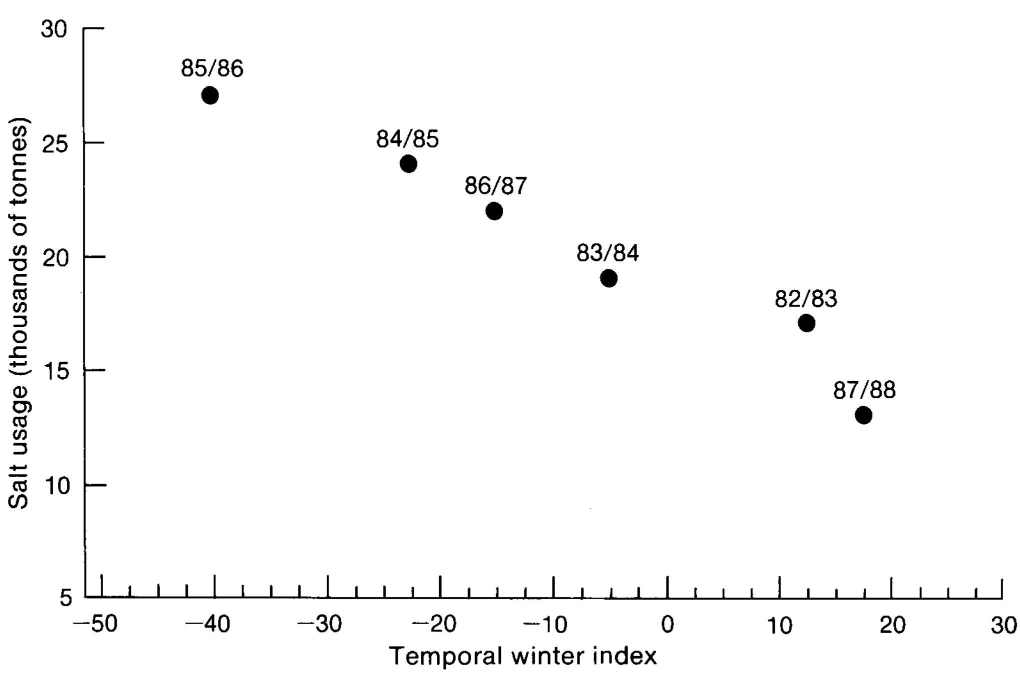

Figure 5. Cheshire County Council's salt usage for the winters shown plotted against the temporal winter index (TWI) at Manchester (Ringway) for the specified winters.

tear on equipment, etc. increases the annual saving considerably over this figure.

Using the TWI for Birmingham (the nearest available location) the salt usage for 1987/88 was predicted to be 12 333 tonnes based on linear regression of figures for the previous 9 winters, compared with the actual usage of 7950 tonnes. This is a 35.5% reduction in salt usage (equivalent to £88 000) attributable to the beneficial guidance from the ice prediction system in its first winter alone.

5. Conclusion

By careful monitoring of the performance of an ice prediction system it is possible to show that significant real savings have been made by highway authorities that have installed them, but more data are required to confirm and refine the assessment of the benefits. Particularly, the assessment of improved road safety leading to reduction in accidents is required, as well as accountable savings in the cost of road winter maintenance operations. It is hoped that future statistics will show that there are less accidents caused by ice, frost and snow as the increased use of ice prediction systems enable highway authorities to decide more successfully when to salt roads.

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Current techniques for assessing (indirectly) the localized incidence of fog on roads*

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Summary

This paper describes the methods currently employed by the Meteorological Office when required to determine the likely incidence of fog on planned or existing roads.

1. Introduction

The effect of fog on roads is well known. It impedes traffic and contributes to accidents, especially on high-speed roads and is reported to be that aspect of the weather that drivers fear most (Musk 1982). The number of occasions with fog in the United Kingdom has decreased over the last 25–30 years (Fig. 1) thought to be due mainly to the introduction of 'clean air' legislation in the late 1950s; although meteorologists had noted a decline in the number of dense fogs in London well before that time (Thornes 1978). However, interest in the subject of fog on roads has increased judging by the number of enquiries received by the Meteorological Office over the last few years. The enquiries usually require the identification of areas where fog is most likely to develop or persist (fog-prone areas) on existing, or planned, main roads and motorways. Occasionally the Office is asked to comment upon two alternative routes for a proposed scheme, e.g. the Department of Transport's preferred route and that of local objectors.

Studies carried out in the Office have concentrated on the identification of areas prone to radiation fog, the formation of which is highly dependent upon topography; hence favoured areas for radiation fog formation are

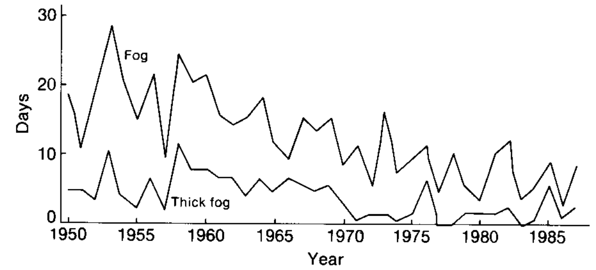

Figure 1. Number of days with fog (visibility < 1000 m) and thick fog (visibility < 200 m) at 0900 GMT at Manchester Airport 1950–87.

*This article is based on a paper presented at the Fourth International Road Weather Conference on 'Meteorology and Road Safety' in Florence, Italy, 8–10 November 1988.

identified relatively easily. Radiation fog is potentially the most dangerous to drivers, as it can be dense and also patchy, and hence the cause of sudden changes in visibility. When appropriate, areas prone to hill fog (caused by low cloud) have also been considered, e.g. areas over 150–200 m above mean sea level. Advection fog is not considered in this paper as it can occur over large areas, regardless of topography and no favoured locations can be identified.

As well as identifying fog-prone areas, an estimate of the number of occasions when fog is likely to occur is also usually required, with emphasis on the lower visibility thresholds (say < 200 m) which would be of most relevance to drivers. In attempting to answer these enquiries, various techniques have been employed and developed by the Meteorological Office. These are:

(a) topographical studies, using maps and route tours,

(b) analysis of visibility and cloud-base data held in computer archives by the Meteorological Office,

(c) obtaining local knowledge from traffic police, local authorities, motoring organizations and weather observers,

(d) aerial thermal mapping by aircraft and satellite, and

(e) deriving the localized fog climatology using a 'fog potential index'.

2. Identification of fog-prone areas

2.1. Topographical studies

When trying to identify areas where fog is most likely to occur, the first step is to study relevant maps or plans. Usually 1:50 000-scale maps or 1:10 000-scale plans together with longitudinal cross-sections, if available, are used. Features such as river valleys, high ground and land use can be identified from the maps, and slope angles can be calculated to estimate potential katabatic drainage into an area. More detailed information about a route can be obtained from the longitudinal cross-sections, which reveal any dips or hollows in the profile, as well as, for example, the size of embankments and cuttings. These cross-sections are especially useful when considering planned routes.

Currently the information concerning land use and topography (e.g. slope angles) is analysed by hand. However, in the future, digitized UK topographic and land-use data sets at 200 m resolution for the United Kingdom could be used to calculate these parameters automatically.

After the map study has taken place, usually at least one route tour of the area is undertaken in order to assess those places already identified as being potentially fog prone and check for any other areas not so apparent from studying maps. The purpose of the tour is not to look for fog, but simply to identify possible fog-prone areas, therefore all tours take place during daylight hours, in fine weather. For a proposed route, an area is generally visited with a local engineer or planner who knows the route and its layout. Such a route is generally viewed from existing roads, before any construction work has begun. Photographs are usually taken of those places thought to be of relevance.

2.2. Use of visibility and cloud-base data

2.2.1 Visibility data

The Meteorological Office's climatological database contains hourly visibility observations from about 70 synoptic stations for at least the last 17 years (many of them have records of over 30 years). Also, daily visibility data (as observed at 0900 GMT) are archived for hundreds of climatological stations for about the last 25–30 years. The data can be analysed in many ways using flexible computer programs to produce averages or frequency analyses.

Visibility information from the nearest Meteorological Office observing station may provide useful initial guidance about fog in the area. However, it is unlikely that conditions experienced at the station will reflect exactly those at a different site because of changes in topography that could occur over a short distance. The visibilities data can, however, be used to reveal trends in fog formation from hour-to-hour, month-to-month and year-to-year, as well as the relationships between the frequencies of occasions with visibility below various thresholds.

As a typical example Fig. 2 shows the variation of the average number of occasions per year at Gatwick Airport with visibility below 200 m as a function of

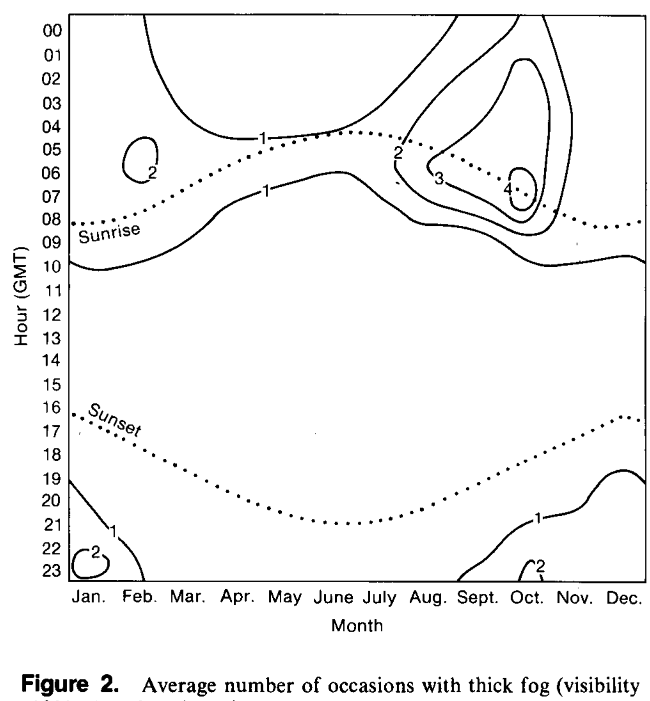

Figure 2. Average number of occasions with thick fog (visibility < 200 m) at Gatwick Airport.

month and time of day. Various features can be identified:

(a) the maximum occurrence of 'foggy occasions' during the early hours of the morning, i.e. the time of maximum cooling on 'radiation' nights,

(b) an absence of foggy occasions during daylight hours irrespective of season, and

(c) the persistence of foggy occasions through more hours of the day during the late autumn and winter months (because of the reduction in insolation).

Analysis of data from many synoptic stations suggests that these features, which are consistent with radiation fog formation, are broadly representative of many low-lying inland sites. Such features can also be identified when lower visibility thresholds are considered.

In general, the times with the greatest occurrence of fog are before the morning 'rush hour', although in the late autumn and winter months there is a risk that the peak traffic flow will coincide with foggy conditions.

2.2.2 Cloud-base data

For those places where hill fog is likely to occur, analysis of visibility data may not be appropriate. This is because almost all of the hourly UK synoptic stations are at relatively low-lying sites and any low visibilities recorded will be due to radiation or advection fog and not to hill fog. However, an analysis of low cloud-base data will give an indication of the number of occasions when hill fog is likely to occur.

For example, if there were a total cover of stratus with its base at a height of 150 m above Gatwick Airport (which itself is 60 m above mean sea level), then visibility might be reduced on nearby high ground with an altitude of greater than 210 m, for instance the North Downs.

The seasonal and diurnal trends in the occurrence of stratus (at inland locations) are similar to those of radiation fog (described earlier). There is a maximum occurrence during the winter months and fewer occasions during the daylight hours of the remaining months (due to the effect of insolation).

2.3. Obtaining local knowledge

When considering an existing road, it is usually possible to identify people who know something about the incidence of fog in the area, such as where patchy/localized fog tends to form first or occurs often, and where fog-related accidents have occurred. Such people include the police and representatives of local authorities and the major motoring organizations, and their local knowledge is very valuable. This information can provide a useful check against locations identified by other means. However, a route tour, after this local knowledge has been gathered, may be necessary to confirm (or otherwise) the locations as being fog prone.

For a study of the M25 London Orbital Motorway, arrangements were made with the motorway police to take note of the locations where fog occurred during a 5-month winter–spring period. Estimates of visibility and brief descriptions of conditions, e.g. patchy fog, drifting fog, blanket fog, etc. were also provided. Obviously, occasions with localized, patchy fog were of most interest.

For a proposed road scheme the police, local authority, etc. may not have any local knowledge about fog in the area, unless the proposed route happens to follow an existing road closely. However, the observers at the weather stations administered by the Meteorological Office, as well as 'amateur' weather observers are often sources of quite detailed and useful information about the incidence of fog in a particular area.

2.4 Identification of fog-prone areas using remote sensing

Two methods have been used to identify fog-prone areas using remote sensing:

(a) directly detecting the presence of fog using Advanced Very High Resolution Radiometer (AVHRR) data from polar-orbiting satellites, on suitable radiation nights, and

(b) detecting fog-prone areas, using an infra-red camera mounted on an aircraft flown on radiation nights, to identify areas which are cooling down quickly and/or those places where cold air may be collecting, i.e. potentially the places where radiation fog may form first.

2.4.1 Satellite data

The identification of fog during the daytime is relatively simple using visible satellite information. However, as radiation fog is the main interest, night-time occasions need to be studied. This causes problems as there are no visible data at night and with infra-red data it is difficult to distinguish the fog from the surrounding area. However, techniques have been developed to detect fog at night based upon the fact that fog and low cloud have different emissivities at different wavelengths, and the use of AVHRR data. AVHRR data are available in five spectral bands, three of which are situated in 'atmospheric windows' in the infra-red region, at 3.7, 11 and 12 μm. At the 11 μm wavelength, fog and stratus have an emissivity of approximately 1.0 and so the brightness temperature (inferred from the radiance) almost equals the temperature of the fog/cloud top. At the 3.7 μm wavelength, the emissivity is approximately 0.8–0.9, and the brightness temperature is significantly lower than the physical temperature. This property is not exhibited by land or sea surface to the same degree, and so this difference in temperature can be used to identify fog on suitable nights (see Eyre *et al.* 1984 for a more detailed explanation). However, the resolution of the satellite data is relatively coarse; each measurement of brightness temperature is an average for an area of 1–2 km^2. Consequently small areas of fog cannot be identified, yet it is on the more local scale that information is required. Also, using this technique, it is difficult to distinguish between stratus and fog, although the satellite information can be chosen to coincide with known foggy nights to eliminate this problem.

2.4.2 Aerial thermal survey

The information obtained from an aircraft-mounted infra-red camera is far more detailed than the satellite data with a resolution of about a metre, so, for example, individual trees and cars can be identified. At a flying height of about 1500 m each frame of information covers approximately 2 km × 2 km, so detailed information about the radiation being emitted by the road surface, and more importantly by the surrounding area, is obtainable. By calibrating the infra-red image with temperature data, collected by instruments on the ground during the flight the image can be converted into a thermal picture. For ease of interpretation, ranges of surface temperature are represented by different colours (Beaumont *et al.* 1987). The spatial variability in emissivity is not taken into account, causing some errors in the estimated surface temperatures. During a survey where 'observed' surface temperatures ranged from −4 to +8 °C, these errors are calculated, using the Stefan–Boltzmann equation (and more appropriate emissivities for different surfaces), to be generally within 2 °C for the typical surfaces of water, bare soil and trees. For a fog study, however, absolute surface temperatures are not as important as the differences between surface temperatures. On radiation nights this thermal contrast between surfaces will be great, especially around dawn, when maximum cooling is likely to take place. On such nights, the areas which appear the coldest are valley bottoms, areas of bare soil or marshy areas and large road cuttings. The warmest are built-up areas and the deeper bodies of water such as lakes and rivers. High ground also appears warmer on radiation nights, as the cold air has drained off the higher ground and collected in low-lying areas. These variations are all as would be expected from physical considerations. For example, the relative warmth of the surface of a deep body of water at night-time is a result of high specific heat and absorption of daytime radiation to a considerable depth, and also good conduction and convective processes transferring heat to the surface at night.

Aerial thermal surveys provide very detailed information about those places which are cooling down quicker or where cold air is collecting. By combining the survey information with the other data described, including proximity of roads to moisture sources, it is possible to identify the places where radiation fog is most likely to develop. An example of an aerial false-colour image of surface temperature is shown in Fig. 3 with areas of different surfaces — roads, houses, grass, woods and water — indicated. This image and the accompanying map show a section of the M25 motorway near Byfleet in Surrey.

3. Estimating the number of days with fog

Having identified areas where fog is likely to develop, an estimate of the number of occasions when fog is likely to occur is required. For places prone to hill fog, cloud-base data may be used (as described earlier). For places

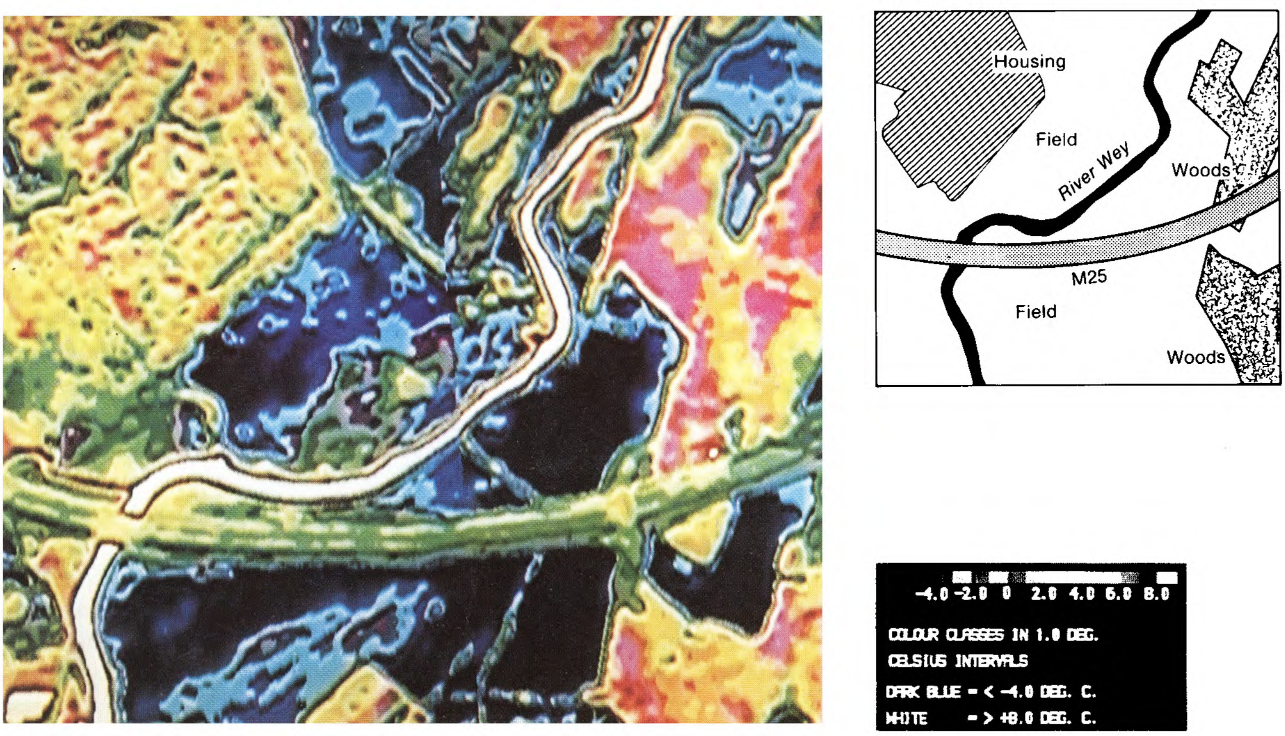

Figure 3. An example of an aerial false-colour image of surface temperature together with a location map of the area.

where radiation fog is likely to be a problem, various techniques have been developed.

A method was proposed by Musk to assess the potential of any site for experiencing radiation fog, known as the 'fog potential index' (Musk 1978). The index attempted to assess a site in terms of those criteria thought most relevant to radiation fog formation, i.e. topography, proximity to water sources, road layout and environmental features. Each criterion was then weighted according to its importance to radiation fog formation to produce the following equation:

$$\text{Index} = 10dw + 10tp + 2sp + 3ep$$

where *dw* relates to water sources (value increases with proximity to water and extent of water body), *tp* relates to local topography (value increases with a site's potential for trapping cold air draining off slopes at night), *sp* relates to site topography (value increases if the road is in a cutting which could trap cold air, or if the road is sheltered), and *ep* relates to environmental features (value increases with proximity to a rural location or pollution source).

To obtain the index for a site, large-scale maps and plans were used to allocate values between 0 and 4 (in increments of ½) to each factor *dw, tp, sp* and *ep*. The maximum value of the index was 100 ($10 \times 4 + 10 \times 4 + 2 \times 4 + 3 \times 4$) representative of, say, a sheltered, rural, river valley. Musk's model did not attempt to estimate the number of occasions with fog, but it provides a very useful method for comparing the potential 'fogginess' of different sites.

Attempts were made to take this technique one stage further and estimate the annual average number of days with fog for different sites. This was achieved by correlating occasions with low visibility at several Meteorological Office stations, with fog-potential indices calculated for each station, using amended forms of Musk's equation (incorporating different weightings and a simplified topography factor). Two approaches were adopted:

(a) indices were calculated for 33 Meteorological Office stations for which annual averages of the number of days with visibility < 1000 m and < 200 m at 0900 GMT had been calculated for the period 1971–86, and

(b) indices were calculated for 14 hourly synoptic stations for which annual averages of the number of days with visibility < 1000 m, 300 m, 200 m and 100 m at 0600 and 0900 GMT had been calculated for the period 1971–86.

The stations chosen were all inland, generally low-lying sites, likely to experience some radiation fog, with the average number of fog days ranging from 10 to 40. Some of these fog days will be due to advection fog, but these make up only a small proportion of the total. The averaging period, 1971–86, was chosen to represent the visibility conditions experienced today as the introduction of the 1956 Clean Air Act has played a major role in reducing the number of occasions with fog since the late 1950s in the United Kingdom.

The best correlation occurred when the lower visibility threshold of 100 m and the hour of 0600 GMT (rather than 0900 GMT) were considered. The correlation enables an index calculated for any site to be readily converted into an estimate of occasions with visibility < 100 m at 0600 GMT.

Further analyses of visibility data from Meteorological Office stations have produced factors relating the number of occasions with visibility < 100 m at 0600 GMT to the number of occasions with visibility < 100 m at 0900 GMT and also to the number of occasions with visibility < 1000 m, 300 m and 200 m at 0600 and 0900 GMT. Hence a fog-potential index can be converted into the number of occasions when visibility falls below these four thresholds at either of the times considered.

The calculation of the fog-potential index is subjective and, when a large number of points has to be considered, time-consuming. Currently, however, the feasibility of using the high-resolution topography and land-use data set (described in section 2.1) to carry out objective calculations is being tested. Computer-plotted colour-coded maps of fog-potential indices in an area with a resolution of 200 m × 200 m have been produced. However, their production is still very much in the experimental stage but it is envisaged that the automatic production of fog-potential indices will play a major role in future fog-study work.

4. Conclusions

The various methods described are available for locating areas prone to radiation fog and for estimating the number of days with fog at each location. For estimating the number of days with hill fog, low cloud-base information can be used as a data source.

The methods have been used to answer many enquiries about fog on roads. Although the format and content of each fog study is generally similar, the use to which this information will be put varies with the stage that a particular road scheme has reached. If a scheme is at the planning stage and several proposed routes exist, e.g. the A34 Newbury Bypass and the A30 Exeter–Honiton Relief Road, then the study can be used to help choose the least foggy route or to avoid potentially foggy areas. If a scheme is at a planning stage but the final route had been decided upon before a fog study was produced, e.g. the M20 (Maidstone–Ashford) and the Birmingham Northern Relief Road, the study will highlight those areas where fog may be a problem and possible changes in road layout (such as using a bridge to cross a valley) or a review of lighting requirements may take place.

For existing roads, e.g. the M42 and M54 motorways in the West Midlands, a fog study can only be used to review lighting facilities in fog-prone areas or suggest areas where extra warning signals may be necessary.

The most recent fog study to be completed was for the 180 km of the M25 London Orbital Motorway. Various locations were identified as being potentially fog prone (mainly radiation fog, but occasionally hill fog). At most of these locations, fog-detecting equipment will be installed in late 1989, which will be linked to warning signals on the motorway. Hence, when a detector records visibility below a predetermined threshold, for a certain length of time, the signals will be activated to warn drivers of potential danger ahead. It is intended that the visibility data will be archived and made available to the Advisory Services Branch of the Meteorological Office. The data can then be analysed to test the accuracy of the estimates of the number of days with fog at each location and hence provide useful feedback about the techniques currently being employed.

Acknowledgement

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Journeys to the North Pole and back

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Summary

This article describes the preparations for and phenomena observed during two Polar flights.

1. Introduction

In December 1987, the Meteorological Office at Kinloss in Scotland was asked by the Royal Air Force to provide details of the expected low-level flying conditions at the North Pole during late April and early May with a view to carrying out an operational task the following year. This is a documentary account of the work done by the Meteorological Office in preparing for the trips which have since been given wide publicity in the national media, along with a brief account of the meteorological aspects of the actual journeys which I was fortunate to undertake.

2. Preparation

In the first instance, contact was made with the Special Investigations Branch of the Meteorological Office. They supplied details of equivalent tail-wind components from Kinloss to 90° N so that some idea of anticipated fuel figures could be worked out. Also supplied, from a variety of publications, were some basic climatological statistics for the area, e.g. mean cloudiness, probabilities of visibility and wind speed falling within given ranges, and mean temperature figures. Along with this information was a print-out of all surface observations in the North Pole area for the period 16–30 April for both 1986 and 1987, taken from the synoptic data bank, and this contained some useful reports from an ice station which reported regularly in SHIP code.

A couple of articles found in locally held copies of *Weather* and a paper (Meyer 1955) found in a dusty box file (keep something long enough and it will eventually come in useful) gradually built up a picture of what conditions would be like at the time of year in question.

Table I is taken from Koerner's (1970) summary of observations made during the British Trans-Arctic Expedition 1968–69 and shows that the frequency of poor visibility and the incidence of low cloud increased dramatically from April to May.

Conditions at the Pole fall into two quite distinct types with winter characterized by anticyclonic conditions. As temperatures fall in the perpetual night to around −30 to −40 °C, the ice pack freezes over and this effectively leads to a continental-type climate with largely clear skies and good visibilities. In spring (from about May) as the temperature rises, the ice gradually becomes more broken, allowing more and more liquid

Table I. Summary of the April and May observations from the meteorological log of the British Trans-Arctic Expedition, February 1968–June 1969

	Mean temp. (°C)	Visibility (*miles*)			Cloud			
		< 2½	2½–10	> 10	Mean total (*oktas*)	Low	Medium	High
		% of total occasions				% of total		
1968								
April	−27	3	6	91	3	14	2	84
May	−10	31	40	29	6	69	9	22
1969								
April	−26	26	6	68	4	56	7	37
May	−09	45	18	37	6	81	7	12

water to evaporate leading to a maritime-style climate in the summer season (August and September) characterized by instances of fogs and low stratus gradually increasing from May until July. This gradually clears in the autumn transition back to the winter conditions.

The trips planned from Kinloss were in late April and early May, so we were now in a position to offer some idea of low-level conditions at the Pole. We were reasonably confident that the April trip would have good conditions but the risk of poor visibility and/or low cloud would obviously be higher on the May trip. I understand that on the basis of the information provided, the May trip was brought forward to as early a date in May as was feasible. It was at this time that I was invited to go on the trips, which covered the route shown in Fig. 1.

Nearer the time of departure, upper-wind charts were ordered from Headquarters Strike Command. These were initially in the form of planning winds which were issued the previous day and based on 1200 GMT data for 36 hours ahead (T+36). The following morning, a further set of upper-wind charts was issued to Kinloss based on 0000 GMT data for T+12, T+18 and T+24 to cover the entire flight. This procedure was repeated for the second flight in early May.

A few weeks prior to the actual flights, it was noticed that another ice station was reporting surface observations from a position very close to the Pole. A regular check was kept on these reports up to the actual flights, and they proved to be most useful when it came to assessing the more detailed low-flying conditions required by the aircrew.

3. The first trip

For the trip in late April there was an anticyclone centred north of Iceland with a ridge extending south-east into the North Sea and a north-westerly airflow from the Pole extending towards northern Scandinavia.

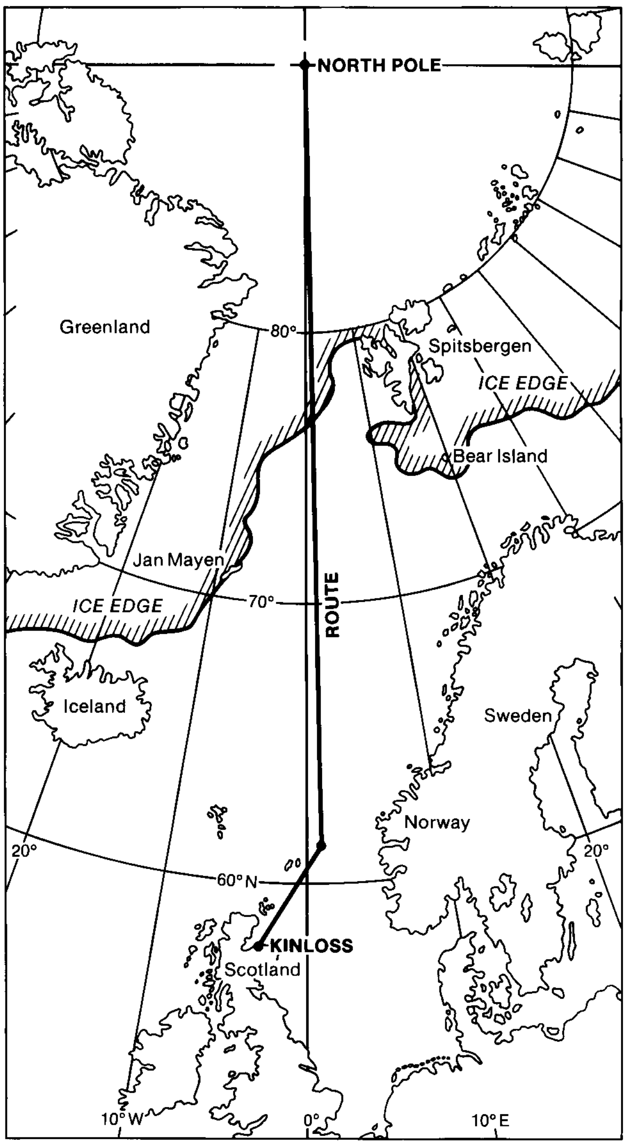

Figure 1. Map showing the route taken on the trips and the position of the ice edge during the period.

This gave an Arctic Maritime air mass over much of the route. Fig. 2 shows the ice edge at 77° N, 01° E from 26 500 feet (FL265) and is a good example of convective cloud streets forming over the open water as the flow moves out from over the ice.

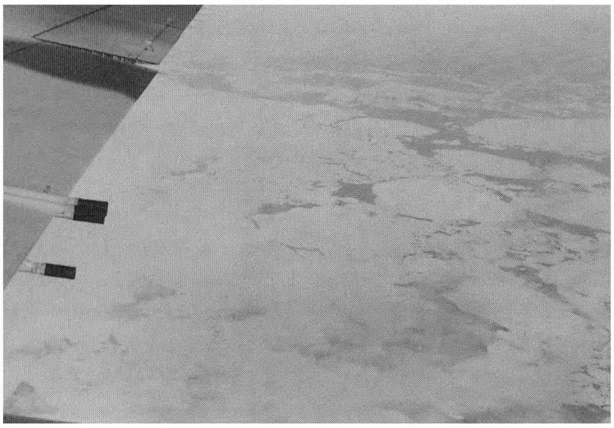

Figure 2. The ice edge with clouds streets forming over the sea.

The latest report from the ice station near the Pole suggested a good deal of altostratus and cirrostratus (Cs) cloud. A good deal of layer cloud was certainly evident as we crossed the ice-cap, but as we approached 90° N I was surprised to find that the ice-cap was visible from our cruising level of FL270. A gradual descent to low level revealed that no cloud actually existed, although a general haze layer extended from around FL230 down to the surface. The airborne visibility slowly improved during the descent until at around FL10 the visibility was estimated at around 30 km in some directions, while in others it was no more than 10–15 km. The visibility did not appear to alter much for the duration of the time we were operating in the region around the Pole.

At low level, the sky did have the appearance, exaggerated by the very low sun, of a layer of Cs but as mentioned earlier no cloud was actually seen. Surface temperatures were reported by the ice station as −17 °C with a surface wind of 15–20 kn giving some low drifting snow. This agreed reasonably well with the values measured from the aircraft at FL10 of −19 °C and a wind of 27 kn.

The ice, as can be seen from Figs 3 and 4, appeared to be very uniform with only a few very narrow cracks which were obviously freezing over rapidly. Many pressure ridges are also in evidence, giving a mosaic pattern as seen from the air. Drifting snow can also be seen in Fig. 4. I was struck by the haziness of the visibility which, as mentioned above, was very variable and quite poor in some directions. However, it did not present too much of a problem for operations at low level. The return trip to Kinloss was largely in darkness and therefore uneventful from my point of view.

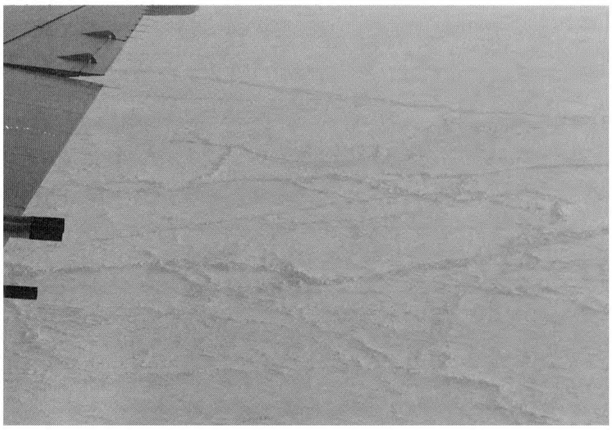

Figure 3. The ice-cap near the Pole.

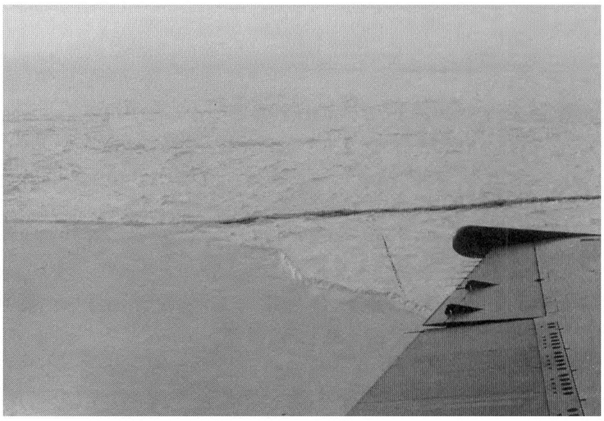

Figure 4. The ice-cap near the Pole, with crack and refrozen water.

4. The second trip

The second trip in early May was some 10 days after the first. With a depression over northern Scandinavia and its associated occlusion extending south-west across the United Kingdom, an unstable northerly type covered much of the Norwegian Sea as typified by the cumulonimbi in Fig. 5 taken at 69° N, 01° E from FL295.

Figure 5. Cumulonimbi over the Norwegian Sea.

Figure 6. The ice-cap near the Pole, with extensive cracks (compare with Fig. 3).

Figure 7. The ice-cap near the Pole, with areas of open water (compare with Fig. 4).

The latest report from the ice station in the region of the Pole showed that the surface temperature had now risen to −10 °C, but apart from this conditions were very similar to those of the previous trip with a reported visibility of 20 km, full cover of upper cloud, and a surface wind of 12 kn. As with the previous trip, although there was a good deal of layer cloud evident as we first crossed the ice-cap, as 90° N was approached, the ice-cap became visible from FL290, and a gradual descent to low level once again revealed no cloud but only a haze layer extending from FL250 down to the surface. The visibility at around FL10 was initially around 20 km but during the time actually spent in the region of the Pole, the visibility became very variable and reductions to around 2000 m were estimated just prior to our departure for home. The poor visibility caused some problems for the aircrew in that all horizontal references became non-existent and the expression 'flying in a goldfish bowl' was used more than once. Once again, the sky had the appearance of a layer of Cs.

The principal difference from the previous trip was the state of the ice-cap, which had now developed many more cracks, some of which were evidently becoming quite wide, with ice only just beginning to form in the open water, see Figs 6 and 7. The trip home was again uneventful, being largely in darkness.

5. Comments

It is now clear that the transition from winter to summer had already begun at the edges of the ice-cap with the ice becoming more broken allowing liquid water to be evaporated into the atmosphere, which then quickly cools by advection over the still-cold ice to form the fogs and low stratus typical of the Arctic summer. The gap in the cloud cover at the Pole itself indicates that the transition had not quite reached 90° N and suggests that the data supplied to the Royal Air Force were both accurate and useful.

Acknowledgements

I am indebted to K. Grant in the Special Investigations Branch and S. Wattam at Headquarters Strike Command for all their patient support during the preparation for these trips. I am also indebted to Squadron Leader Heppenstall, 206 Squadron, Royal Air Force Kinloss for allowing me to go on journeys not likely to be repeated for quite some time.

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The summer of 1988 in the United Kingdom

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Summary

Most parts of the United Kingdom had a somewhat average summer, although the seasonal rainfall values tend to conceal a very wet July which compensated for a dry June.

1. The summer as a whole

Mean temperatures during the summer were generally near normal. Most parts of Scotland, the Isle of Man and parts of North Wales were a little above normal, reaching 0.6 °C above normal in central Scotland, whereas in most other areas temperatures were slightly below normal, and in some parts of southern England nearly 1 °C below normal. A dry June followed by a very wet July and a wet August gave rainfall amounts close to average in the east but above average in western areas, reaching nearly twice the normal in parts of Cumbria. Eastern Kent, however, had less than half the normal. Sunshine amounts were near or below average generally; the brightest conditions were in eastern Scotland and north-east England, but it was dull elsewhere, especially in western areas.

Information about the temperature, rainfall and sunshine during the period from June to August 1988 is given in Fig. 1 and Table I.

2. The individual months

June. Mean monthly temperatures were slightly above normal in most areas, but below normal in parts of the east Midlands, East Anglia and south-east England, ranging from nearly 2 °C above normal at Ronaldsway, Isle of Man to more than 0.5 °C below normal in East Anglia and eastern Kent. Monthly rainfall amounts were generally below normal and at Glasgow Airport only 17% of the average fell. However, over parts of South Wales, the Midlands and East Anglia, amounts were locally above normal, reaching 143% at Aberporth, Dyfed. England and Wales as a whole had the driest June since 1976, and Scotland the driest this century. Many places had record low rainfalls; Glasgow Airport had only 10 mm, equalling the amounts recorded in 1921 and 1925 for the driest Junes in a record which, at various sites around Glasgow, goes back to 1868; Worthing, West Sussex had as little as 9 mm of rain during the whole month. Monthly sunshine amounts were generally above normal in Northern Ireland, North Wales, northern England and most of Scotland, reaching 123% of normal at Eskdalemuir, Dumfries and Galloway, but below normal in northern Scotland, South Wales and the remaining parts of England, and as low as 59% of normal at Cromer, Norfolk.

Many areas had some rain during the first few days of the month, with heavy falls and thunderstorms locally. Further rain affected western areas on the 6th, and an area of quite heavy rain moved south-westwards over England and Wales on the 8th and 9th. Dry weather

Table I. District values for the period June–August 1988, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+0.3	+1	113	85
Eastern Scotland	+0.3	+2	109	98
Eastern and north-east England	0.0	+2	121	69
East Anglia	−0.3	+3	106	90
Midland counties	−0.1	+3	118	91
South-east and central southern England	−0.5	+2	94	90
Western Scotland	0.0	+3	133	97
North-west England and North Wales	−0.2	+2	113	94
South-west England and South Wales	−0.4	+4	133	85
Northern Ireland	+0.1	+2	116	93
Scotland	+0.2	+2	120	93
England and Wales	+0.3	+3	115	92

Highest maximum: 30.2 °C in the Midlands in August.
Lowest minimum: 0.6 °C in western Scotland in June.

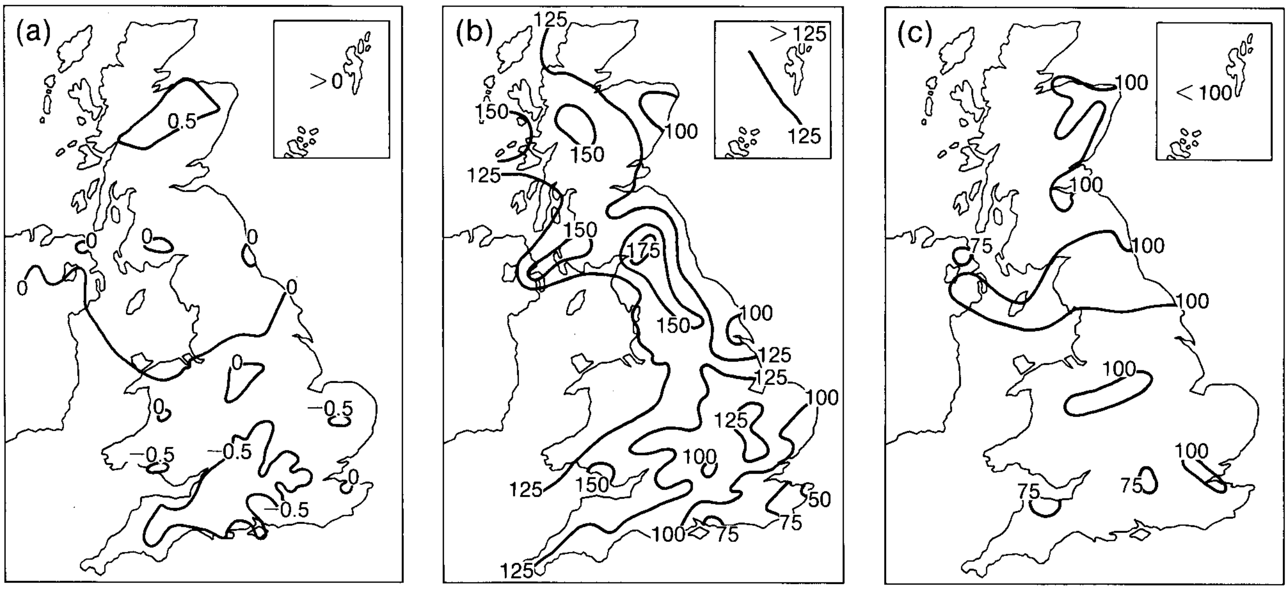

Figure 1. Values of (a) mean temperature difference (°C), (b) rainfall percentage and (c) sunshine percentage for summer, 1988 (June–August) relative to 1951–80 averages.

then prevailed until the last week of the month, apart from some heavy thunderstorms in the south-east on the 20th. Scotland had a very pleasant summer month, the best since the fine summer of 1984, although low cloud and fog affected coastal areas from time to time, keeping temperature and sunshine near normal in some places. For the closing days of the month the weather turned showery with thunder in places although there was still some dry, sunny weather, especially in Scotland.

July. Mean monthly temperatures were below normal everywhere except northern and eastern Scotland and ranged from 1.0 °C above normal at Lerwick, Shetland to 1.9 °C below normal at Lyneham, Wiltshire. Rainfall amounts were well above average in most places, although in the extreme south-east of England amounts were near or below normal in some places, ranging from more than three times the normal at Carlisle, Cumbria to 83% of normal at Manston, Kent. Some long-standing records were broken: it was the wettest July over England since 1936 and Wales since 1939, and the wettest July in Scotland since records began there in 1869. Sunshine totals were below the average nearly everywhere, although some places in eastern Scotland and in the Western Isles had near or just above average totals, ranging from 115% of average at Tiree, Strathclyde Region to 64% at Exeter, Devon.

Rain or showers, the rain heavy at times and sometimes accompanied by thunderstorms, occurred over some parts of Great Britain on nearly every day. Between the 18th and 20th it was generally dry, but with some rain in western parts of Wales. Many of the month's major events were disrupted in some measure: the Royal Agricultural Show ground at Stoneleigh, Warwickshire became waterlogged after heavy rain on the 4th and among sporting fixtures disrupted were the Tennis Championships at Wimbledon, which were virtually washed out on the 3rd, and the Open Golf Championship at Lytham St Anne's. Both these championships had to be extended by a day to allow the competitions to be completed, and the British motor racing Grand Prix at Silverstone, Northamptonshire was run in very wet conditions. Thunderstorms occurred widely between the 1st and 8th, mainly over England. There were further thundery outbreaks from time to time, widespread over southern England on the 26th.

August. Mean monthly temperatures were near or below normal nearly everywhere in the United Kingdom, ranging from above normal in some eastern parts to more than 1 °C below normal in parts of north Devon. Monthly rainfall totals were above normal in most of Scotland, Wales, Northern Ireland and parts of north-west and south-west England and below normal elsewhere, ranging from half the normal in the coastal areas of East Anglia and Kent to more than twice the normal at Tiree, Strathclyde Region. Sunshine amounts were generally above normal in England and Wales north-east of a line from about Rhyl on the coast of North Wales to Southampton on the south coast, but below normal elsewhere, ranging from more than 120% in places in north-east England and on the Suffolk coast to less than 60% in western Scotland.

The month began rather unsettled with occasional rain chiefly in northern areas. However, it was dry nearly everywhere from the 5th to 8th, and at Anvil Green, Kent it was dry for the first 17 days. It was very wet on the 12th in parts of northern England and in central and northern Scotland, particularly around Glenmore and the Moray Firth. Most places in northern and western areas of Great Britain had a wet day on the

14th and, after two generally dry days on the 15th and 16th, another wet day on the 18th. The unsettled weather persisted for the rest of the month, with rain falling on almost every day in some western areas of England, more especially during the last three days. Thunder, sometimes with hail, occurred around the Firth of Forth and the coast of north-east England on the 1st, and across central and eastern parts of England on the 2nd; scattered thunderstorms occurred in western Scotland on the 14th, central Scotland on the 18th, eastern England on the 19th and 20th, and east and south-east England on the 28th and 31st.

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Climatological data processing in the Synoptic Climatology Branch of the Meteorological Office

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Summary

A description is given of the collection, quality control and archiving of world-wide climatological data carried out by the Synoptic Climatology Branch of the Meteorological Office.

1. Introduction

The availability of climatological data on a global basis is becoming increasingly vital to many users both inside and outside the Meteorological Office. The data are requested by a wide variety of commercial and industrial bodies, for instance, who may need it for applications such as agriculture, civil engineering or aviation. They are needed for research, such as that carried out in the Synoptic Climatology Branch into atmospheric variability on time-scales from 10 days (which benefits long-range forecasting) to a season (used as the basis of the successful seasonal tropical rainfall forecasts). Also, the increasing concern that man may be changing the climate of the earth through emissions of greenhouse gases has lent an urgency to the monitoring of global climate change.

To fulfil such needs it is essential to maintain a comprehensive, accurate and up-to-date bank of climatological data on a world-wide scale extending back over a large number of years. This has been the responsibility of the CLIMAT section of the Branch for many years, with an increasing emphasis recently on the use of computers for both storing and retrieving the data.

2. The CLIMAT system

A selection of meteorological observing stations throughout the world are designated as CLIMAT stations by the parent country, at the request of the World Meteorological Organization (WMO). At the end of each month these stations are required to transmit their climatological data for the month using the CLIMAT (surface) and CLIMAT TEMP (upper-air) codes. At present (1988) there are over 2000 CLIMAT stations and about 450 CLIMAT TEMP stations.

The CLIMAT code is used to report monthly mean and total values of surface data and the CLIMAT TEMP code reports monthly mean values of upper-air data, together with the number of days of data used to compute the monthly mean. Ocean Weather Ships report similar data using the CLIMAT SHIP and CLIMAT TEMP SHIP codes.

This article is concerned primarily with the CLIMAT (surface) data processing system used by the Synoptic Climatology Branch of the Meteorological Office. An outline flow chart of the processing is shown in Fig. 1. A similar system for handling CLIMAT TEMP (upper-air) data is in an advanced stage of development.

3. Sources of data

3.1 Recent data

The primary means of data reception since 1980 has been the Global Telecommunication System (GTS). Data are received via the GTS at the Meteorological Office telecommunication centre and are fed automatically into the Synoptic Data Bank (SDB) where the CLIMAT messages are separated from the synoptic messages, ready for processing by the Synoptic Climatology Branch.

Unfortunately not every country's data survive the passage through the GTS, either through faulty transmission in the country of origin, or perhaps through loss at a collecting centre *en route*. It is usually possible to fill in most of the gaps by means of confirmatory teleprinter messages or, somewhat in arrears, by data sent through the mail or (even more in arrears) from the publication *Monthly climatic data of the world*, issued by the National Climatic Data Center (NCDC) at Asheville, North Carolina. This publication makes use of data received on forms as well as via the GTS. It is the ambition of the WMO to make the dissemination of CLIMAT data fully automatic, but this is a long way from being realized at present.

3.2 Historical data

Data for the period from 1738 to 1980 are derived primarily from a magnetic tape supplied by the NCDC, supplemented by unpublished manuscript data collected by the Meteorological Office, dating back to about 1937. Data published by other National Meteorological Services and the NCDC publication *World weather records*, issued at 10-year intervals, are also proving useful sources of historic data.

4. Content of the data

At the present time, CLIMAT stations are required by the WMO to report monthly means or totals of the following elements:

station-level pressure,
mean-sea-level (MSL) pressure,
air temperature,
vapour pressure,
number of days with rainfall equal to or exceeding 1.0 mm,
rainfall, and the quintile into which it falls,
hours of sunshine, also expressed as a percentage of the monthly normal, and
sea temperature (Ocean Weather Ships only).

Data collected prior to the 1960s normally consist only of pressure, air temperature and rainfall.

5. Quality of the data

Since the automation of the Meteorological Office CLIMAT system in 1986, comprehensive automatic quality control has been carried out, supplemented by visual inspection of data on screens, print-outs and plotted charts. See section 8 for a description of the automatic quality-control procedures.

Some of the earlier manuscript data were subjected to visual scrutiny for gross errors. They were then plotted on charts and their deviations from climatological means were compared with values for the same month at neighbouring stations, as well as with other months and years at the same station. Values judged subjectively to be unacceptable were deleted, unless a corrected value was found later in the relevant issue of *Monthly climatic data of the world.*

No systematic quality control of data on the NCDC magnetic tape has been carried out, but some discrepancies have been detected and corrected, where possible, in the course of using the data. Typical errors found have been incorrect temperatures, apparently due to double conversion from degrees Fahrenheit to degrees Celsius;

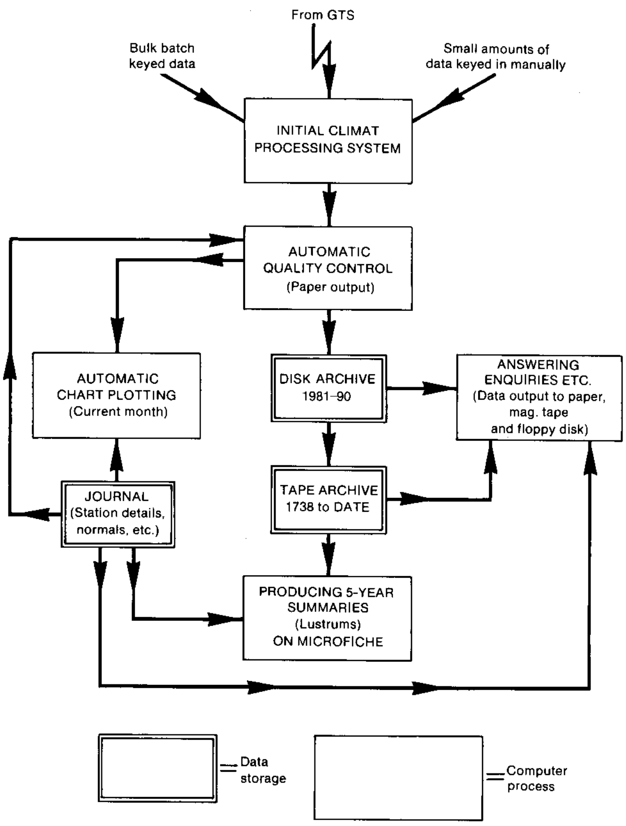


Figure 1. The logical flow of data through the CLIMAT system.

WMO procedures for reporting or correcting to MSL pressure at very high-level stations not being followed; and discontinuities resulting from stations changing site while retaining the same WMO station number. There are also significant gaps in the records for some stations. These are being filled in, if the data are available from our manuscript records or from *World weather records*, as resources permit.

6. Storage of the data

Data for the current decade are stored on disk and updated every month, one month in arrears. At the end of each month the tape of NCDC-derived data is also updated using the disk data, thus producing a comprehensive magnetic tape archive covering the period from 1738 to date. The data are stored using a software system developed by the Meteorological Office, known as GPACCESS. This makes storage and retrieval as efficient as is possible with magnetic tape.

7. Presentation and accessibility of the data

7.1 Lustrum books

Five-year summaries of the data, on a station-by-station basis, are produced on microfiche at regular intervals. This is a continuation of the long-established practice of entering CLIMAT data manually in 'lustrum books'. The 'old' lustrum books are still available in the Synoptic Climatology Branch.

7.2 Monthly charts

These are now plotted automatically by the computer and drawn up by hand. The latter process provides a useful final stage of quality control. The charts produced are as follows:

Northern hemisphere

MSL pressure and its anomaly from 1951–80 climatological means,
temperature and anomaly,
rainfall and percentage of 1951–80 normals, and
sunshine and percentage of normals.

The MSL pressure analysis uses a gridded monthly average of the daily operational 00 GMT analyses as well as the CLIMAT data. The MSL pressure anomaly chart is produced by gridding the MSL pressure and normals charts.

In order to examine the relationship between upper-air and surface features, an additional northern hemisphere chart is formed from a composite of:

mean monthly MSL pressure,
500 mb ridge and trough lines,
50 kn isotach at 300 mb (40 kn in summer), and
rainfall percentage of normals.

Southern hemisphere

MSL pressure and anomaly, and
temperature and anomaly.

Some southern hemisphere charts are received from the Australian Bureau of Meteorology in Melbourne.

A selection of northern hemisphere charts for the most recent 3 months is displayed, for ready appraisal, on the wall of the CLIMAT Laboratory in the Synoptic Climatology Branch. These are frequently used in providing background information to global weather events, such as the Bangladesh floods in 1988.

7.3 Retrieval of data

A standard retrieval program is available which will extract data in chronological order for any given station. An alternative program will print out all the data for all stations for any given month. If required, the data can also be copied to magnetic tape or floppy disk.

7.4 The Journal

Details of all the stations for which data are collected are stored on a disk data set, commonly referred to as the 'Journal'. These details include the station name, its latitude, longitude and height together with 1951–80 normals for each of the elements (temperature, pressure, etc.) if these are available. This information is required by the computer programs which plot, quality control and retrieve the data (see Fig. 1).

8. Automatic quality control

The main part of the quality control is performed in three stages for each element for each station.

(a) Each value is checked to see whether it lies outside previous extreme limits.

(b) Each value is checked against upper and lower confidence limits which are (apart from rainfall) three times the standard deviation above and below the normal. In the case of rainfall an empirically defined upper limit is used, derived by adding to the average 1.5 times the second highest monthly anomaly recorded for the station. The lower limit is derived similarly but, if negative, is set to zero.

(c) The normalized anomaly (i.e. anomaly divided by standard deviation) for each value is compared with the normalized anomalies at six neighbouring stations and is queried if, for most elements, it differs by more than 0.7 from the mean of them and by more than 3.0 times their standard deviation. For vapour pressure and all three rain indices (rain-days, rainfall and quintiles) these limiting criteria become 1.5 and 4.0 respectively.

In addition:

(d) A check is made of the relation between MSL pressure and station-level pressure and, if possible, surface temperature and station height.

(e) Rain-days and rainfall are compared — a day with 1.0 mm of rain or more must be classed as a rain-day. Also, if the rainfall is zero, the number of rain-days must also be zero.

(f) Vapour pressure is checked to ascertain that it is not greater than saturation vapour pressure.

(g) Sunshine and its percentage of normal are used to check that 100% of the implied normal sunshine does not exceed total daylight.

(h) A check is made for lack of negative correlation between MSL pressure and rainfall.

Except in the case of (a) suspect values are not rejected outright, but are examined on plotted charts and if they look inconsistent with surrounding stations are compared with the mean of daily values from the SDB and replaced if possible. It is sometimes also possible to replace a suspect value at a later date with one from *Monthly climatic data of the world.* Changes are made to the data via a computer terminal.

Acknowledgements

Much of the initial design work and computer programming for this system was carried out by M. Jackson and J.R. Lavery, while the procedures for computing the 1951–80 normals and for quality controlling the data were developed by B. Collison. Subsequent implementation and further development have been in the hands of the author, assisted by J. McCoy who, together with B. Harlock, also looks after the day-to-day running of the system.

Notes and news

Joint Opportunities for Unconventional or Long-term Energy supply (JOULE)

The European Economic Community funds a programme of Research and Technological Development in the area of non-nuclear energy and the next phase of the programme covers the period 1989–92. JOULE is a 3¼-year programme which was scheduled to start on 1 January 1989 but which now comes into force in spring 1989, when it is due to be ratified by the Community Council.

The objectives of JOULE are:

(a) Increasing long-term security of energy supply and reducing energy import by Community countries.

(b) Alleviating environmental problems related to energy use.

(c) Improving the Community competitiveness through reduced energy costs.

(d) Establishing standards for energy production assessment.

(e) Solving technical problems in energy production.

The Commission of the European Communities has recently issued the invitation to research organizations in the Community countries to apply for funding. Two areas of research and development under the general title of 'Solar-derived renewable energy sources' may be of interest as having meteorological associations. These are:

(a) Wind energy — The principal objective of this programme is to decrease the cost of wind-derived electricity through improvements to cost, performance and lifetime of wind turbines. Part of the programme is devoted to the study of the types of site to be favoured for turbines, such as those with complex topography which concentrate the wind naturally; this could involve modelling and measurement of turbulent winds in mountainous terrains.

(b) Biomass — In this area, the main objective is the development of techniques for the production, conversion and use of fuel from plants with the ultimate aim of providing 10% of Community energy requirements. Research is being promoted on specific promising 'energy crops' and their preferred areas of growth, and also their harvesting, transport and storage.

The Meteorological Office has climatological data available to support these programmes of research, particularly measurements of wind, temperature and rainfall, and derived quantities such as soil moisture deficit. Recently, *Climatological data for Agricultural Land Classification* for England and Wales have been compiled and published by the Meteorological Office.

Further details about JOULE are given in an information package obtainable from:

Commission of the European Communities
Directorate XII/E
200, Rue de la Loi
B-1049 Brussels
Belgium

for the attention of:
Mr G. Caratti di Lanzacco (Wind energy)
or Mr D. Pirrwitz (Biomass).

Alternatively further information can be obtained from:
Dr S.E.R. Hiscocks
Department of Energy
Energy Technology Division
Thames House South
Millbank
London SW1P 4QJ.

Reviews

An introduction to boundary layer meteorology,

by R.B. Stull. 165 mm × 246 mm, pp. xii+666, *illus.* Dordrecht, Boston, London, D. Reidel Publishing Company, 1988. Price Dfl.220.00, US $99.00, £64.00.

In preparing this book, the author set himself some daunting goals — to combine in a single volume, a wide-ranging textbook for students, a reference work for researchers as well as a literature review of current ideas and methods. Professor Stull is an established researcher in the field of boundary layer meteorology although inevitably, as he himself admits, not an expert in all the areas covered. Perhaps equally inevitably, the book is not a complete success but nevertheless represents a brave attempt to reach an ambitious goal. Although there are already a number of fine textbooks concentrating on various aspects of the subject, there is nothing else which provides as broad a coverage as this volume.

The book starts with a general description of the physical characteristics of the boundary layer, after which the basic statistical tools (means and first-order correlations) used to describe turbulence are introduced. These tools are then employed to derive the Reynolds-averaged equations for means, variances and turbulent fluxes. The physical processes that generate turbulence and their relative importance are analysed with reference to the turbulent kinetic energy budget, leading on to a discussion of stability and scaling. A chapter is then devoted to turbulence closure techniques and another to boundary conditions and external forcings. There is a useful, basic introduction to time-series and the methods used to analyse them, followed by a chapter which calls on some of this material to discuss spectral similarity, after first considering mean-flow similarity. The final five chapters are more in the form of a literature review covering measurement and simulation techniques, convective and stable boundary layers, boundary layer clouds and geographic effects. Throughout the book, copious use is made of data from observations and simulations to illustrate the phenomena discussed and the range of values of parameters which might be encountered. Within the text there are numerous worked examples, while a large number of exercises (without answers) are provided at the end of each chapter. A list of general references, mainly other text books, is given in chapter 1, while each of the other chapters contains numerous references to research papers, many of them very modern. A useful list of field experiments is included, as are tables of scaling variables and similarity relationships which have been used in the literature.

In order to obtain the desired, wide-ranging coverage, the author has clearly been obliged to restrict the detail in which each particular topic is covered. I do not feel, however, that he has achieved the optimum balance. Given that the major audience is intended to be students with an undergraduate background in meteorology, it seems inconsistent to assume that their mathematical knowledge is so low as to warrant the detail in which simple algebraic manipulations are given in chapters 2–4. The space devoted to this could have been better used in providing further detail where the analysis is less straightforward. Students would also have been better served if specific references to other textbooks, rather than research papers had been given, where appropriate. One might also question the wisdom of devoting whole pages to sequences of diagrams which merit only one or two sentences of comment in the text. The coverage of slightly less material in slightly more detail would have been more satisfactory.

There is a tendency throughout the book not to discriminate clearly enough between actual observations and model simulations of data. The author's style is, on the whole, descriptive rather than critical, which is unfortunate in a subject where so much uncertainty exists and, in particular, leads to an over-optimistic impression of the capabilities of models. It also means that it is often unclear whether or not a particular assertion is generally accepted. There are certainly numerous statements with which some other workers would take issue and at least one to which everyone should take exception: the aerodynamic roughness length is *not* 'the height where the wind speed becomes zero', as claimed on page 378. Any student who accepts this statement at face value will indeed have been done a significant disservice.

Turning finally to editorial matters, the text appears to have been produced directly using a fairly unsophisticated desk-top publishing system. This has generated an aesthetically unpleasing change of line spacing where superscripts or subscripts appear in the text and a crude representation of broken lines in the diagrams. There are also a significant number of typographical errors, the most annoying of which are references to equations which don't exist!

In spite of its shortcomings, the book does provide a useful, broad introduction, both for students and researchers new to the field. It could provide a useful basis for courses in which a limited amount of the material was treated in more detail. It is a good source of references for the more experienced researcher, although inevitably, those substantial sections which are in the form of a literature review will rapidly become outdated. I suspect that few individuals will be prepared to pay £64 for the hardback edition, although the paperback should be more attractive.

M.K. MacVean

Applications of remote sensing to agrometeorology, edited by F. Toselli. 164 mm × 236 mm, pp. viii+326, *illus.* Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Price Dfl.200.00, US $99.00, £64.00.

This book is one of a series on remote sensing, based on courses held within the framework of 'the ISPRA-courses'. It is aimed at scientists active in agrometeorology and related fields; the course objective was to provide information on the state of the art and on prospective developments in this field.

My interest in this book was caught by the word 'Applications'. When I last looked, remote-sensing techniques were yet to have such impact in the day-to-day management of agriculture. They remained a solution in search of a problem, with an application limited to the wide open spaces, flat terrain and cloud-free skies of Africa, USSR or North America, not to the cloud-covered agriculture of north-west Europe. Had things changed?

To say 'Not much' would be unfair. If you are looking for a list of novel, off-the-shelf, remotely sensed products ready to supplement or replace existing, surface-based instrumentation, then it is true that you will be disappointed. But that would be asking too much of the technology in its present state of development. The message implicit in this book is: that to use those products that do exist, and certainly to develop new ones, it is still necessary to have a considerable understanding of the mechanics of remote observation.

Over two-thirds of the book is devoted to the science of remote sensing, with only passing or token reference to plants or agriculture. The subject matter is treated in satisfactory depth, progressing from 'fundamentals' through 'sensors' and 'platforms', before devoting a large number of pages to 'data' and 'image processing'. It goes sufficiently beyond the principles, that it is possible to find, for example, the orbital characteristics of various operational satellites. A particularly pleasing aspect of the book is the wealth of tables, and quantitative and well produced diagrams.

The reader interested in the practical use of tele-detection will with relief reach the last five chapters which deal with applications: 'surface temperature', 'surface radiation budget', 'soil moisture', 'rainfall', and the derivation and interpretation of a 'vegetation index'. For the first time we are able to leave behind the technology, and begin to be persuaded that, in spite of the difficulties, much can be inferred about the growth, moisture, status and even the yield of a crop. I was glad to learn, for example, that microwave techniques now offer an operational method of routine soil moisture estimation. In the USSR, radiometer data from aircraft contribute soil-moisture information for the management of a land area of 150 000 km^2, with substantial cost savings over conventional techniques.

Overall the book delivers what it promises. The scientist already experienced in remote-sensing technology, but not in its practical use, will find the 'applications' chapters very useful, particularly those on 'vegetation index', and 'soil moisture' and 'evaporation', and will discover principles that govern a whole philosophy of applications: for example, 'Radiance properties of vegetation provide more information about the processes than about the state of crops'. Thus it is easier to estimate growth stage, say, than biomass or leaf area. The scientist who is about to get seriously involved in using or developing remotely sensed products in a soil-related discipline will find this an excellent primer. No doubt the subjects of 'sensors', 'platforms' and 'data processing' separately fill many textbooks, but this book gathers them under one cover in sufficient detail to equip the reader to venture, where necessary, into more advanced volumes.

B.A. Callander

Ice shelves of Antarctica, by N.I. Barkov, translated from the Russian by Lt Comdr P. Datta, 160 mm × 245 mm, pp. viii+262, *illus.* Rotterdam, A.A. Balkema, 1985. Price Hfl. 85.00, £20.75.

This book was first published in Russian in 1971. At that time it represented a valuable compilation of material related to the study of ice shelves — an almost exclusively Antarctic phenomenon. These large floating plates of ice, fed by the outward flow of grounded inland ice and by surface snow accumulation, are important and sensitive indications of the general health of the Antarctic Ice Sheet, and hence of climatic influences. In their own way they provide a restraining force on potentially unstable areas of ice such as that grounded below sea level in West Antarctica. Ice loss by bottom melting yields cold, high density water, important oceanographically in the production of Antarctic bottom water. The calving of large tabular icebergs is both spectacular and hazardous, providing the greatest single component of ice-sheet ablation.

At the end of the 1960s, when this book was written, only very preliminary reconnaissance information was available on ice shelves. Some had been studied during the IGY and a primitive understanding had emerged of their dynamics, thermodynamics, mass balance and role in climate-related processes. This book should therefore be reviewed as an historical summary of information and ideas available up to the 1970s. It is not a state-of-the-art summary.

Chapter 1 provides a brief historical review of the exploration of ice shelves. Chapter 2 examines factors relevant to the formation and continued existence of ice shelves (topographic, oceanographic, climatic). Chapter 3 describes morphologic features of ice shelves and chapter 4 the mass balance of ice and snow to ice shelves. Chapter 5 is concerned with snow and ice structure, principally from bore-hole studies, and chapters 6 and 7 with the thermal regime and motion of ice shelves, with theoretical treatments. Chapter 8 deals with the present state of ice shelves, their response to climate and past fluctuations, and the final chapter considers this classification.

The overriding weakness of this book is its age. The bulk of the references centre around 1961–66. No account is taken of the enormous advances to ice-shelf studies during the last 15 or more years, particularly the results of the Ross Ice Shelf Project (surface glaciology, core drilling, observations beneath the ice shelf, associated oceanography, ice thickness and other geophysical measurements) and the substantial contribution from studies of the Amery Ice Shelf and the on-going Filchner-Ronne Ice Shelf Project. Concepts developed during the last decade of the role of ice shelves in the stability of the West Antarctic Ice Sheet, and the former extent of these ice masses, do not figure.

The illustrations, mainly reproduced from the Russian edition, vary in quality — the black and white photographs are totally unacceptable. There is no index, and the translation into English leaves much to be desired. Typographical errors abound and many place names or scientific terms have curious and inconsistent forms. In summary, it is good to have Barkov's book in English translation, but it is just years too late!

D.J. Drewry

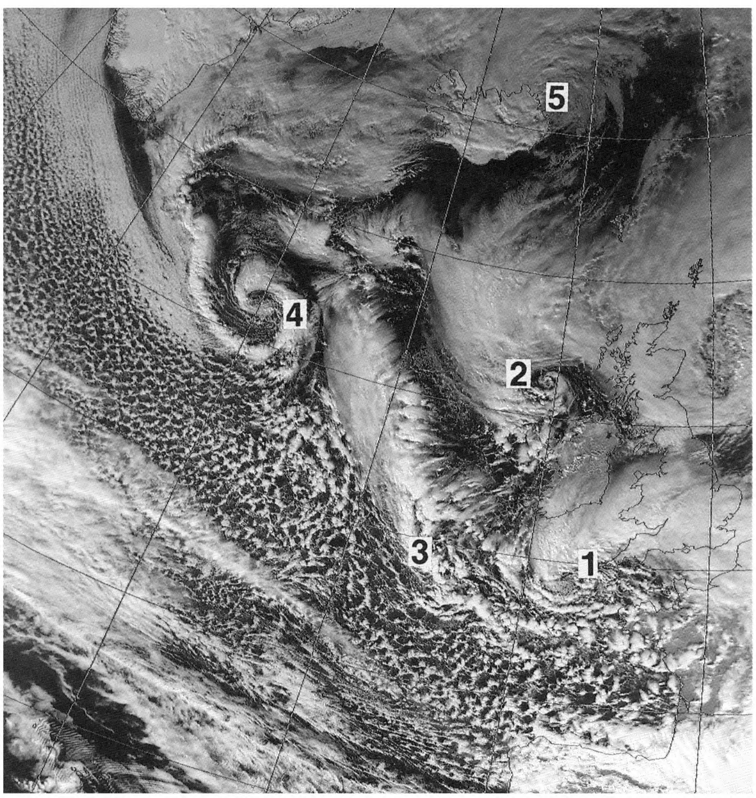
Correction

Meteorological Magazine, March 1989, p. 60, ll. 8–11. The sentence 'In flight, ... below −76°C.' should have read: 'For these flights, forecasts were required for the diversion airfield of Rio Gallegos in southern Argentina as well as forecasts of areas of CAT and regions of ambient temperatures below −76 °C.'

Satellite photograph — 25 February 1989 at 1418 GMT

This visible image illustrates an excellent example of convection over the Atlantic Ocean during a cold north-westerly airstream. Open cellular convection is seen within a broad zone from the Davis Strait to France and Iberia. This convective regime is bounded in the south by a weak but distinct surface front lying west to east (note the rope cloud near the southern edge of the picture) and to the north-east by several polar lows (labelled 1–4), themselves containing convective cloud, but mostly surrounded by regions where considerable suppression of convection is apparent. The circulation labelled '5' was the filling remains of the frontal depression behind which the cold air outbreak was initiated.

Small-scale troughs or convergence zones where surface pressure gradients change markedly (Fig. 1) are associated with polar lows 3 and 4. The life histories of the vortices 1 to 5 derived from NOAA-10 and -11 images are shown in Fig. 2. Most persisted for several days, and circulated cyclonically near the periphery of a deep upper-tropospheric vortex centred over northern Britain. The apparently innocuous vortex labelled 1, had a central pressure of 950 mb, a value which it retained as it moved eastwards across southern England. Exceptionally strong winds occurred on its southern flank, leading to the sinking of at least one ship, considerable other damage and related loss of life over southern France and Iberia.



Photograph by courtesy of University of Dundee

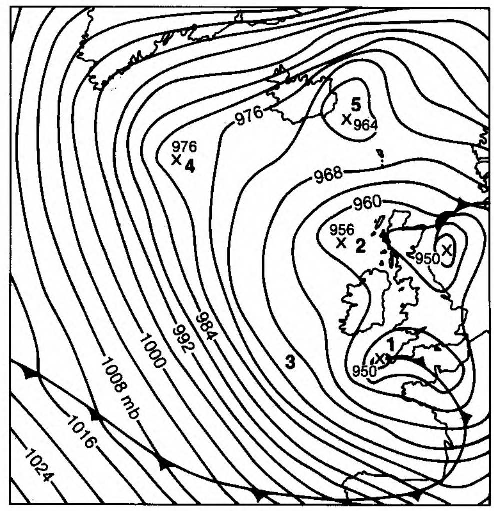


Figure 1. Surface analysis at 1200 GMT 25 February 1989.

Key

D = First or last observation of vortex
Adjacent figures give dates
○ NOAA-11 0220–0450 GMT
+ NOAA-10 0825–0940 GMT
□ NOAA-11 1225–1435 GMT
△ NOAA-10 1845–2035 GMT
■ NOAA-11 1415 GMT 25 Feb.
Adjacent figures refer to vortex number

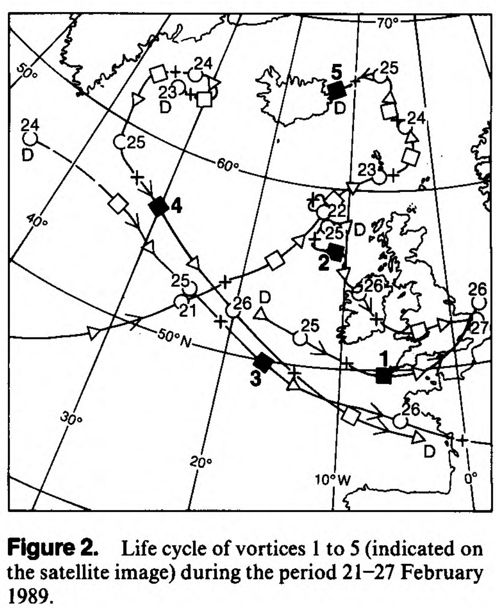


Figure 2. Life cycle of vortices 1 to 5 (indicated on the satellite image) during the period 21–27 February 1989.

Meteorological Magazine

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Climatic change
Weighing tipping-bucket rain-gauge
Groves Prizes and Awards

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The
Meteorological
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Trajectory and plume analysis in the Meteorological Office Atmospheric Dispersion Group

R.H. Maryon
Meteorological Office, Bracknell

Summary

This paper discusses the problems associated with modelling trajectories and outlines the facilities for trajectory and plume analyses available in the Meteorological Office.

1. Introduction

Before describing the trajectory facilities developed using the Meteorological Office numerical weather prediction (NWP) models, it is worth pausing to consider what we understand by the word trajectory. A trajectory is defined as the path followed by a projectile or object moving under the operation of given forces. In our context, it is the path of a passive particle or fluid element being carried along by the ambient wind. An equivalent expression is 'particle path'. A plume needs no definition; an instantaneous plume is the position at a given instant of all the material, previously emitted from a source, which is still in suspension. The source may be simple, multiple or areal. In the real atmosphere the air, with any gaseous or particulate matter suspended within it, is continually being mixed by diffusive motions over a range of scales. The trajectory followed by a molecule of gas in the atmospheric boundary layer (broadly, the 1 km or so adjacent to the earth's surface) is very complicated indeed, although in general it will move along in the direction of the mean wind, where 'mean' is taken to be the wind time-averaged over a period much longer than the time-scale of the turbulent eddies. The mean wind can itself, of course, change significantly over a few hours, or almost instantaneously across an active weather front. It should be said that, in strictness, what constitutes a mean wind and what constitutes turbulence depends upon the period or volume over which averages are calculated. It is assumed, for purposes of the present paper, that the mean wind is that stored at the grid points of a synoptic-scale NWP, and that by turbulence we mean those motions that are too small in scale or lifetime to be so represented.

There is a requirement for accurate estimates of both 'forward' and 'backward' trajectories for use in a range of scientific and environmental applications. Forward trajectories enable the transport of suspended material emitted from a known source to be traced downwind, while backward trajectories enable material detected in the atmosphere to be traced upwind, usually with a view to identifying the source.

As an aid to visualizing the uncertainties attaching to a horizontal trajectory calculated from NWP data, consider these questions: how quickly do two particles in the real atmosphere, released 1 mm apart, start to lose the 'memory' of their initial velocity and follow diverging paths? What if the particles start 10 m apart?

Or 10 km? The processes operative are discussed in section 2. Assuming they are neutrally buoyant, how would the trajectory of a toy balloon compare with that of a 20 m diameter balloon which 'integrates' a greater range of turbulent motions? How serious is the presence of strong horizontal shear, or diffluence, or stagnant regions of the flow? What if a motion system of marked 3-dimensional character is traversed?

The methods we use to compute trajectories from NWP motion fields use the values of the wind components which are stored over a 3-dimensional mesh of grid points — each grid-point value represents a volume average of (commonly) hundreds of cubic kilometres in which the smaller, sub-grid scale, motions are parametrized to give realistic bulk values of the turbulent fluxes. The small-scale motions are not, then, available for computing trajectories (ways of giving effect to turbulence in a statistical sense have, however, been developed, as will be shown later). Clearly a trajectory computed using a NWP model can only follow the model mean wind, i.e. the wind stored at the model's grid points. This usually necessitates interpolation in both time and space, that is, between grid points and between the available times of analysis or forecast. A particle 'released' into the model's boundary layer, then, behaves like no particle or small fluid element of air in the real atmosphere. It may be argued, however, that it can be taken to represent the centroid of a parcel comprising many particles, which is large compared to the small-scale turbulence. The main influence of the smaller scales of motion on such a parcel is, it may be hoped, to diffuse or 'expand' it (within the boundary layer, say) without influencing the position of the centroid too much. A real parcel, however, will be affected by mesoscale motions which a model such as the operational fine-mesh NWP cannot represent; whatever the model resolution there will be a range of eddy sizes too large to be mutually self-cancelling in their effect and too small to be explicitly represented. This all leaves to one side the central problem of the accuracy of the model's mean wind.

Nonetheless, over regional or continental distances, where a trajectory crosses many model grid squares, and an expanding parcel in reality may engage sufficiently varied sub-grid-scale regimes for the net effect on the centroid not to be too serious, the model mean wind is a useful first approximation to actual long-range transport in the sense that one may infer that there is a high probability that 'some of the material travelled thus'. How reliable this inference is, over a given distance, is a matter yet to be investigated in any detail. The effect of trajectory error is clearly more significant if the transport of a single puff of pollutant is being simulated than in the case where time-integrated concentrations are used, as in modelling, say, the seasonal exports of sulphur species across a national boundary. A single trajectory gives no information on the total area which might be affected by a release: a sequence of trajectories may, but it is usually preferable to use puff or plume analysis (of which trajectory analysis is the foundation) for this purpose.

2. Transport and dispersion in the atmosphere

When a pollutant, such as the plume from a factory chimney or the exhaust fumes from a stretch of motorway, is released into the atmosphere, it is dispersed by two processes which act together but are effective over different time-scales. From the moment of its release the material is carried along in the ambient wind and at the same time starts to spread out. This process of diffusion is initiated by the turbulence of the source emission and carried on by the 3-dimensional turbulence of the boundary layer (in which energy is cascaded to successively smaller eddies until it is dissipated at the smallest scales). The diffusion process is effected most vigorously by eddies of similar size to the puff or cloud of material, and, as it diffuses, the puff will engage larger and larger eddies. On a much larger time-scale the wind-field itself (with any suspended material) is undergoing distortion due to the movement and changes in intensity of the weather systems.

These processes account for the slope of the spectral density (kinetic energy per unit wave number) illustrated in the schematic power spectrum of atmospheric wind velocity components in Fig. 1. For wavelengths above about 1000 km the spectrum has a slope proportional to the wave-number, k, raised to the power -3, which reflects the transfer of eddy enstrophy (root-mean-square vorticity) to motions of smaller wavelength by

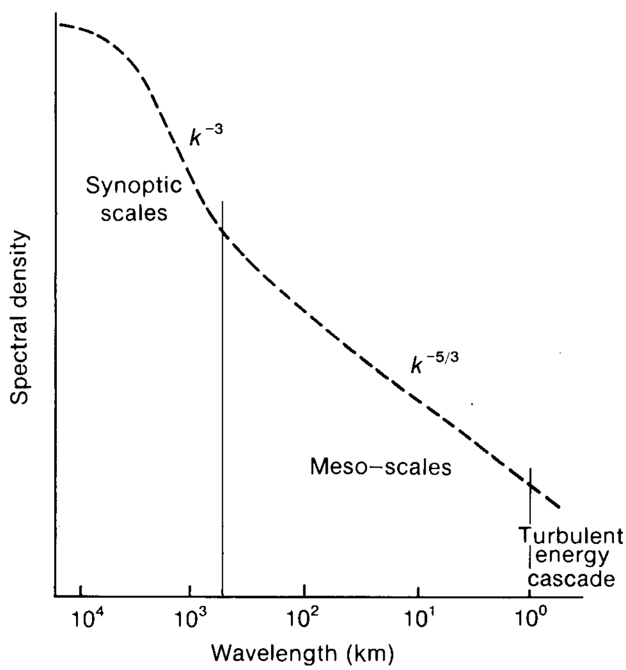

Figure 1. Schematic variance power spectrum for horizontal wind velocity components, based upon spectra in Gage and Nastrom (1986) of data from commercial aircraft (the GASP project). Spectral density is the kinetic energy per unit wave number. Wave number (k) is defined $2\pi/\lambda$, where λ is wavelength.

the relative motions of the velocity field (the 'enstrophy cascade'; see Tennekes 1978 for a discussion). This is, to an approximation, a 2-dimensional, area conserving process: absolute vorticity is conserved so that the vorticity field becomes more convoluted as the horizontal variations are driven towards smaller scales of motion. Fig. 2 is based upon a dish-pan experiment by Welander (1955) which has been used by Tennekes and others to illustrate the phenomenon; a patch of dye is released, and becomes increasingly contorted by the fluid motion. Material is dispersed in this way by the enstrophy cascade in the atmosphere, but it is a stirring process, not, strictly, a diffusive one. Theory suggests that the rate of separation of particles in the enstrophy cascade can become exponential: this satisfies a criterion for 'Lagrangian turbulence', more succinctly known as chaos.

The role of the meso- and sub-synoptic scales between the enstrophy and turbulent energy cascades (through which some authors consider a reversed energy cascade towards larger scales occurs) is less easy to define. A $k^{-5/3}$ slope extends across a wide range of meso-scales into the 3-dimensional turbulence of the boundary layer (Fig. 1); it is easily demonstrated to be appropriate to the turbulent transfer of kinetic energy. Motions initiated by storm systems, orography, breaking gravity waves, it has been suggested, might cascade energy in two ways, 3-dimensional to smaller scales, 2-dimensional to larger. Thus Lilly (1983) analyses the reverse cascade in terms of the decay of 3-dimensional turbulence into 'stratified' 2-dimensional turbulence and gravity waves. As far as macro-scale dispersion is concerned the mesoscale motion systems can be considered as contributing to the diffusion process, albeit in ways as yet little studied. The presence of a mesoscale gap in the spectrum of atmospheric velocities has been suggested from time to time, although clear evidence of its existence remains elusive.

In summary: over long time-scales, a plume is distorted by the evolving synoptic pattern and, as a result of the stretching and thinning of the polluted air parcels, the area of contact with clear air is increased, allowing the energy cascade diffusion processes to continue to operate on individual elements of the cloud. Sometimes the distortion can fold or wrinkle up a plume to form clumps of polluted air, but air concentrations of the pollutant cannot, of course, be increased in this way (some phenomena involving particulates can result in increasing concentrations, but this is not due to the kinematics of the airflow).

3. Practical difficulties in simulating the transport and dispersion of pollutants

An accurate representation of the mean wind is, of course, of first importance when simulating plume transport. Either observations or the wind as resolved on the grid of a NWP model can be used. Observations may require a mass-continuity condition to be imposed (Sherman 1978); they may be sparse in space and/or time, or perturbed by local effects. Modelled winds, strictly grid-volume means, are subject to adjustment and smoothing in the analysis process and perhaps less representative of real terrain and conditions. In either case a good deal of interpolation is usually required. Trajectories may be determined using winds at a single level (e.g. on a pressure surface or a mean boundary-layer wind), or in 3 dimensions, or on isentropic surfaces. Trajectories derived from NWPs can be subject to error of various kinds (section 4), including systematic errors associated with the particular model or resulting from the choice of level used to simulate the trajectory. Most NWPs, as we have noted, fail to represent properly the mesoscale motion systems which can be generated, for example, by land–sea juxtapositions or orography, or indeed changes in surface topography, type and roughness which can influence the transports or the diffusive process. One advantage enjoyed by the long-range modeller, however, is that the effects of surface inhomogeneities and of small-scale motion systems encountered over a track of hundreds or thousands of kilometres will, in ensemble, tend rather to modify the diffusion than to influence the mean path very strongly. The net error due to these influences should accordingly be small, in a simulation, at least in comparison with other sources of error. Where a plume is required it must be so modelled that both the turbulent spread and the effects of synoptic-scale distortion (section 2) are adequately represented.

Figure 2. Four stages in the evolution of a patch of dye on the surface of a pan filled with liquid, illustrating enstrophy cascade dispersion. Based upon Welander (1955).

The mean vertical motion of the air can have a critical effect upon a trajectory, particularly near a region of marked mass ascent, such as a front or active depression. A 2-dimensional trajectory entering such a region of horizontal convergence can 'stagnate' and the apparent concentration of a pollutant in the boundary layer (which might, for example, have been computed using the area of a simulated plume segment as described in section 7) show a spurious increase. Conservation of area can only apply with strictly 2-dimensional motion systems, and certainly not in the real atmosphere.

Plumes can be spread laterally by wind shears in the vertical. Within the boundary layer the turbulent motions will convey parcels up and down so that they experience, ultimately, the motion at all levels — the plume centreline responds to a mean boundary-layer wind — but above the boundary layer, material extended through any significant depth can be fanned out by the shear (this is illustrated in Fig. 6). Should a developing convective boundary layer extend into such a region, material is quickly brought down to what might be a previously unaffected surface — a process analogous to plume 'fumigation'. Material can also be vented out of the boundary layer by convection, e.g. in cumulus clouds, which can 'vacuum up' pollutants, carrying them up into the free troposphere and releasing them through detrainment or in the dissipation stage. Frontal cloud may do this on a large scale.

It is clear from the foregoing that the static stability of the atmosphere, the diurnal changes in the boundary-layer depth, and associated shears (including those due to the 'nocturnal jet' which can develop above the stable night-time boundary layer), all influence the transport and spread of pollutants, their dispersion in depth, or their appearance at the surface. The treatment of these factors requires careful consideration.

There remains the problem of estimating accurately the strength (and sometimes position!) of the source of the pollutant, and its profiles in time and space. Loss processes also have to be parametrized. The latter include the flux of material to the surface in dry air (dry deposition) which may or may not involve gravitational settling, and the removal of pollutants in rainfall. Wet deposition processes are of profound importance — witness the acid-rain problem and the washout of radioactive species following the Chernobyl release. Radioactive decay can be treated as a loss process. (See Smith and Clark 1989.)

4. Techniques for calculating trajectories

Given a wind field stored at the grid points of a rectangular mesh the simplest method of computing a trajectory is to use

$$\mathrm{d}\mathbf{x} = \mathbf{u}(\mathbf{x},t)\mathrm{d}t \qquad (1)$$

where $\mathbf{x}$ is a position vector, t is time and $\mathbf{u}$ the mean wind vector; $\mathbf{u}$ will, of course, have to be interpolated from the adjacent grid points and between the time-intervals for which winds are available. If the interval is long (6-hourly NWP output has commonly been used) there is an immediate loss of accuracy. Interpolation is usually linear in time, bilinear in 2-dimensional space, etc. — more sophisticated methods of interpolation can be used but it is debatable whether the generally slight increase in accuracy justifies the additional processing. Maryon and Heasman 1988 (henceforth referred to as MH88 in this paper) look at this question.

Expression (1) can be solved numerically, using finite differences. For example, the solution at time $r+1$ can be obtained from

$$\mathbf{x}_{r+1} = \mathbf{x}_r + \mathbf{u}(\mathbf{x}_r)\Delta t \qquad (2)$$

where Δt is the forward time-step. The accumulated error, however, is proportional to the size of the time-step used. A more reliable technique of integration was originated by Sykes and Hatton (1976) using Runge-Kutta methods. A 5th-order Runge-Kutta-Merson formula is now used, the solution of which is equivalent to the first six terms of a Taylor expansion about $\mathbf{x}_r$. The truncation error can be estimated; if the error exceeds a chosen small magnitude the time-step Δt is halved, $\mathbf{u}$ re-interpolated, and the calculation repeated. This method has performed so well using 6-hourly data that lengthy trajectories over the domain of the fine-mesh NWP can be reversed in direction to terminate very close to the starting point.

Clearly there are a number of components to the error of a simulated trajectory. These are discussed and compared in MH88. To the numerical errors due to interpolation and forward integration we must add forecast error or, if only NWP analysed fields are used, those due to the differences between the analysed and 'real' wind fields. The numerical errors are not large, if due care is taken, although they will accumulate with the time into integration. Forecast error, however, can be very large — Table II of MH88 shows a mean angular divergence from validation of over 6° after 24 hours when a large sample of trajectories was 'released' at the start of fine-mesh forecasts, increasing to over 10° after 36 hours. For coarse-mesh trajectories not released until the forecast has already run 36 hours the corresponding deviations are no less than 22° and 24° respectively. The validation, however, was against trajectories computed using NWP-analysed and short-period forecast wind fields. Validation against reality is very difficult, and requires the tracking of constant-density balloons (tetroons). MH88 briefly reviewed a number of tetroon experiments and suggest that a mean angular deviation of 12° or more must be expected for trajectories of some hundreds of kilometres computed using the best available analysed fields, although the results are very variable — the statistics are very sensitive to the onset of the stage, which occurs sooner or later, when the divergence of the computed trajectory and the validation begins to accelerate. This, and the forecast error (as defined above) are not, of course, simply additive, but it does suggest that the forecast errors quoted are the minimum ensemble means to be expected.

Computing a trajectory is only the start of the problem of simulating dispersion in the atmosphere; methods of treating the spread due to vertical shear and boundary-layer turbulence will be described briefly in section 7.

5. Two-dimensional trajectory facilities

The following brief account of the trajectory facilities available will be confined to those developed and maintained by the Atmospheric Dispersion Group of the Boundary Layer and Atmospheric Chemistry Branch (Met O 14) although similar facilities are available elsewhere in the Met. Office, such as the Central Forecast Office (CFO) and the Forecasting Research Branch (for example, 3-dimensional trajectories can be obtained from the operational mesoscale model). The Met O 14 routines are described in more detail in Dickinson (1984a, 1984b), Ephraums and Macari (1987) and Macari (1987a, 1987b). Trajectories may be run from the current print-files of the operational fine- and coarse-mesh models (print-files are the standard data sets containing output from the operational NWP models; each consists of the latest analysed fields and a sequence of forecasts), or from archived data. This archive accumulates, on tape, 3-hourly fine-mesh wind analyses at the 950, 850 and 700 mb levels which are extracted from the operational print-file. The archive is 'rolled over' approximately on a 2-year basis. Routines are available to restore winds for the period and levels required to a direct access data set on disk.

There are five trajectory packages available, which have certain features in common. They all produce 2-dimensional trajectories using winds at the standard output levels of the operational NWP suite. Winds in all cases are linearly interpolated between the available data times, bilinearly interpolated in space from the four surrounding grid points and the trajectories integrated using the 5th-order Kutta-Merson scheme. The trajectories are continued until they reach the edge of the model grid, exhaust the sequence of wind fields available or reach a limiting period (in the case of archived winds, 360 hours). The data are available every 3 hours (fine mesh) or 6 hours (coarse mesh).

The successive trajectory coordinates are transferred from grid values to latitude and longitude, and printed out in tabular form. Alternatively a facility is now available for plotting trajectories directly onto suitable map backgrounds. An example showing two back-trajectories is given in Fig. 3. As each trajectory is calculated it is stored on disk: repeated runs from the current print-files create a sequence of trajectories based upon analysed or forecast wind fields, or both, those with a forecast component being overwritten as time passes. The routines available are:

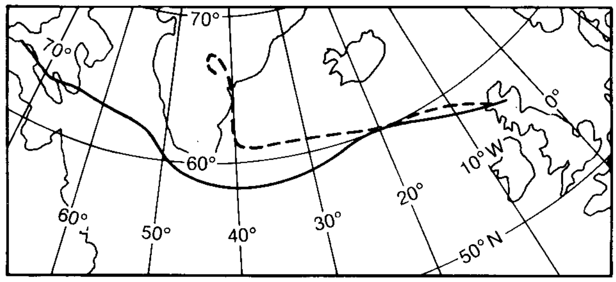

Figure 3. Sample plots of back trajectories released 12 hours apart, 0600 and 1800 GMT on 5 December 1988, computed using the fine-mesh backward trajectory model.

(a) Fine-mesh forward trajectory and rainfall forecast model — this model utilizes fine-mesh forecast print-file data. Trajectories of up to 36 hours (at present) are computed from the forecast wind fields. In addition to the position reached by the trajectory, local dynamical and convective rainfall rates are output. These data are printed every 3 hours. Only one start point is permitted.

(b) Coarse-mesh forward trajectory and rainfall forecast model — this version concatenates fine- and coarse-mesh forecast wind fields, using the former for the first 36 hours of a forecast, the latter for a further 36 hours. Again, the dynamic and convective rainfall rates are plotted, and only one start point is available. With repeated updates, the trajectories are eventually overwritten by revisions based upon fine-mesh analyses.

(c) Fine-mesh backward trajectory model — this version computes back trajectories from archived fine-mesh wind fields using 3- or 6-hourly input data; the resultant trajectory is always defined on a 3-hourly basis. Up to 54 trajectories can be processed concurrently using any combination of start locations and levels, and times of release.

(d) Fine-mesh forward multi-point and multi-time models — these versions compute up to 60 forward trajectories from the archived winds using 3- or 6-hourly input data. One version releases all the trajectories simultaneously, but from different starting positions, as required; the other can compute consecutive trajectories from the same start point.

In addition, isentropic trajectories (paths along surfaces of constant potential temperature) can be produced by the Atmospheric Chemistry Group in Met O 14. These provide more realistic paths through the free atmosphere than 2-dimensional standard-level trajectories, and are particularly useful in the upper troposphere and stratosphere, and in the study of air transports through synoptic weather systems.

6. Applications of trajectory and plume analysis

The tracing of trajectories has a wide range of applications both in the atmospheric sciences and in more practical aspects of pollution control. Atmospheric chemists need to determine the sources, and simulate the transports and mixing, of reactive species and of substances such as the hydrocarbons and nitrogen oxides which produce oxidants (hydroxyls and ozone) in the presence of sunlight. Oxidants figure prominently in a number of important and indeed urgent ecological investigations, which are currently the subject of intensive study. One of these is the acid-rain problem, where trajectory and plume analysis help to model the transport, intermixing and chemical interaction among species which result in the solution of sulphates and nitrates in rain-water. In this connection MH88 attempted to assess the feasibility of using forecast trajectories for acid precipitation control strategies. Simulation of the dry deposition of gaseous and particulate pollutants to the surface equally requires the employment of trajectories. There are applications in stratospheric photochemistry, where the transports of trace species and coupling of dynamical and photochemical processes are under investigation.

Trajectory analysis has application in acute, as well as chronic, pollution problems. Back trajectories can be used to trace the source of noxious or hazardous materials released into the atmosphere, or forward trajectories to predict their destination. Recent (relatively short range) examples of such contingencies are the chemical fire at Nantes, and the release of ash and asbestos among the combustion products from a conflagration in the north Midlands (Evans and James 1989 describe the tracking of this material using radar). A long-range study was made of the release of volcanic ash from the Mount St Helens eruption (Crabtree and Kitchen 1984). Potentially the most serious of accidental releases is that of radio-nuclides, a subject returned to in section 7. Pollution associated with mesoscale-motion systems can in principle be studied using trajectories from appropriate models; a classic example is the complicated fate which befalls a plume which is entrained into a sea-breeze circulation (Lyons *et al.* 1983).

Other examples requiring back-trajectory studies include the transport of Saharan dust eventually rained out over the United Kingdom and the contamination of Highland or Arctic snow by industrial effluents. No doubt the reader can supply other applications — a few that come to mind are biology (the atmosphere has its plankton!), epidemiology (for example, the foot-and-mouth disease models) and of course navigation — an Atlantic crossing by hot-air balloon would be ill-advised if the fine- and coarse-mesh trajectories projected a diversion to Thule.

7. Plume analysis over long range

Many ways of modelling plume spread close to the source exist, the most widely used for practical purposes being the Gaussian plume (Pasquill and Smith 1983) which in its basic form assumes constant wind speed (without shear), constant diffusivity and a homogeneous surface for the plume to traverse. This is not the place to analyse the strengths and weaknesses of the Gaussian (or other short range) formulations except to emphasize their complete unsuitability for use over long range, in view of the variable meteorology and terrain that will be encountered by the plume, and the absence of provision in most short-range techniques for all the influences described in section 2.

Another paper of this length would be required to do justice to a description of the variety of techniques developed for long-range transport modelling. Attention will be confined to two models recently developed in Met O 14 for simulating the transport and spread of neutrally buoyant pollutants over continental scales: the Basic and Main Models associated with the national nuclear accident response programme. Both are Lagrangian models — that is, estimates of concentration etc. are made as the material is followed through the domain rather than by solving equations at fixed points (the Eulerian method) — and are accordingly entirely relevant in an article dealing with trajectories. These models will have uses other than nuclear accident response: any large-scale chemical emergency can be handled, while the Main Model in particular could form a 'chassis' for chemical modelling and other research projects.

7.1 The Basic Model

The National Response Plan initiated by the Department of the Environment following the nuclear accident at Chernobyl required the development of a fast-response model capable of simulating the transport, dispersion and deposition of radio-nuclides released into the atmosphere from any European installation. The Radiation Incident Monitoring Co-ordinating Committee (RIMCC) requested that a basic model be produced as quickly as possible, that is, by the end of 1987, while plans were made for a more comprehensive version (now known as the Main Model). The modelling project bears the acronym NAME.

The Basic Model requires a prescribed emission profile. The model can run in forecast or hindcast mode using data from the operational fine-mesh NWP, and the runs updated as time passes. To facilitate this process, an archive has been created by staff of the Forecasting Products Branch which accumulates analysed fields from the fine-mesh print-files and stores them on a 10-day 'roll-over' basis. The plume is initiated with a 2-dimensional, single-point, single-level trajectory with successive points being released at hourly (or longer) intervals, and the plume is expanded empirically about its centre-line to give effect to turbulent diffusion and shear. Winds are linearly interpolated in space and time, and the 5th-order Kutta-Merson integration is used. The young plume is divided across its width into segments by an array of equidistant points so that the full plume is defined by quadrilaterals. With each quadrilateral is associated a mass of material released during a time-step: initially this mass is distributed across the plume in a Gaussian manner. When they are 24 hours old, the points defining the plume segments are advected individually in the evolving synoptic wind field, and the plume allowed to deform. In fact this technique cannot cope very well with the deformation beyond a couple of days, and further refinements would be necessary to prolong its usefulness. An example of the output is shown in Fig. 4.

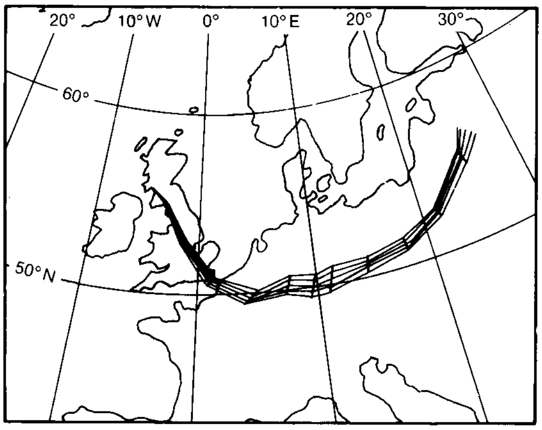

Figure 4. The NAME Basic Model: the 950 mb plume at 0000 GMT on 20 December 1988 following a notional release of a pollutant from an arbitrarily chosen location in the south-west of Scotland, starting at midday on 18 December. In this run the plume was divided into 3-hourly segments.

The boundary layer is dealt with in a simple fashion; an initial depth, and upper and lower limiting values are prescribed, and a conservation of volume principle applied to prevent unwarranted changes in pollutant concentration resulting from convergent/divergent 2-dimensional flows. With strong horizontal divergence the pollutant can be diluted to allow for boundary-layer entrainment, while in the case of marked convergence a proportion of the material is vented from the boundary layer in response to the associated (but unrepresented) vertical motion. Boundary-layer concentrations of the pollutant are computed by projecting the plume segments (Fig. 4) onto the fine-mesh grid, and assessing the contribution to each grid-square from each overlapping segment. The accumulated dry deposition and time-integrated dosage are also computed for up to four radio-nuclides, after allowing for radioactive decay.

7.2 The Main Model

In view of the difficulties involved in representing 3-dimensional motion fields with 2-dimensional techniques, a completely different approach has been adopted for the Main Model. A 'random walk' or 'Monte Carlo' formulation is used: the plume is simulated by releasing a large number of particles at the source (in batches at hourly intervals, reflecting the emission profile in time and space) and allowing them to be transported by 3-dimensional winds taken from the fine-mesh forecast print-files or the roll-over archive. A time-step of 15 minutes is used (an appropriate eddy turnover time in the convective boundary layer) and at each step a random perturbation is added to the horizontal displacements to account for turbulent diffusion, giving

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \mathbf{u}(\mathbf{x}_i)\Delta t + \mathbf{A}r, \qquad (3)$$

where Δt is the timestep, r a random number from the standard normal distribution and **A** a coefficient which can be identified with $\sqrt{2\Delta t K}$ in conventional parametrizations of diffusion (K being the horizontal diffusivity). In addition, the particles in the boundary layer are randomly re-assigned in the vertical so that over a period of time each particle will sample the mean wind at each level within the boundary layer. The effect of vertical wind shears above the boundary layer can be allowed for, to some extent, by 'stacking' the particles in the vertical when they are released.

The model is multi-level, with a realistically evolving boundary layer and several layers above (currently up to 700 mb). The boundary-layer depth is diagnosed from the fine-mesh wind and temperature profiles using a gradient Richardson number. This depth, taken with the positions and vertical velocities of the particles, automatically if rather simplistically allows for entrainment and detrainment through the inversion (although the venting effects of deep convection are yet to be parametrized).

A mass of pollutant or quantity of radioactivity is associated with each particle at the outset, and concentrations in air are calculated simply by counting the particles in each grid volume. Of course, statistical reliability requires the release of large numbers of particles, and this technique is much more expensive computationally than the Basic Model. However, given adequate resolution and sufficient particles it is far more realistic in that any 3-dimensional motion system can, in principle, be handled. There is no question of using a sophisticated integration scheme in this case — apart from the overriding problem of computational expense, the random fluctuations would blur the slight differences, given that there are no systematic errors.

At this stage, the output diagnostics are similar to those of the Basic Model. Two major components of the (as yet incomplete) Main Model are the real-time, high-resolution rainfall archive now under development by staff of the Nowcasting and Satellite Applications Branch to underpin the crucial wet deposition parametrization, and the radiological package being planned at the Safety and Reliability Directorate of the United Kingdom Atomic Energy Authority, which will enable observed radiation from any future accident to be used to modify the model assumptions and products. Examples of recent output from the current version are given in Figs 5–9. Fig. 10 shows an application of the Main Model to the release of radio-nuclides from Chernobyl. The particles in Figs 5, 7 and 10 represent material suspended in the atmospheric boundary layer; those in Fig. 6 material in the 850–700 mb layer.

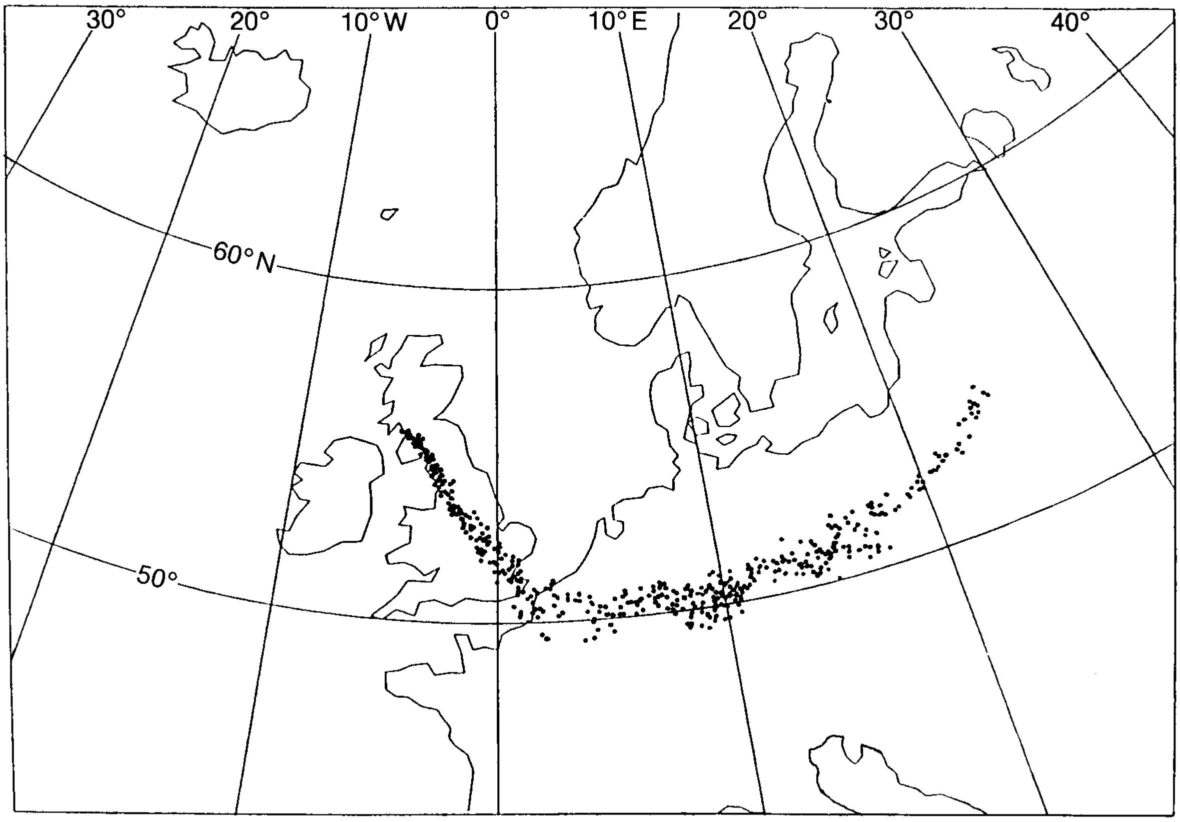

Figure 5. The NAME Main Model: multiple particle boundary-layer plume corresponding to Fig. 4. Note that the 950 mb wind used in the Basic Model carried the plume a little further than the full profile of boundary-layer winds used here.

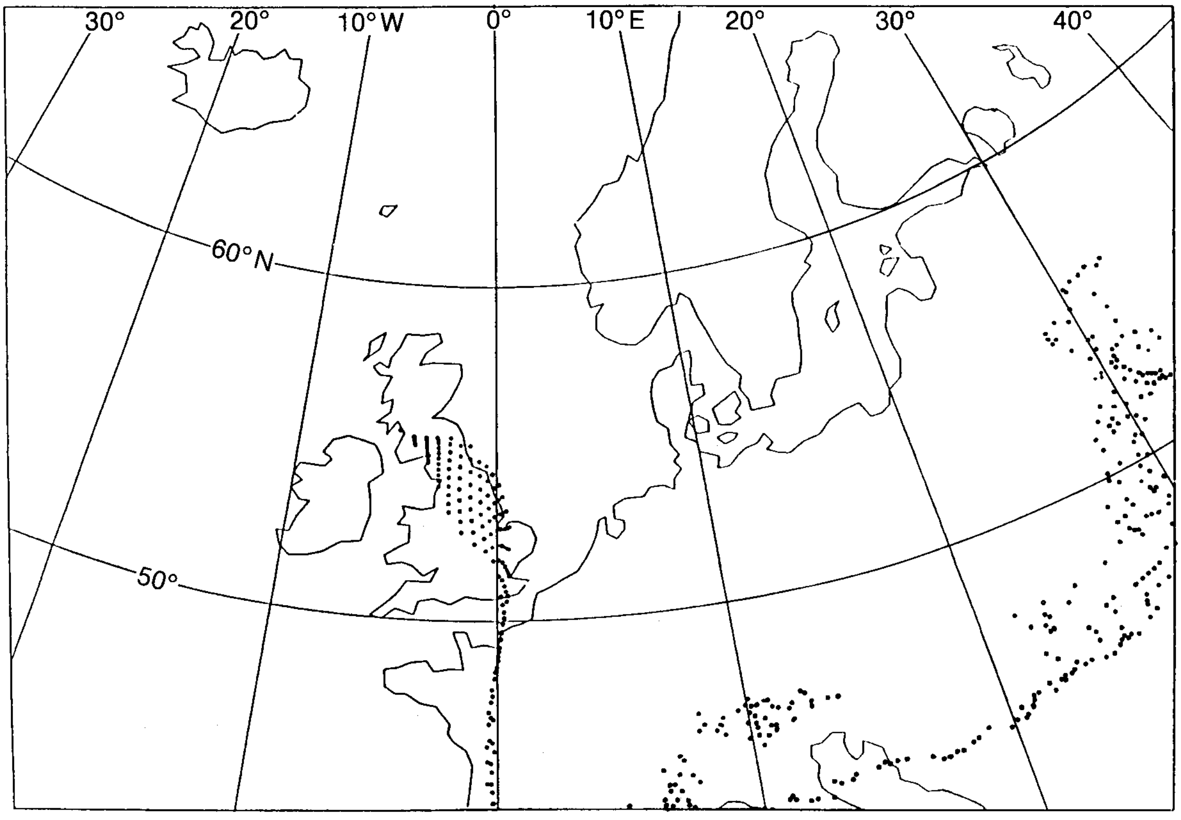

Figure 6. The 850–700 mb plume 12 hours later than Fig. 5 at 1200 GMT on 20 December 1988. No random perturbations have been applied at this height, but the particles released 'stacked' in the vertical. Note the effects of wind shear over northern England. Some of the particles have been lifted to this level in ascending air.

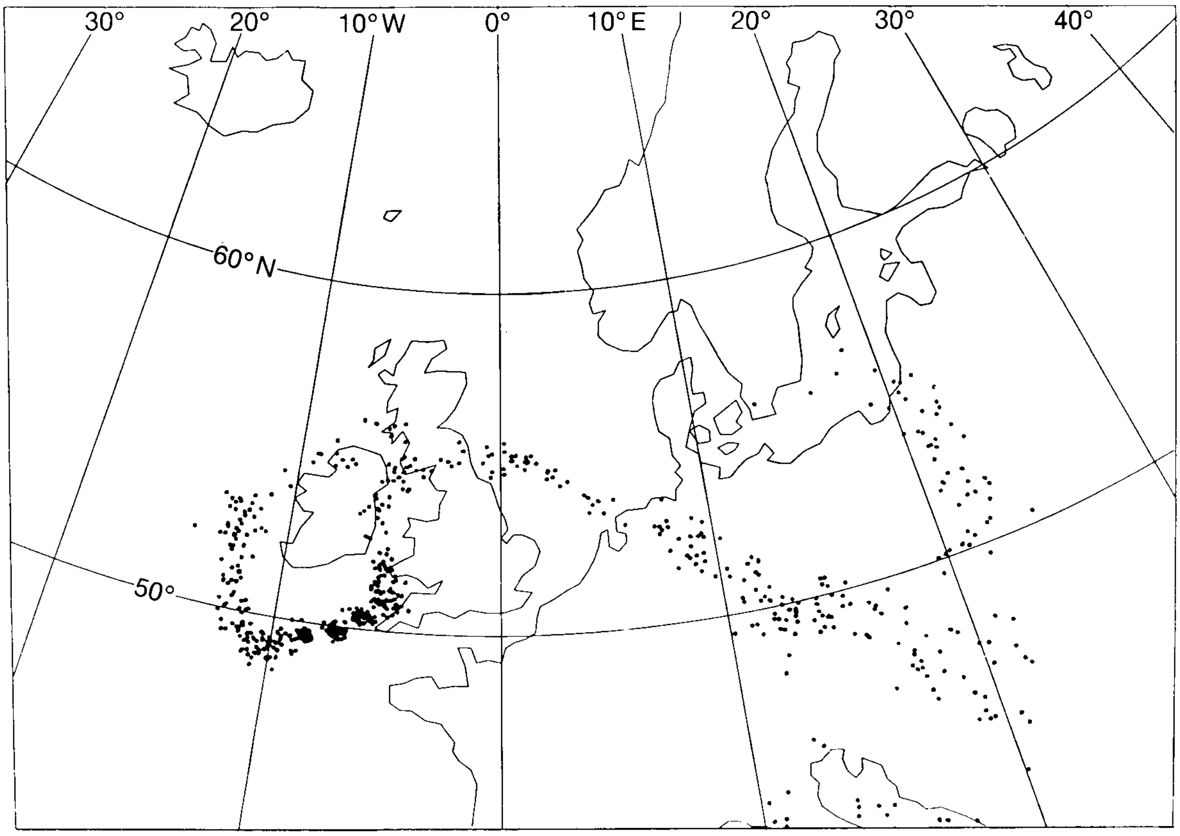

Figure 7. The NAME Main Model: boundary-layer plume at 0000 GMT on 3 March 1989 from an imaginary source at 50° N, 10° W starting 1200 GMT on 28 February. This interesting case shows some of the material spiralling back around Ireland to merge with fresh emissions at the source.

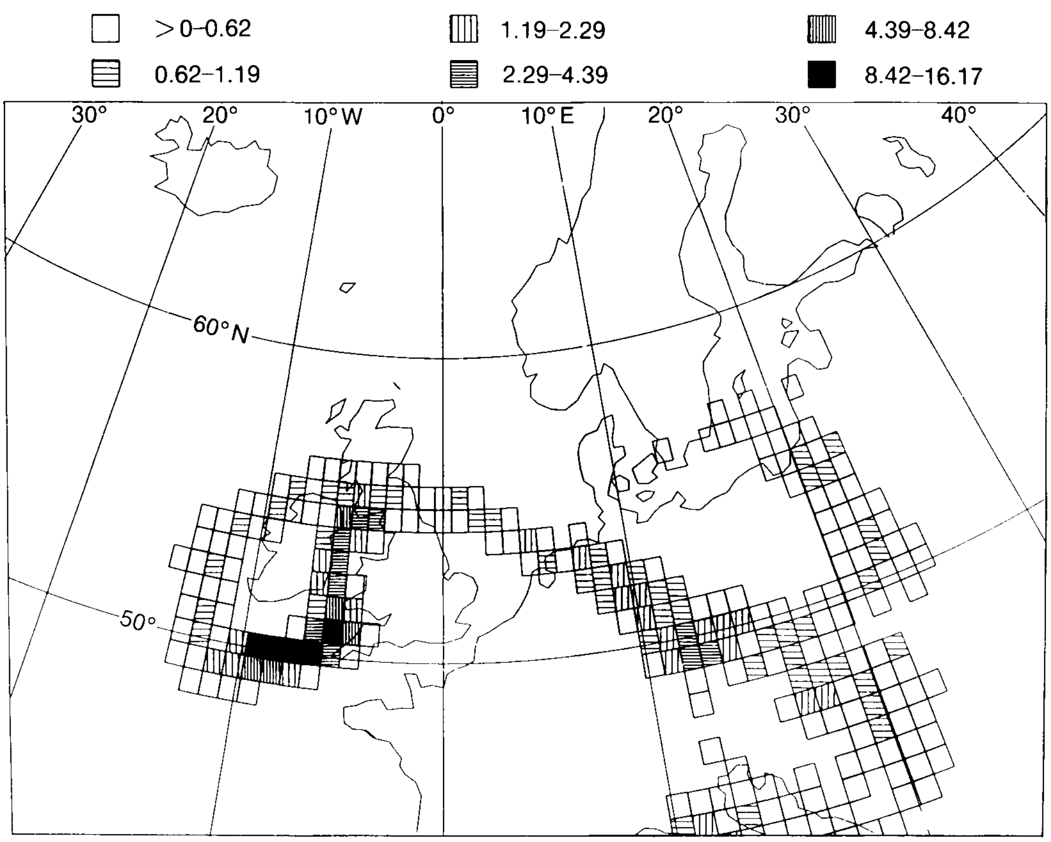

Figure 8. Boundary-layer air concentrations (Bq m^{-3}) of the pollutant corresponding to the plume in Fig. 7, assuming a release strength of 100 TBq h^{-1}.

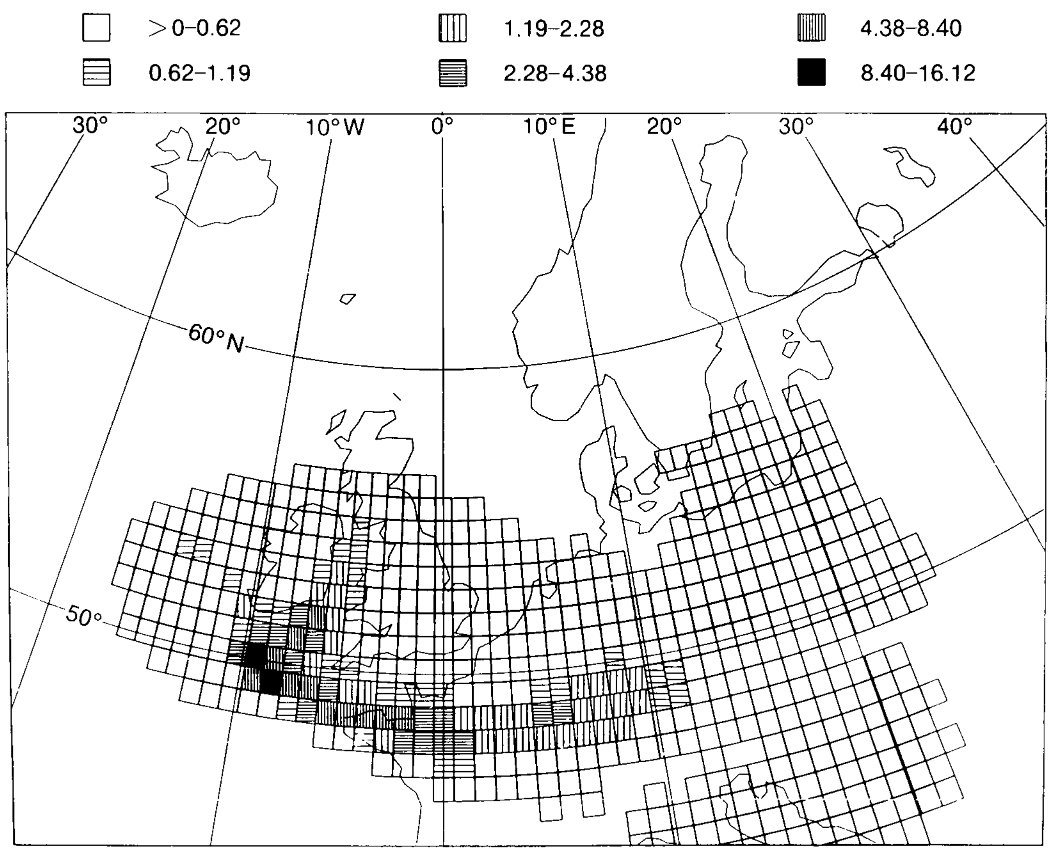

Figure 9. Accumulated dry deposition (kBq m^{-2}) of the pollutant by 0000 GMT on 3 March 1989.

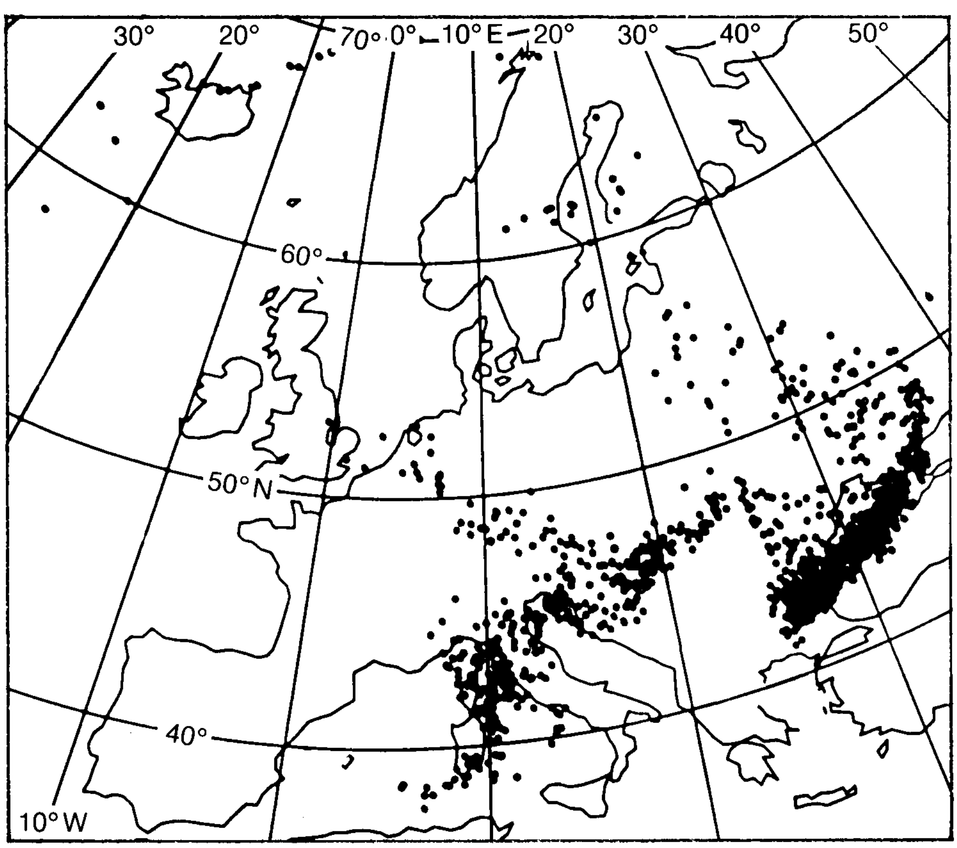

Figure 10. Airborne material from the first day's release from Chernobyl (2123 GMT on 26 April 1986 to 0000 GMT on 27 April 1986) at 1200 GMT on Friday 2 May. Again, the boundary-layer plume is reproduced.

Considerations of economy prevented the release of sufficient particles to give a statistically significant pattern over the United Kingdom in Fig. 10, but the arrival of material from Chernobyl on 2 May 1986 and the presence of the plume over eastern England by midday were quite well indicated.

8. Conclusions

The difficulty in conceptualizing precisely what is being simulated when boundary-layer trajectories are derived from NWP wind fields does not prevent their frequent use in a range of applications. Most importantly, trajectories are the foundation of plume analysis, which is extensively employed in current ecological and pollution studies. Of the various sources of error that may be associated with trajectory analysis, those due to numerical and sub-grid-scale effects are considered to be of less importance to the long-range modeller than forecast error (which can be severe) and error in the mean wind (as analysed). Such errors can be systematic, depending upon the model and the method used to calculate the trajectory. In the case of analysed winds, error magnitude is difficult to determine with any accuracy — such measurements as are available show wide variation but suggest that the difference between 'real' and analysed trajectories (over some hundreds of kilometres) averages at around 12° of arc. The utility of trajectory analysis has, however, been demonstrated in many contexts.

A necessarily brief account has been given of the Atmospheric Dispersion Group's trajectory facilities and of recent work on long-range plume modelling, which is associated with the national nuclear accident response programme (but should have other applications). All of the facilities described in this paper, with their comprehensive operational databases, are available to the wider scientific community.

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Observed climatic change, and the greenhouse effect

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Summary

The observational evidence is reviewed for the possible past and present impact of changing atmospheric concentration of carbon dioxide, and other greenhouse gases, on climate.

1. Introduction

Since the early nineteenth century, atmospheric carbon dioxide (CO_2) concentration has increased from about 280 parts per million (ppm) to 350 ppm in recent times (Fig. 1) as a result of deforestation and the burning of fossil fuels. Because of increasing concentrations of other greenhouse gases such as methane and chlorofluorocarbons, the overall radiative effect is equivalent to an increase of 40% in the CO_2 concentration, at least half of which has taken place in the last 30 years. The annual cycle in Fig. 1 results from the seasonal growth and decay of the vegetation of the northern hemisphere, which dominates the global land biosphere. The trend in Fig. 1 is a potential cause of global climatic warming.

There are already observational precedents for relationships between atmospheric CO_2 and climate. The pre-industrial atmospheric CO_2 concentration ranged between 250 and 310 ppm in the Holocene (since the last ice age, i.e. about the last 10 000 years) and in the previous interglacial, but was about 200 ppm at the peaks of the last two major glaciations (Barnola *et al.* 1987, Neftel *et al.* 1988, Webster 1985). The changes in atmospheric CO_2 concentration accompanied or slightly lagged the glacial–interglacial periods, so they did not cause them, but they were of the correct sign to have amplified them. They may also have forced the observed synchronism of glaciations in the opposite hemispheres (Broccoli and Manabe 1987), which cannot be explained in terms of the Earth's orbital changes believed to underlie the Pleistocene ice ages, because these changes result in largely interhemispheric redistributions of a fixed annual total supply of solar radiation.

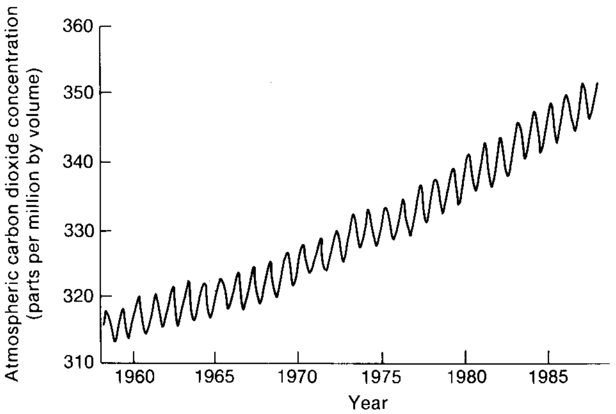

Figure 1. Atmospheric carbon dioxide concentration at Mauna Loa Observatory, Hawaii. All the data were obtained from C.D. Heeling (Scripps Institute of Oceanography).

Numerical models indicate that, in equilibrium with doubled atmospheric CO_2, the following broadscale changes of climate are likely (see Schlesinger and Mitchell 1987):

(a) A global mean surface warming of about 3–4 °C, and more confidently between 1.5 and 4.5 °C. Most of the larger warmings are obtained by the more recent models, and are likely to have resulted from the more comprehensive treatments of clouds which appear to induce a positive feedback in addition to that from increased atmospheric water vapour.

(b) A stratospheric cooling of between 3 and 5 °C.

(c) An increase in warming with height in the tropical troposphere. In the models, the magnitude of this feature depends on the convective parametrization scheme.

(d) Enhanced warming at the surface in high latitudes in winter. In the models, the magnitude of this feature depends on the treatment of sea-ice and albedo, and the resulting feedbacks.

(e) Generally greater precipitation in equatorial regions and in middle and high latitudes, and a tendency to decreased precipitation in the tropics away from the equator. Regional details are very uncertain.

In practice, the thermal capacity of the oceans will delay the development of these changes — the lag may be of the order of half a century (Spelman and Manabe 1984). Also, natural fluctuations of the climate system will continue, and constitute 'noise' above which the greenhouse-gas induced 'signal' must be detected. For temperature, the natural fluctuations are greatest at high latitudes (Jones and Kelly 1983) so (d) above may be obscured. The signal to be sought has to be assumed to be that defined by the numerical models, with the uncertainties specified above. Observations made since the mid-nineteenth century, and particularly in the past few decades, have been analysed with the above considerations in mind.

2. Analysis of air and sea temperatures

After independent adjustment for systematic biases in the data, sea surface and marine air temperatures show very similar global trends since the mid-nineteenth century (Fig. 2). The corrections to sea surface temperature were made using a numerical model of an uninsulated canvas bucket and succeeded in removing the spurious annual cycles in pre-World War II data (Folland and Parker 1988) which had been caused by the enhancement of heat transfers from uninsulated buckets in winter. The corrections to marine air temperatures compensated for long-term trends in deck elevation and for non-standard observing procedures during World War II. Night-time marine air temperatures were used, in order to avoid spurious on-deck heating. The corrected oceanic temperatures are in fair agreement with island station data (Fig. 3) but land areas as a whole were relatively colder in the nineteenth century except, apparently, in summer in the northern hemisphere (Fig. 4). Urban heating may have slightly accentuated the trends measured over land (Hansen and Lebedeff 1987, Karl *et al.* 1988).

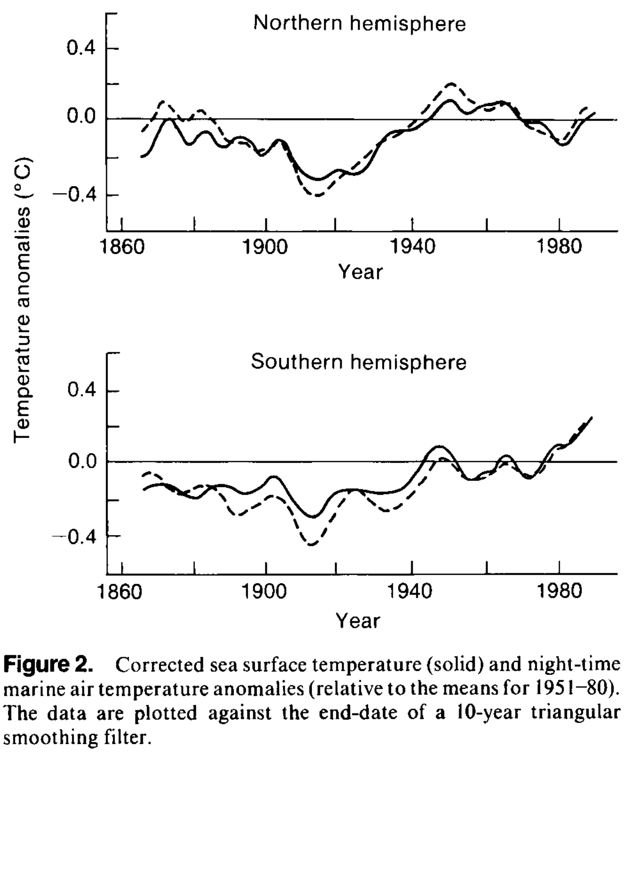

Figure 2. Corrected sea surface temperature (solid) and night-time marine air temperature anomalies (relative to the means for 1951–80). The data are plotted against the end-date of a 10-year triangular smoothing filter.

The twentieth century global surface warming has been a little less than 0.5 °C but much of this was before 1940 (Figs 5 and 6) when the enhancement of greenhouse gases was small. The more recent surface temperature trends agree with tropospheric trends derived from radiosonde data (Angell 1988). The most recent warming does not, however, show the enhancement expected in winter at high latitudes (Jones 1988), or the anticipated amplification in the tropical upper troposphere (Angell 1988, Parker 1985b). Also, lower-stratospheric cooling has only been evident since the early 1980s (Angell 1988), and even this may reflect the recent depletion of stratospheric ozone. Furthermore the radiosonde data may be affected by changes in instrumentation (Parker 1985a), which tend to involve improved shielding from radiation, leading to lower observed temperatures. The global surface and tropospheric warming since the early 1980s (Fig. 5) can be partly ascribed to the two strong El Niño events of 1982–83 and 1986–88. El Niño events warm the tropical surface and troposphere in particular for a year or two (Pan and Oort 1983, Parker 1985b).

Since the 1950s, there has been a warming of the southern, relative to the northern hemisphere, especially over the oceans (Figs 2, 4 and 6: see also Fig. 6 of Parker and Folland 1988). This is not an anticipated result of increasing atmospheric greenhouse gases, and appears to involve natural modes of oscillation of the atmosphere and ocean, associated with major changes of atmospheric circulation in the tropics, and marked fluctuations of rainfall in sub-Saharan Africa (Folland *et al.* 1986). The world-wide precipitation changes expected by the models with enhanced atmospheric CO_2 have not yet been unambiguously identified in the observations, which may have been affected by changes in gauge design (Bradley *et al.* 1987).

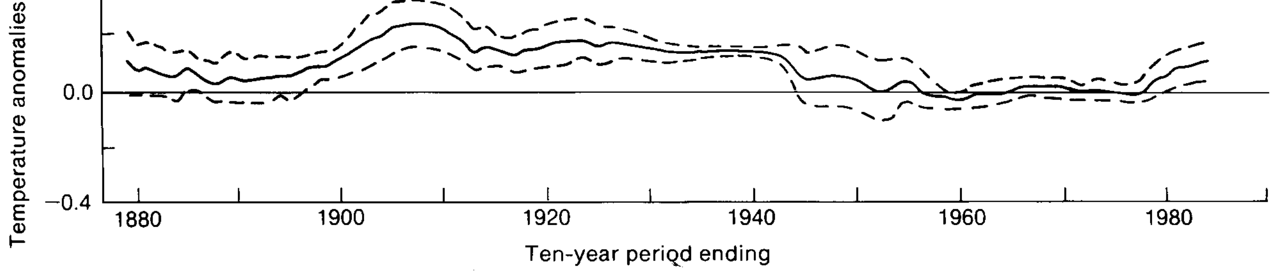

Figure 3. Average differences (solid line), and plus and minus twice the standard errors, between decadally averaged anomalies of island air temperature and nearby corrected sea surface temperature. Land air temperature data were provided by P.D. Jones (University of East Anglia).

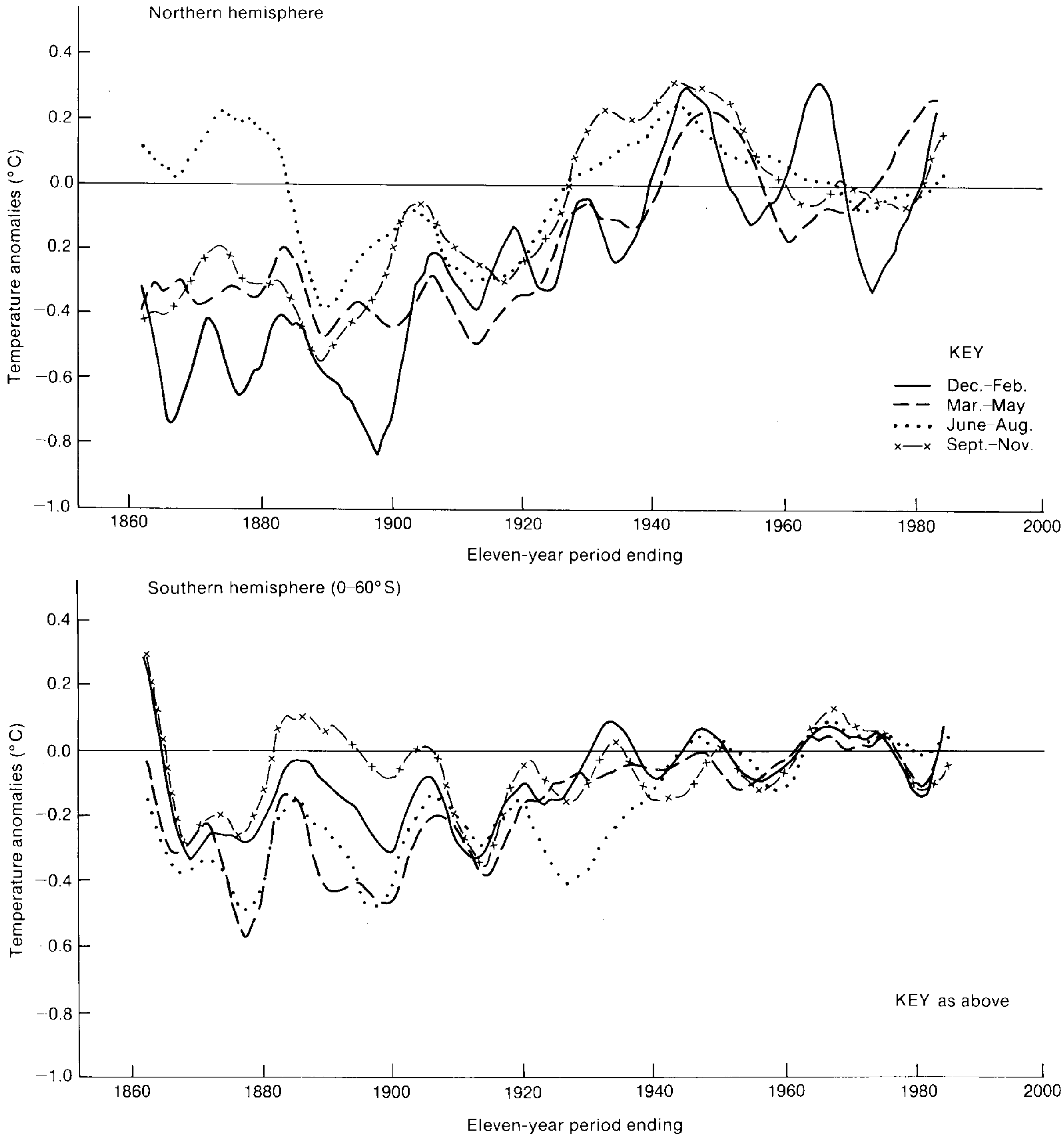

Figure 4. Seasonal land surface air temperature anomalies (relative to means for 1951–80) plotted against the end-date of an 11-year triangular smoothing filter. Data provided as in Fig. 3.

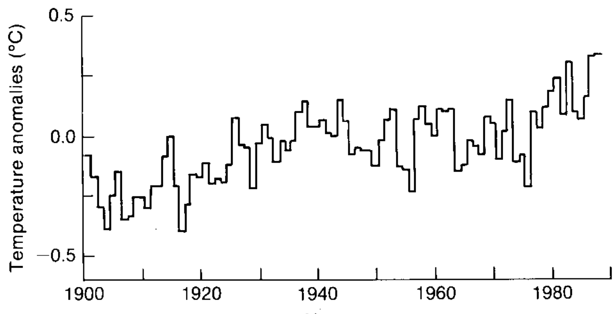

Figure 5. Anomalies of global surface temperature, 1901–88. Data are combined land air temperatures and sea surface temperatures. Land air temperature data provided as in Fig. 3, and sea surface temperatures were adjusted as in Jones *et al.* (1986).

3. Conclusion

There is growing evidence for the importance of the role of variations of atmospheric CO_2 concentration in the climatic changes of the late Pleistocene and early Holocene. The broad-scale atmospheric and oceanic effects to be expected as a result of the recent increase of greenhouse gases are becoming more clearly understood as numerical modelling studies develop, but regional details and the time-scale of the response of the ocean remain uncertain. Observational evidence corroborates the anticipated climatic changes to some extent, but may yet be ascribed to other, natural causes.

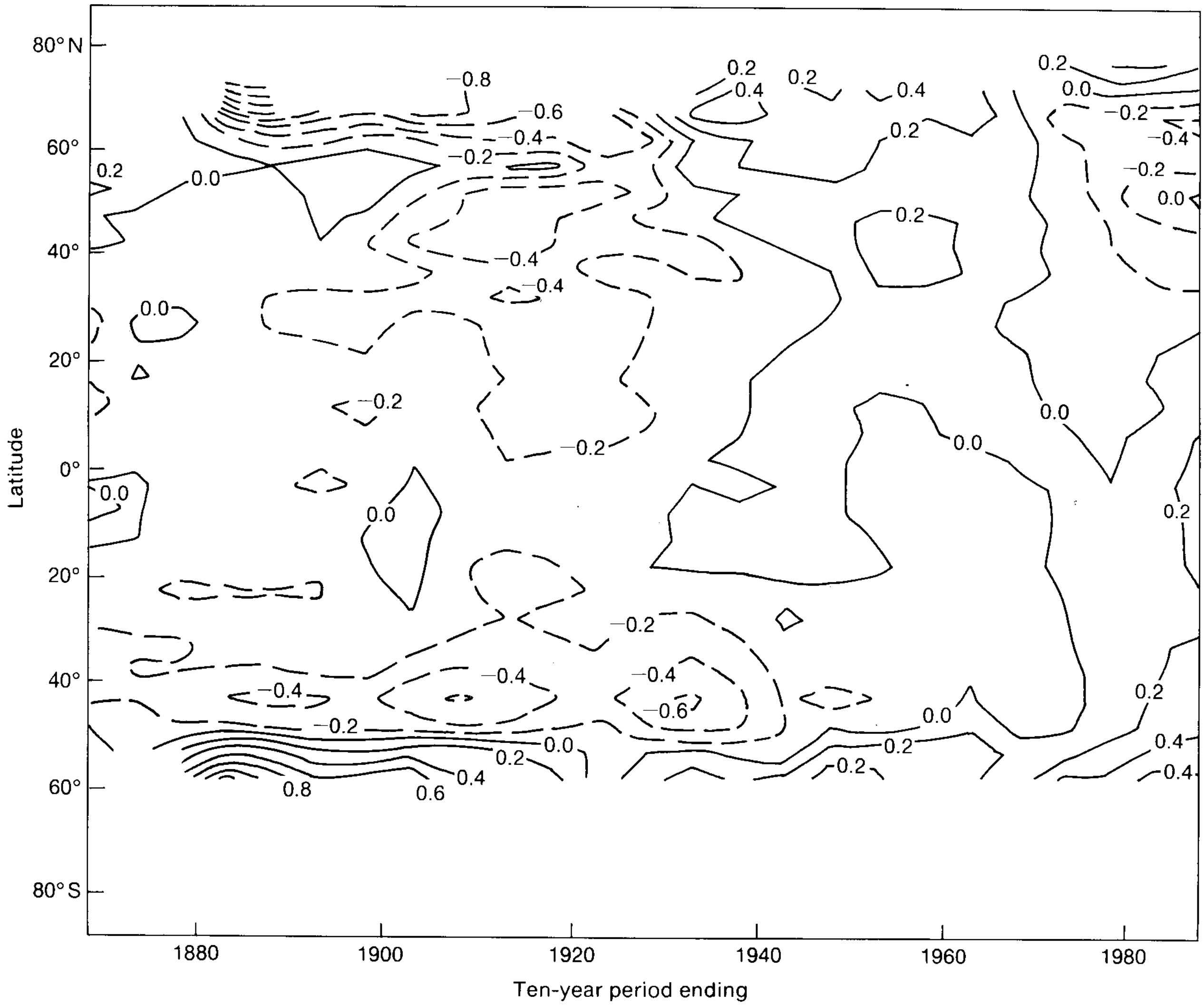

Figure 6. Zonally averaged decadal mean sea-surface temperature anomalies (°C) relative to means for 1951–80. The anomalies are updated every 5 years from 1859–68 to 1979–88. Values are calculated for every 5° of latitude, and at least 10% of the ocean of a zone had to be covered for a value to be plotted.

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Trials use of a weighing tipping-bucket rain-gauge

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Summary

This article explains the need for a state-of-the-art rainfall rate recorder for use in trials of modern weapon systems and describes a weighing tipping-bucket rain-gauge (WTBR) which has been developed by the Operational Instrumentation Branch of the Meteorological Office. Measurements made by the new instrument and by a nearby standard tilting-syphon rain recorder, obtained during evaluation trials, are compared.

1. Introduction

All modern weapon systems pass though an extensive programme of testing under field conditions during their development. As part of this, it is required that some trials are carried out in rain. There are several aspects where rainfall affects the operation of weapon systems — two of the more important are the effect of rain on the target detection and tracking systems, and its effect on the actual firing mechanism (the fuse).

The various target detection and tracking devices now used operate over a wide range of electromagnetic frequencies. For example, heat-seeking thermal sensors detect electromagnetic radiation at frequencies within the atmospheric window. Also, targets may be illuminated by infra-red lasers with sensors detecting the reflected laser energy. Such electro-optic devices are adversely affected by the presence of water in the atmosphere, and their use is particularly restricted in rainfall.

Modern fuses are more sophisticated than those of the past. The long-standing impact fuse operates on physical contact with the target and when this occurs the fuse is triggered, causing the detonator to ignite the main explosive. Some ultra-sensitive modern impact fuses can be triggered when passing through heavy rain, which creates a risk to the operator of the system, particularly when the munition is fired from an aircraft as it may subsequently fly through the debris left by the round. Modern larger missiles often also carry a second (proximity) fuse which is designed to identify a near-miss situation and to initiate a detonation without actually making contact with the target. This type of fuse monitors the strength of the emissions of electromagnetic radiation from the target and is designed to trigger at a predetermined level, or when the strength of the emissions has peaked, e.g. as the missile or shell flies past the target. The presence of rainfall can cause a reduction in the strength of the emissions received and so can lead to premature detonation. Clearly, in the testing of modern weapon systems, these effects need to be simulated in trials, and this requires accurate monitoring of the rainfall.

2. Earlier rainfall monitoring devices.

In the past, various devices for rainfall monitoring have been used in trials of military equipment. Some early and ingenious techniques include one in which discs of blotting paper were exposed to rainfall for a short period of time. These discs were impregnated with potassium permanganate dust; impacting raindrops left a clear mark, and the rainfall rate was determined by counting and sizing the impact signatures. Other instruments were developed to make a direct record of the rainfall. These include the 'Jardi', which used a float suspended in a cylinder attached by levers to a pen arm, and the Meteorological Office instrument which consisted of a funnel with a constricted exit so that the channelled raindrops operated a counter switch. The disadvantage of both of these instruments was that only a narrow range of rainfall rates could be measured.

This limitation is largely overcome by the rain-gauges currently in use at most observing sites. The current instruments are the tipping-bucket rain-gauge which registers each 0.2 mm fall of rain, and the tilting-syphon rain recorder which produces a trace for manual post-event analysis. These devices are, however, still unable to meet the requirements for monitoring rainfall in the trials of modern weapon systems, which are:

(a) The accurate measurement of rainfall rate, for all intensities between drizzle and heavy rain, with a sampling period of as short as 10 seconds, and

(b) a real-time read-out facility, so that the actual weapon firing can be made at a particular rainfall intensity.

3. The standard tipping-bucket rain-gauge

Most meteorological observing sites are currently equipped with either a Mk.3 or Mk.5 tipping-bucket rain-gauge (TBR). These gauges consist of a collector in the shape of a funnel, with an internal rim diameter of 309 mm providing a collecting area of 750 cm^2. The collected rain then passes through the funnel tube and into a stainless steel bucket with two identical compartments which is mounted on a spindle. When 15 cm^3 of rainwater (equivalent to 0.2 mm of rainfall) has been collected in one compartment, the bucket tips and the rainfall is then directed into the other compartment. Each time the bucket tips a magnet actuates a reed switch. In addition, the Mk.5 incorporates a second magnet and reed switch providing two outputs.

The outputs from the reed switches are usually fed to one of two types of counter, namely an electromagnetic counter or a solid-state event recorder. The electromagnetic counter simply consists of a four- or five-digit counter which increments by one each time a reed switch is closed by the bucket mechanism. Solid state recorders are now often used as they store the number of tips and the time of their occurrence on a data cartridge.

Obviously, the output from the standard TBR gives information on the time taken between successive increments of 0.2 mm of rainfall or the mean rainfall rate over this time. This duration is usually from about 1 minute or longer (mean rainfall rate 12 mm h^{-1} or less) but at the largest rates the TBR can lose accuracy due to water splashing out of the buckets. In any case, with the TBR changes of rainfall rate within the time between bucket tips cannot be detected. This restriction is overcome with the weighing tipping-bucket rain-gauge.

4. The weighing tipping-bucket rain-gauge

A detailed description of the weighing tipping-bucket rain-gauge (WTBR) is given by Pettifer *et al.* (1980) and Molyneux (1984) and so only a brief summary will be given here. A schematic diagram is shown in Fig. 1. The device is based on a Mk.5 TBR and maintains continuity with the current standard. However, the tipping-bucket mechanism is now suspended from a back plate by a strain wire between the poles of a magnet. This wire is excited electrically at its resonant frequency, which is dependent upon the tension in the wire due to the mass of the tipping-bucket mechanism. As rain-water from the collector enters the bucket, the tension in the wire increases and the resonant frequency of the wire increases. As the rate of change of mass of the tipping-bucket mechanism is proportional to the rate of change of frequency, by measuring the change in the resonant frequency of the wire, the rate of rain-water accumulation in the bucket can be calculated. The sharp reductions in frequency which occur when the bucket tips are taken into account in the rainfall rate calculations.

The instrument used in these trials is a prototype. It is anticipated that refinements in both hardware and software, which are currently nearing completion, will mean that the instrument will be suitable for more widespread use in the near future.

5. Comparison of results with an open-scale tilting-syphon rain recorder

To illustrate the performance of the instrument, some results comparing the rainfall rates obtained from the prototype WTBR with a standard tilting-syphon rain recorder are shown in Fig. 2(a). Here, 1-minute averaged rainfall rates from the WTBR have been plotted together with 3-minute averages estimated from the tilting-syphon chart for the period 0710–0730 GMT on 30 July 1986 near Aberporth. Both instruments show similar results, with a steady increase in the rainfall rate to 0720, followed by a sharp decrease, then remaining fairly steady at about 2 mm h^{-1}. From 0710 to 0730 the WTBR collected 1.57 mm of rain, which was in reasonable agreement with that estimated from the tilting-syphon chart, which was 1.7 mm. Analysis of

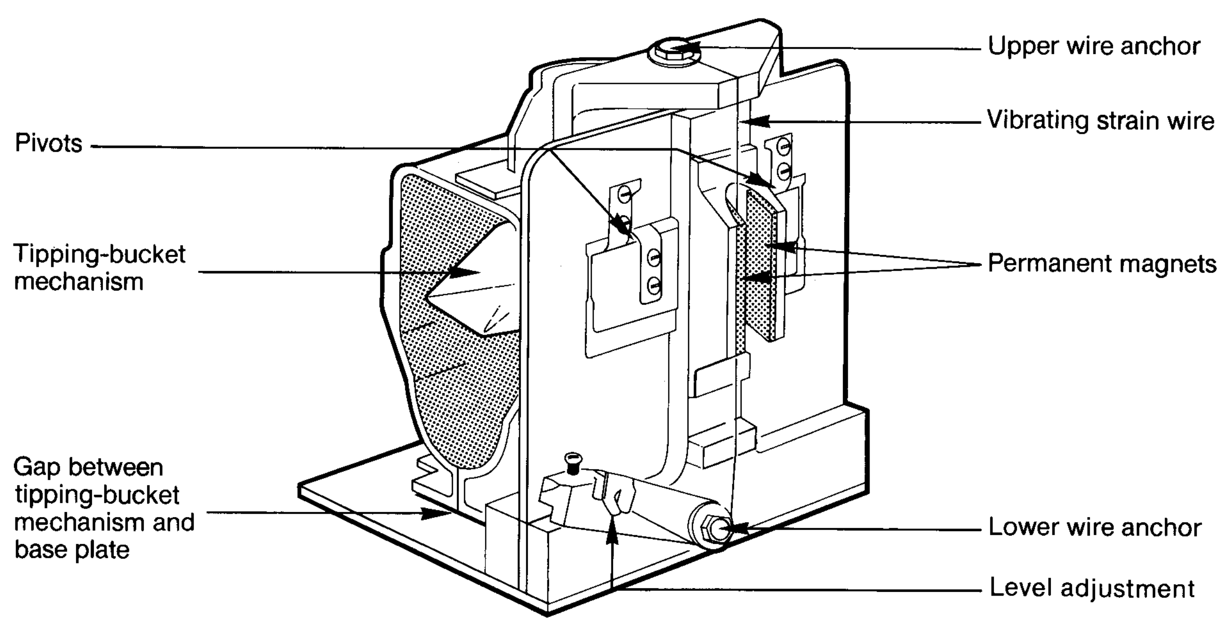

Figure 1. Schematic diagram showing the construction of the weighing tipping-bucket rain-gauge.

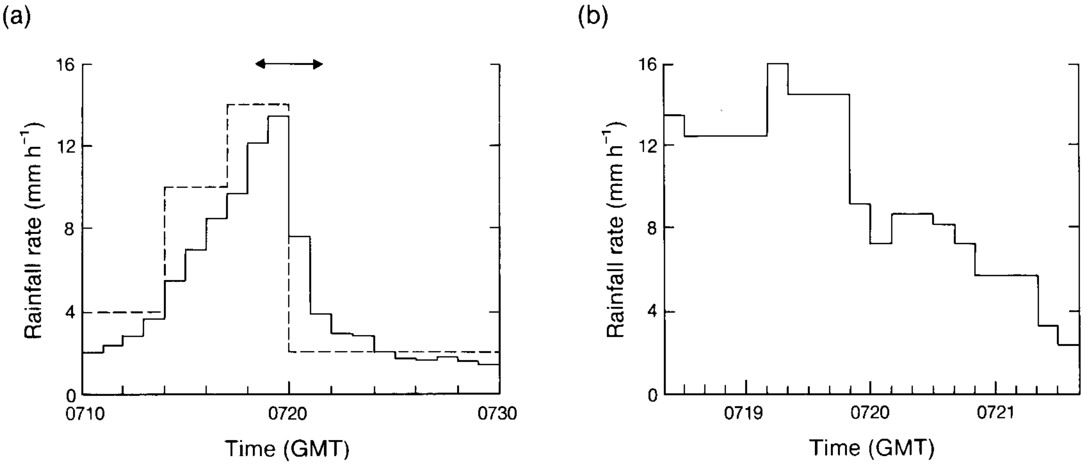

Figure 2. (a) Comparison of rainfall rates derived from the weighing tipping-bucket rain-gauge (solid bars, 1-minute averages) with those from a standard tilting-syphon rain recorder (dashed bars, 3-minute averages) for 0710–0730 GMT on 30 July 1986, and (b) expanded section of the WTBR rainfall-rate record around 0720, indicated by the arrow in (a), with 10-second averaged rainfall rates.

data on other occasions have also shown similar agreement between the two instruments.

Fig. 2(b) shows an expanded section from around 0720, denoted by the horizontal arrow in Fig. 2(a), where the 10-second rainfall rates from the WTBR are plotted. This shows the detailed structure of the rainfall rates, with a peak value of 15.8 mm h^{-1} being recorded.

6. Conclusions

The prototype instrument offers, for the first time, the facility to monitor rainfall rates in real time. This is essential for trials which have to be conducted specifically in predetermined rates of rainfall. Whilst there is an increased degree of error in the 10-second values, experience suggests that it is not excessive. Also, in practice, most trials specify a range of rainfall rates within which the firing must take place, so this is not a problem.

Practical considerations of conducting trials in rain suggest that conclusions drawn from point sampling of the rain at the firing point should be treated with care. In frontal conditions the measured rainfall rate is probably representative for small ammunition with a range of 100–200 m. However, shell ranges from artillery are typically 5000 m upwards, whilst air-to-air and ground-to-air missiles have a range up to several tens of kilometres. The spatial and temporal variations in rainfall rate over these distances are likely to be very significant. As a result, developments in this field of trials support are moving towards the use of weather radar data, combined with the WTBR for local real-time calibration, to define the rainfall over the longer trajectories.

In the future it is likely that weapon target detection and tracking systems will need to be able to select the optimum of several available electro-optic sensors, depending upon the weather conditions, to enable the detection of the target at maximum range. Even with the specialized instrumentation described here, the challenge to forecasters participating in these types of trials is daunting. An accurate assessment of the time of onset of suitable rainfall is needed, not just at the firing point, but along the trajectory. Also required are estimates of the likely duration and short-term changes within a time-scale of minutes. Such weapon systems will also require forecasts of cloud base, wind strength and visibility, so that their performance can be evaluated. This will require forecast products from many sources, e.g. output from sophisticated numerical models and real-time on-site interpretation of weather radar and satellite data.

Acknowledgements

Thanks are due to the Surface Instrument Development Group of the Operational Instrumentation Branch of the Meteorological Office who designed and built the modified instrument.

References

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Pettifer R.E.W., Westbury P.R. and Molyneux M.J., 1980: A new continuously indicating raingauge for use on Automatic Weather Stations. WMO Instruments and Observing Methods, Report No 1, pp 25–28. Geneva, WMO.

Awards

L.G. Groves Memorial Prizes and Awards for 1987

The memory of Sergeant Louis Grimble Groves, RAFVR, who was killed in September 1945 while serving as an Air Meteorological Observer with 517 Squadron Coastal Command, is perpetuated through the endowment of the annual L.G. Groves Memorial Prizes and Awards by his parents, Major and Mrs Keith Groves. The 1987 awards were presented by Air Marshal Sir Kenneth Hayr, CB, CBE, AFC, RAF on 25 November 1988 at HQ Strike Command (High Wycombe), and the citations were read by the Inspector of Flight Safety Air Commodore G.R. Profit, OBE, AFC, RAF. The ceremony was attended by representatives of the RAF and the Meteorological Office, and by the wives of the award winners, but, sadly, no members of the Groves family were able to be present at this, the 41st anniversary of the awards.

Dr A.P. Cluley and Mrs Cluley on the left, Mr T.S. Hills on the right and Air Marshal Sir Kenneth Hayr.

Meteorology Prize — Dr A.P. Cluley, Mr T.S. Hills

The citation for this award was:

'By the early 1980s there was extensive use of computing to support forecasters in large offices such as the Central Forecasting Office at Bracknell and the Principal Forecasting Office, HQSTC, but small offices on RAF stations were wholly reliant on teleprinter and facsimile channels for the receipt of meteorological data. A long-term strategy, which came to be known as Weather Information System (WIS), was conceived whereby these channels would be replaced by an advanced digital communications network, and the reams of paper by a small computer in each office. This latter element of WIS was called the Outstation Display System (ODS) and its purpose was to hold a database of observations and processed data from which the forecaster could retrieve information in a variety of formats. The ODS concept was refined using a prototype during 1984/85 and the first batch of 15 systems was procured and installed at 8 key RAF stations early in 1987. Subsequently, a second batch of ODS equipment has been installed early in 1988 extending the coverage to a further 8 RAF stations plus HQSTC, Met O College and Manchester Weather Centre.

ODS is the result of much teamwork, but two individuals stand out. First, Dr A.P. Cluley was the project manager from the inception until the first batch of systems were operational. His leadership and energy were vital ingredients in driving the project through the stages of requirement specification, prototyping, procurement, initial systems development and installation. He overcame many technical and administrative problems and achieved installation of the first batch on schedule. Second, Mr T.S. Hills, now project manager, was responsible for the software design. The high quality of his own work and his success in blending together the contributions of his team of programmers have resulted in a system which meets the requirement, is very reliable and is, above all, a model of 'user-friendliness'. The design shows real understanding of the working environment of the forecaster serving military aviation.'

This award was made to Paul Cluley for work undertaken whilst in the Systems Development Branch of the Meteorological Office, a period from 1983 to 1987. His career in the Meteorological Office started in 1972 and he worked in the Meteorological Research Flight (MRF) at Farnborough from 1973 to 1978. After a short spell at Headquarters, he was promoted to Principal Scientific Officer in 1980 and spent three years at Heathrow Airport as Deputy Chief Meteorological Officer. In August 1987 he was promoted to Grade 6 and appointed as Assistant Director for Data Processing.

Trevor Hills joined the Meteorological Office in 1976 and worked on computer modelling of the world climate until 1983. His work in this field varied from examining the effect of varying the model's grid resolution in polar regions to automating the long-running programs required for climate modelling. He was one of the first Meteorological Office staff to use the Cyber 205 supercomputer, visiting the USA to gain experience with the machine while it was still in the factory. After a short spell at the forecasting bench he spent a year working in the IBM mainframe operating system team. In 1985 he was posted to the Systems Development Branch where he worked with Dr Cluley to specify the hardware and develop the software for the ODS project. In 1987 he took over full responsibility for ODS and for other computer systems to support outstations.

Award for Meteorological Observation —Mr K.J. Dewey

The citation for this award was:

'During 1987 the aircraft of the Meteorological Research Flight (MRF) took part in two highly successful major international experiments. The success of these experiments relied heavily upon the dedication and professionalism of all the air observers, of which Mr Dewey (HSO) is singled out for his particular contributions both to instrument development and to flying duties. During the two years prior to the experiments, Mr Dewey was responsible for solving the mechanical, electronic, data processing and environmental problems of adapting a 16-channel radiometer for deployment on the aircraft. This radiometer was originally designed as a prototype satellite instrument, and is considerably more complex to maintain and operate than most scientific equipment installed on the aircraft. The radiometer was crucial to the success of MRF participation in the first international experiment, and was operated successfully, often under stress, by Mr Dewey on all 14 flights of that experiment. During the second experiment (for which the radiometer was not required) and during other, home-based operations, Mr Dewey participated regularly in flight duties, and, as a flight leader, has earned the respect of everyone who has worked with him. Much of this work involved long hours including some weekend and night flying.'

Ken Dewey joined the Office in 1961 as an Assistant at Uxbridge. He made the most of his opportunities to travel and between 1964 and 1969 he was posted to Labuan, in Borneo, Gan and Bahrain. After a spell at Gloucester he retrained as an R(M)T and subsequently was posted to Crawley radiosonde station until promotion required a move to Beaufort Park. The lure of the tropics was still strong though and at the first opportunity he went off to Tarawa in the Gilbert Islands (now Kiribati). On his return he joined the Cloud Physics Branch working on the cloud physics and dropsonde instrumentation as fitted to the MRF Hercules aircraft. A promotion to HSO produced another move, this time to the Radar Research Laboratory at Malvern for a short period before joining the MRF at Farnborough in 1985 where he has been mainly involved with the Multi-Channel Radiometer and as a flight leader on the aircraft. This has enabled him to satisfy his continued wanderlust in allowing detachments to places as far afield as San Diego, Dakar and Machrihanish.

Mr K.J. Dewey flanked by Mrs Dewey and Air Marshal Sir Kenneth Hayr.

Air Safety Prize and Ground Safety Award

This year the Air Safety Prize was won by a five-man team from HQSTC — Wing Commander A.J. Thorpe and Squadron Leaders A. Melville-Jackson, B.C. Holding, D.L. Warner and P.J. Bonsall — who produced a series of videos promoting flight safety. The Ground Safety Award was given to Chief Technician D.F. O'Reilly of RAF Cottesmore for devising a set of blanks to protect Tornado GR1 systems when the aircraft is on the ground.

Notes and news

The death of Sir Harold Jeffreys

The death is noted, at the age of 97, of Professor Sir Harold Jeffreys, who as far as is known, was the last surviving link with Sir Napier Shaw, the Director of the Meteorological Office from 1905 to 1918 and from 1919 to 1920. Harold Jeffreys D.Sc. became an 'Assistant' on the secretarial staff of Sir Napier Shaw during the year ending March 1918. By the time of the Annual Report of March 1920 he had gained an MA and had become a 'Professional Assistant'. The Annual Report of March 1921 reveals that by then both Shaw and Jeffreys had left the Office to pursue more academic careers. Ultimately Sir Harold became Emeritus Professor of Astronomy and Experimental Philosophy at Cambridge. Included in his writings were several papers related to meteorology, and copies of them are lodged in the National Meteorological Library at Bracknell. One of his many books, *The Earth; its origin, history and physical constitution*, was first published in 1924, revised by himself through six editions over 52 years, and is still in print. In the early days of the 1960s, when artificial earth satellites were still novel, the Editor (as a young and inexperienced scientist) had the honour to serve with Sir Harold on the Satellite Orbital Analysis Working Group of the British National Committee on Space Research. He is recalled as being very much a classical geophysicist but nevertheless having a keen appreciation of the potential impact on geodetics of studies of the effect of gravitational perturbations on satellite orbits. An obituary of Sir Harold appeared in the *Daily Telegraph* on 21 March 1989 and an appreciation of him written by Dr Raymond Hide was published in the April 1989 issue of the *Quarterly Journal of the Royal Meteorological Society*.

Reviews

Long and short term variability of climates,

edited by H. Wanner and U. Siegenthaler. 164mm×242mm, pp. 175, *illus*. Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1988. Price DM 48.00

For a number of years, the Climatic Research Unit at the University of East Anglia has been involved in teaching a third-year undergraduate optional course on Climatic Change. The course falls naturally into three segments: evidence, causes and impacts. In the past, it has never been possible to recommend a set book for the course that would cover more than one of the three components to the required depth. This fact, combined with the impecunious state of the student body, has meant that we have opted to dispense with a set book, and have relied instead on journal papers. As all lecturers will be aware, this approach has certain disadvantages — some students will take it as a licence to read nothing at all, some will attempt to read everything, and inevitably, by the end of the academic year, most of the journals will have gone missing anyway. With a good set book, on the other hand, a certain minimum body of knowledge should be within the reach of every course participant. Here we have such a book, covering at least two aspects of our course, evidence and causes, both thoroughly and in a most up-to-date manner.

The book is the sixteenth in a series called Lecture Notes in Earth Sciences. Whereas others in the series have been primarily concerned with geology and geomorphology, this is the first to deal with atmospheric sciences. It contains eight papers by a number of eminent European scientists, divided under the loose headings 'Observational Studies' and 'Modelling Studies'. Papers on evidence and causes are included under both headings. Thus, under 'Observational Studies' there are contributions on the detection of climatic change in the instrumental record (Jones and Kelly), on tree growth rings (Schweingruber) and on documentary records of, for example, harvest dates (Pfister). Papers on causes are by Fröhlich (on the variability of the solar constant) and by Duplessy, Labeyrie and Blanc (on variations in Norwegian Sea deep water over the last climatic cycle). Under 'Modelling Studies' there is a general essay by Grassl on numerical models – how they work, what their inherent errors are and how they can be used for detection studies. The following papers are on forcing by the orbital parameters (Tricot and Berger) and a very comprehensive study of the causes and effects of carbon dioxide variations in glacial–interglacial cycles (Siegenthaler).

The book is softback and the text is camera-ready. As such, the price (which is not available to me) should be reasonable and within the reach of students. This is a good thing, as the text is clearly aimed at the later years of undergraduate study and/or the postgraduate market. The book is very successful at achieving this aim. However, for three reasons it deserves to be more widely read as a reference text by scientists working in the field of climatic change. Firstly, the articles are written by scientists working at the forefront of their field in countries where, with one exception (Jones and Kelly) English is not the mother tongue. As such, it presents a European view of the science of climatic change to English-speaking researchers accustomed to the North American or British stance. Secondly, camera-ready production has meant that the book has appeared very quickly, and therefore the essays are all state-of-the-art. Thirdly, most of the papers are accompanied by extensive, and very useful, reference lists.

The real strength of the book is in bringing together a collection of up-to-date papers on research on the frontiers of the science of climatic change. In this and other aspects, the book is most timely and most valuable. My only regret is that, without a section on climate impacts, it is not the perfect teaching textbook. I can only hope for a second edition.

J.P. Palutikof

How to write and publish a scientific paper,

third edition, by R.A. Day. 155 mm × 235 mm, pp. xi+212, *illus*. Cambridge University Press, 1989. Price £7.95 (paperback), £20.00 (hardback).

This book, written in Anglicized American, is a joy to behold. The author describes it as a 'cookbook', not for cooking results but for providing recipes for success in scientific writing — it should sell like hot cakes. Every question the reader has ever wondered about asking in this subject appears to have an answer provided. Practical advice is given generously in all areas, without necessarily expecting it to be taken, but at the same time challenging and encouraging the reader, from an experienced position, to think of something better, if possible. The language and presentation are very clear and succinct while at the same time being amusing, anecdotal and eminently readable — open at any page and one is captured.

The book commences with a definition of scientific writing, its history and then a definition of a scientific paper. Each chapter has its pithy, italic quote for starters, something which I always enjoy in a book. The title of the book is slightly off-putting if one thinks that one will never aspire to write a scientific paper, but other forms of writing science, such as conference reports and reviews are covered — the latter read avidly by this reviewer, with this result.

In following chapters, the scientific paper is dissected into nine component parts which are considered separately. Incidentally, dissection is an appropriate term, the slant if anything being on biology, but this does nothing to detract from the book's general application to science. The few illustrations are medical/biological, but are mainly used to give advice on whether diagrams or tables should be used for various topics, or that often a sentence of text can be better than either. Beside the crackling text, the Peanuts cartoons, although a good idea, appear pedestrian. In most publications they provide the comic relief.

Further chapters, on associated information, deal with editors, proofs, where and how to submit, ethics (including copyright), use of English, etc., the last being a potential minefield for English purists. More useful information is provided by six appendices, a glossary and references; the index is interesting and varied, and is headed by an acknowledgement to the compiler, which is rare but thoughtful, because a good index is a labour of love.

For less than £8 (in paperback), this is a bargain for anyone with the vital task of setting science, in its many forms, on the printed page. It represents a saving akin to the author's example of spending a lot of money on a piece of equipment and then 'saving' by not spending a little to have it drawn properly for your scientific report on it. One wonders how scientists have managed without it, but since it is the third edition ('larger and better') perhaps many authors have been referring to a previous edition for years.

S.H. Barker

A glossary of computing terms, fifth edition,

edited by the British Computer Society Committee Glossary Working Party. 147 mm × 209 mm, pp. xii+73, *illus*. Cambridge University Press, 1987. Price £1.95, US$3.95.

The glossary consists of two parts; in the first part there is an alphabetical index of terms, each with a numeric code of chapter and paragraph, which in turn directs the enquirer to a location containing the relevant definition in the second part of the book. The chapter headings tell the reader what types of definition he will find therein, such as Communications, Documentation, Input and Output, Programming, etc.

Ideally, a book of this type should be independent of any particular manufacturer's wares, and it was a pleasure to read it and find only minimal references to any company names. The book is not really one to be read through from beginning to end, nevertheless it is short enough for that task not to be too arduous. The type-face and lay out are clear, easy to read and up to the usual high standard of the Cambridge University Press, but a few errors have crept in — why is it that, in these days of word processing, there seems to be a school of thought which says that proof reading is no longer necessary? It was at least ineffective for the definition of 3.6 (bit), which appears to have a repetition of the text for 3.7 (block). The use of cross-references by the numeric codes in the main body of the book has resulted in some of the errors, probably caused by insertions of new definitions. Where cross-referencing is necessary, it would be better to use the relevant term and leave the reader to look it up in the index.

The reviewer would take issue with the authors on a few definitions. If Kbyte is defined for computers as 1024 (2 to the power of 10) then surely Mbyte is 1 048 576 (2 to the power of 20). There is also something slightly amiss with the definition of 3.67 (variable record) as one where the number of bits (or characters) is not predetermined. The length of a variable record is contained within a preliminary descriptor word or series of bits, and may well be predetermined. Perhaps a future edition could clarify this under a separate heading 'record type'. A similar treatment has already been given to 2.4 (character codes), but this needs the addition of

ASCII, ANSI and EBCDIC to the index for completeness. As far as 2.2 (baud) is concerned, the authors are at odds with some other reference books in assuming 'for convenience' that it is one bit per second.

Nevertheless, having said all this, it is only fair to point out that there are no more than a dozen errors to be seen in 800 definitions. Despite the above criticisms, this book must be on the shelf of every school and technical college library for quick and easy reference. The authors clearly set out to provide them with an inexpensive *aide-memoire*, and have successfully achieved this, also reaching a much wider audience in the process.

J.W. Prince

The weather journals of a Rutland squire, edited by J. Kington. 185 mm × 245 mm, pp. xii+217, *illus.* Oakham, Rutland Record Society, 1988. Price £15.00.

By bringing together so many of the writings of Thomas Barker of Lyndon Hall and providing also a potted biography of the man, John Kington and the Rutland Record Society have done a good service for the climatology of the eighteenth century. They have clothed the dry records with a sense of the presence of a keen and methodical observer both of the weather and the countryside, whose position allowed him to indulge his interests to the full. That meteorology was one of them is to our benefit.

As a boy Barker met Gilbert White of Selbourne, a friendship which continued and deepened throughout their lives, and reference to the Lyndon Squire and his records occur in many of White's writings. Throughout his long life he maintained his enthusiasm and produced consistent records over a period of more than 60 years. Unfortunately, as with so many similar records and diaries, the manuscripts have suffered through the carelessness of posterity, volumes have been lost and all are scattered. It is a tribute to the editor's energy that so much is made available.

Like all his contemporaries Barker was free to set his own standards and expose his instruments as he desired. For his 'temperature abroad' we only know that the thermometer was 'outdoors in the shade', while his rain cistern is on top of a wall where it meets another at right angle, 7 ft 3 ins on the north side, 8 ft 6 ins on the south-west and 10 ft on the south-east.

But in spite of these limitations the records at Lyndon covering the period 1733–98 have long been accepted as one of the better sources for that period and it is strange that until now there has been no single volume dealing with them. The Annual Reports which he submitted, through friends, to the Royal Society from 1771–98 have previously only been available in the few remaining copies of the *Philosophical Transactions*. They expand and supplement his own *Meteorological Journal* 1733–95 given in earlier chapters. In all of his records he deals with the effects of weather on nature and on agrigulture, and so provides ample material for a social history of the period.

As a contribution to the records of the sadly departed Rutland this book fills an important niche, to a climatologist both the text and bibliography will be of considerable benefit, whilst to the general reader there is much of interest with source material of the 'Coldest/wettest...' type, and all this for a not excessive £15.

F.J. Ayres

Books received

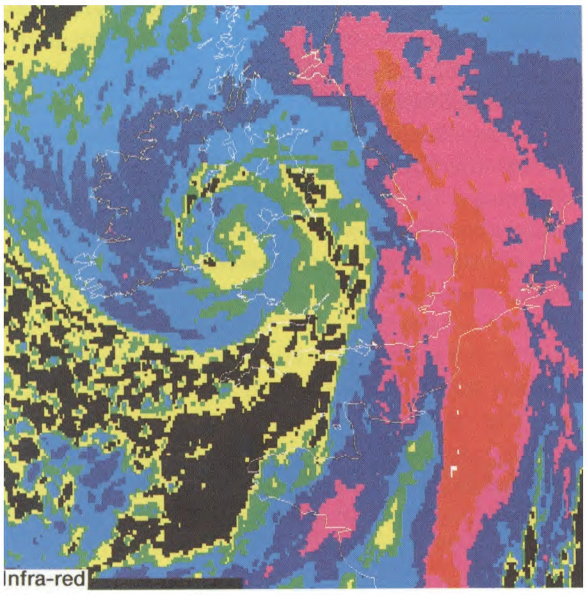
The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

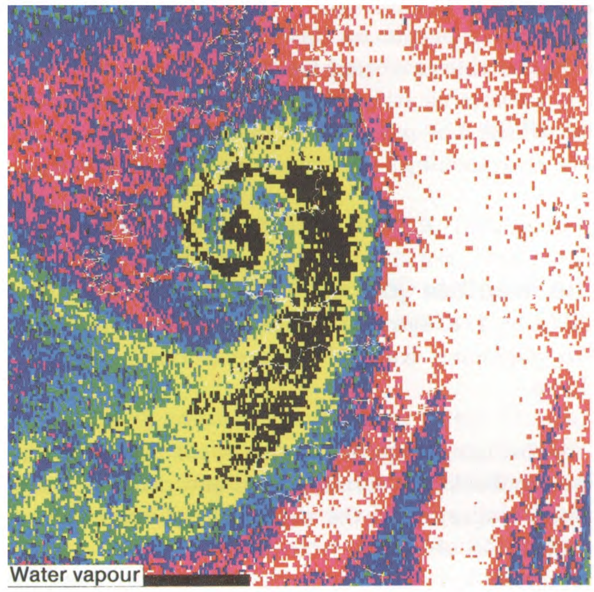
The geostationary applications satellite, by P. Berlin (Cambridge University Press, 1988. £30.00, US$49.50) gives an overview of the design, construction, launch and orbital flight of the subject, with a section on meteorological payloads. It has been written from a background of practical involvement in a project management team.

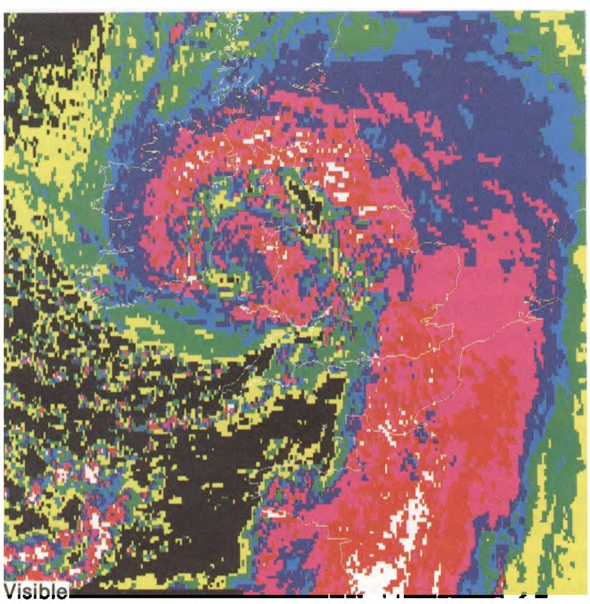
Solitons: an introduction, by P.G. Drazin and R.S. Johnson (Cambridge University Press, 1989. £11.95, US$19.95 (paperback), £32.50, US$59.50 (hardback)) is a textbook on the theory of solitons and its diverse applications to non-linear systems that arise in physical sciences. The generation and properties of solitons are explained, and the mathematical technique known as the Inverse Scattering Transform is introduced.

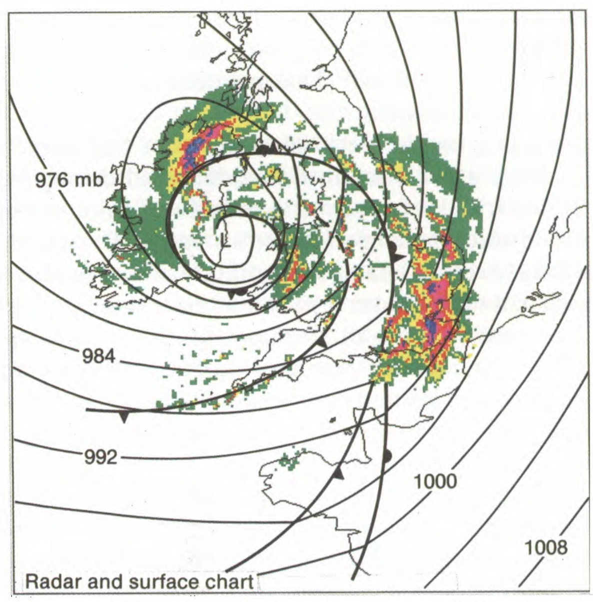
Glacier fluctuations and climatic change, edited by J. Oerlemans (Dordrecht, Boston, London, Kluwer Academic Publishers, 1989. Dfl.195.00, US$109.00, £64.00) contains papers dealing with glacial geology, mass balance studies, snow drift, modelling studies and energy balance and climatology of the glacier surface. Collectively they form a unique book on the central theme of how retreat and advance of glaciers is related to climatic change.

Satellite and radar photographs — 11 April 1989 at 1300 GMT









The Meteosat and UK radar network images portray a remarkably well-defined spiral of cloud, upper tropospheric moisture and precipitation, associated with an intense depression that had deepened explosively over the preceding few hours. The spiral is composed of alternating bands of dry air (where upper cloud and precipitation are largely absent) and moist air (considerable upper cloud and precipitation present). A surface occlusion can be drawn along the rear (or inner) edge of the moist air into the centre of the vortex. Note that on the radar image, the precipitation gaps within the spiral over southern Scotland and the Celtic Sea are due to poor radar coverage.

In the satellite images (which are slightly mis-registered) the colour sequence: black, yellow, green, cyan, blue, magenta, red and white represents warm to cold in the infra-red, dry to moist in the water vapour and dark to bright in the visible. The radar colour sequence: green, yellow, red, magenta, blue and cyan represents progressively increasing rainfall rates.

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Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in 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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Sensitivity of forecasts to humidity

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Thermodynamic indices for forecasting thunderstorms in southern Sweden

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Summary

Several verification scores have been used to investigate the performance of three thermodynamic indices as summer-time thunderstorm predictors. They are most efficient during the afternoon, when the 'best' index has a probability of detection near 100%. Combinations of two indices give better scores than single ones. Forward step-wise regression has been used to select the best predictors and estimate the lightning frequency. The analyses show a significant correlation between some indices and the frequency of lightning. Nomograms for estimating lightning probabilities and frequencies are suggested.

1. Introduction

The efficiency of some thermodynamic indices, used by the Swedish Meteorological and Hydrological Institute (SMHI) for forecasting purposes, has been investigated. The main use of these indices has been as 'yes/no' indicators. A thunder index is also needed in the new Swedish forecasting system (PROMIS).

Ideally, it should be possible not only to make yes/no forecasts, but also to give an indication of the lightning frequency. Even if simple indices such as these cannot be sufficient, some more information may perhaps be extracted from them. We have therefore also tried to use them, or combinations of them, to estimate the expected lightning frequency (expressed as the frequency of synoptic thunder observations). The main thunderstorm season in Sweden is summer, and only summer data were used. Hence, the results apply to summer. It may well be that these indices perform differently during other seasons, when thunder is much more rare. Also there are indications that the efficiency of the indices is dependent on the time of the day.

2. Lightning data and indices used

Since no lightning location system data were available to us, we used the observations made at ordinary 3-hourly synoptic stations to estimate the thunder frequency. Observations from about 20 synoptic stations, located as in Fig. 1, within the investigation area were used. The number of available observations was not constant since some stations make observations during only part of the day. Since we wanted an index expressing the thunder frequency during each 3-hour period, the code figures ww and W_1 in the present SYNOP code (World Meteorological Organization 1988) were used. The thunder index, *TH*, is defined as:

$TH = 100 \times$ (number of thunder observations)/(total number of observations).

A 'thunder observation' was defined as:

Thunder was observed during the last hour (ww = 29, 91, 92, 93 or 94 according to the present SYNOP code of the World Meteorological Organization) or during the observation period (ww = 17, 95, 96, 97, 98 or 99).

Thunder was observed during the last 3 hours preceding the observation ($W_1 = 9$).

If both conditions are satisfied the observation gives a contribution of 2 to the numerator of *TH*. Hence, the maximum possible value of *TH* is 200. Some ambiguity arises here because W_1 describes the weather since the last main synoptic hour (0000, 0600, 1200 or 1800 GMT), not since the last 3-hour observation. Consequently some old thunder observations may linger, for instance thunder observed at 1330 GMT gives a contribution to *TH* for 1800 GMT.

We have tested three indices used by the SMHI:

$$K = T_{850} - T_{500} + T_{d850} - (T - T_d)_{700},$$

$$KO = (\theta_{e500} + \theta_{e700} - \theta_{e1000} - \theta_{e850})/2, \text{ and}$$

$$EI = -R_d \int_{p=p_m}^{p=400} (T_p - T_e) \times d(\ln p) \qquad \text{(Stone 1984)}$$

where p is in hectopascals (hPa) and

T = temperature (K) at the pressure levels (hPa) given by the index,
T_d = dew-point (K) at the pressure levels (hPa) given by the index,
θ_e = pseudo-adiabatic equivalent potential temperature (K) of the pressure levels (hPa) given by the index,
R_d = the gas constant for dry air,
T_e = environmental temperature (K),
T_p = temperature (K) of the rising parcel, allowing for an entrainment of 10% per 5000 m, and
p_m = the pressure level below 850 hPa where θ_e has its maximum.

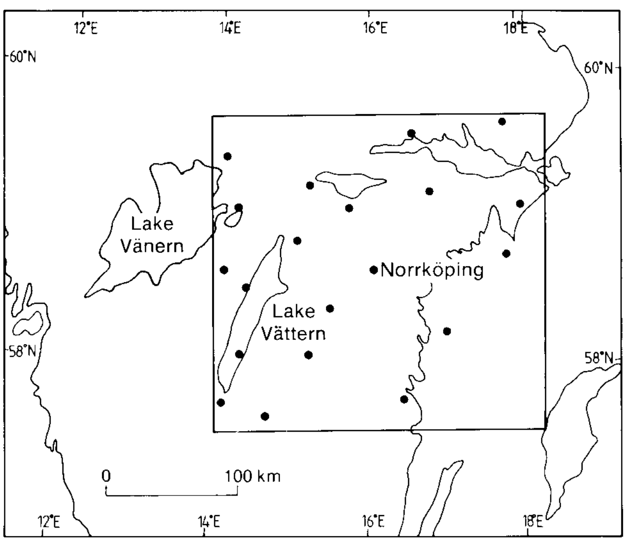

Figure 1. The investigation area and positions of the synoptic stations.

The index *EI*, also called the energy index, is thus an area on a thermodynamic diagram, expressing the change in energy for the moving parcel.

The *K* and *KO* indices were available both from analyses and from forecasts, while the energy indices, *EI*, were available only from analyses. The analysed indices were computed from the 0000 GMT data, and extracted from maps. Those indices were considered valid during the following 24 hours, i.e. from 0000 to 2400 GMT and will here be denoted by *KA* and *KOA* respectively.

Eighteen- and 30-hour forecasts of *K* and *KO*, valid at 0000 and 1200 GMT from the SMHI's limited-area model, will be denoted *KP* and *KOP* respectively. Those valid for 0000 GMT will be considered valid from 1800 GMT the preceding day to 0600 GMT, and those for 1200 GMT from 0600 to 1800 GMT. A diurnal variation of these indices will thus be at least crudely depicted by *KP* and *KOP*, but not by *KA, KOA* and *EI*.

3. Occurrence and non-occurrence

If $X11$ = number of cases when the event is forecast and observed,
$X12$ = number of cases when the event is not forecast but observed,
$X21$ = number of cases when the event is forecast but not observed, and
$X22$ = number of cases when the event is not forecast and not observed,

then the following are defined:

$pd = 100 \times X11/(X11+X12)$ = 'probability of detection',
$pf = 100 \times X21/(X11+X21)$ = 'probability of false alarm',
$ps = 100 \times X11/(X11+X12+X21)$ = 'threat score',
$V = (X11 \times X22 - X12 \times X21)/\{(X11+X12) \times (X21+X22) \times (X11+X21) \times (X12+X22)\}^{1/2}$, which is Yule's index (Meteorological Office 1975),
$yi = 100 \times V$, and
$pei = 100 \times \{X11/(X11+X12) + X22/(X21+X22)\} - 100$, which is Peirce's index.

For perfect forecasts $X12 = X21 = 0$, $pd = ps = 100$, $pf = 0$, $yi = pei = 100$, i.e. all occurrences of the event are detected and no false alarms are given.

For totally wrong forecasts $X11 = X22 = 0$, $pd = ps = 0$, $pf = 100$ and $pei = yi = -100$.

The indices *pd*, *pf* and *ps* only give measures of the efficiency of the method when the event occurs and/or is forecast, but do not involve correctly forecast non-occurrences. The indices *yi* and *pei* also take into account the latter, and hence are better measures if non-occurrences are important. If 'occurrence' is denoted by 1 and 'non-occurrence' by 0, Yule's index, *V*, is the correlation coefficient between forecast and observed events. For a thorough discussion of verification parameters the reader is referred to Daan (1984) or Ivarsson (1982).

Thresholds of K and KO used are those applied by the SMHI (Nilsson 1987):

$K \geqslant 20$,
$KO \leqslant 4$ (note that KO decreases with decreasing stability).

EI has not been used before by the SMHI so we had to choose a threshold. The *EI* are computed from the night soundings (0200 hours local summer time). It is remarkable that they were always negative. In reality the *EI* should have a daily variation with higher values in the afternoon, but the daytime–night-time difference should be fairly small. It would be interesting to see how forecast *EI* works, and we plan to include this index in future work. From our sample we chose −70 as the threshold.

As 'ground truth' we have used the thunder index, *TH*, described earlier. Inland summer thunderstorms have a pronounced daily variation. Since our analysed indices are considered valid for 24 hours, they certainly cannot represent this variation. Moreover, *K* depends only on conditions at and above 850 hPa and can hardly have any diurnal variation. Hence, its efficiency should have a diurnal variation. Inspection of our data confirms this and Fig. 2 moreover shows a diurnal variation of the efficiency of forecast indices when considering the conditions below 850 hPa. The efficiency has a pronounced night minimum. It is, however, noticeable that radar thunder indices, which actually measure some physical properties of the cumulonimbi, show a similar behaviour (Lopez *et al.* 1986, Andersson *et al.* 1989).

We have therefore confined our analyses to daytime, 0900–1800 GMT. For the first tests we have used the three 3-hour periods of each day, though these data are not independent. As Table I shows, *KOP* and *EI* perform best, though *KA* has the highest probability of detection. The latter feature was also noticed by Nilsson (1987). It is remarkable that the forecast *K* does not perform better than the analysed one.

When interpreting these figures we must remember the definition of *TH*. *TH* is the frequency of thunder observations. The highest *TH* recorded for this period is 53, i.e. at most about half the stations have recorded thunder during a 3-hour period. Even if thunder is known to be difficult to observe and several thunder occasions are not reported by the stations, we must conclude that even a 'correct' thunder forecast implies that several stations will not report thunder. This is even more true if a 'thunder day' is defined as a day when any station in an investigation area has reported thunder at any observation period.

Pickup (1982) noted that a kinematic parameter (curvature of the flow at 500 hPa) added valuable information to a thermodynamic index. Michalopoulou and Jacovides (1987) made the same conclusion for afternoon thunderstorms during spring over Cyprus. The curvature of the flow is not the only possible parameter; the relative vorticity or the horizontal divergence are others. In a qualitative sense the curvature of the flow is, however, easier to extract from forecast charts.

To test this effect on our data we made a subjective classification of the 500 hPa flow into anticyclonic, indeterminate or 'straight', and cyclonic, at 0000 and 1200 GMT. The 1200 GMT value was considered valid between 0600 and 1800 GMT and the 0000 GMT value between 1800 GMT the preceding day and 0600 GMT. The 0000 GMT data were extracted from the 36-hour forecasts from the European Centre for Medium-range Weather Forecasts and the 1200 GMT data from the 24-hour forecasts.

When testing the *KOP* index, using the combined criteria:

$KOP < 4$, and cyclonic curvature at 500 hPa,

we found a slight improvement in the sense that *yi* and the threat score, *ps*, increased somewhat, as shown in Table I. However, both the probability of detection, *pd*, and of false alarm, *pf*, decreased. The *pd* decrease is

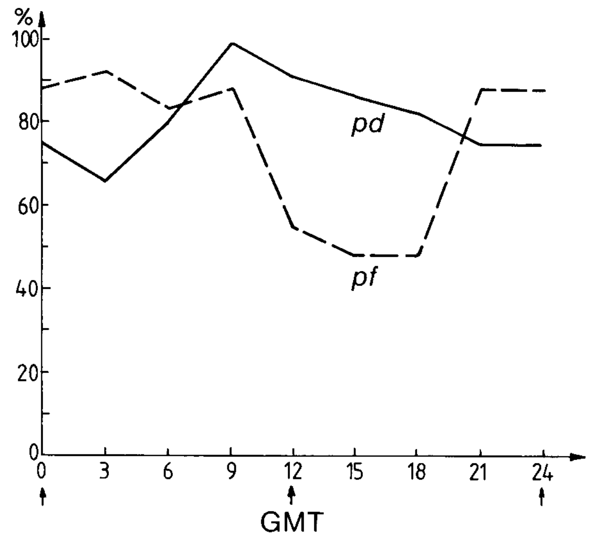

Figure 2. Diurnal variation of 'detection probability' (*pd*) and 'false alarm probability' (*pf*) using the thunderstorm indicator *KOP*. Arrows indicate validity times for *KOP*.

Table I. Verification scores for thermodynamic indices versus thunder ($TH > 0$) for the Norrköping area, from 27 May to 17 August 1987, 0900–1800 GMT

Index	Threshold	*pd*	*pf*	*ps*	*yi*	*pei*
KA	20	93	63	35	44	56
KP	20	71	67	28	29	36
KOA	4	58	59	31	34	38
KOP	4	86	50	45	55	66
EI	−70	84	51	44	52	64
KOP/curvature	4/cyclonic	80	41	51	60	68
KOP/*EI**	5/−85	100	37	62	70	80
KOP/*KA**	5/15	100	40	55	64	74

* One 9-hour period. Entries without * contain three periods of 3 hours.

unfavourable. The increase of *yi* is not as large as that found by Michalopoulou, though our *yi* for the period 0900 to 1800 GMT reaches 60.

Hitherto we have used 3-hour periods. Often forecasts are made for a longer time-period. We have therefore combined the three 3-hour periods between 0900 and 1800 GMT into one. A thunder observation in this data set then only requires thunder to have been observed in one of the 3-hour periods. Repeating the tests on this data set showed, however, only small improvements.

In this study all kinds of thunderstorms are included. Some indices may be better in forecasting air-mass thunderstorms, while others may treat the environment for squall lines and frontal thunderstorms better. Unfortunately our data set is too small to make such subdivisions, which moreover would introduce a new element of ambiguity. However, we have combined the 'best' thermodynamic indices. When using such combined indices one may choose less restrictive thresholds for each index. The best result ($ps = 62$, $yi = 70$, $pei = 80$) gave a combination of *KOP* and *EI*, as in Table I.

Stone (1985) has computed point biserial correlation coefficients between various thermodynamic indices and the occurrence or non-occurrence of radar echoes above different reflectivity thresholds, as well as similar correlations for 'severe weather'. Stone used only daytime data. Amongst his indices were *K* and *EI*. The highest correlations were found for the occurrence of reflectivity above 41 dBz, which 'is generally considered the lowest level associated with thunderstorms'. The maximum correlation (0.65 and 0.59 for the periods 1800–2400 and 0000–0600 GMT, respectively) was reached with *EI*. The corresponding figures for the *K* index were 0.53 and 0.53. For 'severe weather', considerably lower correlation coefficients were found, about 0.2, but also here the *EI* performed better than the *K*. We also found *EI* a better thunderstorm predictor than *K*. Roughly, Stone's correlations can be compared to our *yi*. Our figures, as well as those we have quoted, indicate then that only modest success can be expected from this type of index. Improvement needs the introduction of some new input data, which could be some parameters from numerical forecasts, as indicated earlier. Such parameters could be the relative vorticity, a measure of the baroclinicity, a measure of the accumulated convective precipitation, etc. It is of course also possible to design a new thermodynamic index, but there is already an overwhelming number of these, containing more or less probable combinations of temperature and humidity at different pressure levels, and none has proved to have an outstanding efficiency. The *KO* and *EI* indices at least have a sound background in the ideas of potential instability and parcel convection.

4. Skill score and a nomogram for lightning probability

For these analyses we have used the period 0900–1800 GMT, combined into one data set.

The skill score, *S*, is defined as (Daan 1984, Ivarsson 1982):

$$S = 100 \times (1 - B/Bk)$$

where B = Brier score for the forecast, and
Bk = Brier score for a control forecast.

The Brier score is defined as:

$$B = \Sigma(f-d)^2/N$$

where $d = 1$ if thunder is observed ($TH > 0$),
$d = 0$ if thunder is not observed ($TH = 0$),
f = forecast probability of thunder, and
N = number of observations.

We then have to assign a sample climatological probability for thunder, i.e. a probability that at least one station in the area shall report thunder on at least one of the three observations within the period 0900–1800 GMT. The probability that a single station reports thunder during the day is about 0.13, but the probability that any station does so is higher, because a thunder area may cover only part of the investigation area, and few flashes may pass unnoticed.

We have chosen the sample climatological probability as 0.25. Climatological forecasts, i.e. forecasts always giving the probability 0.25, give $Bk = 0.25 - 0.25^2 = 0.19$ and $S = 0$, while perfect forecasts give $B = 0$ and $S = 100$.

We also have to assign probabilities to each value of our predictand or, if we have chosen a combined index, to each pair of predictands. Probabilities used are shown in Fig. 3. The reason for choosing *KA* and *KOP*

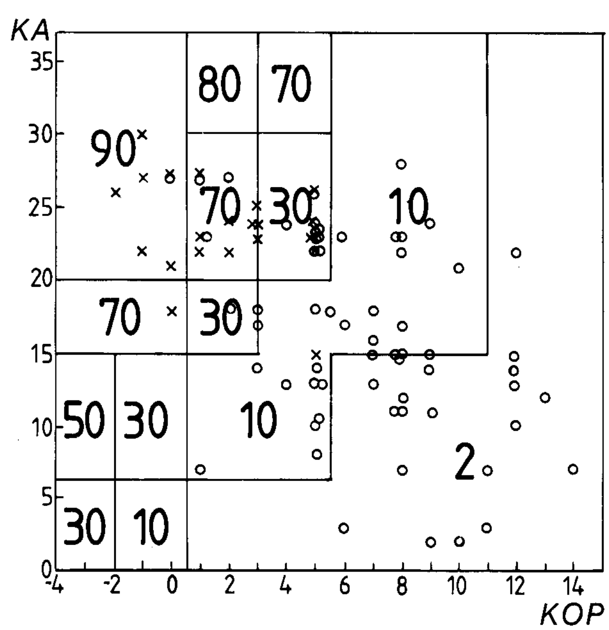

Figure 3. Nomogram for expected daytime lightning probability. Crosses indicate thunder ($TH > 0$), open circles indicate no thunder ($TH = 0$).

instead of *KOP* and *EI*, which gave somewhat better scores according to Table I, is that *KA* and *KOP* are selected by the regression analysis in section 5.

For the combined index *KOP*/*KA* in Table I we have used a threshold of 15 for *KA*. In Fig. 3 we have supposed thunder also for lower *KA*, provided *KOP* is low, that is the air mass is convectively (potentially) unstable. If lifted, the initially stable air mass (small *K*) will increase its lapse rate. During the summer of 1986 we noted some cases of thunderstorms with low *K* and *KO* values (Nilsson 1987). From a forecasting point of view it is also reasonable to lay some more weight on *KOP*, since it is a forecast value and may depict a weather change.

Table II gives skill and Brier scores for the indices used and some combinations of them (the assigned probabilities are only shown for the combination of *KA* and *KOP* in Fig. 3). It is apparent that combinations of two indices give better scores than a single one. We also believe that the nomogram in Fig. 3 is a more efficient forecasting tool than the 'yes or no' answers from single indices or combinations of them.

Table II. Skill and Brier scores for thermodynamic indices versus thunder ($TH>0$) for the Norrköping area, from 27 May to 17 August 1987, 0900–1800 GMT

Index	Skill score	Brier score
KA	22	0.15
KP	2	0.19
KOA	32	0.13
KOP	38	0.12
EI	41	0.11
KOP/*EI*	54	0.08
KOP/*KA*	52	0.09

The sample climatological probability is 0.25.

5. A nomogram for lightning frequency

The analyses of 'occurrences and non-occurrences' are useful for probability forecasts. However, the frequency of lightning is also important. An index should be able to give an acceptable estimate of the thunder activity as expressed by *TH*, which can be regarded as a crude measure of the lightning frequency within our area. We have used forward step-wise regression to select the best predictors and estimate *TH*.

The frequency distributions of our indices are quite different from that of *TH*, which is positively skew. To transform our indices to positively skew distributions we made the transformation:

$$e^{(\text{index}-rr)/tt}$$

where *rr* and *tt* are values to be chosen and e is the base of natural logarithms. The transformed distribution should be such that to the left of the value *rr* the transformed index is constant or grows very slowly, but to the right it grows quickly without attaining unreasonably high values for possible values of the index. The following transformations were chosen:

for *K*: $e^{(K-15)/5}$,
for *KO*: $e^{(6-KO)/2}$, and
for *EI*: $e^{(EI+100)/25}$.

Making the regression on the daytime (0900–1800 GMT) data with the confidence levels 0.01, 0.01 (for acceptance and rejection) gave:

$$TH = -0.47 + 0.48 \times e^{(KA-15)/5} + 0.48 \times e^{(6-KOP)/2} \quad (1)$$

with an explained variance of 37%.

This analysis indicates that *KA* and *KOP* are the 'best' predictors. The explained variance, corresponding to a coefficient of correlation of about 0.6, is low. However, bearing in mind the absence of good methods for thunder forecasting, the relation should have some prognostic value, especially since it gives not only a 'yes or no', but also an indication of the lightning frequency. For such purposes a classification scheme is needed, which takes account of the fact that the constant term in the equation is a 'statistic' effect, which of course does not mean that a negative number of lightnings should be expected or that lightning should always be expected. Such a classification is suggested in Fig. 4.

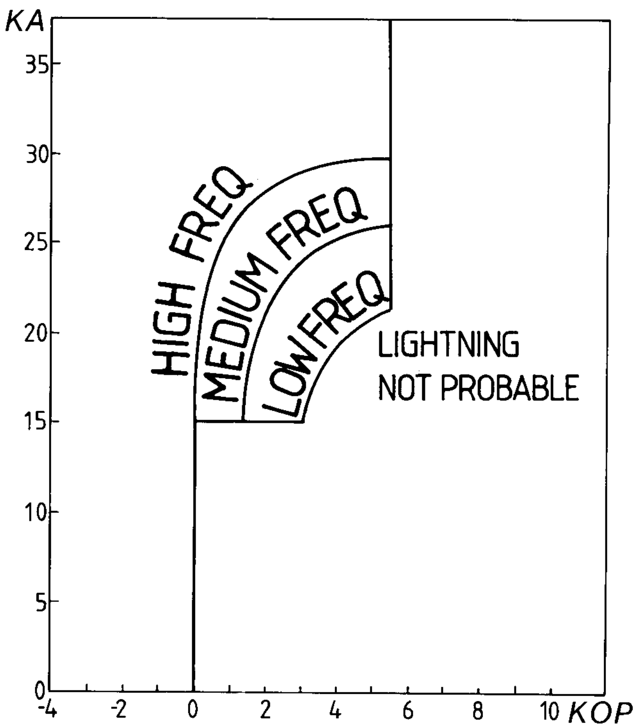

Figure 4. Nomogram for expected daytime frequency of lightning.

6. Conclusions

Three thermodynamic indices for thunderstorms have been tested. Their efficiency has a diurnal variation with maximum during the afternoon. The best scores were obtained for daytime thunderstorms with a combination of two indices. A combination of *KOP* and *EI*, as well as of *KA* and *KOP*, detected all daytime thunderstorms with a probability of false alarm of about 40%. This level of performance will probably not be achieved in a new independent sample, but nevertheless improvements seem possible. The use of a forecast *EI* valid at the actual time as well as the introduction of a kinematic parameter from numerical forecasts are possible ways to achieve this.

A nomogram of expected daytime lightning probabilities is presented as a possible forecasting tool. There is a significant correlation between the *K* and *KO* indices and our measure of the lightning frequency, though the correlation is fairly low. With the inherent difficulties in forecasting thunderstorms it nevertheless may have a prognostic value, and a nomogram for the expected daytime lightning frequency is presented as a possible forecasting tool.

Acknowledgements

We have had valuable discussions with Drs H. Alexandersson, S. Gollvik and P. Kållberg. Mr K.-I. Ivarsson has computed the Brier and skill scores and also given many valuable suggestions. Funds were granted by the Swedish Natural Research Council.

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The weather of 16–17 July 1797

D.A. Wheeler

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Summary

Historical data sources from the late eighteenth century are used to reconstruct the synoptic conditions during a thundery outbreak that affected much of England on 16 and 17 July 1797.

1. Introduction

This paper uses contemporary sources to reconstruct conditions of mid-July 1797 when severe thunder was observed over a wide area of England. The apparent severity of the weather served to provide an unusually rich legacy of accounts, not only from the weather enthusiasts of the time, but also from a welcome diversity of other sources. However, it must be stressed that the study is offered for its intrinsic interest and as an example of how far sources from such distant times can be used by those with an interest in 'historical meteorology'; by itself it does not indicate any essential difference between the climate of the 1790s and that which prevails today.

Even in the normal course of events, weather information from the late eighteenth century is not scarce, but caution must be exercised in the use of its seeming abundance. Instrumental data may have the appearance of accuracy but, being taken in an age before either observational procedures or the instruments themselves were standardized, interpretation must be undertaken with great care. Even qualitative descriptions do not free the reader from the hazard of misinterpretation. Terms such as 'hurricane', 'tornado' and 'great storm' (the latter too often cited as 'the worst in living memory' for comfort) are employed with inconsistent abandon, while descriptions such as 'fair', 'fine' and 'cloudy' are used so frequently that they cannot but embrace a wide range of conditions. Nevertheless, the pioneering work of Manley (1974), Lamb and Johnson (1966) and, more recently, Kington (1988) have amply demonstrated the rich harvest that may be garnered by the judicious sifting of old material.

2. The weather of July 1797

Manley's Central England Temperature (CET) record reveals the month to have been unusually warm. The CET figure of 17.3 °C is well above the 30-year mean of 16.1 °C. Lewis (1947) has also suggested the summer to have been London's warmest since 1780. Lamb (1982) has observed '...the 1790's and the first years of the new century produced a number of pleasant summers in England...'.

Turning to the specific events of 16 July 1797, the clearest and most evocative picture is created by the contemporary descriptions. The following citations are drawn from meteorological diaries as well as more general accounts by non-meteorologists who were clearly much impressed by the events they witnessed. It would be helpful for the reconstructions to have a better time-scale by which to gauge the progress of the storm; sadly such detail is lacking and diary entries tend to be by days with little reference to precise hourly timing.

The story begins on the night of 15/16 July with a record in the log of HMS *Director*, moored in Yarmouth Roads (Norfolk), of thunder to the east but with no further record until the evening of the 16th at which point several land stations pick up the story. At Shukborough (near Daventry) [now spelt as Shuckburgh] the weather diary reads '...thunder and rain in west...'. While at Modbury (Devon) one finds '...much distant thunder and some rain...'. Neither diary gives any indication of the time of onset of thunder. In the north of the country the Newcastle-upon-Tyne publication *Local Records* (Sykes 1833) contains the following entry:

> July 16th. There was a most terrible tempest of thunder and rain in the neighbourhood of Newcastle. To the eastward of that place it was truly awful. At Whitley Camp the lightning set fire to the whins placed as a facing to the sheds of the East and West Lothian Cavalry and the wind blowing briskly, the whole line was almost instantly ablaze.

A subsequent note in the *Gentleman's Magazine* for September 1797 gives the time of this event as between 5 and 6 o'clock but it is uncertain whether the writer refers to that time on the evening of the 16th or the early hours of the following day. The former interpretation places it five hours earlier than any other land station for which we have evidence of timing. On the other hand the latter interpretation would be accommodated more easily within the general thunder period which from all other records is placed between dusk (about 2200 hours) on the 16th and dawn on the 17th. Baker's *Record of the Seasons* makes reference to the night of the 16th as '...extremely dark and tempestuous...'; unfortunately no indication of place is given. However, for the most complete and vivid description of the storm the same edition of the *Gentleman's Magazine* as cited above has no rival and it repays lengthy recounting:

> PARTICULARS OF THE LATE STORMS. At Lewes, on Sunday 16th July, with little wind and a cloudless sky, the thermometer before 2 o'clock was 80 deg. of Fahrenheit's scale; the barometer at 30 deg. 20 min at which degree it had been stationary 24 hours... the sun set with great splendour, though some broken clouds were seen in the western horizon. Soon after sun-set the inhabitants of the Western parts of this country (*sic*) observed extensive cloud approaching from the South West, with little wind, but the flashes of lightning were very frequent, and the peals of thunder extremely loud with rain falling in heavy showers. The first storm had spent its force about twelve o'clock; and before one an extensive cloud, with brisk gale, had again overspread the horizon; the flashes of lightning succeeded each other so incessantly, that the interval seldom exceeded 12 or 13 seconds of time... the obscurity of the intervening spaces, and the rain pouring down in such a continual stream, could only be exceeded by a tropical tornado. On Monday by noon, the levels were completely inundated, as they generally are after 24 or 36 hours rain in the winter season. The storm was felt with equal severity in this town and the neighbourhood, where it commenced with twilight, and did not fully subside until four the next morning.

The anonymous reporter goes on to cite storm damage at places as widely separated as Yateley (Hampshire), Stamford Bridge (Humberside) and Oxford. A later edition of *Gentleman's Magazine* contains a report of thunder over London. The newspaper entry is again eloquent testimony to its intense activity:

> July 16th. We experienced in London a thunderstorm, accompanied by immense torrents of rain, more awful and tremendous than anything of the kind ever before remembered by the oldest inhabitant of the metropolis. From about 12 at night till 4 in the morning the Eastern sky presented the most terrific appearance, the fiery agitation of the firmament seeming momentarily to threaten the earth with universal conflagration. Of the dreadful flashes and the awful peals of thunder that prevailed, no adequate description can possibly be given; the mere recollection of them is painful, and the consequences cannot be contemplated without emotions of horror — The storm passed over the Continent previous to visiting this country. It was felt at Lille on Saturday afternoon, and continued till three o'clock without intermission.

The subsequent list of places similarly affected included Croydon, Petersfield, Gosport, Isle of Wight and Church Watton (Wiltshire) while at Prior's Lee (Shropshire) it was observed that '...a great ball of fire fell upon a large stack of two-year old hay, and passed through it making a large perforation into the ground.' It is a matter of regret that no indications of times are given in the records of those locations.

The record of an approach of a storm from the east, implicit in the second *Gentleman's Magazine* account contrasts with the western approach cited in the first of the apparently two storms to strike Lewes. The log of HMS *Director*, then moored at Yarmouth, records thunder and lightning to the east during the early hours of the 16th, but to the north-west later in the day when the weather is described as 'hot and sultry'. The storm(s) appear to have subsided over England on the 17th. The entry in William Bent's (London) diary for the 17th describes the events of the previous night; '...much vivid lightning in the west last night and early this morning a most tremendous storm...', but nothing thereafter.

Baker's note for the 18th (*sic*) refers again to the events on the night of the 16th and is a somewhat garbled version of the *Gentleman's Magazine* report. Only in Edinburgh is there reference to thunder on the 17th exclusively. George Waterston's diary entry for that day reads '...thunder and lightning — day very warm. Thermometer 70.' The prefix 'M' to this note indicates 'morning' but the precise hour is unknown. There is no corresponding entry for the previous evening.

It is against this tempestuous background that the instrumental record covering the storm period and the days immediately beforehand can be examined. As many instrumental data as could be gathered have been used. In most cases standardization or correction of the data is impossible without increasing the further likelihood of error. Data are presented as they were recorded. Exposure, recording times and the quality of instruments are all variable but to an unknown degree, these inconsistencies being reflected, for example, in the contrast between the temperatures recorded at two of the London sites (Table I). Both records, however, appear to be well kept and dutifully observed. The absolute figures must be treated with caution, and in isolation can convey little information. But when set against the record for the year as a whole one significant fact emerges; the period 14 to 18 July was, in all cases save one, the warmest of the year. The single exception was Modbury where late July was marginally warmer. Table I summarizes the recorded temperatures for the period.

Table I. Daytime maximum temperatures (° F) for various sites for mid-July 1797

Location	14th	15th	16th	17th
London (Royal Society)	84.0	81.0	84.0	83.0
London (William Bent)	73	72.5	74	74
London (Clare Street)	76	74	72	75
Derby	78	78	75	76
Modbury	59.0	59.3	60.0	61.0
Shukborough	76	79	80	80
Stroud	67	63	65	67
Edinburgh (as reported in the *Edinburgh Magazine*)	74	66	70	68

Readings were all taken between the hours of 12 noon and 2 p.m. local time and may be considered as the maxima. Fractional parts are given when recorded as such, elsewhere the absence of a fraction denotes that whole numbers only were entered in the source document.

The rainfall record shows a dry month for England, although Edinburgh was much wetter than normal. Adie's record (see Forbes 1861) for the city gives a total of 5.19 inches against a 1795–1850 mean of 2.89 inches. Most English stations were drier than average; William Bent (London) recorded only 1.42 inches. There was little rain in the days before the thunder, most stations recording 'nil'. The Royal Society record, however, notes 0.42 inches for the 16th out of a monthly total of 1.29 inches.

Of equal importance in any attempt to reconstruct past synoptic conditions is wind direction. Here, more than with temperature and rainfall, individual site inaccuracies are easily detected in wind directions that are inconsistent with those from surrounding stations. Wind data are summarized in Table II. The only anomaly is the easterly wind recorded for the London sites. In view of the general care exercised in the preparation of both data sets and the consistent records shown at other times, the easterly winds are best interpreted not as errors but as evidence of sea-breezes working along the lower Thames valley and created in an otherwise settled and very warm spell. Their disappearance with the onset of less settled weather later in the month supports such a hypothesis. The dominant winds were from between south and south-west. Wind speeds are less easy to determine. Royal Navy logs appear to have used a system all but identical to that later codified by Admiral Beaufort and give the best indications of speed in terms likely to have a similar meaning today; the values from HMS *Director* are used to supplement Table II. Many land-based stations preferred a much coarser scale of resolution ranging

Table II. Wind directions for various sites for mid-July 1797

Location	14th	15th	16th	17th
London (Royal Society)	E	E	SW	S
London (William Bent)	S(2)	SSW(1)	E(1)	SW(2)
London (Clare Street)	E	SE	SW	S
Derby	SE	SW	S	SW
Modbury	S	S	calm	SW
Shukborough	S	SSW	SSW	SW
Stroud	SbW(0)	SbW(1)	SbW(0)	W(1)
Yarmouth (HMS *Director*)	var(4)	SbW(4)	var(1)	var(1)

Figures in parentheses are wind forces given on an increasing scale of 0 (calm) to 4 (storm) for land stations and on the Beaufort scale for HMS *Director*.

from 0 (calm) to 4 (storm). Where available these 'forces' are listed in the table. The general impression gained, however, is one of light winds. Estimates must be approximate but an average of Beaufort force 3 gusting to force 5 is possibly representative.

Finally, the barometer records for the month are shown in Fig. 1. The data have not been reduced to sea-level equivalents because of the lack of information on the types of instrument used and their altitude above sea level (the record of the Royal Society barometer has been corrected by Eaton 1880). Although differences are apparent the records' series are remarkably, and encouragingly, consistent. Spells of high and low pressure can be easily distinguished and, with the exception of low pressure around the 6th and 30th, the conditions seem to have been dominated by high pressure. The mid-month period shows little tendency for any abrupt pressure changes although pressure on the 16th was consistently, but modestly, higher than on the 17th when a drop of some 3 mb occurred at all sites. It might be added that no evidence of steep pressure gradients across the country could be found on any day between the 12th and 25th; a conclusion confirmed by the light winds over the same period.

3. General conclusions and interpretation

In the most general terms, the accounts present a picture of severe thundery weather setting in on the night of 16 July and persisting till dawn over England, but possibly longer in Edinburgh. Even allowing for journalistic licence, the conditions must have been extreme. There is inevitable uncertainty concerning the number of storm cells and their movements. The Lewes report, detailed as it is, clearly indicates development from the west, but possibly only for the first of two periods of thunder. The Shukborough record also notes an approach from the west. Having observed thunder to the east only 24 hours earlier, the midnight watch (16/17 July) on board HMS *Director* note thunder to the north-west. At the same time William Bent's printed record also refers to thunder from the west. On the other hand the *Gentleman's Magazine* refers to the eastern sky as having '...presented the most terrific appearance, the fiery agitation of the firmament seeming momentarily to threaten the Earth with universal conflagration.' But might this refer not to an approach, but the retreat of the storm since no specific mention of 'approach' prefaces the latter observation? The same report also suggests this to have been the same thunderstorm that struck Lille in northern France (and lying due south-east of London) 24 hours earlier. This continental outbreak seems unlikely to be so closely linked with the London events particularly in view of the absence of any record of daytime thunder before the clearly documented onset of activity at dusk on the 16th. William Bligh's log kept on board HMS *Director* records thunder to the east as early as the night of the 15th/16th and this may well be part of the Lille thunderstorm, but there is no other mention in the record of thunder between that time and midnight of the 16th/17th. Whatever the precise timing, thunder was recorded extensively across England on the 16th from the Isle of Wight to Newcastle-upon-Tyne, and from Yarmouth to Devon.

The 16th had been, almost everywhere, the hottest day of the year with winds a light south to south-westerly, with perhaps some east coast sea-breeze

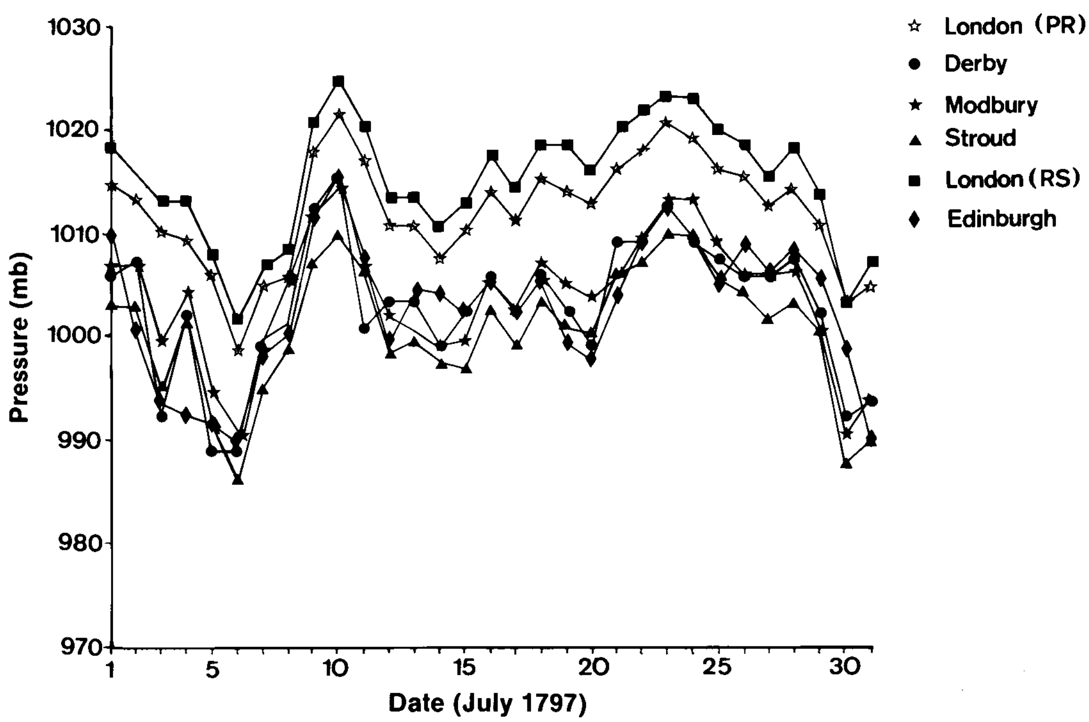

Figure 1. Barograph traces for various sites (see key) for July 1797 drawn from several sources. The two London sites are at Paternoster Row (PR) and the Royal Society offices (RS).

activity. There is no evidence in the barometer records of low pressure in the immediate vicinity and pressure was high everywhere and had been so for several days (cf. *Gentleman's Magazine* report and Fig. 1). In England the month had been generally dry, but much heavy rain clearly accompanied the thunder of the 16th.

The necessarily hesitant picture to be drawn from this information is of severe thunder approaching from some south-westerly point. With possible evidence from Newcastle, and the firmer evidence from Edinburgh, it appears that the disturbances moved northwards.

The degree of instability required to produce such thunderstorms indicates that, however poorly developed the pressure fields may have been at sea level, the middle- and upper-tropospheric circulation may well have been dominated by a cold pool or trough which, combined with known high temperatures at ground level, would create the necessary steep environmental lapse rates.

Some recently published case-studies are instructively comparable with this broad interpretation. Most importantly, Morris (1986) offers an example of the phenomenon known as 'the Spanish plume'; a situation in which warm Iberian air is drawn northwards beneath an advancing upper trough, leading to severe thundery outbreaks in France and the British Isles. Morris's example was of 19/20 May 1986. The sea-level and 1000–500 mb thickness charts for 0000 GMT on 20 May 1986 are shown in Fig. 2 and might indeed be similar to the prevailing situation on 16 July 1797. The southerly air flow, indeterminate sea-level pressure gradients and general state of the weather for 20 May 1986 are in broad agreement with those already described for 16 July 1797. The main period of thunder on the night of

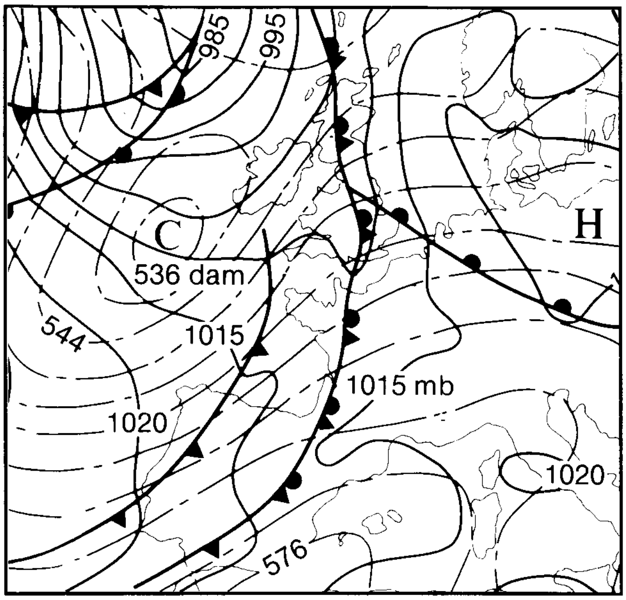

Figure 2. Surface pressure and 1000–500 mb thickness chart for 0000 GMT on 20 May 1986. (Redrawn from the charts of the *European Meteorological Bulletin*.)

the 16th/17th was so extensive that, together with the possibility of progressive north or north-eastward movement following an advance from the west, it suggests the activity of an organized frontal feature ahead of a weakly developed surface low swinging across the country in the manner suggested in Fig. 3. The absence of strong winds and the persistently high pressure rule out any possibility of a deep low. The degree of instability necessary to induce thunder of such intensity is accounted for by the presence of a trough or cold pool above the low. The isolated thunder noted by

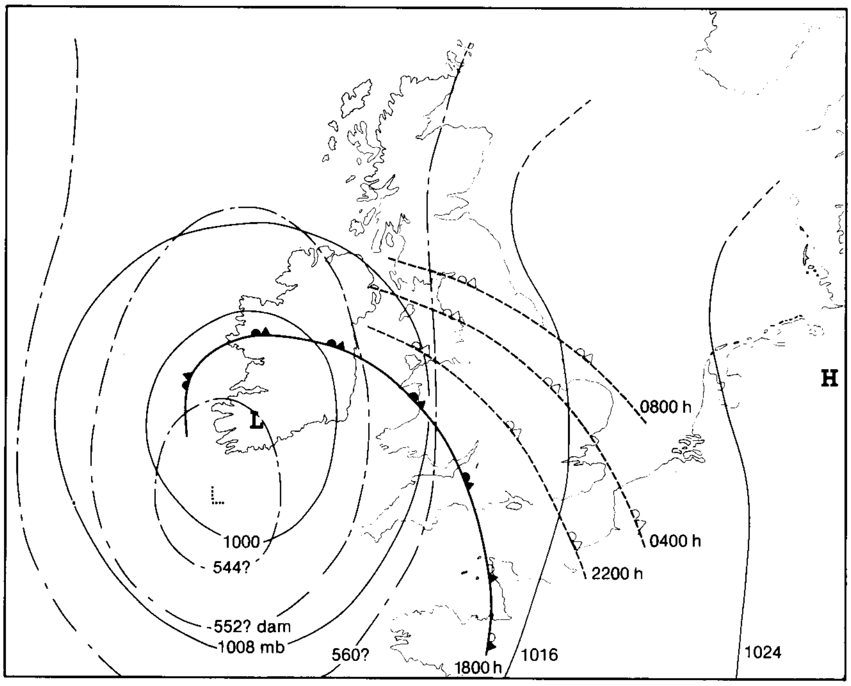

Figure 3. Generalized reconstruction of positions of pressure systems from 1800 hours on 16 July 1797 to 0800 hours on the 17th. Sea-level isobars and 500 mb height contours are shown, the question marks on the latter stressing their speculative values.

William Bligh on board HMS *Director* and the Lille thunder noted in the pages of *Gentleman's Magazine* are attributed to the general instability in the southerly air stream ahead of the front and not directly connected with it.

The importance of the ambiguity in the Newcastle record is now critical. If the events described took place at 5 or 6 o'clock on the morning of the 17th then, together with Waterston's Edinburgh record of thunder later that morning, a picture of steady north-eastward progress is complete. But if the events relate to 5 or 6 o'clock the previous evening there is less evidence of 'organization'. Reference to the stabling of the cavalry horses that broke away in fear hints at a night-time and not a late afternoon event but is scarcely conclusive. If the Newcastle thunderstorm did take place on the evening of the 16th then the picture created is one of much less regular and organized activity, suggesting random outbreaks within a generally unstable southerly air stream; a situation for which recent analogues have also been reported. In a study of an unusually severe hailstorm on 7 June 1983, Dent and Monk (1984) draw attention to the importance of '...warm advection of moist air ahead of an advancing upper trough.' The prevailing situation, though not reproduced here, was not unlike that described by Morris (1986). A shallow pressure gradient existed across western Europe between an anticyclone to the east and a shallow low north-west of Cape Finisterre (Spain). The consequent southerly air flow was overlain by an advancing trough. Hill (1984) and Wells (1983) also examined severe hailstorms from two days earlier along the southern coast, but within the same general synoptic conditions. The contrast with the events described by Morris is the absence of extensive thunder or hail organized along a well defined front. The outbreaks also occurred over a much longer time period than that in question. Such conditions might equate with a persistent run of sporadic outbreaks of the type hinted at by Bligh's record of thunder and the reference to thunder over Lille.

In conclusion, Fig. 3 is offered as the more probable of the two types described above. It is all but impossible to be confident but the marginal balance of evidence, the short time span of the various outbreaks over Britain, the likelihood (though not proven) of regular north or north-eastward movement, leans towards an organized frontal pattern of thunder, heralded by activity in the unstable southerly air stream to the east in the preceding 24 hours.

4. Supplementary note on data sources

Material used in this paper was drawn from a number of sources. The printed weather diaries of William Bent, who lived in Paternoster Row, London, were a most valuable source. These, together with the handwritten manuscripts of Thomas Hughes of Stroud (Gloucestershire), Thomas Stanwick of Derby, Sir George Shukborough-Evelyn of Shukborough, the Royal Society (then at Somerset House), Charles Soan of Clare Street, London, and the Modbury Diaries (author uncertain), are held at the National Meteorological Archives at Bracknell. These Archives also hold the collection of material forming Baker's *Record of the Seasons*. The log of HMS *Director* was prepared by Captain William Bligh, then recovered from the embarrassments of the '*Bounty* affair'. The vessel was then part of Admiral Duncan's North Sea fleet moored at Yarmouth Roads. This particular log was chosen because of Bligh's meticulous attention to detail, his seeming interest in the weather and, although a purely subjective assessment, the document's feel of accuracy. The log is held at the Public Records Office at Kew. The diary kept in Edinburgh by George Waterston is one of a number preserved in the Archives of the Royal Society of Edinburgh. The same Archives hold Robert Mossman's monumental accumulation of data and observations for Edinburgh including the volumes of the *Edinburgh Magazine* which contain some data used in this study. Numbers of the *Gentleman's Magazine* are held in the National Lending Library at Boston Spa. In addition to the written accounts, each month's edition also includes a statistical meteorological summary.

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The sensitivity of fine-mesh rainfall and cloud forecasts to the initial specification of humidity

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Summary

The problems associated with the objective analysis of humidity are discussed and a technique for amending the initial fine-mesh humidity fields is described which results in close comparison between the fine-mesh model cloud analysis and satellite imagery. Three case-studies illustrate the impact of the amended initial moisture fields on subsequent cloud and rainfall forecasts. The results of these and other cases allow us to conclude by suggesting circumstances in which the initial moisture specification is likely to be important.

1. Introduction

The humidity analysis is perhaps one of the weakest points of the operational data assimilation scheme for the fine-mesh model. There are several problem areas which have held back improvements in the objective analyses. The major difficulty is the deficiencies in the observing network which are particularly acute over the North Atlantic. At present the operational assimilation relies solely on humidity data from radiosondes, so the analysis over data-sparse areas is almost totally dependent on the background field provided by the model.

The objective use of other data types has been considered but their benefits have proved rather doubtful. The operational fine-mesh analysis has tried to make use of surface ship reports of dew-point in the past, but these are now excluded after it was found that reports indicating large positive humidity increments could occasionally trigger the convection scheme into giving large amounts of rain, with unfortunate consequences. In such cases the observations may have been perfectly valid but the model felt the influence of those increments over too large an area. One such case was the operational fine-mesh analysis for 1200 GMT on 26 December 1985 (Smith, personal communication). Other analysis schemes have attempted to make use of surface observations to infer humidity at upper levels. Illari (1986) describes how such reports are used in the analysis scheme from the European Centre for Medium-range Weather Forecasts (ECMWF) but at the same time notes that their use is highly empirical and of little value except perhaps in conditions of complete cloud cover. The ECMWF scheme also attempts to make use of the precipitable water content (PWC) information provided by the satellite soundings; however, the cases quoted by Illari to justify their use all involve tropical impact studies where the PWC is large. Clearly the precision demanded of the fine-mesh humidity analyses for accurate rainfall prediction cannot be achieved by relying on sounding data which give information over very thick layers (only two pieces of information to describe the moisture profile below 500 mb).

The dependence on model background in data-sparse areas gives humidity analyses whose characteristics follow closely the characteristics of the model. Bell (1986) discusses the deficiencies of the model profiles in the lower part of the atmosphere. Common problems noted include excessive moisture in moist south-westerly warm sector situations, excessive dryness in anticyclonic south-westerly flow, collapsed boundary layer in anticyclones, and excessive dryness above capping inversions. In our repeated-insertion data assimilation scheme, where the observation increments are used to nudge the model fields towards the observations during a forward integration of the model, the hope is that analysis fields remain consistent with what the model expects. Thus, even where observations are available, there will be a tendency for features which the model represents poorly to be also poorly represented in the analyses. Good analyses will only be obtained if the model background fields are realistic. Recent changes to the physical parametrization schemes (Hammon 1987) have gone some way towards improving the unrealistic features mentioned above.

One method of overcoming the problem of data sparsity is to generate bogus humidity reports based on information, such as satellite imagery and synoptic reports, which is not easily amenable to direct assimilation into the objective analysis. The interpretation in terms of relative humidity observations is very subjective. The intervention forecasters usually bogus in order to insert areas of high humidity indicative of cloud, but uncertainties in the value to be assigned as well as the depth of cloud make results unpredictable. The operational data assimilation scheme (Bell and Dickinson 1987) treates these bogus reports in a similar way to conventional radiosonde data. The observation increments are used at nearby model grid points in the horizontal to a range of about 600 km and in the vertical over several model levels. In the statistical interpolation analysis, the weights given to the data as a function of distance from the observation position are determined according to a forecast error correlation which is quite broad. Thus, it is almost impossible to force the model to accept thin cloud layers or sharp discontinuities in the horizontal without saturation coverage of bogus humidity ascents. Some modest improvements in rainfall forecasts have been achieved using bogusing when applied with some care, particularly in the early stages of the forecasts (e.g. Smith 1986). But on other occasions the over-zealous intervention forecaster has done more harm than good. One such case was the fine-mesh forecast from 0000 GMT on 28 July 1987 which resulted in excessive rain over Scotland (Smith, personal communication).

The 10-level rectangle model analysis of relative humidity (Atkins 1974) included a non-isotropic weighting function dependent on the gradient in the background field in an attempt to retain sharper gradients in the humidity field associated with frontal rainbands. Unfortunately the statistical interpolation–repeated insertion scheme which replaced it has not proved very flexible and a similar approach was not carried over to the 15-level model. However, the revised repeated insertion algorithm (Lorenc *et al.* 1989) to be implemented during summer 1989 is more flexible.

In this paper, we are investigating the likely improvement in fine-mesh rainfall and cloud forecasts following a very detailed re-analysis of the model humidity fields. This re-analysis was univariate and no attempt was made to correct for any deficiencies in the mass and wind fields. Taking a lead from the mesoscale interactive analysis system (Golding 1988), we examined the analyses after the data assimilation stage and compared the model relative humidity fields and diagnosed cloud fields against cloud imagery and synoptic reports. We then simply amended each of the model levels directly as required in the area of study to make them compatible with what observations were available. The amendments were made directly to the model sigma-level fields so no further interpolation was required. Clearly a subjective interpretation of cloud base and top was still required and usually only one layer of cloud was catered for. Where cloud had to be removed, rather arbitrary values of 50–70% relative humidities were assigned. Where cloud was present, the model was assigned a value of relative humidity above the threshold used by the radiation scheme according to the same criteria used by that scheme, namely:

$$Q = (U - U_{\text{crit}})^2 / (1 - U_{\text{crit}})^2$$

where Q is the cloud fraction, U is the relative humidity when $U > U_{\text{crit}}$, and $U_{\text{crit}} = 85\%$ threshold relative humidity.

Eleven cases were chosen from those highlighted by forecasters during the past 2 years. For many of the cases, the forecasters in the Central Forecasting Office (CFO) provided a subjective cloud analysis giving base, top, geographical extent and degree of coverage. This is referred to here as the CFO cloud analysis. This cloud analysis was of great help in the preparation of the modified initial humidity field. We studied several cases for each type of situation likely to be encountered in the United Kingdom including frontal types, wave developments, convective cases and anticyclonic stratocumulus cases. All 11 cases are discussed in Bell and Hammon (1988). Here, we shall illustrate our findings by reference to three of those cases. Although we have concentrated for the most part on the evolution of cloud and rainfall, many other model products have also been examined.

2. A frontal case-study — data time 1200 GMT on 23 July 1987

During the 24 hours commencing 1800 GMT on 23 July 1987, a frontal system moved slowly southwards over the United Kingdom. Although accumulations were fairly small (no more than 5 mm), there were nevertheless persistent and locally moderate bands of rain associated with the warm and cold fronts. The radar picture (Fig. 1(a)) shows the rainfall distribution at 0600 GMT on 24 July, with the heaviest most widespread rain over northern England and southern Scotland. The narrow band of rain lying from East Anglia to south-west England is associated with the weaker warm front. As the cold front moved southwards, it weakened in the west, giving only a trace of rain over South Wales and south-west England, but the rain persisted in the east, especially over East Anglia.

This case was chosen because the fine-mesh model failed to predict the rainfall over the United Kingdom during the 24-hour period. In Fig. 1(b) we show the operational fine-mesh forecast of rainfall rates and surface pressure for T+18, which can be compared directly with the radar image. The forecast is much too dry over the United Kingdom, with the cold front rainfall non existent and the warm front rainfall confined to the North Sea.

The cause of this poor rainfall forecast is attributed partly to too much subsidence (the forecast pressure at T+18 is 2–4 mb too high over the United Kingdom), but mainly to dryness in the model's analysed relative humidity fields to the west of Scotland. In Fig. 2(a) we show the NOAA-10 visible satellite image for 0905 GMT on 23 July, showing the cloud areas to the west of Scotland. At this stage, the fronts seemed relatively weak, with little cloud showing on the infra-red image. The observed freezing levels at 1200 GMT were 12 000 feet over the United Kingdom ahead of the cold front, falling to 5000 feet well to the rear. The operational relative humidity analysis for 1200 GMT at 700 mb (Fig. 2(b)) shows that the frontal zone is defined in the model by only the 55% relative humidity contour and the model has only a small band of cloud associated with the front. The aim of intervention in this case was to improve the model's forecast rainfall associated with the cold front by increasing humidity in the analysis at

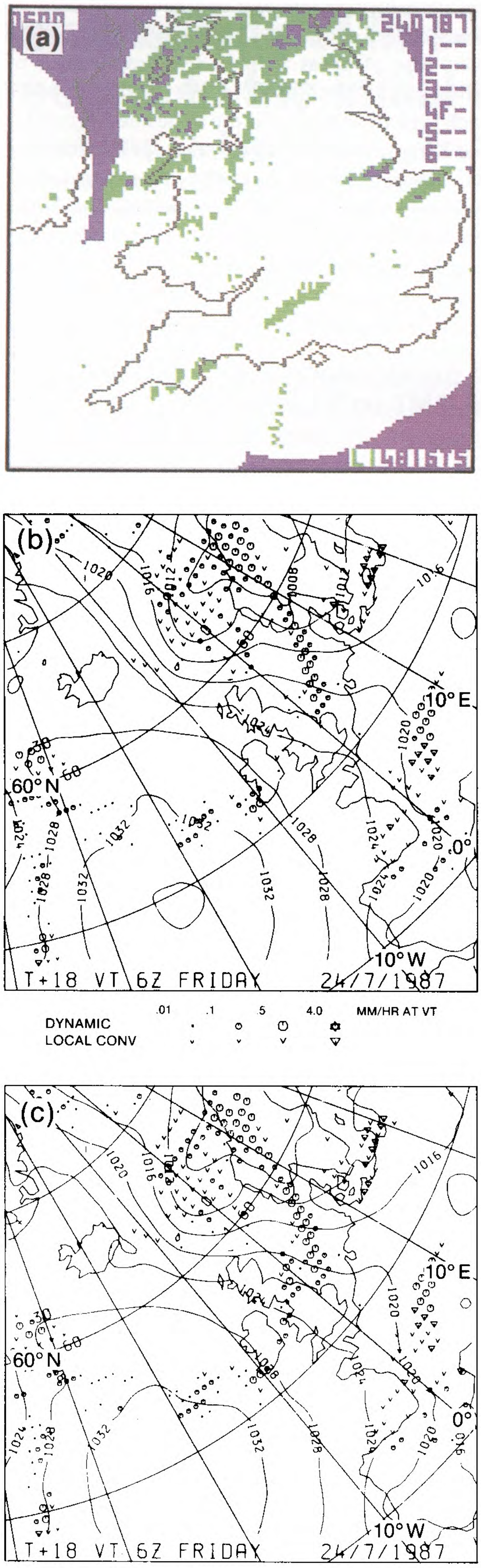
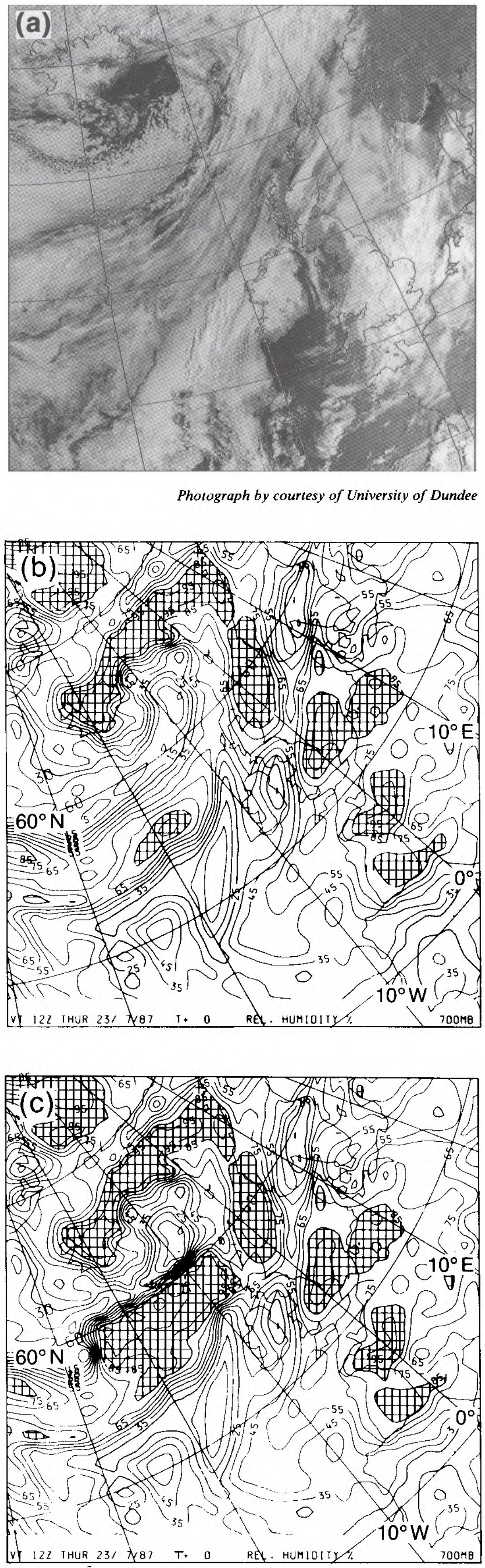


Figure 1. (a) Radar rainfall distribution for 0600 GMT on 24 July 1987, (b) operational fine-mesh forecast of rainfall rate (see key) and surface pressure (mb) for T+18 verifying at 0600 GMT on 24 July 1987, and (c) as (b) but based on modified analysis.



Photograph by courtesy of University of Dundee

Figure 2. (a) NOAA-10 visible satellite image for 0905 GMT on 23 July 1987, (b) operational fine-mesh analysis of relative humidity (per cent) at 700 mb for 1200 GMT on 23 July 1987, and (c) as (b) but after modification.

700 mb (level 6). We decided to increase the relative humidity at level 6 to 97% (approximately 5 oktas of cloud) in the analysis in the area bounded by 57–60° N, 05–25° W. The modified analysis is shown in Fig. 2(c).

The T+18 forecast based on the modified analysis (Fig. 1(c)) shows substantial improvements over northern England. The increased rainfall forecast over the United Kingdom on the cold front resulting from the modified analysis lasted at least to T+18. At T+24 the forecast rainfall west of the meridian had died out although slightly bigger amounts were forecast in the North Sea.

3. A wave development case-study — data time 1200 GMT on 19 August 1987

During the 18 hours from 1200 GMT on 19 August 1987, a cold front remained slow moving just to the west of southern Ireland, with its eastward progress retarded by a succession of waves moving up from the south-west so that eastern Ireland remained mostly dry until late in the night. The significant weather chart for 0000 GMT on 20 August (Fig. 3(a)) shows the observed rain area from one of these waves over Scotland and Northern Ireland at midnight, although a further wave brought rain back into south and west Ireland later.

The fine-mesh forecast from 1200 GMT on 19 August predicted the cold front and associated waves to be slightly too far east with heavy rain over eastern Ireland several hours too early. Fig. 3(b) shows the operational fine-mesh forecast of rainfall and surface pressure for 0000 GMT on the 20th. Comparing this with the corresponding significant weather chart, we see that the forecast rain area is too far advanced and in fact there is a timing error of at least 6 hours.

This timing error in the fine-mesh model forecast has been attributed mainly to a small spurious area of high humidity and cloud at 700 mb in the analysis at 47° N, 12° W, which we can see in Fig. 4(a). The modified analysis (Fig. 4(b)) had the relative humidity reduced to 80% in this area.

The T+12 forecast run from the modified analysis is shown in Fig. 3(c). The main impact has been to delay the forecast arrival of rain over central Ireland until after midnight. If we compare the forecasts at T+12, the modified forecast is more accurate over central Ireland but less over Northern Ireland. At T+18 (not shown), the operational and modified forecasts are very similar.

4. An anticyclonic stratocumulus case-study — data time 1200 GMT on 5 April 1988

On this occasion, an anticyclone was slow moving over the North Sea and northern England with a strong easterly air stream to the south. The Meteosat visible satellite image (Fig. 5(a)) for 1200 GMT on 5 April 1988 shows a large area of stratocumulus covering the North Sea and eastern England. Most of England and Wales, excluding the far west, had a cloudy night as stratocumulus continued to be advected inland from the

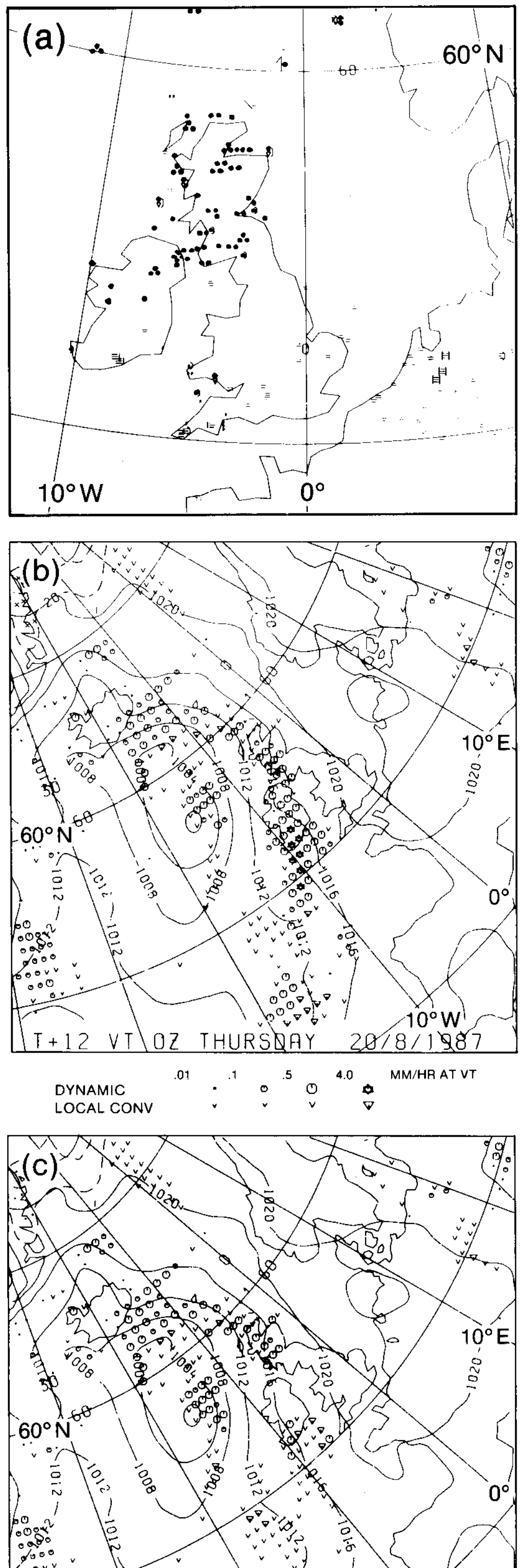


Figure 3. (a) Significant weather chart showing observed rainfall for 0000 GMT on 20 August 1987, (b) operational fine-mesh forecast of rainfall rate (see key) and surface pressure (mb) for T+12 verifying at 0000 GMT on 20 August 1987, and (c) as (b) but based on modified analysis.

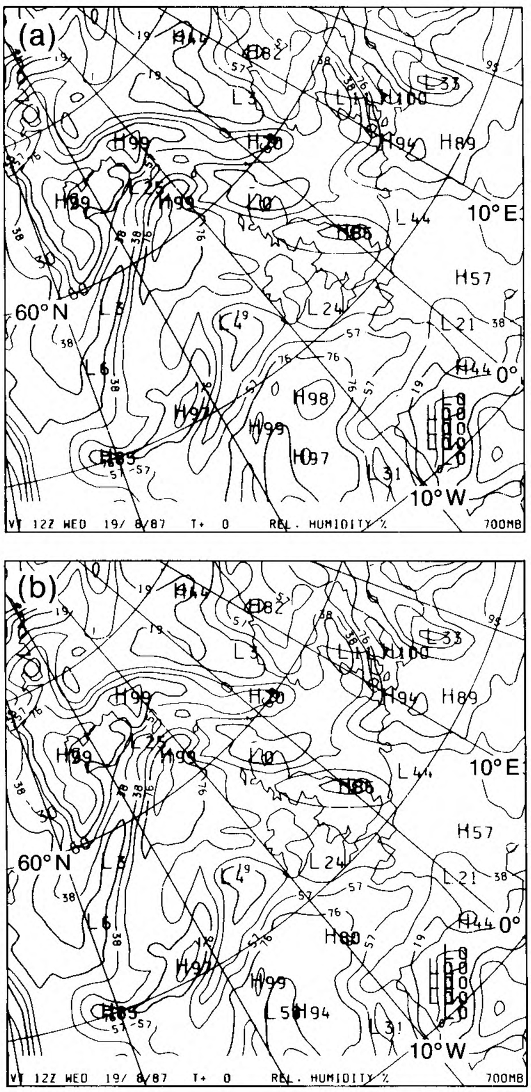


Figure 4. (a) Operational fine-mesh analysis of relative humidity (per cent) at 700 mb for 1200 GMT on 19 August 1987, and (b) as (a) but after modification.

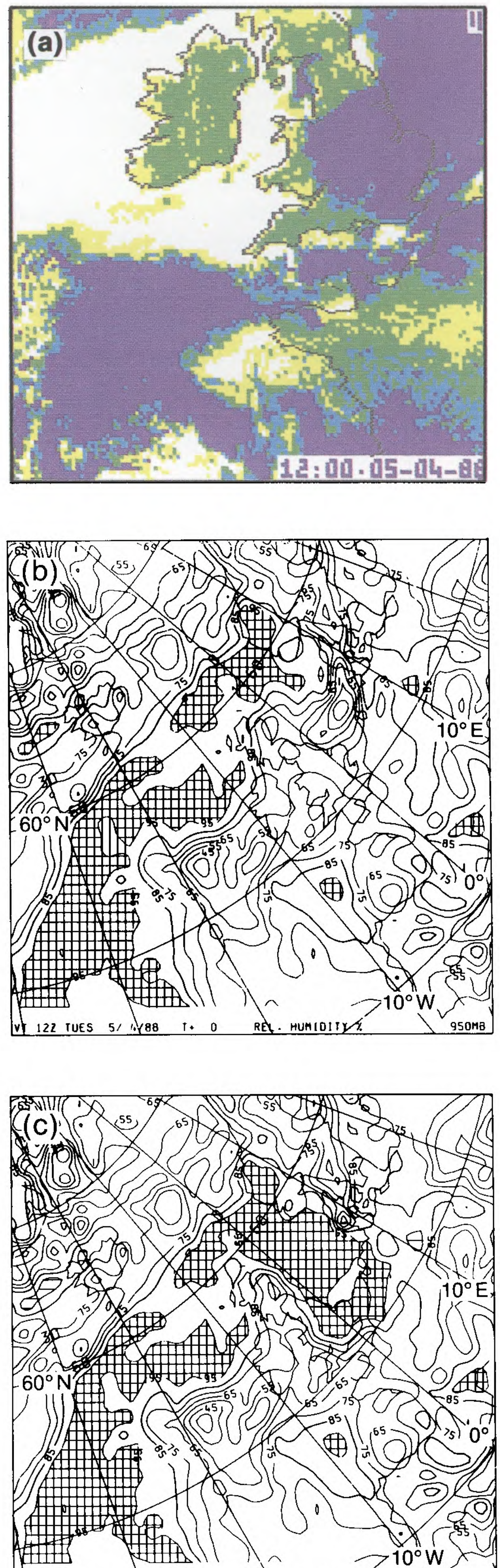


Figure 5. (a) Meteosat visible satellite image for 1200 GMT on 5 April 1988, (b) operational fine-mesh analysis of relative humidity (per cent) at 950 mb for 1200 GMT on 5 April 1988, and (c) as (b) but after modification.

North Sea and temperatures remained well above freezing.

The operational (T+18) fine-mesh model low cloud forecast for that night is shown in Fig. 6(a). Apart from a small amount of low cloud in the south-east at 0600 GMT, the model predicted mainly clear skies and the Model Output Statistics minimum temperature forecast incorrectly suggested a slight frost for south-east England and the Midlands.

The base of the observed cloud at 1200 GMT was 1500–2000 feet with tops 3000 feet. The model's inversion started at 950 mb. The 1200 GMT analysed relative humidity at 950 mb is shown in Fig. 5(b). The analysis is much too dry in the observed cloudy areas when compared with the visible satellite picture. A cloud layer was inserted by increasing the relative humidity at level 3 to 100% and this modified analysis is shown in Fig. 5(c).

The low cloud forecast run from the modified analysis is given in Fig. 6(b). Clearly there is a substantial

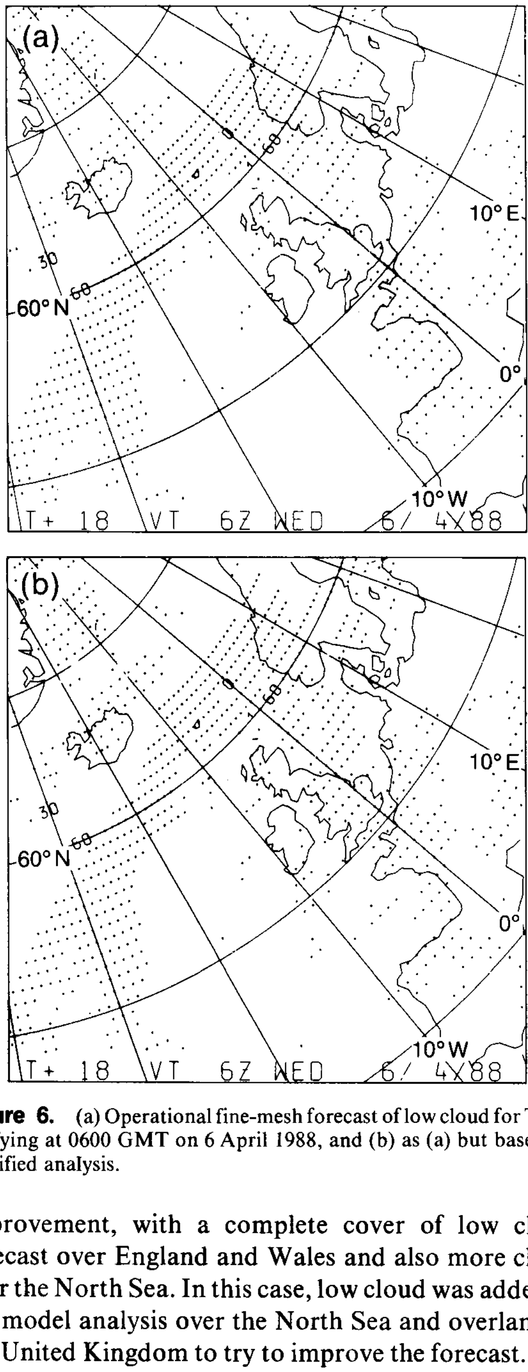


Figure 6. (a) Operational fine-mesh forecast of low cloud for T+18 verifying at 0600 GMT on 6 April 1988, and (b) as (a) but based on modified analysis.

improvement, with a complete cover of low cloud forecast over England and Wales and also more cloud over the North Sea. In this case, low cloud was added to the model analysis over the North Sea and overland in the United Kingdom to try to improve the forecast. The low cloud added overland disappeared within the first 6 hours of the forecast but the low cloud added over the sea remained. This cloud was advected across England and Wales during the forecast.

5. Concluding remarks

We have demonstrated that the relatively simple technique adopted here, involving the 'painting over' of the model relative humidity field after the assimilation stage, can result in a significant impact on the forecast rainfall on most occasions and also a noticeable impact on model cloud on some occasions when a problem with the initial moisture field has been noted. Where the addition of partial cloud cover was involved, we were careful to provide the model with a relative humidity value which could be interpreted as the same partial cloudiness in the model. We also avoided interpolation problems by inserting data at the model's sigma levels. In some instances we took careful note of the initial vertical profiles of moisture and temperature in order to insert information at a level where it would be most likely to be retained even if such a level was different from that inferred from the observations. This was particularly the case when thin layers of cloud were being inserted which needed to be correlated with changes in model lapse rate. The method adopted here gives much more control over the outcome than the conventional bogusing technique. The most difficult task is the interpretation of the satellite imagery in terms of model relative humidity fields. Ideally the imagery should be available reprojected on to the model grid before it can be fully useful. Clearly the technique could not be adopted for the main fine-mesh runs as there is not time to amend the fields; however, corrections to the assimilation cycle at an earlier stage are likely to remain useful in the following forecast run.

The frontal case demonstrated that the impact is greater in the first day and less towards the end of the forecast where presumably evolution errors begin to dominate. This result was supported by other case-studies, where noticeable improvements at T+18 were not evident at T+30. The wave development case presented here showed that erroneous waves can be suppressed. Other cases have shown that waves that are too weak can be emphasized. It was very clear in several frontal and wave cases that it was futile to try and adjust a fast-moving frontal system, or any case where the dynamical forcing was strong. Also no amount of tinkering with the initial moisture field could correct a serious positional error, which is likely to be related to an error in the initial mass and wind fields.

The impact in the anticyclonic case is less predictable. The main signal appears to be that some impact is obtained as long as the model's inversion is not too low (preferably at level 3) and the additional moisture is inserted over sea points. Inserting cloud over land or where the model inversion is very low does not appear to be very productive. It would appear that further improvements to the boundary-layer parametrization are required before observations of cloud can be retained in such cases. Some convection cases were also considered, but the impact on forecasts was very modest, indicating that deficiencies in the convective parametrization scheme are more likely to be the cause of poor forecasts of showers.

We did not attempt any compensating change to other model variables. Such changes might provide additional improvements if an appropriate method of achieving them could be devised. In the longer term, cloud liquid water is likely to be a prognostic model variable and the direct assimilation of cloud observations should be integrated with the assimilation of other observation types. The iterative nature of our assimilation scheme will then allow the cloud observations to have an indirect impact on other model variables.

Acknowledgements

We are grateful for the help and encouragement provided by R.M. Morris.

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Reviews

Atmospheric tidal and planetary waves, by H. Volland. 163 mm × 246 mm, pp. x+348, *illus*. Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Price Dfl.210.00, US$99.00, £59.00.

The author aims to provide a unified view of wave-like planetary-scale oscillations of the earth's atmosphere between the ground and a height of about 400 km on time-scales ranging from 1 day to 11 years. Motivated strongly by the desire to obtain analytical solutions to the linearized primitive equations, he constructs idealized models of, for instance, the tidal and planetary Rossby wave response to prescribed heating functions, estimating typical magnitudes of the forcing and comparing the solutions with observations. Unlike most textbooks on dynamical meteorology, this one tackles the full rigours of Laplace's tidal equations by summarizing the findings of Longuet-Higgins (from his classic 1968 paper) and introducing a classification scheme for the various modes. The difficulty in this approach stems from the use of spherical geometry which, of course, is essential if one expects some quantitative agreement of wave periods with observations, but does not aid physical interpretation. The book does not set out to answer the question 'What is a gravity or Rossby wave?' — these distinct species of wave motion just emerge as different branches of a complicated dispersion relation.

The dominance of linear theory in the book, and planetary scales considered, leads to mathematical problems of the harmonic oscillator type for which resonance is possible; most of the nonlinearity is assumed parametrizable as Newtonian cooling or Rayleigh friction. By virtue of the geometry, series expansions in spherical harmonics are the principal representation of the horizontal structure of wave modes. It is nice to see all of the standard formulae required for manipulating associated Legendre functions in one place, though I would have preferred to see them for the usual normalized functions.

The author states in the preface that he has tried to treat the lower, middle and upper atmosphere on an equal footing. Given the vast range of densities covered (a factor of 10 for every 16 km of height) this can be disconcerting. For instance, in chapter 3 on 'External energy sources' one has to take in the size of the solar constant (and the one third of it available for driving tropospheric flows) in the same breath as a discussion on 'lunar gravitational tidal energy' which is tiny by comparison. The importance of electromagnetic forces in the ionized upper atmosphere reinforces the difficulty in giving equal emphasis to the different atmospheric layers. For those interested in learning a little about the motion of the ionized atmosphere (e.g. dynamo effect of tidal winds) I do not recommend reading the relevant sections of this book — too high a level of familiarity with the subject is assumed.

Chapter 7 on 'Nonlinear wave propagation' collects various ideas and theoretical treatments of nonlinear wave dynamics such as wave–wave interaction, two-dimensional turbulence, nonlinear normal mode initialization and the Lorenz attractor. There is even a subsection on a 'logistic difference equation' which has some bearing on the strange attractor. It looks interesting but seems out on a limb given the 'harmonic oscillator' feel to the rest of the book. It is a pity that more emphasis was not given to numerical simulation of large-amplitude planetary-scale motions when discussing nonlinearity — the topics discussed here are quite restricted.

On the positive side, one can only be impressed by the wide range of material covered, with sections on Ertel potential vorticity, Eliassen–Palm fluxes, length of the day fluctuations and global angular momentum, El Niño and quasi-biennial oscillation — to mention a few familiar to the meteorologist. The author's combined understanding of the upper and lower atmosphere must be quite unusual. One must certainly respect his opinion on the long-standing and controversial subject of 'sun-weather relationships'. He states that most claims of correlations between solar indices and tropospheric disturbances are the result of the careless use of statistics.

Specific points of terminology that I found misleading were the use of the word 'interference' instead of 'interaction' and, that old favourite, 'standing' instead of 'stationary' (waves). The generally high standard of the physical explanations slipped in places with, for instance, on page 292 talk of 'the conversion of energy of waves with $m>0$ into fluctuations of the absolute angular momentum'.

I do not foresee a great demand for this sort of book but it does fill a gap in the literature and should be welcomed for that reason at least. Its highly technical content means that it will be used only by those active in research — particularly those with a passion for spherical harmonics.

G.J. Shutts

The geostationary applications satellite, by P. Berlin. 157 mm × 235 mm, pp. xvi+214, *illus.* Cambridge University Press, 1988. Price £30.00, US $49.50.

This book comprises 15 chapters describing the orbital dynamics, construction, payload, testing, launch and telemetry systems of satellites in geostationary orbits (at 36 000 km altitude). The author is an engineer rather than an applications scientist, and so for many meteorologists who come into contact with satellite data there is a considerable amount of jargon to master. However, this book represents a clear and successful attempt to introduce the non-specialist to satellite engineering, and a considerable amount of useful information is contained within the 214 pages.

Contained within the first chapter is an interesting account of how China acquired satellite expertise from the USA, enabling them to produce a launch vehicle, CZ-1, in spite of the McCarthy era of communist 'witch-hunting'. Further interesting facts emerge; for example, China's launch site is in Sichuan Province, and launch opportunities are confined mainly to the winter months due to the occurrence of heavy rainfall during the summer months. This is quite different from the European Ariane launch site at Kourou in French Guiana, where the hot and humid climate and the absence of hurricanes pose no limitation on launch opportunities. Likewise there are no weather problems at the USSR launch site at Baykonyr, 250 miles north-east of the Aral Sea in the Kazakhstan Republic, where very hot dry summers and cold winters are the norm. However, at Cape Canaveral in Florida thunderstorms may have to be monitored very closely around launch times.

Chapters 2 and 3 deal with orbital geometry and include a description of the geostationary orbit in which the sub-satellite point describes a figure-of-eight around the nominal longitude on the equator. There are interesting diagrams in chapter 4 showing accelerations during the ascent phase of launch. For example, for China's Long March-3 rocket, over 5 *g* is experienced within the first 200 seconds of flight compared with 4 *g* for the Ariane-4. The 'quality of life' of a satellite is described as being 'abysmal', the systems being subject to large accelerations, radiation, cosmic particle bombardment and electrostatic discharges.

Several short chapters follow, on the structure of satellites, the trade-off between usefulness and reliability in designing satellite mechanisms, thermal control (differences between active and passive), power supplies and propulsion. There is a longer description of attitude stabilization including gyroscopic theory — classical physicists will enjoy this! The problems of telemetry tracking, control and communications are outlined.

Chapter 13 deals with the meteorological payload. The description of a radiometer is of an infra-red detector. It is a pity that there is no mention of microwave systems. Whilst Meteosat is discussed, prospects for Meteosat Second Generation are, strangely, not mentioned. Unfortunately the section on meteorological data extraction is weak, although to be fair this is not the main thrust of the book. Statements such as 'air pressure can, to some extent, be inferred from wind speed and direction' are made, and the difficulties of extracting geophysical parameters from radiance measurements are glossed over.

The book concludes with discussion of product assurance which is useful to those not familiar with the 'bath-tub' curve of component failure rates. Likewise, for readers with only a passing contact with the procurement of complex instrumentation, the final chapter on spacecraft development and testing is a very useful introduction. A full schematic representation of an Ariane launch campaign is recorded.

Overall, this book is a useful reference to many of the things concerning geostationary satellites that meteorologists may come across. It is clearly written, but is somewhat unbalanced — chapter 6 is just over three pages long including figures, whereas chapter 10 is 28 pages. The reviewer did not notice any significant presentation errors and, whilst the meteorological section is disappointing, the book is to be recommended as a handy and practical guide to the subject.

C.G. Collier

Satellite photographs — 4 May 1989 at 0856 GMT

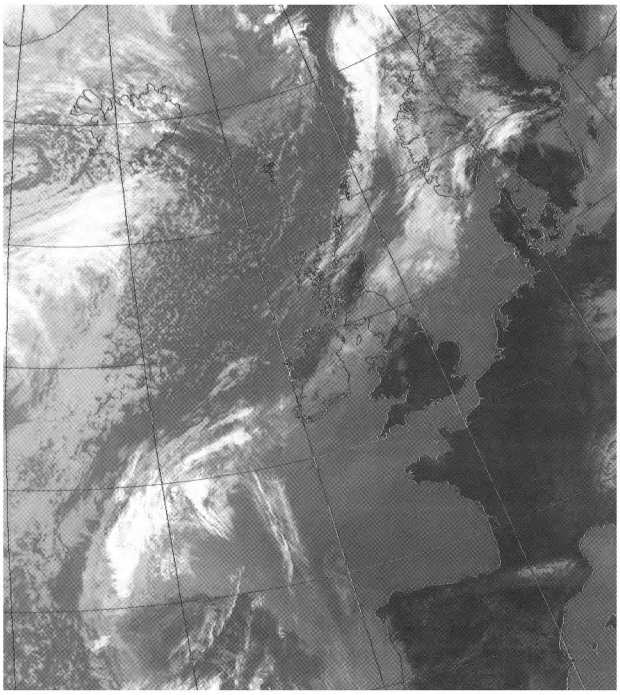

Figure 1. NOAA-10 infra-red image for 0856 GMT on 4 May 1989.

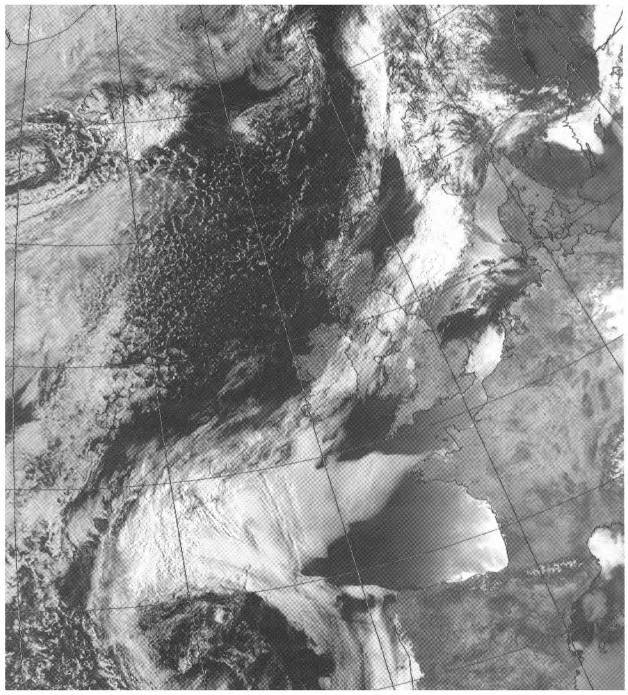

Figure 2. NOAA-10 visible image for 0856 GMT on 4 May 1989.

Photographs by courtesy of University of Dundee

A forecaster analysing the NOAA satellite imagery (Figs 1 and 2) in isolation from other data sources would be quite justified in concluding that low stratus and/or fog covered much of the southern North Sea and adjacent coasts (see Fig. 2). In reality, however, surface-based observations showed the area to be virtually cloudless, as it was on the satellite imagery 2 hours previously (not shown).

The conspicuous bright area on the visible image was in fact due to sun glint — the phenomenon caused by reflection from a calm or near-calm water surface. The synoptic situation for 0900 GMT (Fig. 3) shows that the area in question was under the influence of a slack easterly air stream, close to the centre of a high pressure cell. Sun glint can also be observed in Fig. 2 in the Bay of Biscay, particularly near the coasts of France and Spain. Another feature of interest on the visible image is the delineation of extensive areas of mainly low stratiform cloud associated with the weak fronts and warm sector of a system south-west of the United Kingdom.

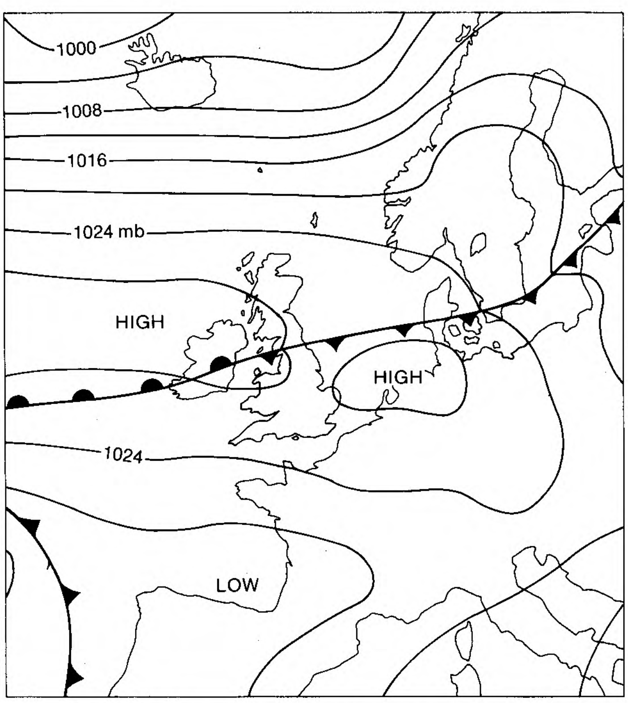

Figure 3. Surface analysis at 0900 GMT on 4 May 1989.

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Westward-moving disturbances at Ascension Island

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Defence Services Branch 50th Anniversary. Part I: Historical aspects

S.J. Caughey and P.W. Davies
Meteorological Office, Bracknell

Summary

In January 1939 Met O 6 (then M.O.6) was designated the Meteorological Office Branch responsible for serving the Royal Air Force within the United Kingdom. Thus began an association with Defence work which has lasted 50 years. To mark the occasion this article briefly outlines Meteorological Office activities in support of the Armed Forces from the earliest days of military aviation to the major expansion of air power and services during the Second World War and, more recently, the Falklands Campaign. An accompanying article (Turton and Caughey 1989) reviews the current organization for Defence and the services provided and also assesses likely future trends and requirements.

1. Introduction

Weather has always been a major factor influencing the conduct of military operations. There are many famous instances throughout history of the tactical use of weather by astute military commanders. At Salamis in 480 BC, the Greeks relied upon a freshening southerly sea-breeze to cause ship-handling difficulties amongst larger Persian vessels before attacking them. Julius Caesar was severely hampered by strong winds and high seas in the Channel during his invasion of Britain in 54 BC. In more recent times it is well known that the invasion of Europe in 1944 was crucially dependent upon a suitable 'weather window' (Stagg 1971).

From the few examples quoted above it can be readily appreciated that a military commander must have access to accurate weather information. This requirement becomes particularly important when his forces are outnumbered by their opponents or when resources are limited. The maximum effectiveness must then be extracted from the available resources, and this can often be assisted by intelligent tactical use of weather information and by being aware of the impact of weather on both his own operations and those of his opponent.

As early as 1838, officers of the Royal Engineers on detached duty overseas and consuls serving in foreign ports had been requested to make meteorological observations to build up a climatic database in order to assist the provision of meteorological advice to shipping (both naval and merchant). The Meteorological Office was formed in 1855 as a department within the Board of Trade in response to growing unrest over the unsatisfactory provision of meteorological information to the fishing and merchant fleets. From these earliest days services for Defence formed an important part of the work of the Office. In this article a brief description is given of the growth in services for the military in the early years through to the rapid expansion and development which took place during the Second World War and until the present day.

2. The early years — pre-1939

In the earliest years of the Meteorological Office most work for Defence was concerned with the supply of forecasts and weather information to the Royal Navy, which was still using balloons (Fig. 1) and with attempts to improve the accuracy of artillery fire. There was, however, no satisfactory method of measuring upper-air flow and thus in 1881 experiments were conducted into the detection of upper-air currents by firing light shells vertically. The difficulties of providing a credible forecast service can easily be underestimated in today's world of satellites, fast communications and sophisticated numerical models. All products were generated by laborious manual methods and based on limited data of variable quality.

With the introduction of the first military aircraft in the early part of this century (*circa* 1910) the Meteorological Office appointed (in 1911) J.S. Dines as Officer-in-Charge of a Branch Meteorological Office at the aircraft factory at South Farnborough. He arranged for the provision of weather advice to officers of the Air Battalion and also ran the Upper Air Experimental Station at Pyrton Hill, near Benson. By 1913 the Meteorological Office Forecast Division was routinely supplying (by telegraph) weather reports and forecasts to units of the Royal Flying Corps (Fig. 2), Royal Navy Wing at Eastchurch and the Central Flying School at Upavon amongst others. The Branch

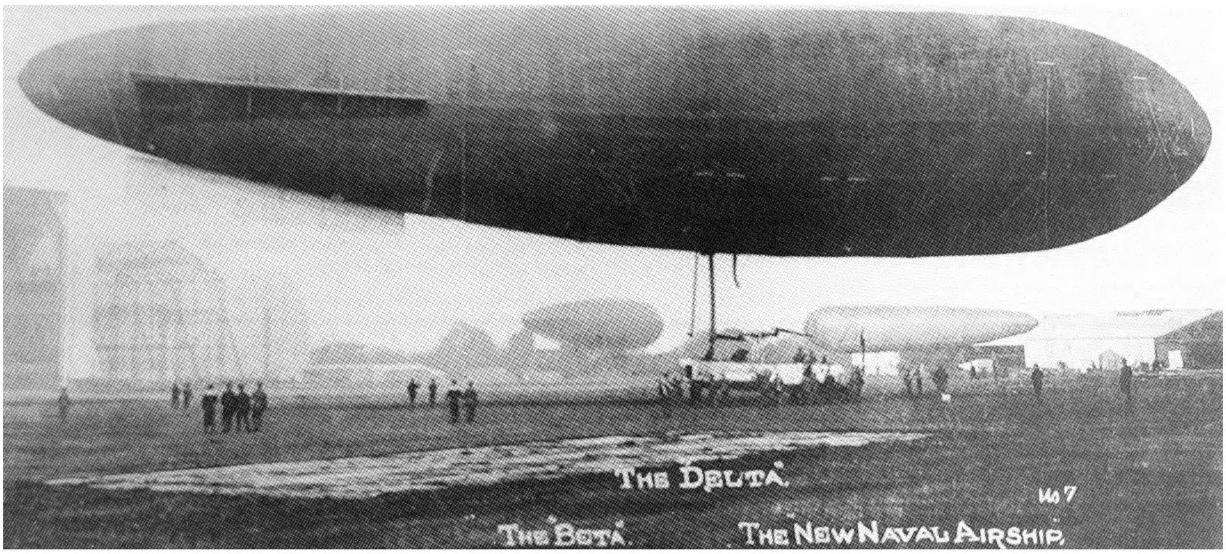

Figure 1. Royal Naval Air Service balloons at Farnborough (*circa* 1912).

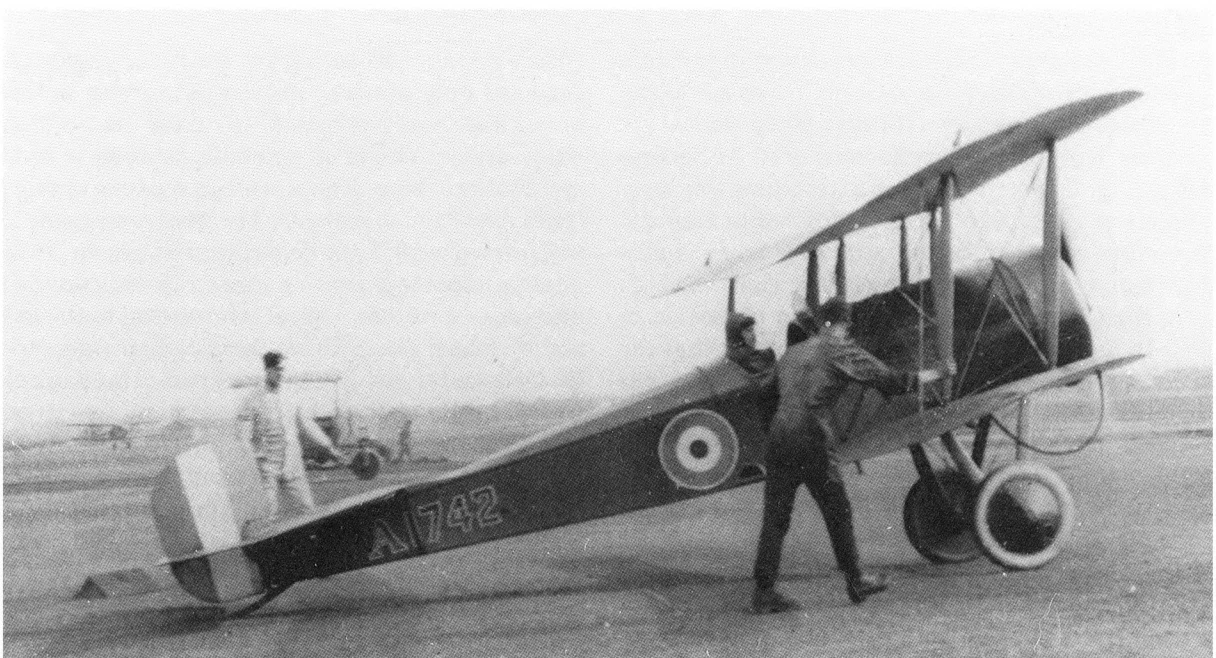

Figure 2. Bristol Scout biplane of the Royal Flying Corps (*circa* 1915).

Photographs by courtesy of RAF Museum, Hendon

Meteorological Office at South Farnborough was made permanent in January 1914 and would thus appear to be the oldest meteorological office serving Defence.

With the approach of the First World War the expansion of services accelerated with reports and forecasts provided for Royal Naval aviation stations, and more frequent night-time observations were introduced to improve the quality of early-morning forecasts. Experiments started with the use of searchlights to monitor cloud-base heights. During the First World War meteorologists were attached to the Royal Artillery for sound ranging and gunnery work and to the Royal Engineers to give advice on chemical warfare matters. The Meteorological Field Service consisted of about 50 officers, mainly from the Meteorological Office, up to the rank of major. Additionally, large numbers of non-commissioned officers (some from the Meteorological Office) and other ranks, drawn from the Royal Navy and the Royal Engineers were trained for service with the various meteorological sections. An example of an actual weather chart from this period which was prepared by E. Gold is shown in Fig. 3.

In 1918 the Royal Air Force was formed from the Royal Flying Corps and although the Meteorological Office initially resisted transfer to the new Air Ministry (Meteorological Office 1919) the move went ahead in 1919. Also in this year the Army Council formally requested further civilian support for artillery work and new offices were opened at Shoeburyness and Larkhill. The growing expertise of the Office in aviation work was recognized with the detachment of forecasters to St Johns, Newfoundland, to forecast for the first successful west-to-east transatlantic flight by Alcock and Brown on 14–15 June 1919.

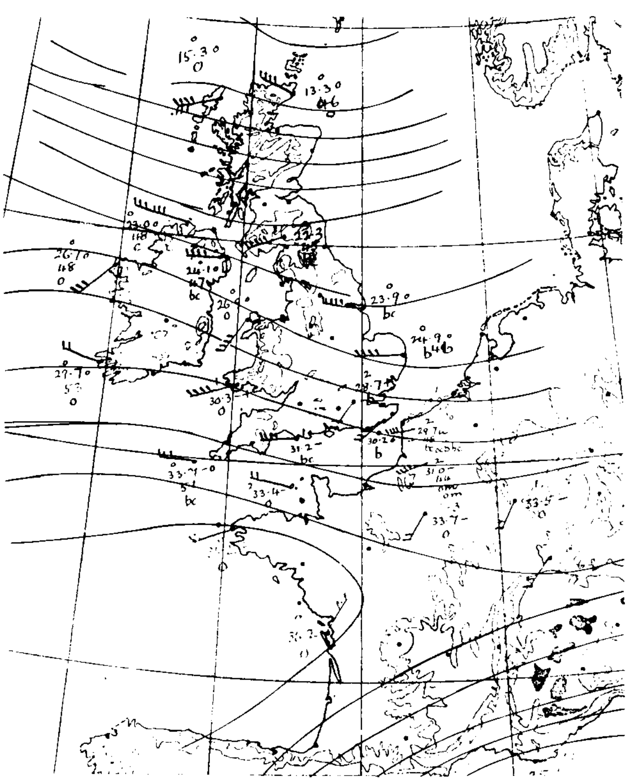

Figure 3. Surface chart for 0100 GMT on 20 November 1917, prior to the Battle of Cambrai.

By 1920 the meteorological organization for Defence consisted of the Distributive Services Division (military and civil aviation), the Army Services Division and the Navy Services Division. All three Divisions received their basic guidance from the Forecast Services Division. Rapid growth continued through the 1920s so that by 1922 the Distributive Services Division (re-titled Aviation Services Division) had ten dependent offices. The Army Services Division had three offices, at Porton, Shoeburyness and Larkhill. Also, 1922 saw the opening of an overseas office at Malta, mainly for Royal Navy and Royal Air Force work. This was followed by eight offices opened in the Middle East during 1926–27 supporting units of the Royal Air Force engaged in pursuance of Trenchard's policy of aerial policing of remote and inhospitable areas. The aircraft in service at this time were mostly biplanes such as the Hawker Hart and Hawker Hind. Further reorganization and expansion took place during the 1930s.

With the approach of the Second World War a rapid expansion of the Armed Forces, particularly the Royal Air Force, took place. In 1936 Bomber, Fighter, Coastal and Training Commands were set up whilst in 1938 Balloon and Maintenance Commands were formed. To meet the growing capabilities of the Royal Air Force, ten new meteorological offices were opened on Royal Air Force airfields in the United Kingdom in 1937 alone. By contrast, in the same year, responsibility for services to the Royal Navy passed from the Meteorological Office to the Directorate of Naval Oceanography and Meteorology. During the period military aircraft increased in sophistication and performance. Also at this time the outstations were supplied with information direct from the then Central Forecast Office but with the approach of war a major organizational change took place which paralleled the changes in the Royal Air Force. The centralized structure was replaced by Command and Group Meteorological Offices, each given control over a number of outstations. Staff from London were devolved outwards to man these new offices and, to mark the event, the Meteorological Office Annual Dinner (Fig. 4) on 27 March 1939, included, after the Loyal Toast, a toast to 'The Decentralized'. Some of the legendary meteorological figures who played an important part in the Second World War can be identified from the photograph.

Prior to this time the Meteorological Office had been organized into a number of rather large Divisions but the increasing demands by the Royal Air Force for more specialized services could not easily be met by them. Smaller, and more manageable, Branches were set up to deal with specific service areas. Hence, late in 1938 the Director of the Meteorological Office signed a letter which authorized the formation of M.O.6 to commence work on 1 January 1939 under the direction of

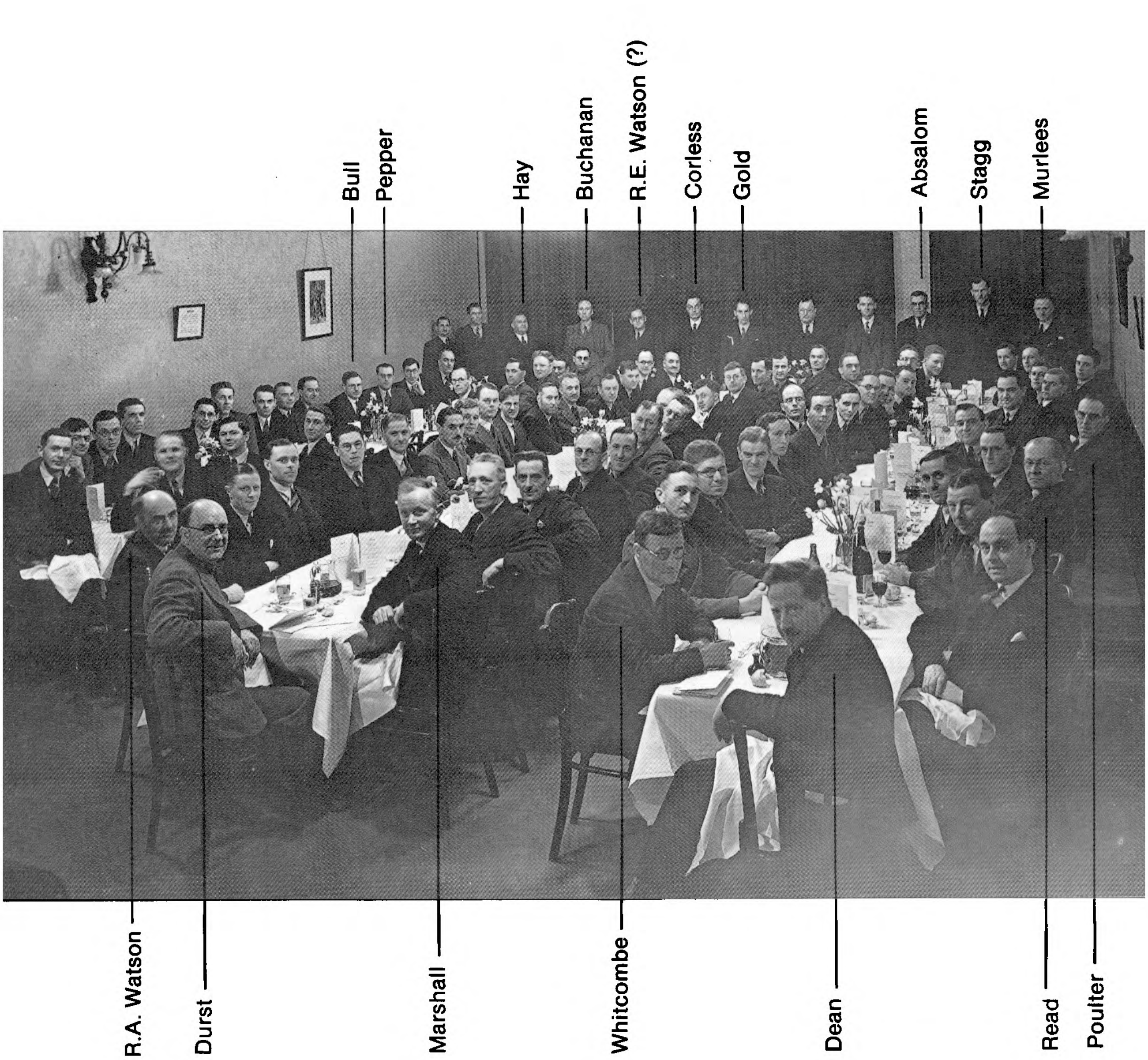

Figure 4. Meteorological Office Annual Dinner on 27 March 1939. *Photograph by courtesy of R.K. Pilsbury*

Mr H.W.L. Absalom. Thus, 1 January 1989 marked the 50th Anniversary of Met O 6 and what is now the Defence Services Branch of the Meteorological Office.

3. The Second World War

In 1939, as a reaction to European political tension, the Armed Forces commenced mobilization. In response to that mobilization the Head of M.O.6 issued, by teleprinter on 26 August 1939, *Emergency Met Instruction No 5*. This was the War Postings List, part of which is reproduced as Fig. 5. It contains some famous names such as Eric Evans and Tom Harrower, both of whom eventually became Assistant Directors of the Defence Services Branch.

At the start of the Second World War M.O.6 was responsible for meeting all Royal Air Force meteorological requirements within the United Kingdom. This period, as one can imagine, was a time of enormous expansion, rapid change and urgent requirements which demanded largely untried products and techniques. By March 1940, and when M.O.6 had been in existence for only 15 months, other Branches (M.O.7 and M.O.8) were already being created to shoulder some of the Royal Air Force burden leaving M.O.6 to deal with RAF Bomber, Coastal and Maintenance Commands. M.O.7 was responsible for RAF Fighter, Training, Balloon and Reserve Commands and M.O.8 for Army Co-operation.

By December 1942 M.O.6 was directly responsible for the meteorological support of Bomber Command, Training Command, Coastal Command (except 15 Group, Liverpool, and 19 Group, Plymouth) and civil aviation in the United Kingdom and north-west Europe (flights to neutral Sweden, Portugal, etc.). M.O.6 was also administratively responsible for the Transferred Training Schools although there is no evidence that staff were sent to them from the United Kingdom. The Transferred Training Schools were Flying Training Schools which had been evacuated to the more peaceful skies of Canada early in the War. The Branch continued

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WAR POSTING
THE FOLLOWING WAR POSTINGS SHOULD TAKE PLACE IMMEDATELY.
 OFFICERS - IN - CHARGE  OF TELEPRINTER STATIONS SHOULD
 ENSURE THAT ALL STAFF AT THEIR AND ASSOCIATED STATIONS ARE
 INFORMED AT ONCE AND JXX MUST REPORT BY TELEPRINTER TONIGHT
 A LIST OF INSTRUCTIONS TO MOVE WHICH HAVE BEEN GIVEN.
 THIS LIST SHOWS THE COMPLETE STAFF AT EACH STATION. THE
 NAME IN BRACKET IS THE HOME STATION OF THE STAFF.
 BOMBER COMMAND ==============
W. H PICK
D W JOHNSTON (SEALAND)
V R COLES
R L SIMS
J S M DAVISON (ABINGDON)
E R THOMAS ( ABINGDON)
D H MILNER (LINTON)
NO 1 GROUP ============
R E WATONS
C WOOD
W L ANDREW
B A COPPING
M E PTIXX PITCHER
S CLARK
NO 2 GROUP ==========
M T SPENCE
E EVANS
W C SWINBANK
C C NEWMAN

                    •

NO 4 GROUP =============
R G VERYARD
H C SHELLARD
A LITTLEWOOD
W A TOMS
C J RYDER (ALDERGROVE)
E C FIELDER
G A COWLING
W D COOPER
NO 5 GROUP ==========
R H MATHEWS
L P SMITH
D G HARLEY

                    •

WEST FREUGH :      T N S HARROWER     B V BISHOP   W D WALLACE
CRANWELL :    P J DRINKWATER W E BILLBOROUGH C H HINKEL
PENRHOS     B J GORST  F M BANCROFT (  SEALAND )
SEALAND     F W WARD  A S SIMPSON   G BUTTLING
TERN HILL   H FORSTER J ANDERSON (  ALDERGROVE )
LOSSIEMOUTH W J CORMACK (  MONTROSE )
NORTH COATES :   L JACOBS  R R ROE
(  TO MOVE WITH SCHOOL )

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Figure 5. Part of the teleprinter signal of the War Postings List sent at 1821 GMT on 25 August 1939*.

* The complete list is incorporated in a copy of this article which is lodged as a pamphlet in the National Meteorological Library, Bracknell.

with this extensive commitment until September 1944 when it was directed to concentrate exclusively on the provision of meteorological support for Bomber Command. This arrangement continued until the end of the War.

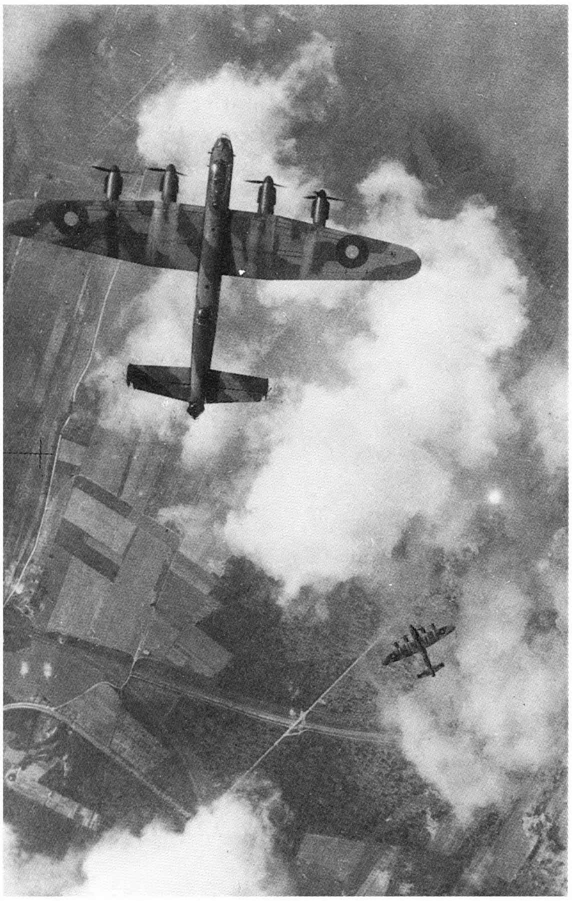
Bomber Command, and subsequently Strike Command into which it was subsumed, has therefore been one of the major customers of Met O 6. During the Second World War M.O.6 maintained a Type 1 Office (equivalent to a Principal Forecasting Office today) at Bomber Command Headquarters at High Wycombe. This Office was in contact with, and provided general guidance to, the other Type 1 Offices at the various Bomber Group Headquarters (1 Group Abingdon, 2 Group Huntingdon, 3 Group Mildenhall, 4 Group York, 5 Group Grantham and 6 Group Norwich). These latter Offices, although designated Type 1, were basically equivalent to a Main Meteorological Office today. The Group Offices, in turn, exchanged forecasts and collected observations by teleprinter within their own network of Bomber airfields.

The techniques of meteorological observing have changed surprisingly little since 1939–45 although the code forms and communications are now far superior and there are more automatic instruments. The wartime observer had no distant-reading thermometers and had to visit the enclosure every hour. He (or, in many cases, she) had no cloud-base recorder but did have a cloud searchlight, and the observation of cloud amounts, types and heights at night was made more difficult by the lack of reflected urban or industrial lighting due to the strict black-out regulations.

It is in the field of forecasting that the major changes have occurred. During the Second World War not only were there no numerical products, no satellite imagery and no weather radar imagery but operational forecasters were just beginning to experiment, in the early part of the War, with thickness fields and Sutcliffe development ideas (Sutcliffe 1947). The upper-air charts were hand-plotted, laboriously hand-drawn and then 'gridded' to produce the final surface prognosis.

At this time the Hurricane and Spitfire had proved their worth as fighters in the Battle of Britain but the Battles, Defiants, Hampdens, Whitleys, Wellingtons and Manchesters of Bomber Command were to be woefully inadequate as the bomber force until the arrival of the Stirlings and Lancasters (Fig. 6) in sufficient numbers later in the War. Coastal Command's Sunderland flying boats were the only really long-range reconnaissance aircraft in the early days until they were joined by Liberators and Catalinas on Lend-Lease from the USA. These, and the Bomber aircraft, carried out long flights with only sketchy forecasts derived from sparse information until regular observations, not only from our own side but also from interceptions of the enemy's data, improved matters.

Fighter aircraft could operate from the surface to 30 000 ft, whilst photo-reconnaissance aircraft were reaching nearly 40 000 ft. The night bombing offensive was



Photograph by courtesy of RAF Museum, Hendon

Figure 6. Avro Lancasters on a Second World War bombing mission (*circa* 1943).

mainly carried out at around the 18 000–24 000 ft level whilst the daylight interdiction raids might be just above the hedge-tops. The long, and often boring, maritime reconnaissance flights were usually flown at around 1500–2000 ft and should be compared with the luxury of the (normally) smooth stratospheric flights of the modern passenger aircraft. These aircraft also made vitally important meteorological observations far out over the Atlantic. The perils of carburettor icing, or of leaving a condensation trail to mark one's position in the sky, were real problems for wartime aviators. It is interesting to note that the 'mintra' line on today's tephigram is still the one originally calculated from the combustion characteristics of a Spitfire engine!

The network of upper-air measurements too, was rudimentary early in the War and it was only when large losses had been suffered by the Bomber Force as a result of scattering due to unforseen or badly forecast jet streams that an Upper Air Forecast Unit was set up at Bomber Command Headquarters. This was to ensure that all the airfields used the same flight winds. It meant that, even if they were in error, at least the bomber streams would stay together and thus be better able to defend themselves. On some occasions when different winds from different stations had been used by navigators of varying abilities the subsequently scattered streams of bombers had suffered enormous losses from enemy night-fighters. The introduction of the Pathfinder Force in 1942, with expert navigators and a single controlling 'Master Bomber', did much to ameliorate the problems and the enormous losses. It is a sobering thought, when one views the relative ease with which a 24-hour numerical wind prognosis can be produced today, to remember just what the Bomber Command upper-air forecaster was trying to produce, by manual methods and with variable data (both in quality and quantity). He alone in the Meteorological Office at that time, knew the target, but everybody knew that if he made an error, the Bomber Force might stray over a heavily defended area with the possible consequence of high losses. There have always been pressures on forecasters but those of the Second World War period were, clearly, quite exceptional.

4. 1945 to the present day

At the end of the War, some 90% of the Meteorological Office staff of 6760 were in uniform. Demobilization started almost immediately as did the reorganization of the various Branch responsibilities. By May 1946 M.O.5 was responsible for the Royal Air Force overseas (including the British Air Force of Occupation in Germany) and M.O.8 dealt with the Army, the Ministry of Supply and Training Command, leaving M.O.6 to deal with the remainder of the Royal Air Force in the United Kingdom. The advent of pure jet fighters (Vampire, Venom, Meteor, Hunter and Swift) with their relatively short endurances increased the emphasis on short-range forecasting. By 1952 M.O.6 was beginning to take on something of today's shape. In that year the last piston-engined front-line bombers, a squadron of Avro Lincolns (descendants of the wartime Lancasters) was detached to Kenya to assist in the control of the Mau Mau uprising. Pure jet aircraft were also making their mark on endurance flying and on 17 December 1953 an English Electric Canberra B Mk2 broke the London–Cape Town record by flying 6010 statute miles in 12 hours 21 minutes at an average speed of 486.6 m.p.h. in celebration of the 50th anniversary of the Wright Brothers' first flight. Forecasting for such distances was a taste of things to come! January 1955 heralded the debut of the first of the long-range 'V' Bombers — the Vickers Valiant — to No. 138 Squadron at Gaydon in Warwickshire.

Further reorganization took place in October 1955 when the responsibility for the supply of all meteorological information to the Army and the Royal Air Force came under the jurisdiction of M.O.6. M.O.5 then became the Communications Branch, while M.O.7 took over responsibility for civil aviation and M.O.8 was tasked with looking after rainfall matters. There were two major military occurrences of note in the mid-1950s. Firstly, in October 1956, the Suez Invasion (Operation Musketeer) took place and some Meteorological Office personnel once again put on Royal Air Force uniforms to advise military commanders, in the field, of the meteorological aspects of operations. The second was the dropping of Britain's 'H-bomb' near Christmas Island (Operation Grapple) in May 1957. At the peak of activity there were some 31 Meteorological Office personnel, under a Principal Scientific Officer, detached to the Pacific. There were also frequent trouble-spots in the 1960s in various parts of the world (Kuwait, Zambia and Borneo) that required some degree of additional meteorological support for the military. As a result of these, and of Suez in 1956, a review of tactical doctrine took place in the Services resulting in an emphasis on mobility and reducing the dependence upon fixed bases. The formation of the Mobile Meteorological Unit (MMU) was a direct consequence of this review. The MMU is a small group of Meteorological Office volunteers commissioned into the Royal Air Force Reserve specifically to provide environmental data and advice in forward areas.

The 1950s and 1960s also saw what was, probably, the peak of M.O.6 world-wide activities when there were staff from the Branch at many locations. These were in Germany, the Mediterranean, the Near East, Africa, the Persian Gulf, the Indian Ocean and the Far East. However, from then onwards Government policy was to progressively concentrate UK forces in support of the North Atlantic Treaty Organization. For example, Habbaniyah (near Baghdad) closed in May 1959 and a Senior Experimental Officer post was established in support of 1 (BR) Corps, Germany in April 1960. Some of the fruits of M.O.5's labours came about in 1962 when all the M.O.6 offices in the United Kingdom were connected to the national facsimile broadcast (NATFAX) for the first time. Confusion had also arisen between the abbreviations for the Meteorological Office and for Military Operations — both 'M.O.'. It was therefore decreed that the Meteorological Office should be shortened to 'Met O' — the current 'Met O 6' title had finally come into existence.

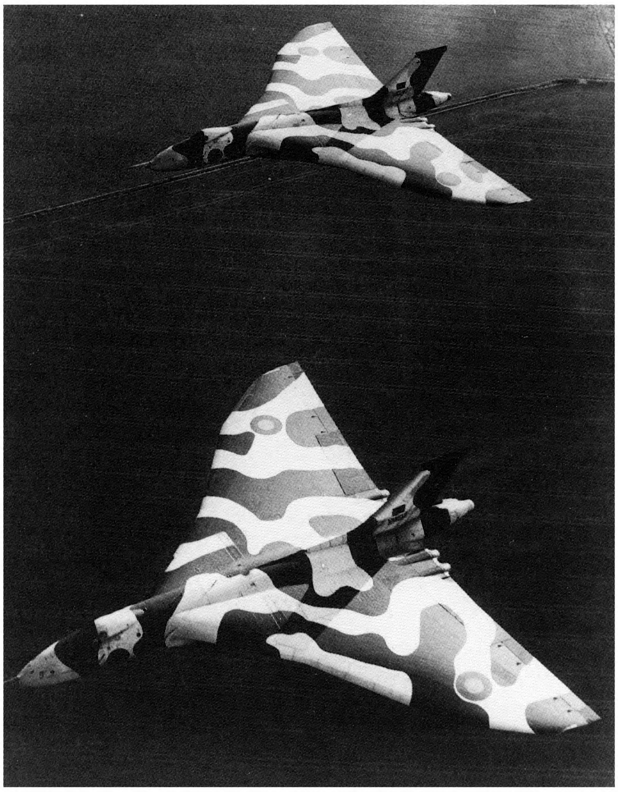
In the late 1960s and early 1970s there were a number of organizational changes as the military withdrawal from east of Suez took place. The meteorological offices in Aden and Borneo were closed in 1967, El Adem in 1970, Sharjah in 1971, Gan in 1976 and Malta in 1978. In 1968 Transport Command became Air Support Command, Bomber and Fighter Commands became Strike Command, and Flying and Technical Training Commands amalgamated to form Training Command. Coastal Command was eventually subsumed into Strike Command in 1969. All these changes had to be mirrored by consequent changes in Met O 6. There were, similarly, a significant number of closures of UK meteorological offices as cuts in the Defence Forces began to bite. For example, Manby was closed in 1974, Abingdon in 1975, West Raynham (for a second time), Andover, Little Rissington, Ternhill and Thorney Island all in 1976, and Pershore and Fairford in 1977.

Simultaneously there were communications developments with the introduction of a number of dedicated military meteorological broadcasts such as the Strike Command facsimile broadcast (STRIFAX), the Strike Command teleprinter meteorological broadcast (STRIMET), the RAF Strike Command Weather Actual System (STCWAS) and the Transport Command meteorological facsimile broadcast (TRANFAX). Numerical weather prediction products of increasing sophistication were being introduced on the Meteorological Office national facsimile programmes at this time.

Also during this period a number of events took place which can be seen as bringing the history of Met O 6 up to the present day. In July 1974 Turkey invaded Cyprus. Quite coincidentally, a detachment of the MMU was on exercise on the island and was able to provide additional support to the ex-patriot staff after the locally employed staff had experienced difficulties in being able to report for duty. A sad occasion took place at Akrotiri in December 1977 when an aircraft crashed on to the meteorological office causing a number of fatalities and serious injuries. However, such was the resilience of the remaining staff (both UK based and locally employed) that a meteorological service was resumed to the military authorities within a few hours.

Easter 1982 saw the start of events in the South Atlantic which culminated in the Falklands Campaign (Operation Corporate) and the subsequent demanding meteorological requirements on the Falkland Island and Ascension Island. Met O 6 was involved within hours of the Argentine invasion. A vast amount of rapid organization was required and provided (Pothecary and Marsh 1983). It is fair to say that the experience at all levels in Met O 6 (and much of the rest of the Meteorological Office) in world-wide meteorological tasks over many years allowed not only a valuable and rapid response to the requirements of the military (Fig. 7) but also the comment that, meteorologically speaking, the South Atlantic was just another place! The MMU played an invaluable role in this operation, setting up makeshift meteorological offices and working in very demanding conditions, both on Ascension Island and, eventually, at Port Stanley Airfield. This expert and immediate response by the Office was recognized by a number of awards and decorations.

For some years the abilities of the meteorologist to assist the military non-aviator had gone largely untapped. Over the years, however, the military appreciation of good environmental support has increased sharply. Warfare, both in the air and on the ground, is becoming daily more scientific and the requests placed before the meteorologists today will require increased skill and ingenuity if they are to be properly met. Several decades ago a major challenge was the accurate forecasting of upper-level winds — today it is the forecasting of very low cloud and visibility and the provision of expert advice concerning the impact of the weather on the operation of electro-optical



Photograph by courtesy of RAF Museum, Hendon

Figure 7. Avro Vulcans of the type used on the Port Stanley Airfield raids in 1982.

systems such as infra-red weapon sights and night-vision goggles. In all cases the meteorologist is working at the extremes of meteorological knowledge and capabilities. Life for the meteorologist serving the military is never dull and does not look as if it ever will be.

Acknowledgement

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Defence Services Branch 50th Anniversary. Part II: Current commitments and the future

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Meteorological Office, Bracknell

Summary

This paper describes the services currently provided by the Meteorological Office Defence Services Branch to the Armed Forces, Ministry of Defence (Procurement Executive) and other government departments, with emphasis on developments in advice for the use of new technologies employed by the Forces and civil emergency services. The meteorological response to chemical and nuclear emergencies is also discussed.

1. Introduction

In the accompanying article (Caughey and Davies 1989) a brief history of services for the Armed Forces is given. This paper describes those services currently provided by the Meteorological Office Defence Services Branch (Met O 6) for the Armed Forces, Ministry of Defence (Procurement Executive) (MOD(PE)) and other government departments. Support for the Armed Forces is given primarily to the Royal Air Force (RAF) and the Army, although the Royal Navy also relies on the Meteorological Office for basic meteorological information. In recent years there has been an increasing emphasis on the MOD(PE) range activities, in developing advice for the new technology employed by the Forces and in the area of civil emergency planning. These services currently account for about 40% of the total cost of the Meteorological Office and employ around 25% of its manpower.

2. Services for the RAF

Services for the RAF currently involve personnel based at over 50 stations in the United Kingdom, Federal Republic of Germany, the Mediterranean and the South Atlantic. On-site forecasters are established to provide meteorological advice for both operational and non-operational activities. The operational activities include air defence, reconnaissance, air transport and air training tasks for which forecasts, warnings, and information on the actual weather are required. In particular, short-period forecasts of detailed boundary-layer conditions, especially cloud and visibility, are crucial for the increasing volume of low-level flying undertaken by the RAF. This entails regular briefings to aircrew, of which over 200 000 were given during 1988. Forecasts are also provided for other RAF units such as radar stations, weapons ranges and signals units.

The Principal Forecasting Office (PFO) at Headquarters Strike Command (HQSTC) provides technical forecasting advice to most Met O 6 offices. The PFO prepares specialized flight documentation (e.g. low-level significant weather and wind charts) and guidance on broad-scale developments. Recently the PFO was relocated into the newly constructed Primary War Headquarters (PWHQ) at HQSTC. Within the United Kingdom there are three Main Meteorological Offices (MMOs) who, with the PFO, are responsible for the forecasting offices at RAF airfields. At a number of these airfields, facilities known as Wing Operations Centres (WOCs) have been built. Each WOC includes a Meteorological Cell which is manned by Meteorological Office staff during exercises.

Similar facilities also exist for Meteorological Office staff at RAF stations in the Federal Republic of Germany. A Mobile Forecasting Unit (MFU), staffed by Meteorological Office personnel, is also established to support the Harrier Force there (Fig. 1).

Overseas there are MMOs at Gibraltar and in Cyprus, to provide meteorological advice for operations in the Mediterranean. In 1986 a permanent forecasting office (an MMO) was established at RAF Mount Pleasant, Falkland Islands (Fig. 2). This office now provides the meteorological information required by all three Services for operations in the South Atlantic theatre.

The Mobile Meteorological Unit (MMU) forms part of the RAF Tactical Communications Wing and its purpose is to provide forecasts and meteorological advice for exercises in areas where there is no nearby meteorological service. The MMU is manned by volunteers from the Meteorological Office who hold active Civil Conditions Commissions in the RAF Reserve, and may be deployed anywhere in the world in support of the Armed Forces. The MMU was deployed during the Falklands conflict, as described in Caughey and Davies (1989).

On the non-operational side, Met O 6 staff provide basic training in meteorology to RAF personnel at the Flying Training Schools. Some 3700 hours a year are involved in teaching, and the setting and marking of examination papers, for students who may end up as pilots of fast jets, transport aircraft, helicopters, or as navigators or air engineers. The subjects taught cover those relevant to flying, such as the characteristics of air masses, visibility, thunderstorms and icing. Also some training in observational techniques is given to air traffic control staff, who may be required to make observations at stations where there is no meteorological office. The initial training is given at the Meteorological Office College, Shinfield Park followed by practical experience on an operational airfield before the student is awarded a certificate of competence.

3. Services for the Army

The Army Air Corps (AAC), which operates helicopters and light aircraft, also has a requirement for close meteorological support. In particular it has a growing need for advice relating to the use of various weapon systems and night-vision aids. Support for the AAC is provided at its UK airfields and at Detmold in the Federal Republic of Germany, where the Staff Meteorological Officer (SMO) for 1(BR) Corps is established. The SMO deploys with the Corps on field exercises and is supported by an MFU. This involves adopting a somewhat 'outdoor' life-style — most staff agree that Army food has improved over the years!

The Army artillery is also very dependent upon meteorology, and the forecasting office at the Royal School of Artillery (RSA) Larkhill provides ballistic forecasts for the Army training camps in the United Kingdom. Larkhill also produces acoustic forecasts to predict gun noise, so as to help minimize noise disturbance to the community living around the ranges, as discussed more fully later. Since 1986 a forecaster has been based at the Royal Artillery range, Hebrides. This forecaster has a vital job in the planning and execution of trials, both near to the shore and out into the Atlantic. The trials include test firings of ground-to-ground missiles (Fig. 3) and warship training against approaching anti-ship missiles.

4. Services for the Royal Navy

Since 1937 meteorological services for the Royal Navy have been provided by the Directorate of Naval Oceanography and Meteorology (DNOM). Close liaison between Met O 6 and the Royal Navy, in particular between the PFO at HQSTC and the Fleet Weather and Oceanographic Centre (FWOC), Northwood, is maintained. The Royal Navy, however, relies on the Meteorological Office for routine forecast information from the operational numerical models and other more specialized support, e.g. wave charts and surface evaporation-duct forecasts (Turton, Bennetts and Farmer 1988).

Figure 1. RAF Harrier on exercise in Germany.

Figure 2. The Main Meteorological Office at Mount Pleasant Airport, Falkland Islands.

5. Services for MOD(PE)

A number of forecasting offices are situated at MOD trials establishments. The role of these stations is to give the meteorological input needed for decision making relating to the safety and success of trials, and to provide the relevant meteorological data for post-trial analysis. The offices at the Proof and Experimental Establishment (P&EE) ranges at Shoeburyness and Eskmeals provide the meteorological information needed for proof testing of ammunition. Shoeburyness also gives support to the Atomic Weapons Establishment (AWE) explosives testing ground at Foulness. The office at the Royal Aerospace Establishment (RAE), Aberporth provides meteorological advice for the various trials held on the range in Cardigan Bay and at the nearby P&EE range, Pendine. Here some specialized facilities are needed, for example accurate monitoring of rainfall is required in trials of weapon fuse mechanisms (Hewston and Sweet 1989). The office at RSA Larkhill, in addition to giving meteorological assistance to the Army, also provides support to RAE Larkhill and the Chemical Defence Establishment (CDE), Porton for its various trials. Full upper-air sounding facilities are established at the Eskmeals, Shoeburyness, Aberporth and Larkhill offices.

One of the tasks of these stations is the provision of acoustic forecasts to predict the levels of noise, resulting from explosions or gunfire, around the ranges (Turton, Bennetts and Nazer 1988). This is important to minimize public disturbance and to avoid complaints, whilst

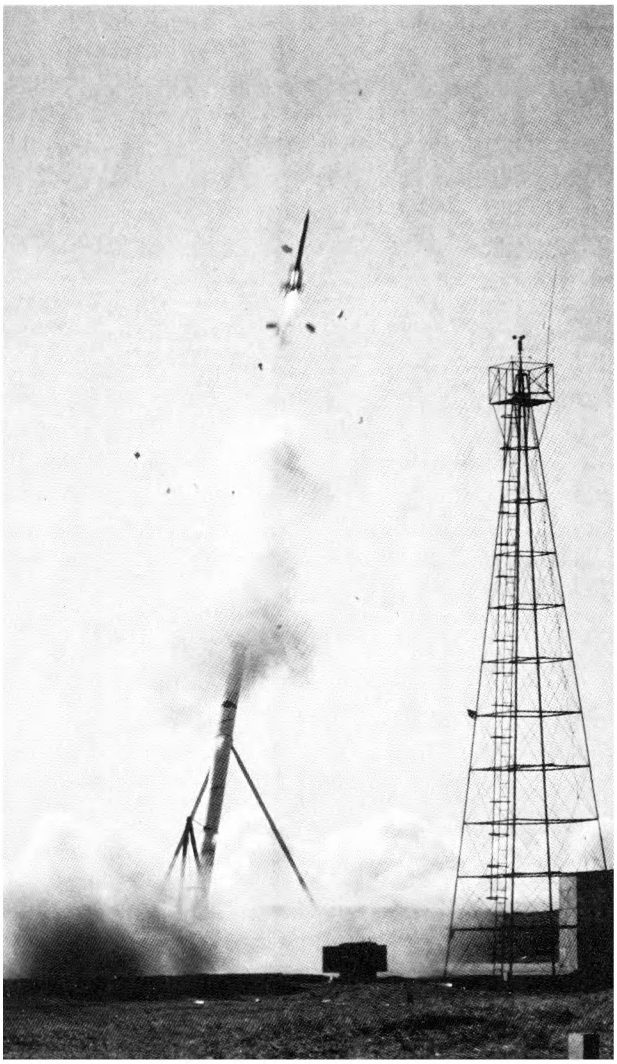

Figure 3. Rocket firing in trials at the Royal Artillery range, Hebrides.

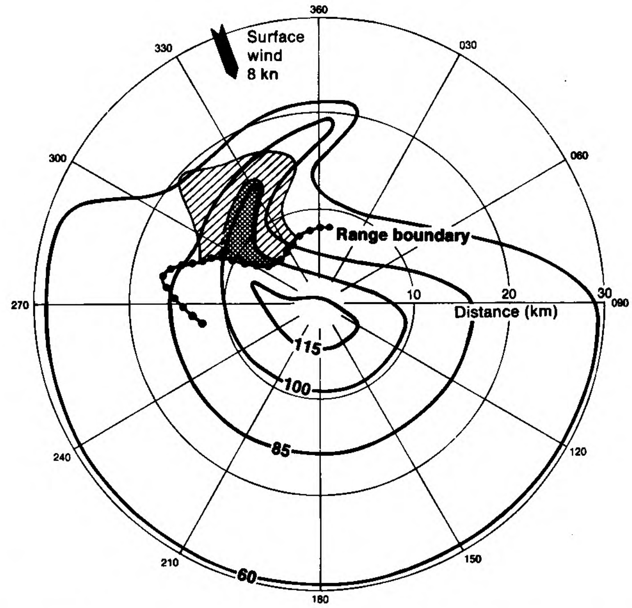

Figure 4. Acoustic forecast showing predicted noise levels in decibels. The shaded and hatched regions indicate areas where the gunfire was reported to be 'very loud' and 'loud' respectively.

maximizing the use of the range facilities. Fig. 4 shows an example of an acoustic forecast for gun noise from Larkhill. An unusual feature in this case was that the reports of noise occurred in an upwind direction from the guns and were due to focusing rather than the more usual downwind noise enhancement. However, the relation between the predicted and reported sound patterns is seen to be reasonably good in the upwind direction.

Met O 6 is currently collaborating with the University of Salford and CDE Porton in a research programme sponsored by MOD(PE) Safety Services Organization to develop improved methods for predicting impulsive noise. The programme includes the development of a new acoustic model, based on more realistic acoustic and meteorological theory, for operational use at the ranges. Also, instrumentation for remote monitoring of the noise levels around the ranges is being developed. Attention is also turning to the prediction of sound from continuous noise sources such as aircraft.

6. Services for the United Kingdom Warning and Monitoring Organization (UKWMO)

The UKWMO, which is part of the Home Office, is responsible for providing warning of an air attack and monitoring any subsequent nuclear fall-out. Knowledge of the meteorology is essential for the prediction of the spread and intensity of the fall-out. The Meteorological Office provides forecasters for the UKWMO sector controls, each of which has responsibility for a particular region. Regular exercises to test the network are held, for which Met O 6 provides meteorological data from which a fall-out pattern is determined.

7. Emergency planning

The Defence Services Branch is responsible for formulating the meteorological response to nuclear and chemical emergencies. These are considered according to the location of the incident and the nature of the hazardous material involved.

7.1 Nuclear accidents within the United Kingdom

The Department of Energy is responsible for co-ordinating the national response to a civil nuclear accident within the United Kingdom. The Ministry of Defence is responsible for co-ordinating the response to any nuclear accident which may occur at a Defence establishment or base, or to nuclear powered warships or to Defence nuclear weapons, reactor or materials whilst being transported. The spread of debris from such an accident is highly dependent on the meteorological conditions and Met O 6 was responsible for developing the procedures known as PACRAM (Procedures And Communications in the event of a release of RadioActive Material) to ensure that the appropriate meteorological advice is available. Each nuclear establishment is associated with a designated Meteorological Office, where arrangements for the provision of advice on weather conditions and the movement and dispersal of released material have been agreed. This involves an initial forecast by the designated Meteorological Office of those factors (e.g. wind speed, mixed-layer depth and stability) which are used to define the initial spread of the plume. The Central Forecasting Office at Bracknell would then be notified and a forecast forward trajectory computed from the fine-mesh model.

7.2 Nuclear accidents overseas

Following the reactor accident at Chernobyl, the Office has played a significant role in the development of the Government's National Response Plan (NRP) which arranges for departments and agencies to react to international nuclear incidents. Her Majesty's Inspectorate of Pollution (HMIP), part of the Department of the Environment which has responsibility for co-ordinating the response to an overseas accident, has equipped 46 Meteorological Office observing sites with gamma radiation monitors (HMIP 1989). This network (Fig. 5) is known as the Radioactive Incident Monitoring NETwork (RIMNET). The gamma radiation measurements are made by Office staff and passed hourly to Bracknell where they are automatically sorted and re-transmitted to HMIP's computer databases in London and Lancaster.

In order to ensure rapid notification of any future accident internationally the World Meteorological Organization (WMO) and the International Atomic Energy Authority have agreed that the WMO Global Telecommunication System may be used to provide initial warning and information. This message would be received at Bracknell, HMIP alerted and the NRP activated if appropriate. A Technical Co-ordination Centre staffed by officials from various government departments, including the National Radiological Protection Board and the Meteorological Office, would assess the effects of the incident on the United Kingdom, assist ministers and keep the public and media informed.

The Meteorological Office would also run a nuclear accident response model which would draw on meteorological and radiological data to predict the movement of radioactive material across the United Kingdom and the pattern of both wet and dry deposition. This model includes those factors that were found to be significant following the Chernobyl accident (Smith 1988).

7.3 Chemical emergency

Hazardous volatile chemicals are stored at thousands of sites throughout the country. In the event of a spillage or leak, meteorological factors will play a large part in determining the area affected. Detailed procedures

Figure 5. Locations of the RIMNET sites.

(CHEMET — CHEmical METeorology) have been developed to help cope with the handling of chemical accidents. Each MMO (and some Weather Centres) is allocated an area of the United Kingdom; if the office receives notification that an accident has occurred within this area then the CHEMET procedure is activated. The essence of the CHEMET service is the provision of timely advice on the dispersal and track of released chemicals to the Police, who will pass this information to the other emergency services (Fire and Ambulance) so that appropriate action can be taken.

8. North Atlantic Treaty Organization (NATO)

Met O 6 staff represent the United Kingdom on the NATO Military Committee Meteorology Group (MCMG) and the Supreme Headquarters of the Allied Powers in Europe (SHAPE) Meteorological Committee. These groups co-ordinate the provision of meteorological support to NATO forces in peacetime and develop appropriate contingency arrangements for crisis situations. The needs of major NATO commanders are considered against the facilities and services provided by the nations of the Alliance. The MCMG also provides a forum for those concerned with the provision of meteorological support to the Armed Forces to meet and discuss advances in techniques and facilities developed by any one nation, leading to benefits for others.

In addition, Met O 6 represents the United Kingdom on the NATO Armies Armaments Group (NAAG) Independent Special Working Group No. 3) (ISWG. 3) on Meteorology, the Target Area Meteorology Instrumentation and Analysis (TAMIA) and the Civil Defence Committee (CDC) groups. ISWG. 3 is concerned with the provision of meteorological data to the Alliance Armies for a wide range of uses, e.g. to provide ballistic messages for the use of artillery in the field. The TAMIA group is addressing the problems of the acquisition, processing and use of meteorological data from the battlefield. These data will be required for use in new Tactical Decision Aids (TDAs) which are being introduced. The CDC is involved with defining the areas at risk from the use of chemical (or biological) weapons.

9. New developments

In recent years the Defence Services forecaster has had access to a wider variety of products as improvements in the forecast models and communication systems have been made. A new communication and information system — the Weather Information System (WIS) — which will provide high-speed digital links to forecasting offices is under development. A simplified form of this facility, known as Outstation Display System (ODS), where stations are being equipped with microcomputers to give them rapid access to processed data and forecast products is under way (Cluley and Hills 1988). This is enabling them to provide more accurate and detailed weather information and forecasts. The improvement in the meteorological service, due to more rapid access to observational data, has been very significant indeed. To date, some 18 offices have had ODS installed; it is expected that all offices should have the full WIS by the early 1990s.

As this new equipment is being introduced the Defence Services forecasters are at last getting timely access to basic meteorological data, of a range and quality that enables them to carry out the demanding and time-critical local forecasting task. However, as new technology and equipment are being introduced by the Services, the role of the forecaster is expanding. No longer are they required just to give information on the general weather characteristics, but increasingly they are being asked to provide advice on how weather will affect the new technology being employed by the Armed Forces. These new developments demand that meteorologists have a good understanding of the new technology and that they combine this knowledge with accurate meteorological forecasts and data to provide the most useful advice to Force Commanders.

In particular, the effects of weather on radar propagation, electro-optic systems and the movement of troops and equipment are areas currently being studied. Forecasters are being asked to provide detailed assessments of the impact of meteorological conditions on the performance of these systems and the movement of resources. To assist them, computer programs and models are being tested and developed. These TDAs provide the military commanders with the specific information which is needed to assist in tactical decision-making.

For example, electro-optic imaging and ranging devices are becoming more widely used as they overcome many of the problems associated with night flying, especially in poor weather conditions. Both the RAF and the AAC use night-vision goggles (NVGs) for night flying, but these devices will only work when the ambient light exceeds a certain threshold level. The light incident at the top of the atmosphere depends upon the positions of the sun and moon relative to the earth. However, the amount of light that actually reaches the surface is reduced because of scattering and absorption by aerosol and water particles in the atmosphere, in particular by cloud and rain. The ambient light-level also includes a contribution due to 'cultural' lighting; this is light from towns and cities which is reflected back by clouds. Fig. 6 shows an example of how the light levels during a night can be affected by the passage of a frontal system when the light level remains low until the frontal cloud cleared by 0100, after which time the light increased. Consequently the use of NVGs would have been, at best, marginal until this time.

Thermal-imaging devices are also being fitted to many aircraft; although these also provide 'night vision' they do not have an all-weather capability. Cloud and rain can obscure the image and reduce the range at which targets can be detected to an unacceptable limit. Computer models which combine the characteristics of such sights with the relevant weather information and then predict the performance parameters for such devices (e.g. target detection and lock-on ranges) are currently being evaluated by Met O 6.

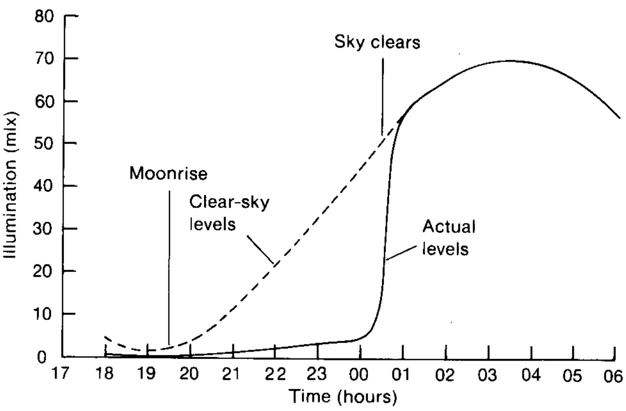

Figure 6. An example of the way in which the passage of a frontal system can alter the natural illumination levels at night; for comparison the clear-sky levels are also shown. A moon phase of 75% was specified with moonrise at 1930 and a front clearing by 0100.

Radars are employed on a wide variety of tasks and platforms by the Armed Forces. It is well known that the coverage of radar systems can be severely affected by the atmospheric conditions (Turton, Bennetts and Farmer 1988). Under some circumstances part of the radar beam can be trapped, forming a duct with coverage out to exceptionally long range. However, above the duct there is a region where less radar energy penetrates, such that targets may escape detection. This is illustrated in Fig. 7, where a radar coverage in ducting conditions is shown alongside the 'normal' coverage of the same radar; here the differences are due solely to the atmospheric conditions.

Weather also affects the mobility of Army ground forces. Previously, assessments of manoeuvrability were made manually by Force Commanders using all the information available to them. This is a formidable task and is well suited to computerized techniques. Detailed databases for evaluating the military options are being developed in the Army TERAS (TERrain Analysis System) programme. TERAS will consist of a detailed topographic database and climate information, together with environmental and battlefield data. The environmental data, which includes meteorology, is a vital part of TERAS and will require the forecaster to regularly update and amend the meteorological input. It is expected that the various TDAs as discussed above will eventually be incorporated into TERAS.

10. Concluding remarks

Part I (Caughey and Davies 1989) of this article gave a description of the way in which services for Defence have developed in the Meteorological Office, since its inception to the present day. Major developments in these services occurred in order to meet the demands of the military during the two World Wars. Just before the Second World War, the Defence Services Branch was formed. Since then, the Branch has been involved in providing meteorological assistance to the Forces world-wide.

This paper has discussed the wide range of services currently provided for the Armed Forces, MOD and other government departments. In recent years advances in computer technology have changed the face of operational meteorology. As forecast models have become ever more sophisticated with higher resolutions, the accuracy of their predictions has improved significantly. High-speed communications (e.g. WIS) are already giving outstation forecasters rapid access to a wider array of observational data and forecast products, enabling them to give much more accurate meteorological advice.

Another development that is likely to prove important in forecasting is the development of artificial intelligence and expert systems. The latter are computer programs which can apply reasoning and judgement to a particular problem. Already, pilot projects on expert systems for predicting precipitation and thunderstorms are under way at the Meteorological Office (Conway 1989). Such techniques are potentially of great benefit to the Defence Services forecaster.

New technology is also being employed by the Services (e.g. electro-optic imaging and ranging devices). However, the performance of such equipment is weather sensitive, and the forecaster is being asked to give advice on the use of this equipment. Computer programs and models (TDAs) are being introduced to assist the forecaster in this area. Another key area of current concern is the acquisition of meteorological information from data-sparse or battlefield areas, required as input to the meteorological forecast models, the TDAs and TERAS.

Given improved observational data, better numerical forecast models, forecasting algorithms and artificial

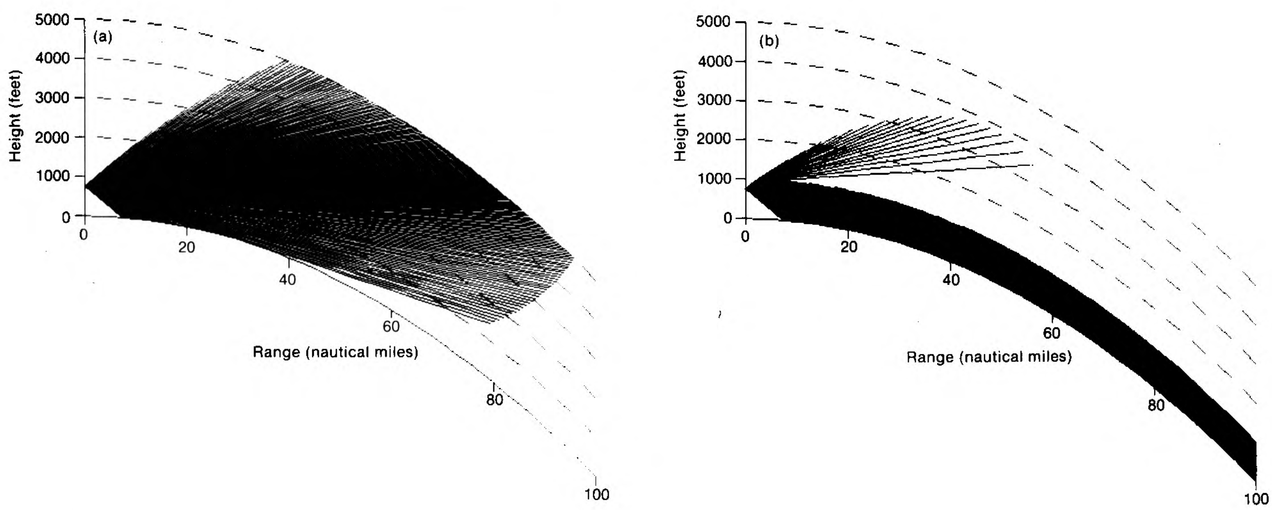

Figure 7. Radar coverage diagrams in (a) normal and (b) ducting conditions, where a surface-based duct 1000 ft deep was specified with the radar at 750 ft height.

intelligence systems, the demanding local forecasting task of the Defence Services forecaster will become more tractable. However, there is an increasingly important need for advice relating to the impact of meteorology on military equipment and operations. The preparation and dissemination of this type of advice will demand the adoption of new skills and computer techniques. The most effective presentation of these new products to the user will require excellent links between Meteorological Office (WIS) and military automatic data processing facilities. As far as one can judge, the outstation meteorologist will continue to have an expanding and important role in support of the Forces, assisting them to conduct vital operations and exercises in the years ahead.

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Westward-moving disturbances in the South Atlantic coinciding with heavy rainfall events at Ascension Island

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Summary

Easterly atmospheric waves in the northern hemisphere have been well documented but much less is known about similar features in the southern hemisphere. A study of upper-wind time cross-sections maintained at Ascension Island during the early part of 1986 suggests that features with similar characteristics to easterly waves affected the island, probably triggering several heavy rainfalls which occurred during that time. Some evidence is produced that the 15-level model of the Meteorological Office is able to reproduce these disturbances.

1. Introduction

Ascension Island is situated at 8° S, 14° W in the South Atlantic (Fig. 1). It is a small isolated island, 1450 km from Africa, over 1600 km from South America and 1100 km north-west of its nearest neighbour and mother colony, the island of St Helena. In recent years Ascension Island has played an important role as a staging post between the United Kingdom and the Falkland Islands.

All available literature about the climate of Ascension Island (see Hodges (1985) for a comprehensive list of references) and the experience of Meteorological Office staff based on the island (Brenchley 1986) indicates that Ascension Island has a very pleasant tropical climate. It is predominantely dry, apart from (in some years) spells of 'drizzly' showers, sometimes several such spells occurring over a period of a month or more. However, in some years there are infrequent rainstorms occurring mostly in March and April. Table I shows some of the heavy rainfalls reported on Ascension Island. It should

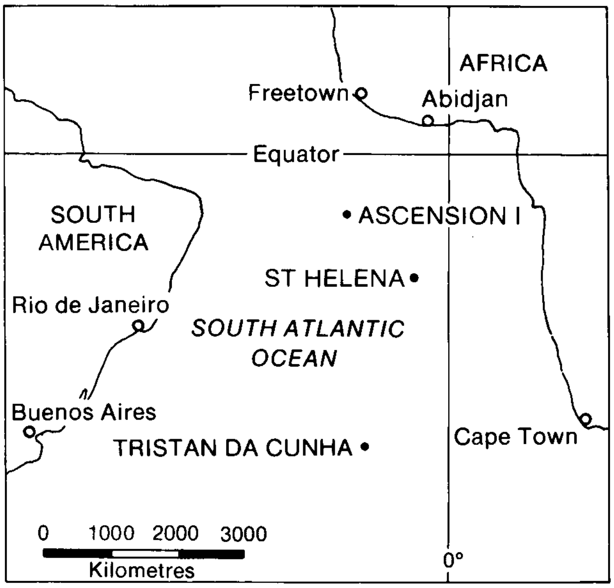

Figure 1. Location of Ascension Island.

Table I. Heavy rainfall reported on Ascension Island

Year	Month (if known)	Event
1831	—	'Dampier's tank*' damaged by heavy rains.
1859	June	'Great rains', 9 inches (229 mm) in a day with damage to roads and crops. 20 inches (508 mm) fell in June and 108 inches (2743 mm) were recorded in the year at Green Mountain (see Farm Site Fig. 2).
1864	April	Very heavy rainfall, thunder and lightning.
1887	April	Great damage to roads. Yearly total 56 inches (1422 mm) at Green Mountain.
1896	—	'Unusual thunderstorm'; Capt. Napier's Japanese steward 'revived by a good brandy' after being struck down when the overhead telephone wire was hit by lightning.
1899	May	Heavy rainfall.
1909	April	Heavy rainfall.
1924	April	'Freak' rains; 5.62 inches (143 mm) fell at Georgetown during the month. Waist-high grass over low ground and a plague of insects.
1934	April	Torrential rains, an 'astonishing cloudburst' —209.6 mm fell in 12 hours 29/30 April at Georgetown.
1950	March	75 mm of rain during the month at Georgetown.
1963	March	'Great rainstorm'; 96.5 mm fell on 29 March at Georgetown. Extensive damage to roads, cemetery flooded, landslides.
1964	April	95 mm of rain during the month at Georgetown.
1974	March	90 mm of rain fell during the month at Georgetown.
1978	—	Annual rainfall total at Two Boats village 48.5 inches (1232 mm).
1979	April	80 mm of rain fell during the month at the Pan Am site at Wideawake Airfield.
1984	March	317 mm of rain during the month at the RAF base at Wideawake Airfield. Runway closed on 4 March due to erosion and boulders; road damage.
1985	April	538 mm of rain measured at Traveller's Hill during the month; 145 mm fell at the RAF base in one day on 7 April.
1986	April	67 mm of rain fell at Traveller's Hill on 9 April; 'spectacular lightning display'.

* Two large stone water tanks built by the famous buccaneer, explorer and Admiralty hydrographer, William Dampier, on the lower slopes of Green Mountain can still be seen today.

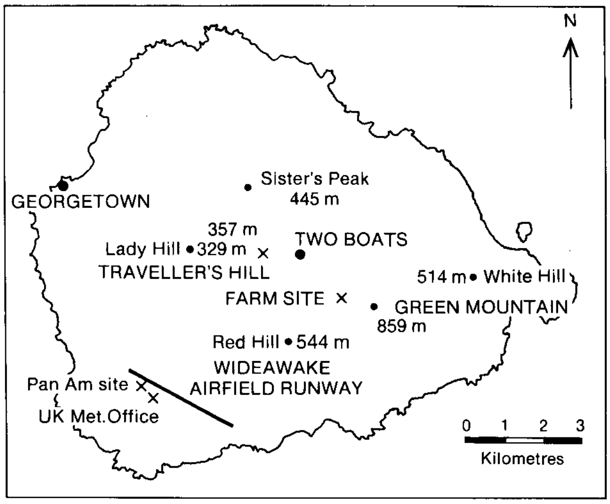

Figure 2. Ascension Island, including the locations of places mentioned in the text.

be noted that records are probably only reasonably reliable since 1924 when regular readings were started at Georgetown (Fig. 2). Not every heavy rainfall event is included in the Table, only those of interest.

In 1984, 1985 and 1986 heavy rainfall occurred on the island — some falls heavy enough to cause flooding, soil erosion and road damage. These events also had serious consequences for aviation. For example, George (1984) described how the pilot of an RAF Hercules aircraft returning from the Falklands had great difficulty in landing his aircraft at Ascension Island (Wideawake) airfield owing to a severe storm on 4 March 1984. The pilot was considering 'ditching' when the navigator spotted the rock-strewn runway through a gap in the cloud; the pilot managed to land the aircraft safely with only 30 minutes of fuel remaining. In another incident, on 15 October 1985, a Boeing 747 was diverted to Abidjan, Ivory Coast, because of low stratus associated with frequent showers. These, and several other less serious incidents, warranted an investigation into the possible causes of such poor weather.

It is important to point out that, as the local investigation proceeded, it became clear that the lighter 'drizzly' showers are usually associated with very shallow low-level instability (cloud tops often limited to 5000 feet under the inversion of the sub-tropical high). Patchy low stratus beneath these showers is a significant hazard to aircraft on descent into Ascension, but is an entirely different forecasting problem. This occurs with the greatest frequency from August through to January with much year-to-year variation and some problem-free years. Here consideration is given to the possible causes of the heavier, deeper instability-controlled showers which occur mainly during March and April and may be associated with easterly waves.

2. Investigation

The heavy rainfall events in 1984, 1985 and 1986 appeared to be linked with the passage of westward-moving disturbances rather than local or diurnal convective development (Johnson 1978, Ross 1985). Studies of the satellite picture sequences leading up to the heavy rainfall events revealed that the origin of the disturbances was Africa, probably over the Congo basin in Central Africa. This suggests similarities with the easterly waves in the North Atlantic which originate over West Africa (Albignat and Reed 1980). The subsequent investigation had three objectives:

(a) To devise some forecasting rules for predicting heavy rainfall on Ascension Island in the South Atlantic.

(b) To establish whether such heavy falls are associated with easterly waves.

(c) To examine examples of 15-level model analyses to see whether they are capable of reproducing the changing wind-field profiles associated with the passage of these disturbances.

Before describing the results it is important to state the limitations of the investigation:

(a) Little success has been achieved locally at Ascension Island in using temperature and humidity soundings to confirm or predict changes in instability. Vertical motion can only be inferred from known changes in upper-wind profiles derived from once-daily soundings (American radiosonde data are available for 1200 GMT only, Monday–Friday inclusive).

(b) Cross-sections of the variation of upper winds with time were only available for the period 20 January–30 April 1986 but model wind-field analyses (including vertical profiles) were available, for the 3 years 1984–86.

(c) To enable direct comparison between radar winds and model wind fields, the investigation has been deliberately limited to horizontal wind components.

(d) Although Ascension Island covers an area of only approximately 35 square miles, it is quite common for downpours to affect one part of the island whilst other regions remain virtually dry. The heavy falls noted in Table I were recorded at a number of different sites (Fig. 2).

3. An example of the changing upper-wind profiles

In order to study temporal changes in vertical wind-structure at isolated locations where radar-wind information is available, vertical wind-profiles can be plotted as time cross-sections. This method was introduced at Ascension Island early in 1986 and produced some interesting results. In January 1986, a heavy rainfall event occurred after a marked change in vertical wind-profile (Fig. 3). On 21 January the strongest winds were at a level of 5 km — north-easterly 25 kn. By 24 January, as indicated by the 25 kn isotach on the profile, the zone of strongest winds had lowered to between 3 and 4 km and veered* to easterly. During the weekend 25–26 January, no upper-air data were available but by Monday 27 January it was evident that the lower-level winds had veered to around 140° (from the usual 110°) and the strong middle-level easterlies had ceased. Over 40 mm of rain was recorded at Traveller's Hill (Fig. 2) on 28 January and by 29 January the winds between levels of 5 and 6 km had backed to 070° whilst at low-levels they had returned to their normal direction and rainfall had ceased. Some kind of 'disturbance' can

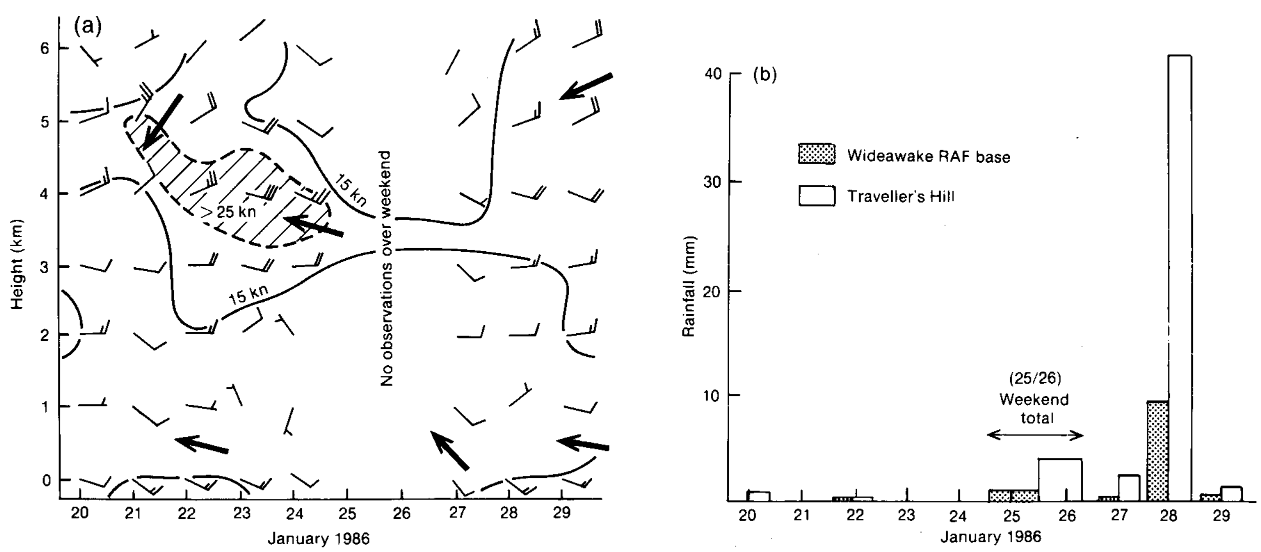

Figure 3. (a) Variation of upper-air winds with time, and isotachs added for clarity, for the period 20–29 January 1986 at Ascension Island. The wind arrows indicate horizontal wind speed and direction as in conventional weather symbol plotting. The bold arrows also indicate horizontal wind direction but, only approximately, speed; they are shown to emphasize the significant changes of wind, and (b) daily rainfall at two sites for the same period.

*In this article veering indicates the wind direction increasing in azimuth (measured N–E–S–W) and vice versa for backing. Among forecasters the opposite convention is used in the southern hemisphere.

readily be seen to have passed westwards over Ascension Island.

4. The onset and duration of heavy rain

A careful analysis of a number of case studies from early 1986 indicated that the structure of the disturbances associated with heavy rain was similar to that of the easterly waves found in the North Atlantic. Fig. 4 shows schematically the low-level structure of the disturbances associated with heavy rainfall found in the southern hemisphere, and their vertical structure is given in Fig. 5. In most cases, small pressure changes (of the order 0.5 to 1.0 mb) occurred over and above the normal diurnal variation. Generally, veering surface winds were associated with pressure falls and backing winds with pressure rises. Vertical motion could be inferred from cloud behaviour near to the rainfall event: ascent, by towering cumulus or cumulonimbus clouds, increasing both in height and extent prior to the falls, and subsidence by clouds decaying rapidly after the trough or wave. In each case studied the trough or wave axis exhibited a slope with height, a similar finding to that of

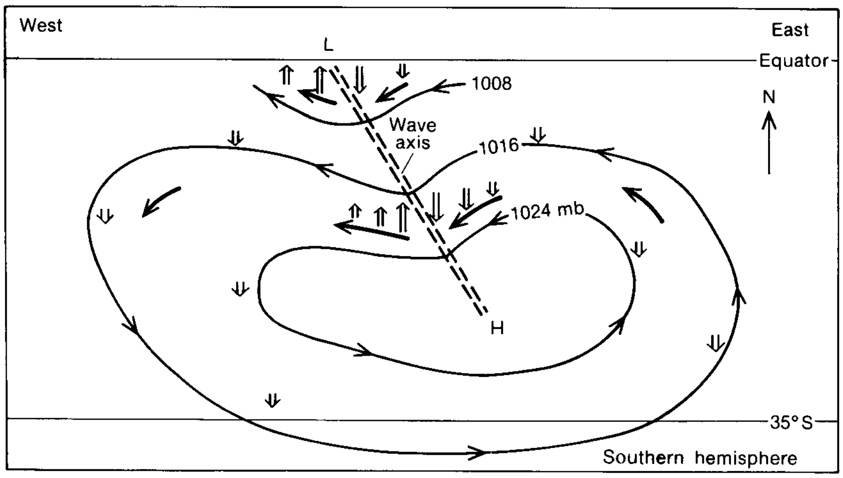

Figure 4. Schematic diagram of an easterly wave in the southern hemisphere (horizontal structure at low levels). The bold arrows are as in Fig. 3 and the hollow arrows give some indication of the direction and magnitude of the associated vertical motion.

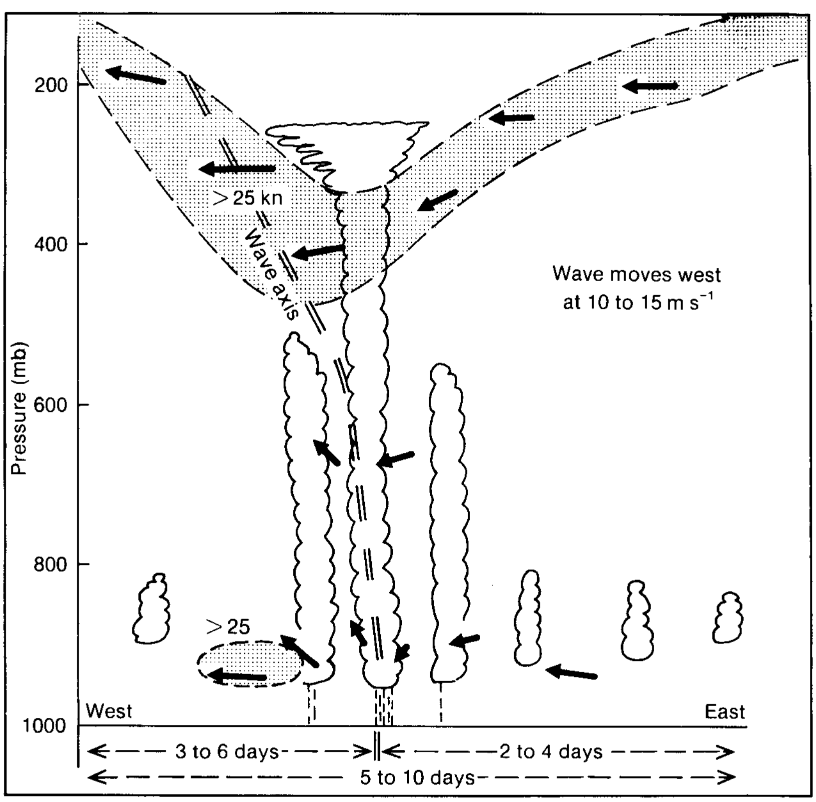

Figure 5. Schematic diagram of an easterly wave in the tropical southern hemisphere (vertical structure). The symbols are as in Figs 3 and 4. The horizontal scale shows the approximate time that the wave takes to travel across the longitude of Ascension Island.

Albignat and Reed (1980) who concluded that easterly waves sometimes show a tilt characteristic of baroclinic disturbances.

In late summer (January and early February) in the vicinity of Ascension Island, as a result of strong westerlies aloft, marked wind shear usually exists at around 10 km, thus limiting vertical stability and allowing isolated moderate to heavy showers rather than violent downpours. However, as autumn approaches and upper winds reverse to easterlies, deep convective clouds can form with cloud tops reaching 12–15 km. It is possible that it is easterly waves which trigger the storms over Ascension Island. A study of the lengths of showery periods during 1986 revealed a strong link between these and the rapidity of onset and lowering of the zone of stronger easterly winds aloft. Prior to short showery periods of only a day or so, the onset of strengthening easterlies was quick (only apparent 1 or 2 days before the showers). However, when the easterlies strengthened to 25–35 kn over a greater depth, say 4–5 km, and over a period of 3 or 4 days, then an unsettled period lasting 3 or 4 days followed. The cessation of showery activity coincided with the return of middle-level easterly wind speeds to the normal values of 10–15 kn.

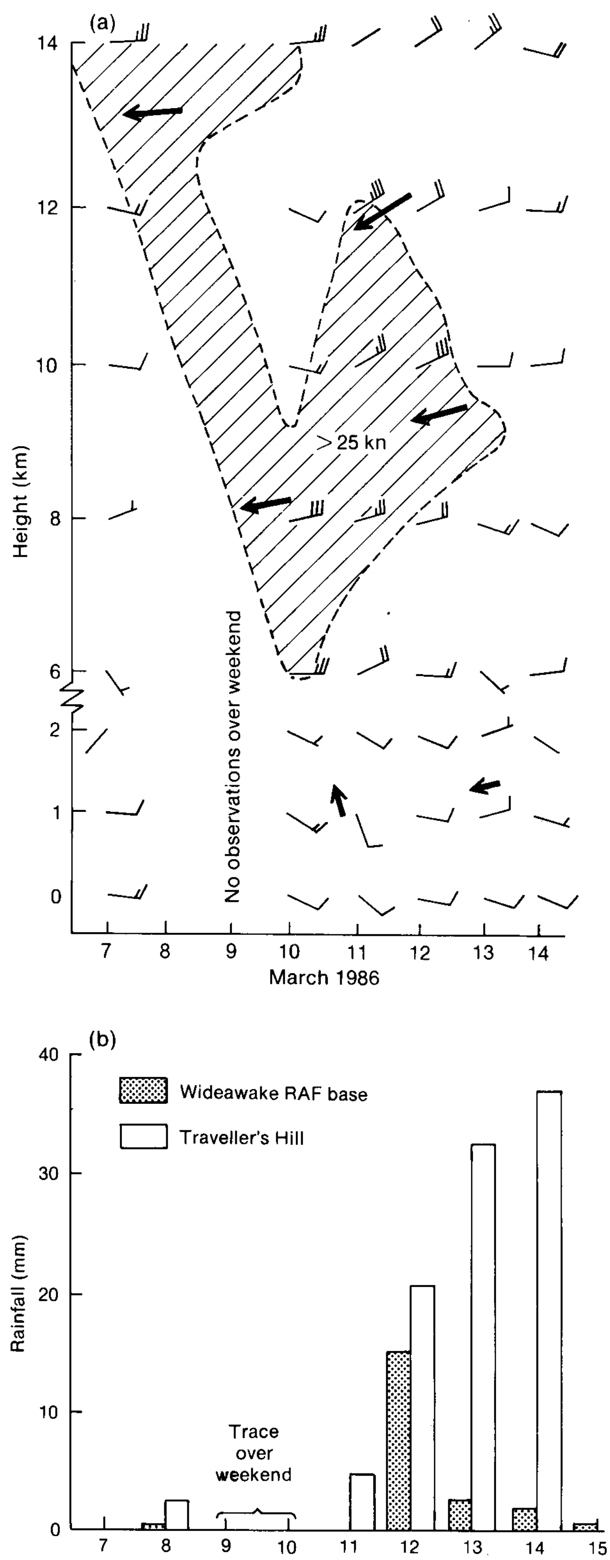

Figure 6. As Fig. 3 but for 7–14 March 1986.

Fig. 6 shows an example of a time cross-section of the upper winds associated with heavy rainfall. The marked 'slopes' indicated by the 25 kn isotach indicate the lowering and subsequent retreat of the stronger easterlies very well. This example confirms the lowering of stronger upper easterly winds prior to a period of heavy rainfall and shows evidence of one or more weather troughs at low level (rainfall was not continuous during this period but comprised heavy, showery bursts). In this instance, lowering of the 25 kn isotach took 3–4 days with the subsequent showery periods lasting also 3–4 days.

5. Analyses from a global model

Divergence and convergence clearly play an important role in controlling the degree of vertical motion involved. Preliminary study of the operational analyses from the global model of the Meteorological Office (Bell and Dickinson 1987) has shown that the model is capable of indicating middle-level (700–500 mb about 3.5–5.5 km height) divergence and low-level (900–850 mb about 1.5 km height) convergence coinciding with rainfall events. An example for 4 March 1986, has been chosen because (unlike the one given in section 4 covering 7–14 March) a short period of heavy rain only was involved with no interruption of radiosonde data, enabling comparison of measured with model winds. On this particular occasion, changes in low-level winds were minimal but at 6–7 km (500–400 mb) both measured wind profile (Fig. 7) and spatial model wind-field (available for 500 mb, about 5.5 km height — Fig. 8) indicate divergence near, or moving away west from Ascension.

A month or so later, during the night of 9/10 April 1986, spectacular displays of lightning, thunderstorms and torrential rain occurred over Ascension Island. The event was different from those observed previously, in that it was preceded by an increase in upper westerly winds at heights between 9 and 15 km. The ability of the model to depict very accurately the changes in wind

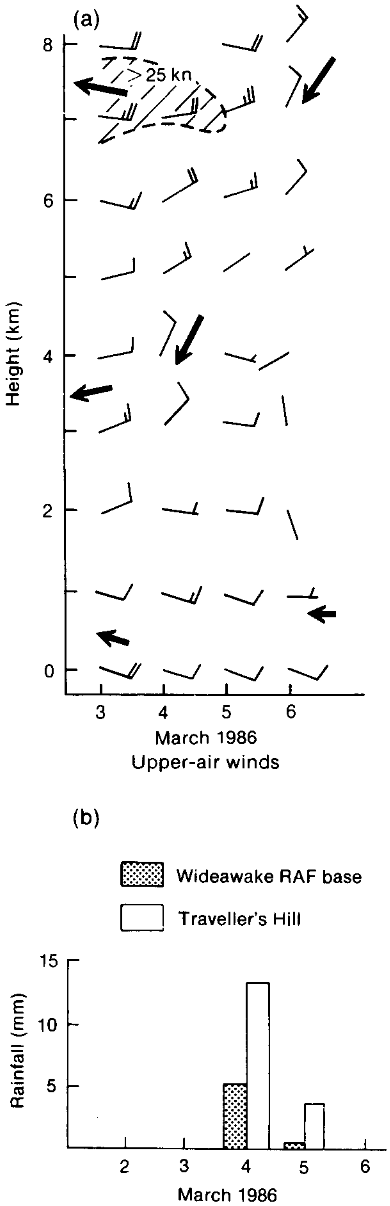

Figure 7. As for Fig. 3 but for 3–6 March 1986.

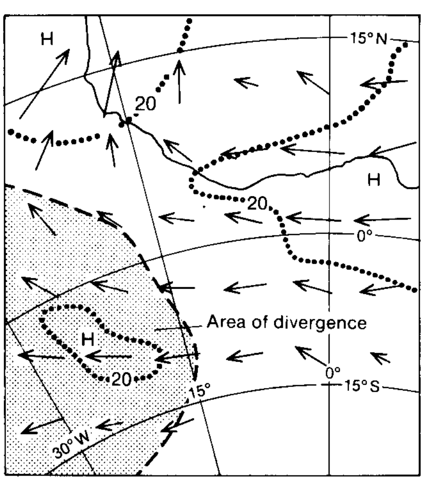

Figure 8. 500 mb horizontal wind-field for 00 GMT 3 March 1986 showing area of divergence west of Ascension Island and the 20 kn isotachs.

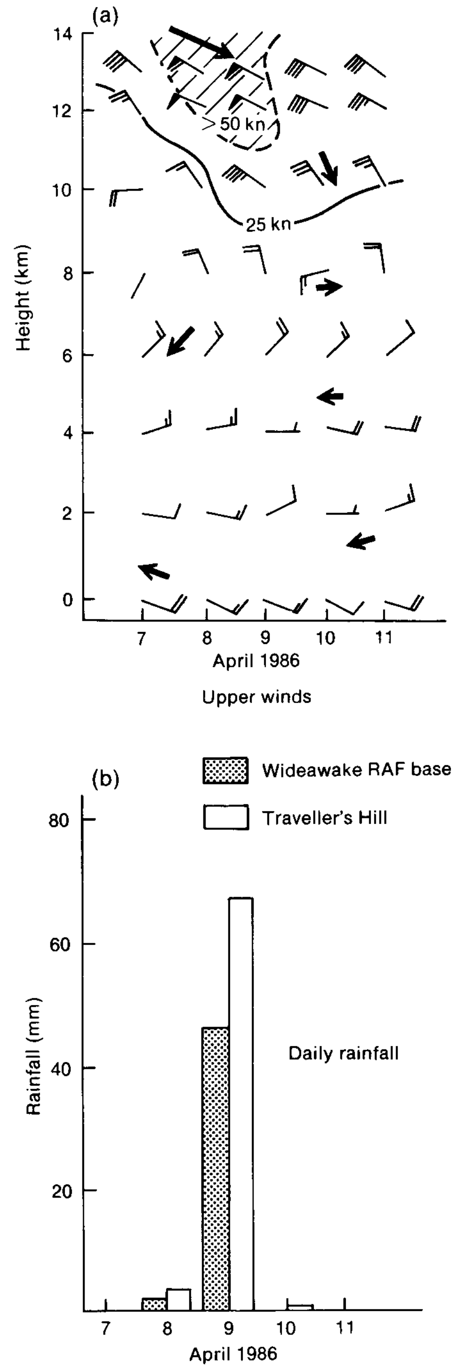

Figure 9. As for Fig. 3 but for 7–11 April 1986.

profile which took place is demonstrated by comparison of Figs 9 and 10.

6. Concluding remarks

A careful study of satellite picture sequences, linked with use of a time cross-section of upper-wind profile changes, can give useful indications of the approach of disturbances likely to give severe weather at Ascension Island. The following are forecast rules based on the study:

(a) On the vertical time cross-section, look for lowering of strong wind zones, combined with a veering of middle-level winds. Initially, strong

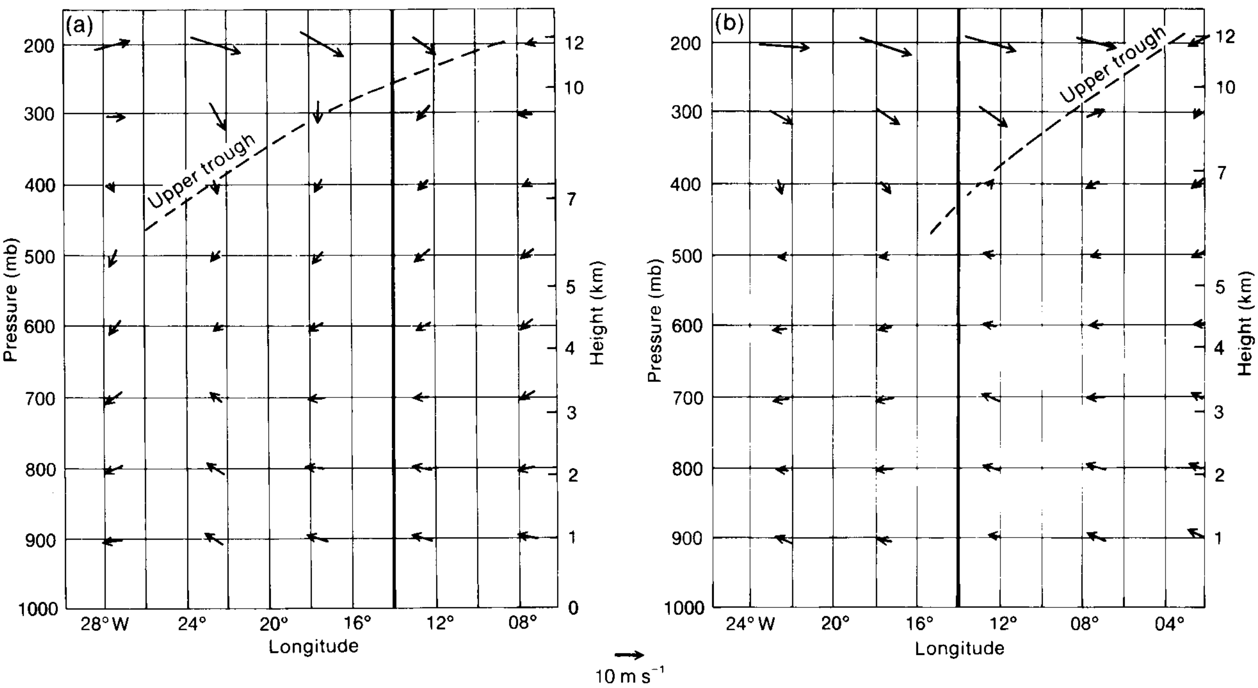

Figure 10. (a) Variation with longitude of the vertical profile of horizontal wind at the latitude of Ascension (8° S) for 12 GMT on 7 April 1986 from the Meteorological Office global model analysis, and (b) as (a) but for 12 GMT on 10 April 1986. The longitude of Ascension Island is highlighted.

middle- to upper-level winds will tend to inhibit shower activity but once the strongest winds have propagated downstream of the station and the height of the 25 kn isotach (for example) starts to increase, heavy showers are likely to develop as wind shear decreases.

(b) A slow lowering of the upper strong wind zone will lead to longer unsettled periods, roughly equal to the number of days that the 25 kn isotach takes to lower. This is simply because the larger the scale of the disturbance, the greater the period of passage over any one point.

It has been found that the disturbances which affect Ascension Island from time to time have the characteristics of the well-documented easterly waves of the North Atlantic. By study of satellite pictures, their origin is almost certainly central equatorial Africa, and rainfall and climate records confirm that March and April are the months of maximum activity. Also, retrospective inspection of the Meteorological Office archive of global operational analyses, using horizontal wind components, has provided encouraging evidence of the ability of the global model's analyses to depict upper-air disturbances affecting Ascension Island, which have the characteristics of easterly waves.

The scope of this paper has been limited by circumstances to model analyses. However, there is a good case for taking the next step in seeing if the global model can forecast the development and movement of easterly waves. If proved successful, then output in a form similar to the examples given should be made available to forecasters at remote locations such as Ascension Island in order to enhance forecasting techniques.

Acknowledgements

To R.M. Morris, Dr R.A. Bromley and Dr R.W. Riddaway for their constructive comments, to forecaster colleagues at Ascension Island for their co-operation during my 6-month detachment, especially the late J. Bush, and to S. Ineson for her help in accessing the analyses from the Meteorological Office global model.

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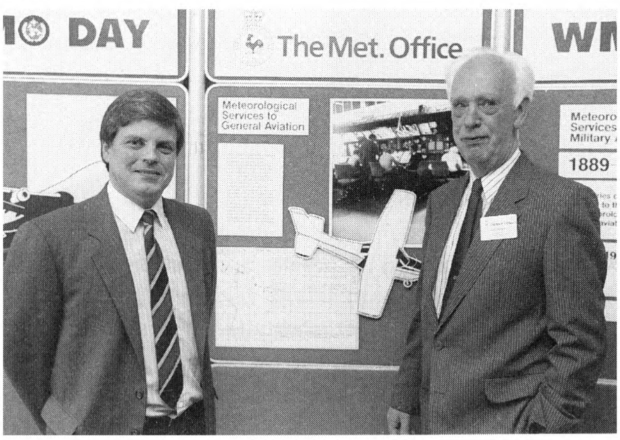
Notes and news

The Meteorological Office celebrates World Meteorological Day 1989

On 22 March this year the Meteorological Office at Bracknell entertained about 50 representatives of the civil aviation industry, as the UK contribution to the celebration of World Meteorological Day (strictly 23 March), and the theme for the year, 'Meteorology in the Service of Aviation'. The visitors represented a wide range of the aspects of aviation — carriers, operations, ground support, technical developments, controlling bodies — and several journalists from aviation publications also attended. Staff from Branches of the Office responsible for Marketing, and for Forecasting, acted as guides.

The guests first assembled in a room containing a series of display boards showing the development of meteorological services to both civil and military aviation. The boards commenced with the crude weather information made available to early balloonists, including a European surface chart for 22 March 1889, exactly 100 years previously, and ended with an example of a flight briefing chart for the same area for 22 March 1989.



Mr Ken Pollard (right), Director of Aviation Services, Meteorological Office, Bracknell and Mr Tim Guest, Manager of Flight Crew Briefing for British Airways, in front of one of the display boards.

The visitors were then welcomed by the Office's director of Marketing Services, Mr Francis Hayes, who introduced Mr Ken Pollard, the Office's Director of Aviation Services. In his address, Mr Pollard started by mentioning the Office's role in aviation meteorology as a World Area Forecast Centre (WAFC), Regional Area Forecast Centre (RAFC) and as a National Forecast Centre. As a WAFC the Office uses its sophisticated 15-level numerical forecast model, supported by powerful computer capability to produce global grid-point forecast fields of relevant meteorological variables. These are issued to RAFCs, with a back-up procedure involving the other WAFC at Washington to guard against rare cases of system failure. As an RAFC the Office uses the grid-point data to produce regional charts and significant weather charts, and these three types of data are interchanged with neighbouring RAFCs. Finally as a National Centre, RAFC-produced charts, low-level weather and wind charts, TAFs, trends, SIGMETs and aerodrome warnings are issued. The provision of equivalent tail-wind components also contributes to the support of general services to aviation.

The method of disseminating weather information to the aviation industry was next described; it was stressed that information transfer often used technologies which were becoming obsolete in contrast to the rapid developments in forecasting, and that this was a handicap for many aviation customers.

Mr Pollard went on to describe other meteorological products which would be of value to aviation operators but which at present were not available because of limitations in communications. These included weather radar and satellite images giving information about rainfall at airfields, forecasts of surface temperature, detailed wind forecasts for Air Traffic Controllers and objective forecasts of significant weather. Finally he spoke briefly about new methods of disseminating information for briefings, operations and flight planning.

The visitors were then shown around the Central Forecasting Office (CFO) where several demonstrations had been organized. These included:

Mr Martin Morris, Head of the Central Forecasting Office, Bracknell talking to visitors to the CFO.

MARS — the Met and AIS Retrieval System (AIS — Aerodrome Information System) being developed by the UK Civil Aviation Authority and due to become operational during 1989. This is an interactive system in which pilots can receive flight weather briefings, aerodrome information or other relevant data via visual display units linked to a central computer at London (Heathrow) Airport. It is planned that the terminals will be installed at all the larger airports in the United Kingdom and that this will become the standard briefing method.

Air Data — a commercial micro-computer-based system developed by Air Data Limited, a British company, for use by airline operators required to make operational decisions concerning the distribution of flight plans, evaluation of aircraft and route costs, and the management of aircrew. The occasion was used to promote their flight planning system which uses equivalent tail-wind components, calculated at Bracknell from all the forecast wind data available. This system reduces the errors introduced by interpolation from the standard coarse grid of data, inherent in all other flight planning systems.

The visitors were also shown a demonstration of the use of document facsimile for transmitting briefing charts (a system which is believed to have considerable potential with the steadily reducing costs of facsimile machines). Users could dial into the facility and automatically receive a pre-determined set of charts or other information. The use of the FRONTIERS weather radar system for producing 6-hour forecasts of rainfall over the United Kingdom and the general work of aviation forecasters were also explained.

The visitors were given copies of the literature from Geneva specially prepared for this important day in the WMO's calendar, including the interesting document WMO-No. 206 by J. Kastelein (President, WMO Commission for Aeronautical Meteorology) which describes the development of meteorological services for aviation.

The 3rd Workshop on Operational Meteorology, 2–4 May 1990, Montreal, Québec, Canada

The 3rd Workshop on Operational Meteorology, sponsored by the Atmospheric Environment Service of Environment Canada and the Canadian Meteorological and Oceanographic Society, will be held on 2–4 May 1990 at L'Université du Québec à Montréal. The principal theme of the workshop will be 'Weather Services of the Future'. A number of other topics in operational meteorology will also be included.

The Program Committee wishes to solicit papers on the following topics:

Short-term forecasting and meso-meteorology (observations, analysis, diagnostics, forecast techniques and dissemination)
Bridging the gap between research and operations
User requirements
Tomorrow's weather offices.

The format will consist of submitted papers, invited papers, panel discussions, and poster and demonstration sessions as well as 1- and 2-hour laboratory sessions. A brief introduction of each poster presentation will be given in an appropriate oral session.

Titles and reviewers' abstracts of 400–1000 words should be sent by 1 November 1989 to:

Stan Siok
Program Committee Co-chairman
Atmospheric Environment Service
3rd Floor
100 Alexis Nihon Blvd
Ville St-Laurent
Québec H4M 2N8
Canada.

Authors should indicate their preference for presenting their paper orally, in a poster session, as a demonstration, or in a short laboratory session (1 hour). Preferences will be considered to the extent possible. Abstracts will be evaluated on their relevance to the theme as well as on their quality. Papers not related to operational meteorology will not be accepted. Authors will be notified by 15 December 1989 with respect to both the acceptance of their abstract and instructions on the format of their papers.

Complete camera-ready papers of no more than eight pages, including diagrams, must be received by the program co-chairmen no later than 1 March 1990. A preprint volume will be prepared and distributed to workshop registrants. Papers and abstracts may be in either English or French. For additional information contact either Stan Siok (514-283-1139) or Peter Zwack (514-282-3304), Program Committee Co-chairmen.

Books received

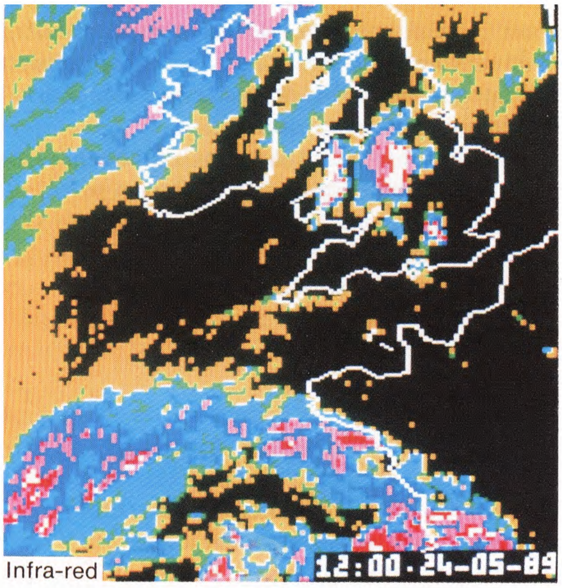
The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

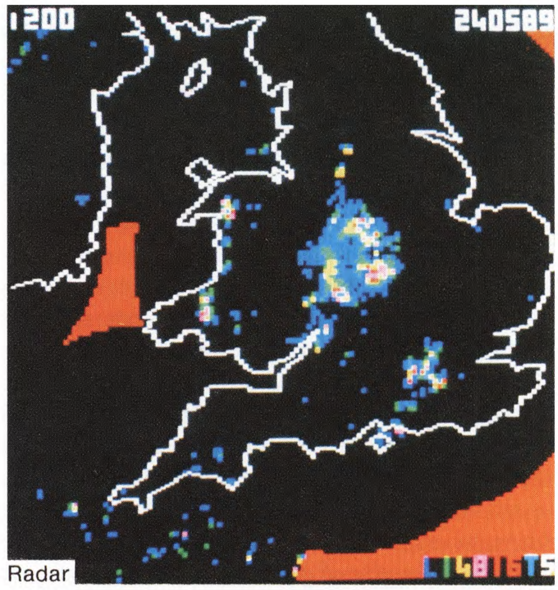
Weather sensitivity and services in Scotland, edited by S.J. Harrison and K. Smith (Edinburgh, Scottish Academic Press, 1989. £25.00) is the outcome of a conference held at the University of Stirling in February 1988. It is an example of the benefits which can be derived from the effective use of weather and climate information, which could be a model to policy-makers world-wide.

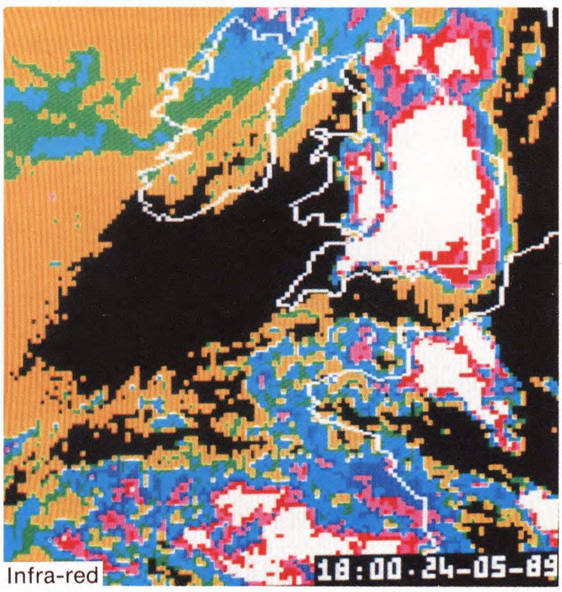
Correction

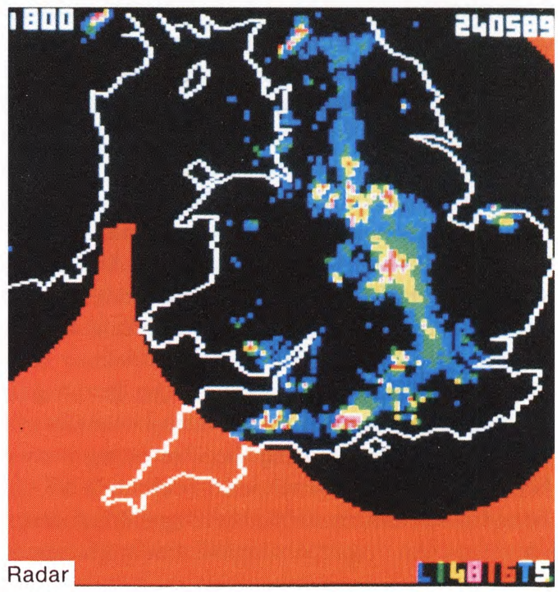
Meteorological Magazine, June 1989, p. 126, caption to Fig. 10. The section in brackets should have read: '(2123 GMT on 25 April 1986 to 0000 GMT on 27 April 1986)'.

Satellite and radar photographs — 24 May 1989 at 1200 and 1800 GMT



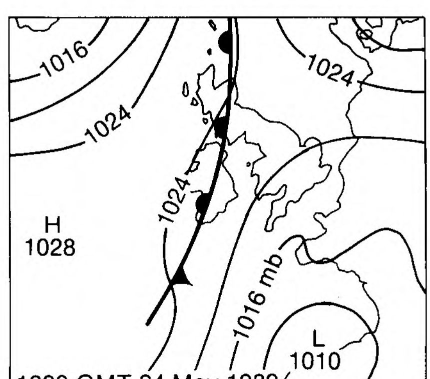






Thunderstorms affected many inland areas of England and Wales on 24 May 1989, and were locally severe with large hailstones, and causing flash flooding. South Farnborough in Hampshire recorded 56 mm of rainfall between 1200 and 1330 GMT.

The development and organization of the storms could be monitored by means of the frequent (½-hourly) images from Meteosat and the UK weather radar network. Shown above are images for 1200 GMT — in the early development phase of the thunderstorm complex to the west of London, and 1800 GMT — by which time the combined anvil cirrus shield of the mature complex covered much of central England. The surface chart for 1200 GMT is included for reference. In the infra-red images, the colour sequence: black, yellow, green, cyan, blue, magenta, red and white represents the transition from warm to cold. The radar colour sequence: blue, green, yellow, pink, red and cyan represents progressively increasing rainfall rates.



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Content

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Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (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.

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'.

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

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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August 1989

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Investigation of a cyclogenesis event, 26–29 July 1988, using satellite imagery and numerical model diagnostics

M.V. Young
Meteorological Office, Bracknell

Summary

This paper examines a cyclogenesis event which was accompanied by heavy rainfall over North Wales and northern England. Satellite imagery revealed a distinct double structure to the cloud pattern prior to cyclogenesis, each cloud element corresponding to a well-defined frontal zone and rain band. The regions of cloud and precipitation were related to distinct ascending warm conveyor belts, the configuration of which bore a marked similarity to some other cases of cyclogenesis. The fine-mesh numerical-model forecast based on data at 06 GMT on 28 July 1988 gave a far superior forecast of rainfall to that based on data received 6 hours earlier. Differences between the two model runs could be attributed to aircraft reports which were available for the 06 GMT model run. Furthermore, clues in the imagery which could have helped the forecaster to improve upon the available numerical-model guidance are presented.

1. Introduction

On 28 July 1988 a deepening depression crossed the British Isles from the south-west giving very heavy rainfall in a band extending from Ireland, across the Irish Sea and North Wales, and into northern England (Fig. 1(a)). In the 12-hour period to 21 GMT on 28 July rainfall totals exceeded 20 mm over much of this area, with 49 mm recorded on Anglesey. By contrast, much of central and south-east Britain remained dry. Fig. 1(b) shows forecast rainfall totals for the period 06–18 GMT on 28 July derived from the fine-mesh model, data time 00 GMT on 28 July. Considerable totals were forecast for southern Britain which remained mostly dry, whereas over northern England, rainfall amounts were underforecast.

This paper examines reasons for the distinctive rainfall distribution, looking in particular for clues in the satellite imagery which could have alerted the forecaster to the poor numerical-model guidance. A simple airflow model is presented relating the cloud patterns to the weather distribution, and comparisons are made with other cases of cyclogenesis. Reasons for the poor guidance from the model's midnight run are also investigated.

2. Broad-scale evolution

The broad-scale evolution from 26 to 29 July 1988 as demonstrated in the imagery, the upper air and at the surface is shown in Figs 2 to 4. Late on 26 July two adjacent cloud structures (labelled F1 and F2 in Fig. 2(a)) accompanied the developing depression which lay within a strong baroclinic zone forward of a confluent upper trough (Fig. 3(a)). The double structure persisted as the system moved eastwards with the upper trough (Figs 2(b) and 3(b)).

A narrow band of cloud (with embedded convection), which extended south-west from F1, marked the

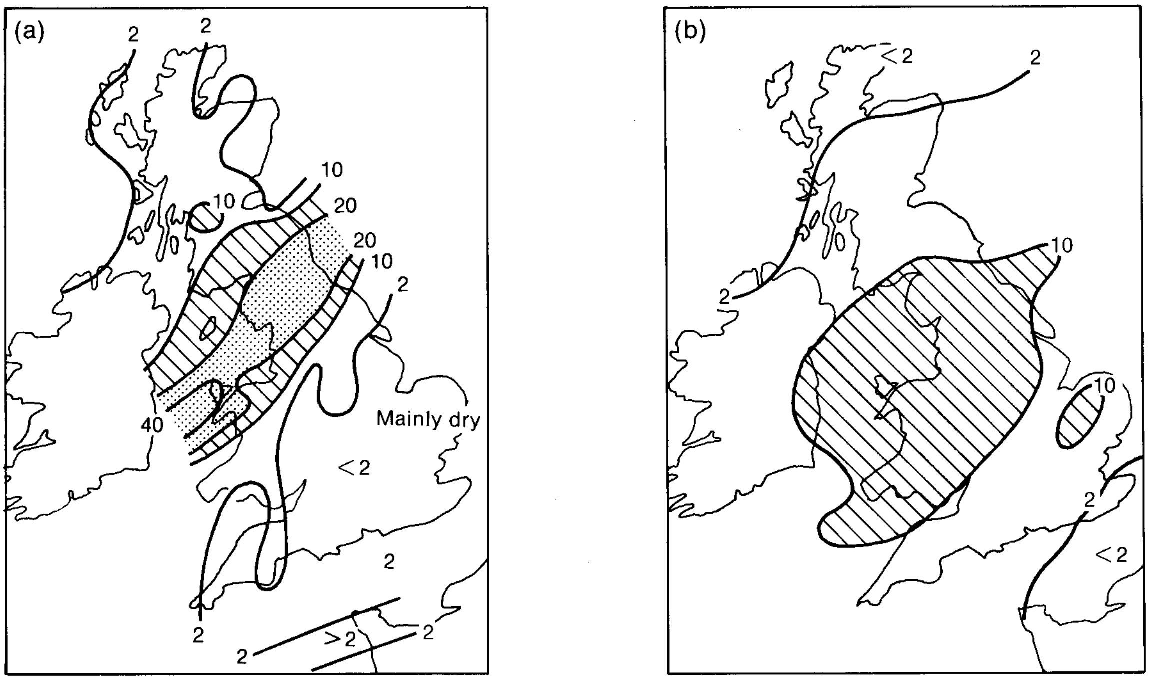

Figure 1. (a) Total rainfall (mm) during the period 09–21 GMT on 28 July 1988 (information derived from the London Weather Centre Daily Summary) and (b) total grid-point accumulations of rainfall (mm) forecast by the fine-mesh model for the period 06–18 GMT on 28 July 1988 using data for 00 GMT on 28 July. Hatching denotes accumulations greater than 10 mm and stippling denotes accumulations greater than 20 mm.

historical cold front (which will be referred to as the 'inner' or 'southern' front). The centre of the surface low lay further north, beneath an area of warm cloud-tops, between F1 and F2. Surface observations (Figs 4(a) and 4(b)) suggested that the surface low was part of a separate northern frontal zone corresponding to cloud mass F2, although this front was difficult to locate using the imagery alone. The relationship between F1, F2 and the surface features was preserved as the system crossed the British Isles during 28 July (Figs 2(d) and 2(e), and Fig 4(b). A movie-loop of Meteosat images highlighted plumes of thin cirrus (for example at 45° N, 25° W in Fig. 2(c)) moving rapidly east-north-east across the system. These delineated the jet-stream axis which lay between F1 and F2, indicated by UU on Fig. 2(d).

During 28 July, cloud area F2 expanded as it crossed northern Britain ahead of the sharpening upper trough, and contained much embedded convection. As the associated surface low deepened and developed a vigorous circulation over the North Sea early on 29 July (Fig. 4(c)), cloud area F2 began to rotate, forming a hook around the deepening low (Fig. 2(f)). Developing bands of deep convection extended southwards from the depression centre towards F1 through the area previously free of upper cloud. However, F1 and F2 were moving further apart in the increasingly diffluent flow ahead of the upper trough, so the two systems never merged completely.

The two separate well defined cloud-bands had important repercussions on the rainfall distribution (Fig. 5). The large area of heavy rain which moved from Ireland to northern England during the day was related to cloud mass F2. Along the north coast of France, a persistent band of heavy rain occurred beneath the narrow band of warmer cloud-tops FF in Fig. 2(d), which corresponded to the inner front. Maintenance of this overall pattern led to the rainfall distribution depicted in Fig. 1(a).

3. Three-dimensional structure

The rainfall distribution can be explained using the simple conceptual model shown in Fig. 6. The configuration of the conveyor belts shown in Fig. 6 was probably maintained throughout the life cycle of the system. This configuration is remarkably similar to that which accompanies 'instant occlusion' events (e.g. McGinnigle *et al.* 1988, Young 1988) Two main ascending warm conveyor belts (WCBs) were identified:

(a) W1, which was a gently ascending rearward-sloping flow giving rise to the broad cloud band extending from south-west to north-east across southern England and northern France. At its southern limit was the inner front marked by the rain band over the north coast of France. The northern limit of W1 was delineated by the band of cirrus, UU (Fig. 2(d)), marking the jet axis. Although UU appears separate from FF in Fig. 2(d), these two cloud bands will be shown to be part of the same frontal zone.

(b) W2, which emerged from beneath W1 and ascended rapidly over the intensifying northern frontal zone, producing the separate cloud canopy F2. This ascent, coupled with release of potential instability within W2 (shown by the lumpy cloud structure over south-east Ireland (Fig. 2(d)) led to widespread heavy rain as shown in Fig. 5.

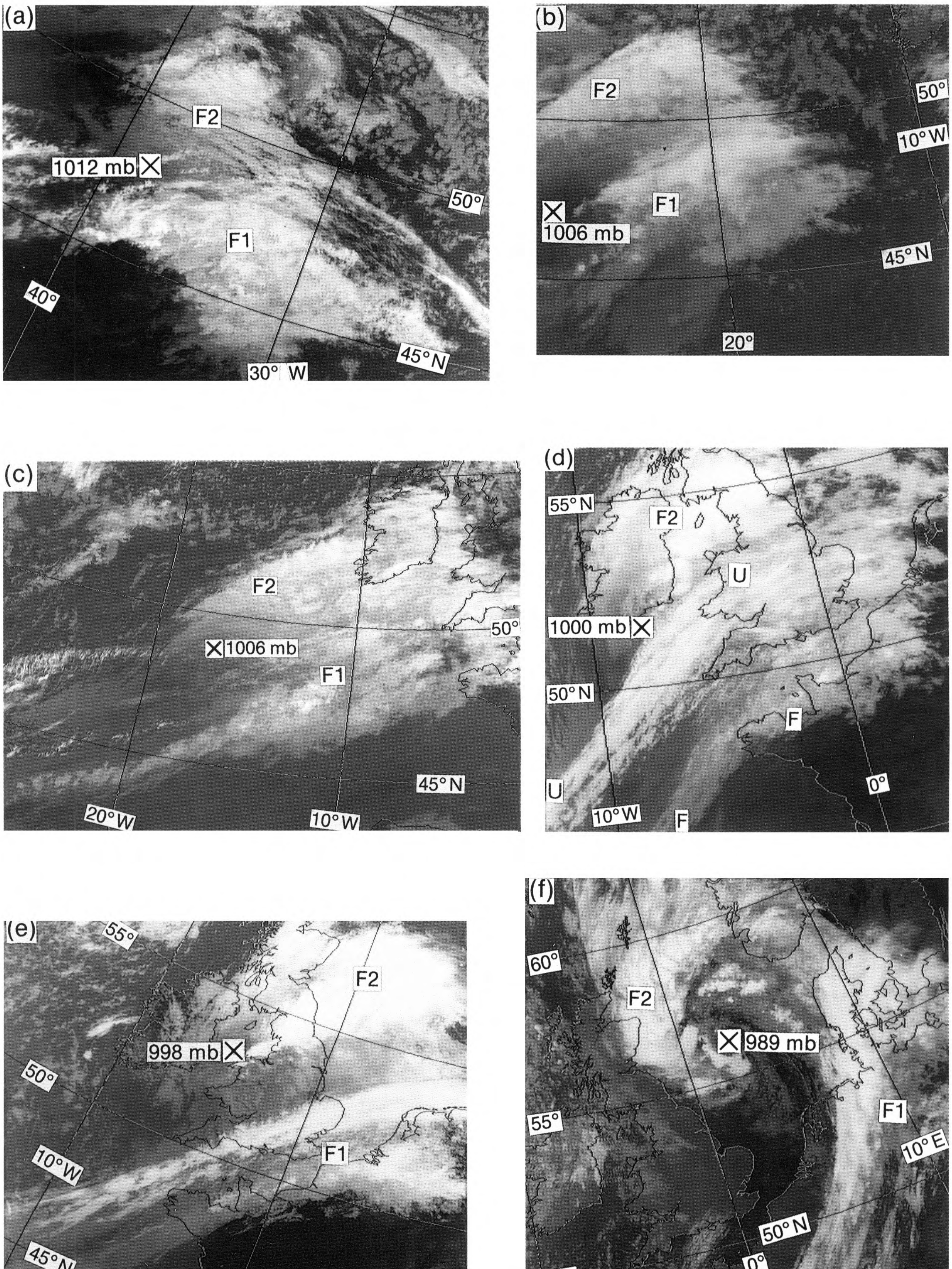

Figure 2. NOAA infra-red satellite imagery for (a) 1657 GMT on 26 July, (b) 0510 GMT on 27 July, (c) 1646 GMT on 27 July, (d) 0759 GMT on 28 July, (e) 1453 GMT on 28 July and (f) 0503 GMT on 29 July 1988. F1, F2, F and U are referred to in the text. The depression centre is shown by a cross with estimated central pressure alongside. Photographs by courtesy of University of Dundee.

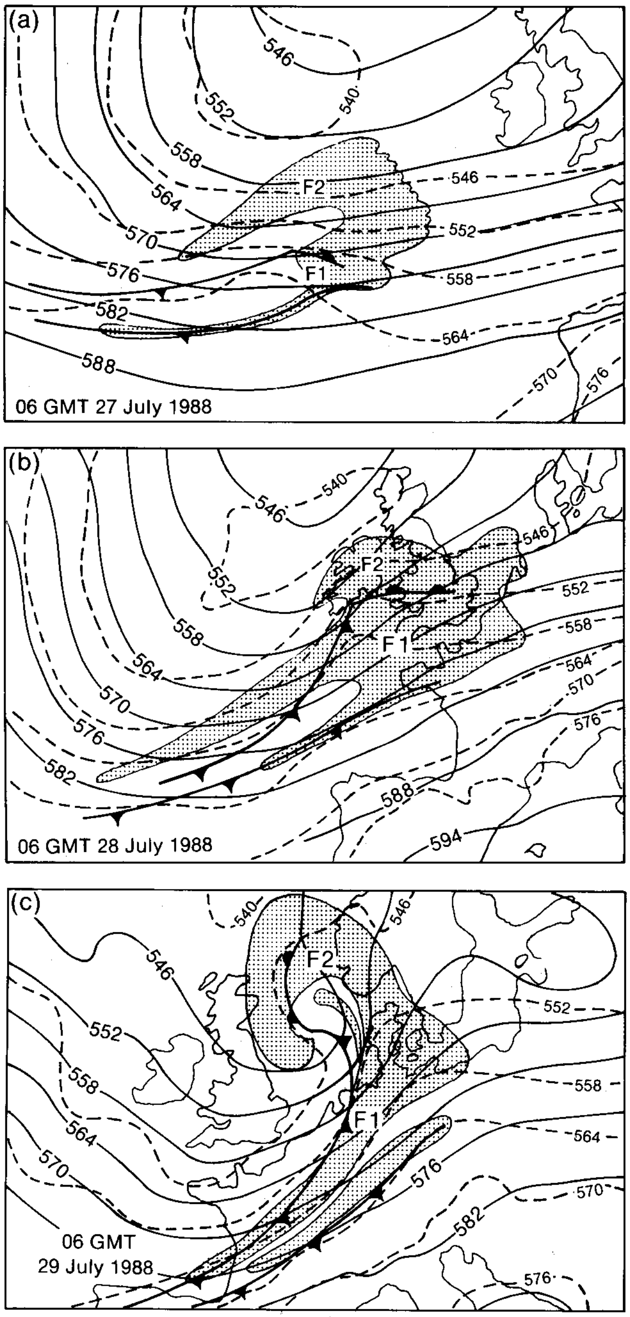

Figure 3. Upper-air analyses (derived from the fine-mesh model), major middle- and upper-cloud areas (stippled) and fronts at 0600 GMT on (a) 27 July, (b) 28 July and (c) 29 July 1988. Continuous lines are 500 mb heights, and dashed lines are 1000–500 mb thickness (both dam). F1 and F2 are referred to in the text. A small phase error between the observed frontal and cloud positions and the model's thermal ridge is present in (a).

W1 and W2 could be identified on the radiosonde soundings presented in Fig. 7. At 00 GMT on 28 July the base of W1 was the marked inversion which lay at 700 mb at Camborne (Fig. 7(a)), rising to 580 mb at Crawley (Fig. 7(b)). W2 was evident below 800 mb on the 12 GMT Camborne sounding (Fig. 7(c)). It was characterized by the moist, stable layer exhibiting well backed flow and a low-level jet of 205° 50 kn at 939 mb. Above 450 mb the sounding penetrated the northern limit of W1.

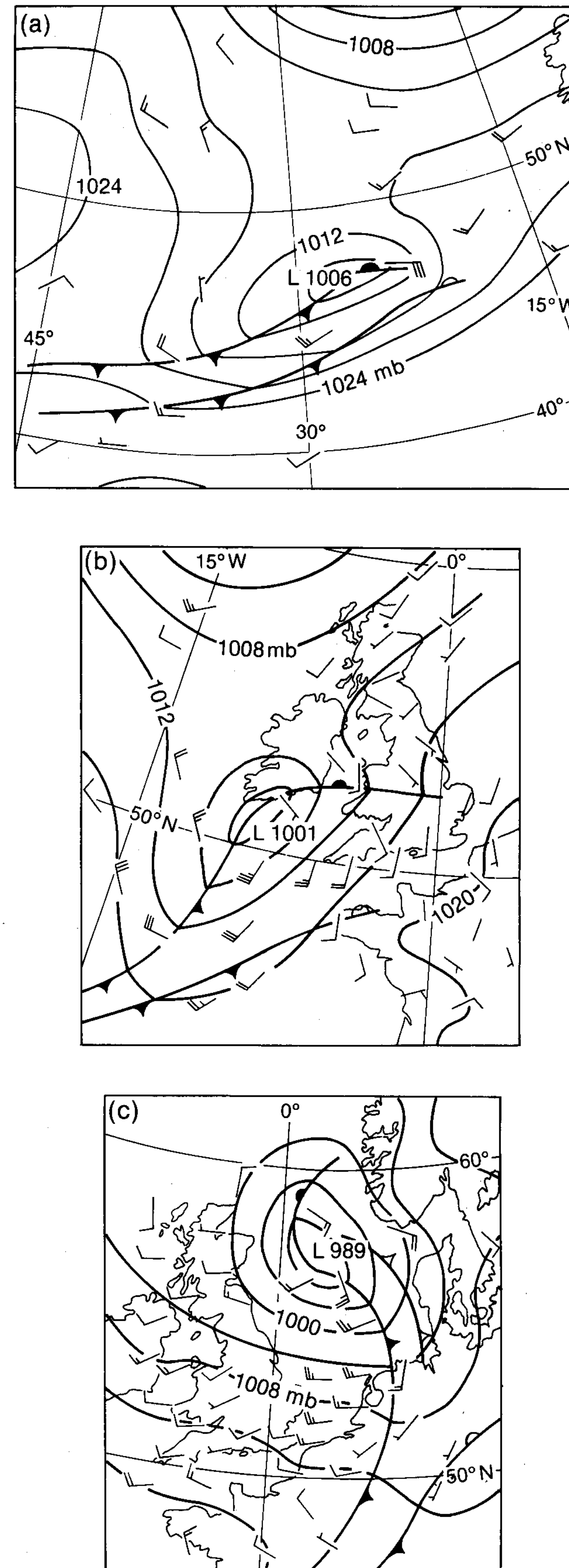

Figure 4. Surface analyses and wind observations for (a) 0600 GMT on 27 July, (b) 0600 GMT on 28 July and (c) 0600 GMT on 29 July 1988. Upper and surface frontal symbols are used where appropriate.

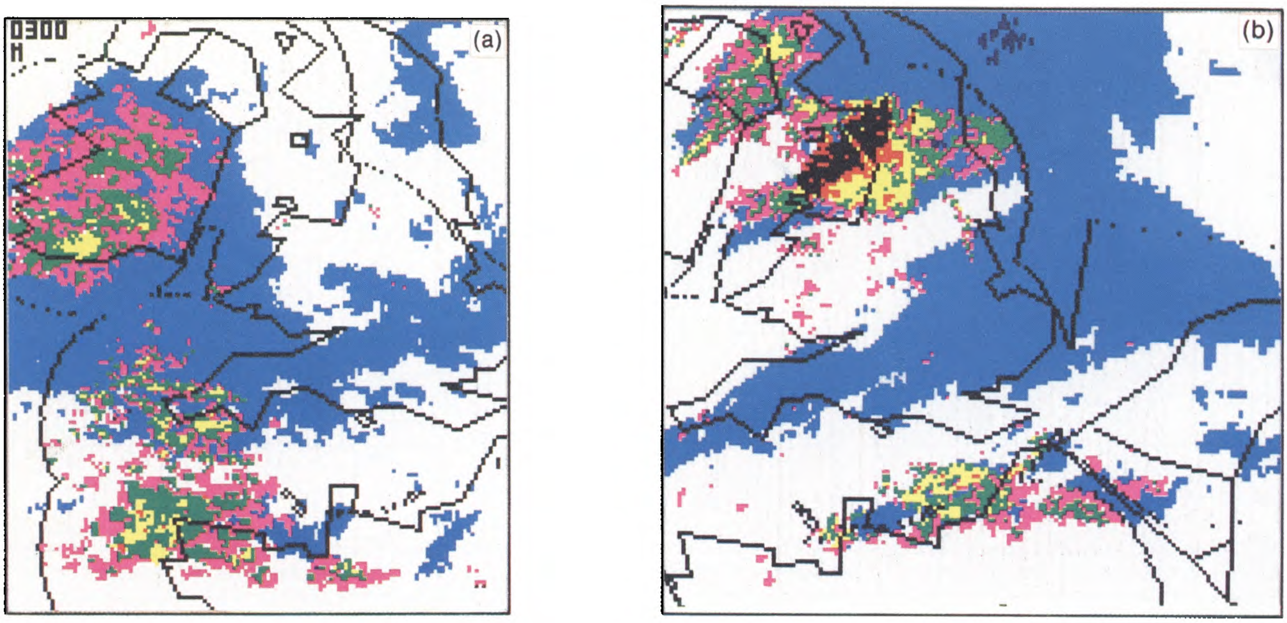

Figure 5. Combined satellite and radar imagery from the European COST-73 network for (a) 0300 GMT and (b) 1200 GMT on 28 July 1988. Blue represents cloud areas colder than −15 °C. Rainfall rates are: pink <1 mm h^{-1}, green 1–3 mm h^{-1}, yellow 3–10 mm h^{-1}, red 10–32 mm h^{-1} and black >32 mm h^{-1}.

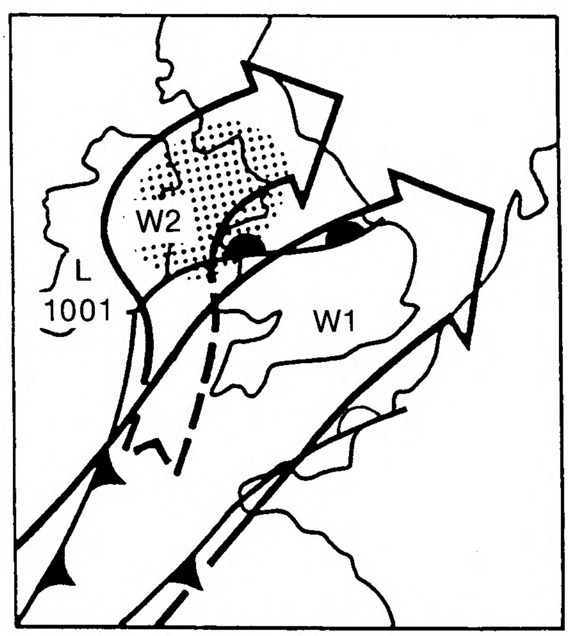

Figure 6. Conceptual model showing major ascending airflows (W1 and W2) and fronts at 09 GMT on 28 July 1988. The model was derived from isentropic analysis of 12 GMT radiosonde data and by inspection of movieloops of images (with conveyor belts displaced to their assumed location at 09 GMT). Stippling denotes the region of heavy rain.

Immediately poleward of W1 lay a tongue of upper-tropospheric dry air which can be seen on the water vapour image for 12 GMT on 28 July (Fig. 8(a)). The cross-section in Fig. 9, was constructed using 12 GMT soundings projected onto line AB on Fig. 8(a). It demonstrates the vertical depth of the dry air (shown as region D in Fig. 7(c)) which partially undercut W1, giving relative humidities below 20% at 500 mb. The dry air over southern England was concealed from view in Fig. 8(a) by the overlying cirrus (UU on Fig. 2(d)). It was this dry air (which isentropic analysis (Fig. 8(b)) showed to have undergone earlier subsidence upstream) that suppressed the depth of the cloud over southern Britain, helping to inhibit the development of precipitation. The role of the dry air will be addressed further in section 4.4.

W1 occupied the region south of the jet axis with wet-bulb potential temperature (WBPT) greater than 16 °C (Fig. 9) and contained cloud areas UU and FF. Almost neutral lapse of WBPT found at mid levels near Brest corresponded to the narrow band of convection over the north coast of France. However, the dynamical processes responsible for the persistent convection are uncertain. The northern frontal zone lay between Aughton and Long Kesh and was most prominent in the lower troposphere as demonstrated by cross-sections of temperature (not shown).

The section portrayed in Fig. 9 bears a striking resemblance to sections through other depressions, one of which is reproduced (from Young 1988) in Fig. 10. Both of these possessed a double structure on satellite imagery, generated by the twin conveyor-belt configuration similar to Fig. 6. Some common features are:

(a) The elevated tongue of warm air aloft corresponding to the WCB of the inner frontal zone. Shallow layers of nearly neutral stability lie along the axis of the warm air (dashed line).

(b) A strong gradient of WBPT exists at middle levels (labelled GU on Figs 9 and 10) along the left-hand side of the WCB. Although the region of tight gradient GU tilts upwards into the cold air, a marked break exists in the strong gradients immediately below. This gap is particularly prominent near

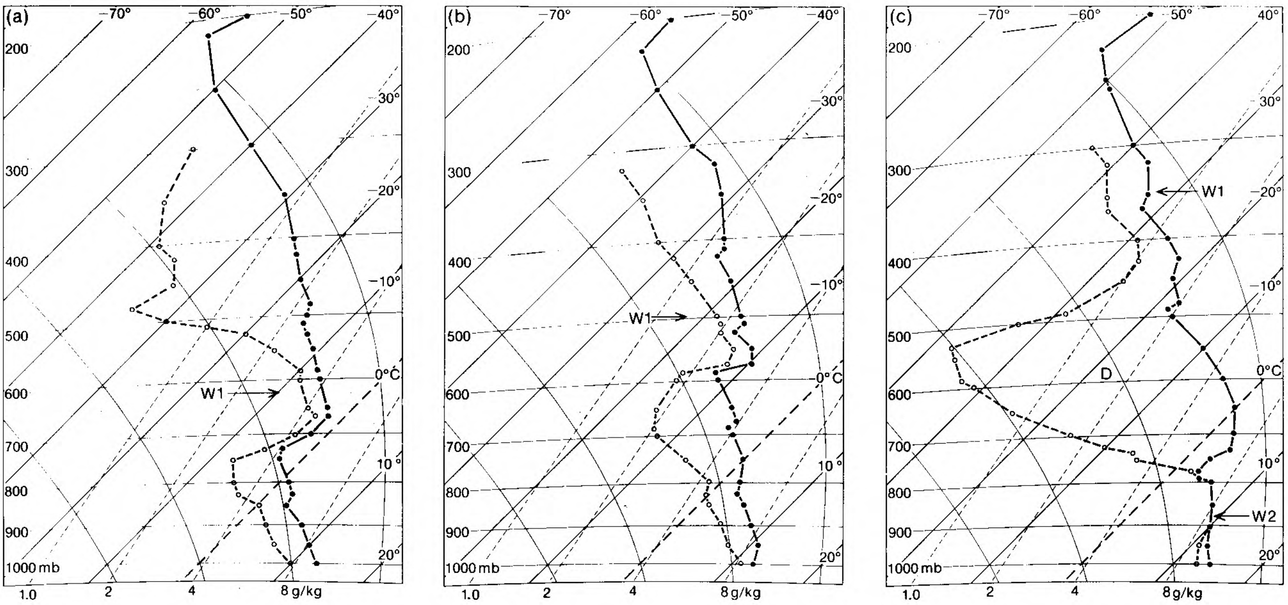

Figure 7. Radiosonde soundings for (a) Camborne and (b) Crawley at 00 GMT on 28 July 1988 and (c) Camborne at 12 GMT on 28 July 1988. The locations of W1 and W2 are shown. The layer of dry air D is referred to in the text.

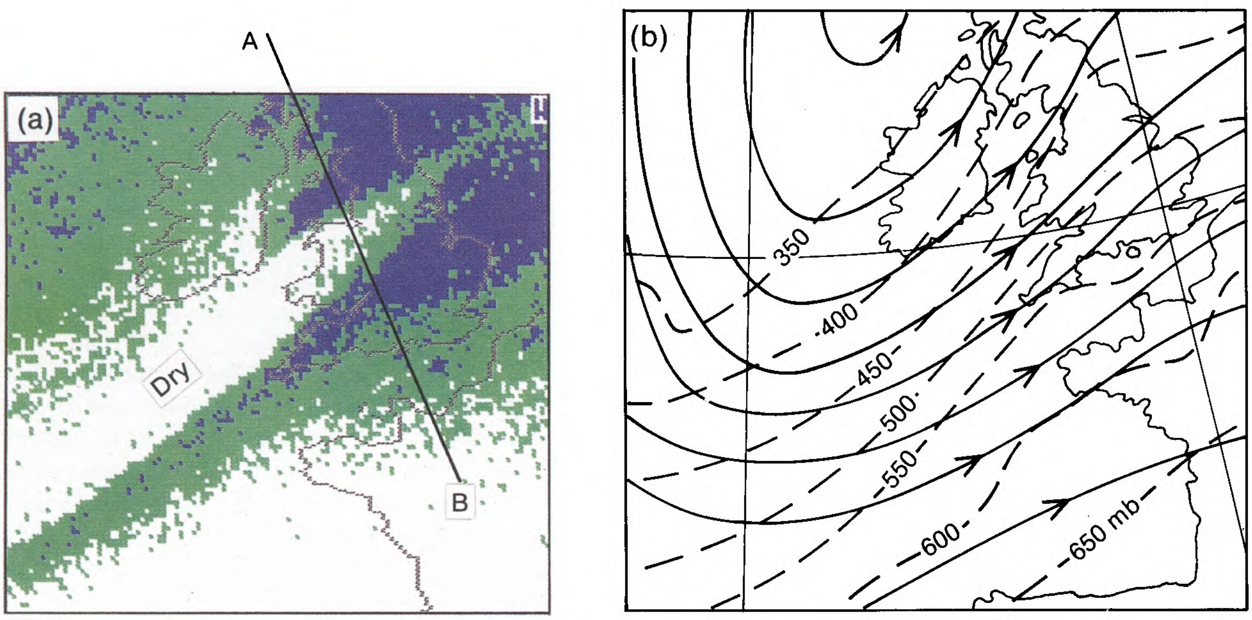

Figure 8. (a) Water vapour image for 12 GMT on 28 July 1988 showing the quantity of water vapour over a depth of the upper troposphere centred around 400 mb. White represents the driest air with successively darker shades representing moister air. AB is the line of the cross-section used in Fig. 9 and (b) isentropic analysis on the 313 K potential temperature surface relative to a system speed of 230° 22 kn. Continuous lines are streamlines and dashed lines are isobars (mb) of the 313 K surface.

750 mb in Fig. 10 and resembles that seen in some of the sections across other cold fronts during the FRONTS87 project (Clough *et al.* 1988).

(c) A marked gradient of WBPT is present in the lower troposphere corresponding to the outer frontal zone, labelled GL in Figs 9 and 10.

4. Fine-mesh model diagnostics

4.1 Performance of the model

This section examines reasons for the poor forecast of rainfall over southern Britain made by the midnight run of the fine-mesh model on 28 July 1988. Fig. 11 shows forecasts of WBPT and rainfall accumulations from runs of the model based on data at 00 GMT and 06 GMT on 28 July. Clearly, the 06 GMT run (Fig. 11(b)) had produced a better forecast of rainfall over England and Wales for 12 GMT (compared with Fig. 1(a)), and the improvement was more pronounced at 18 GMT (Fig. 11(c)). The 06 GMT run had successfully predicted the generally dry conditions over south-east England, and had correctly narrowed the rain band over the south-west, as well as concentrating the heaviest rain over northern Britain. The rainfall totals forecast by the

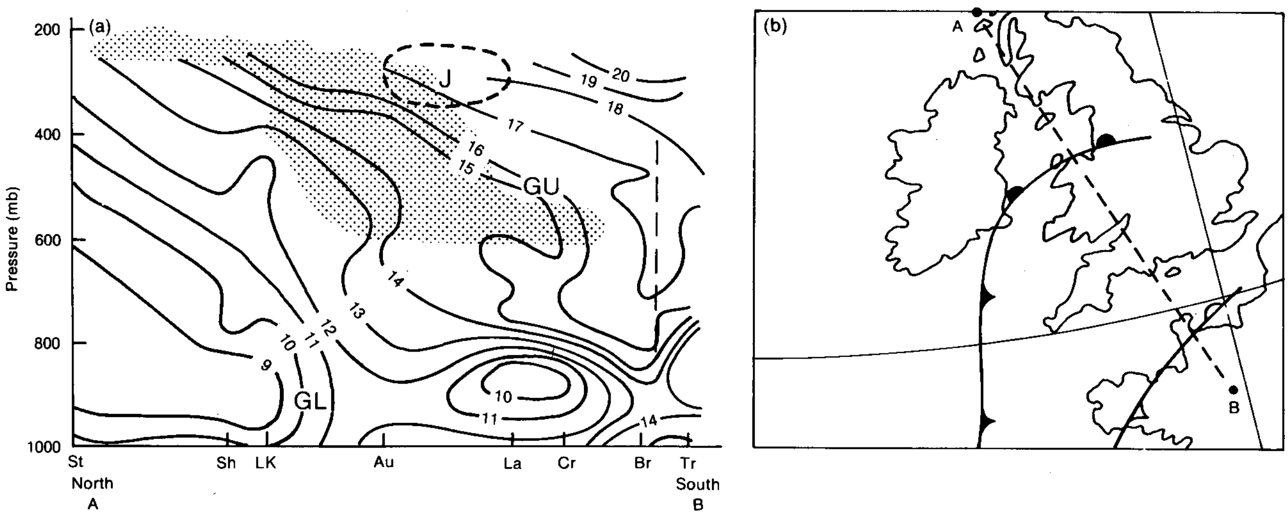

Figure 9. (a) Cross-section of wet-bulb potential temperature (°C) along the line AB in Fig. 8(a) constructed using data for 12 GMT on 28 July 1988. The location of radiosonde stations projected onto the line of the section are as follows: St = Stornoway, Sh = Shanwell, LK = Long Kesh, Au = Aughton, La = Larkhill, Cr = Crawley, Br = Brest and Tr = Trappes. Regions of dry air aloft (relative humidity <50%) are stippled and the jet axis is marked J. GU and GL are regions of strong gradient referred to in the text. The dashed line is the axis of the warm air aloft associated with W1 and (b) line of the cross-section relative to the main surface features.

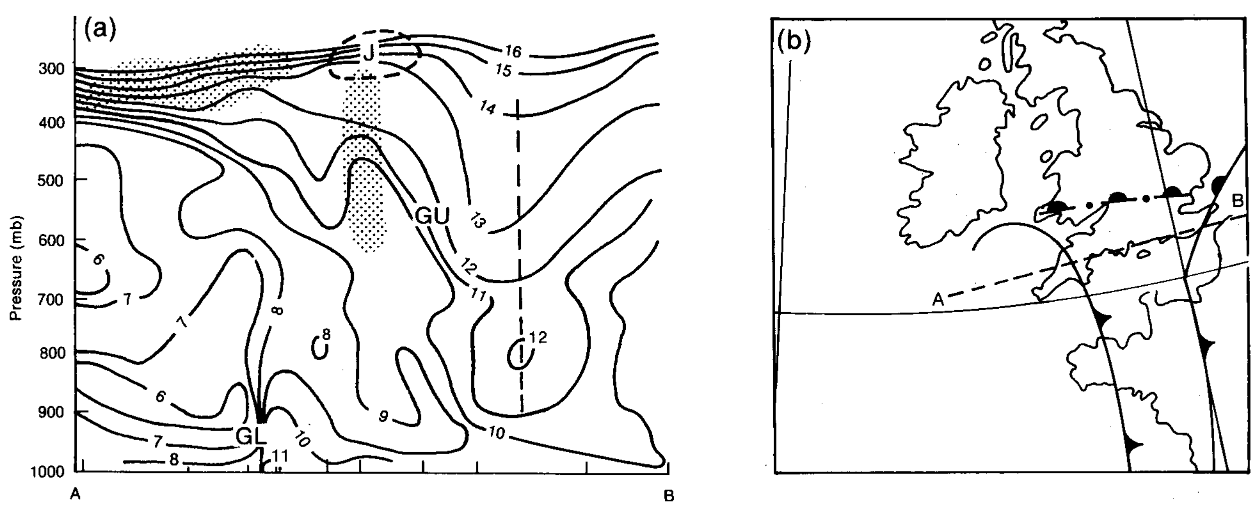

Figure 10. (a) Cross-section of wet-bulb potential temperature (°C) at 0000 GMT on 6 January 1988 and (b) line of cross-section relative to the main surface features. GU, GL, the stippled area and the dashed line are as in Fig. 9. This cross-section benefitted from an enhanced set of radiosonde observations during the FRONTS87 project, the locations of which are shown as short lines intersecting the horizontal axis, and displaced according to the movement of the depression.

mesoscale model (15 km horizontal resolution) based on 00 GMT data (not shown) also exhibited similar errors to the corresponding fine-mesh model. Numerical forecasts based on data from 27 July also produced too much rainfall over southern England despite the humidity analysis appearing essentially correct when compared with satellite imagery.

The elongated tongue of warm air on Fig. 11 characterized by WBPT of 14 °C corresponded to W2. The northern warm front lay at the forward limit of W2 at 850 mb and is depicted in Fig. 11(b). It would be tempting to analyse an occlusion along the entire length of this warm tongue. However, this would be inappropriate because a classical occlusion process did not occur, and secondly, the rainfall distribution (Fig. 5(b)) is not consistent with that implied by a classical occlusion.

4.2 Causes of error in the model's forecast

By comparing the diagnostics from the two runs of the model shown in Fig. 11, it was possible to identify differences in the vertical velocity fields at 12 GMT over the British Isles, which could then be traced back to significant differences in the upper-air pattern at 06 GMT. Differences between the analysis for 06 GMT and the 6-hour forecast valid at this time (run using 00 GMT data) appeared to be related to aircraft reports which were not available for the 00 GMT run of the model. A possible manner in which this data culminated in an improved forecast for southern Britain is described below using diagnostics from both model runs.

The most striking difference between the model fields valid at 06 GMT is in the structure of the jet, shown in Fig. 12. A separate jet streak labelled J, present on the

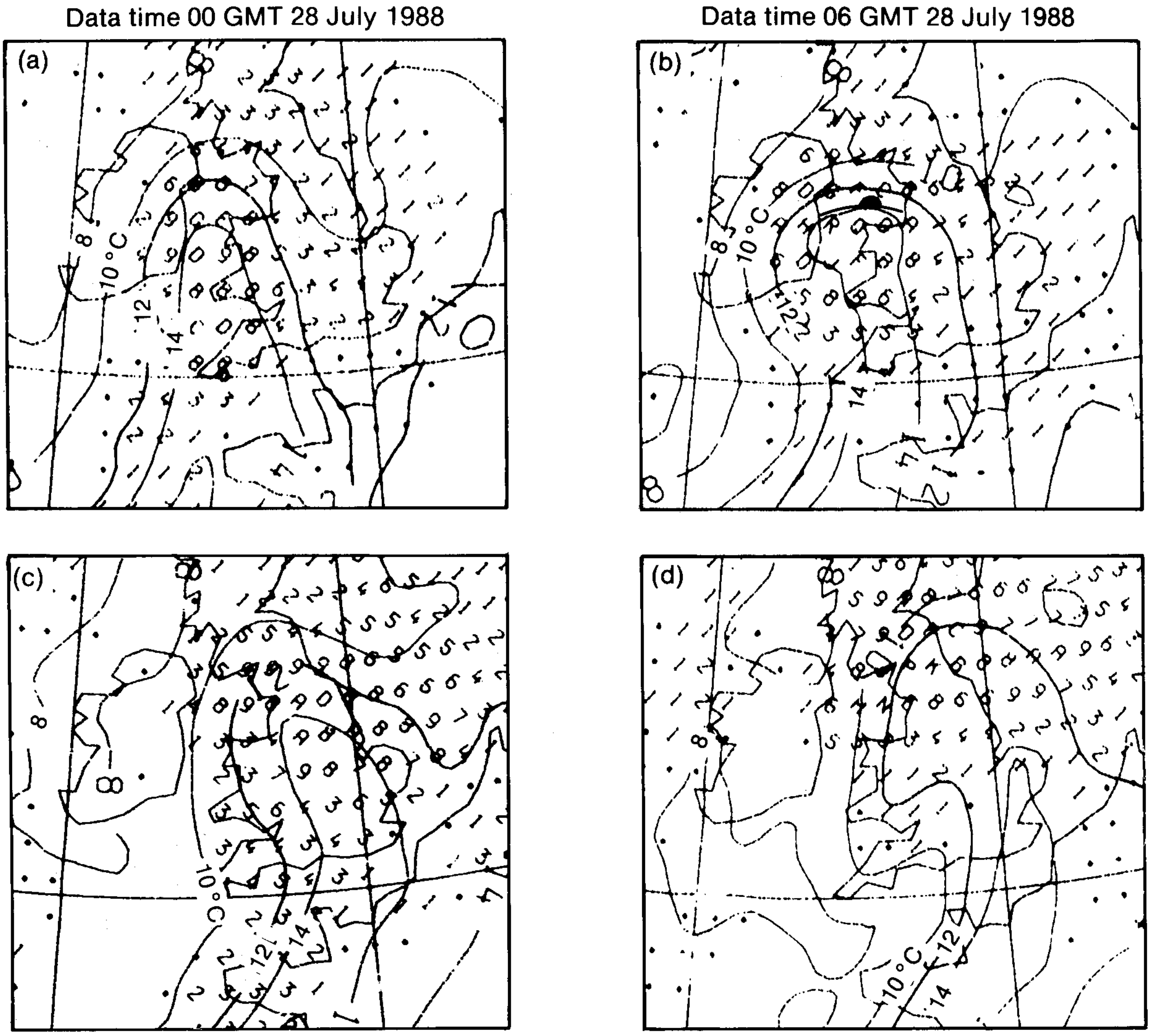

Figure 11. Rainfall accumulations (mm) forecast by the fine-mesh model based on data for 00 GMT on 28 July 1988 (a) and (c) and 06 GMT on 28 July 1988 (b) and (d). (a) and (b) are 6-hour totals up to 12 GMT, whilst (c) and (d) are 6-hour totals up to 18 GMT on 28 July 1988. The letters A, B, C, etc. represent accumulations of 10, 11, 12 mm, etc. Continuous lines are 850 mb wet-bulb potential temperature (°C).

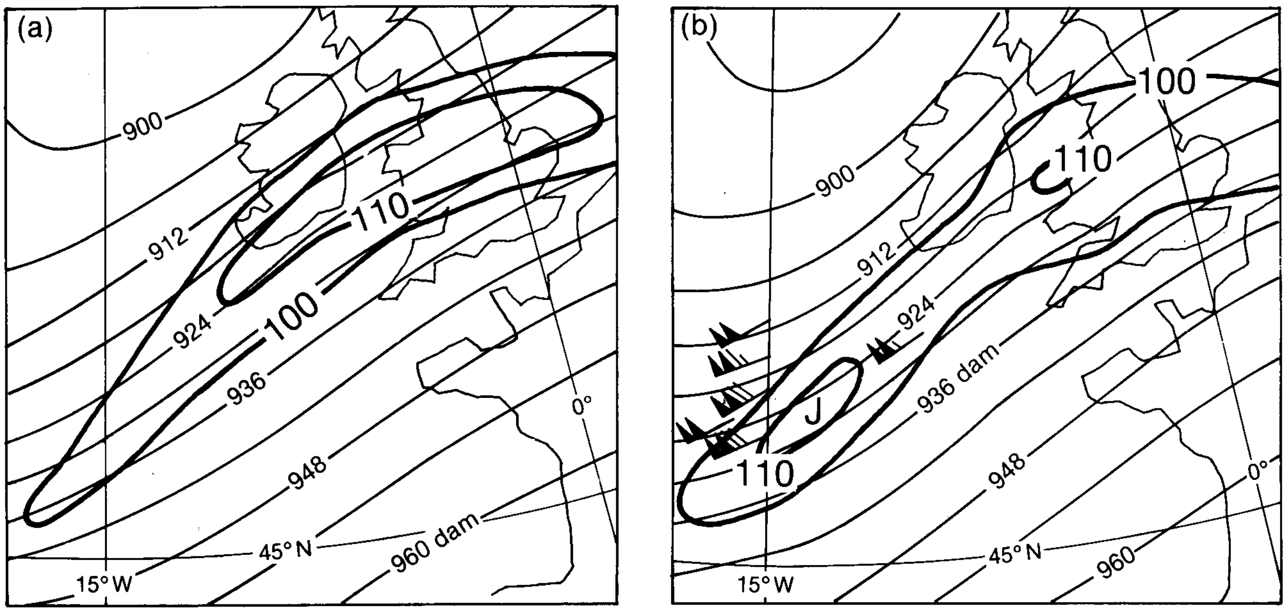

Figure 12. Heights of the 300 mb surface in dam (thin lines) and selected isotachs in kn (bold lines) valid at 06 GMT on 28 July 1988. (a) is a 6-hour forecast and (b) is an analysis. Aircraft observations for 03 GMT are superimposed on (b). J is referred to in the text.

analysis in Fig. 12(b), was not present in the 6-hour forecast in Fig. 12(a) valid at 06 GMT. Its appearance in the 06 GMT analysis was almost certainly due to several aircraft reports at 03 GMT (plotted on Fig. 12(b)) which entered the model via the 03 GMT assimilation. Some of the reported winds were over 20 kn stronger than winds in the same location in the model's 3-hour forecast valid at that time. The jet streak J in Fig. 12(b) may well have existed during 27 July, but could not be resolved by available aircraft reports.

The location of J is shown in Fig. 13 for the same two forecast runs of the model valid at 12 GMT. In the 6-hour forecast (Fig. 13(b)), J had simply propagated eastwards retaining its strength, and much of southern England lay in its pronounced right exit region labelled E. The 12-hour forecast (Fig. 13(a)) had, correctly, developed the same jet in about the right position, despite its absence in the earlier part of the forecast (Fig. 12(a)), but the right exit E was much less pronounced.

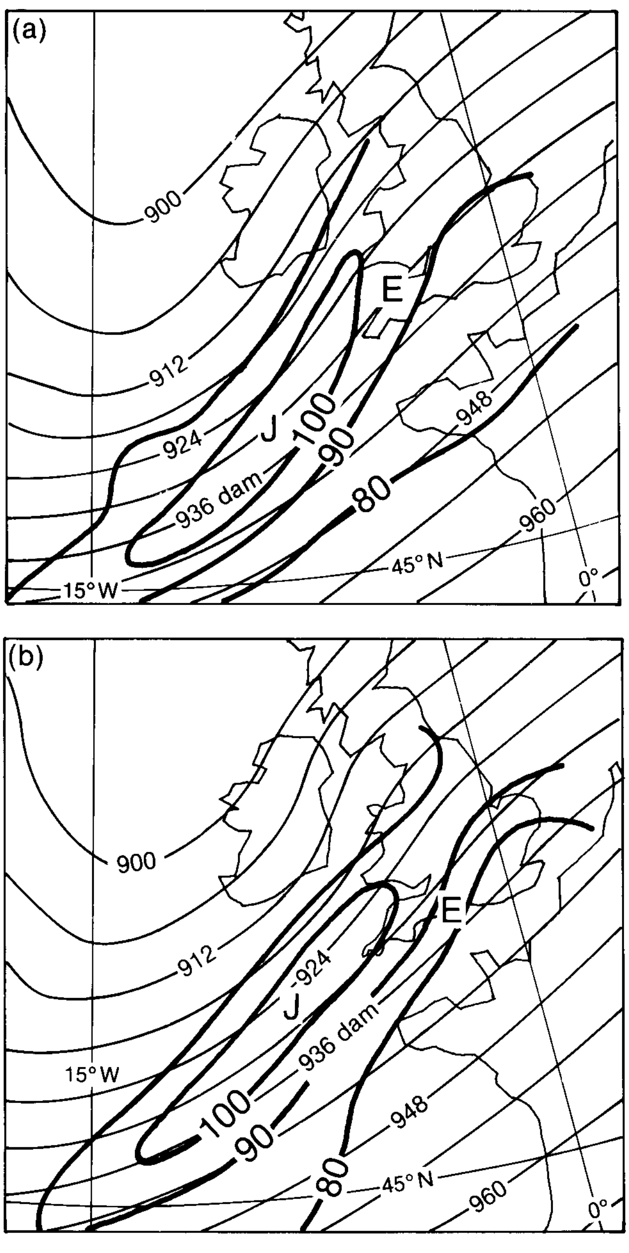

Figure 13. As Fig. 12 except (a) and (b) are 12-hour and 6-hour forecasts respectively. E denotes the right jet exit and other symbols are as in Fig. 12.

At 12 GMT the shape of the elongated region of upward motion on the 12-hour forecast (Fig. 14(a)) over Britain appeared similar to the warm advection field (Fig. 15(a)). By comparing Figs. 14(a) and 14(b), the impact of the jet exit on the vertical velocity field in the 6-hour forecast is marked. With a similar warm advection field (Fig. 15(b)) the upward motion has been doubled in the left-exit region over Wales and the Irish Sea, whereas in the right exit over southern England, the maximum upward motion has been considerably suppressed. These major differences in the vertical velocity fields almost certainly led to the markedly different forecasts of rainfall (Fig. 11) from the two runs of the model.

4.3 Structure of the jet-exit region

Fig. 16 shows vectors of ageostrophic motion valid at 12 GMT on 28 July calculated at 300 mb and 950 mb from both runs of the fine-mesh model. In the 06 GMT run (Fig. 16(b)), at the 300 mb jet exit, there is large component of the flow directed up the geopotential

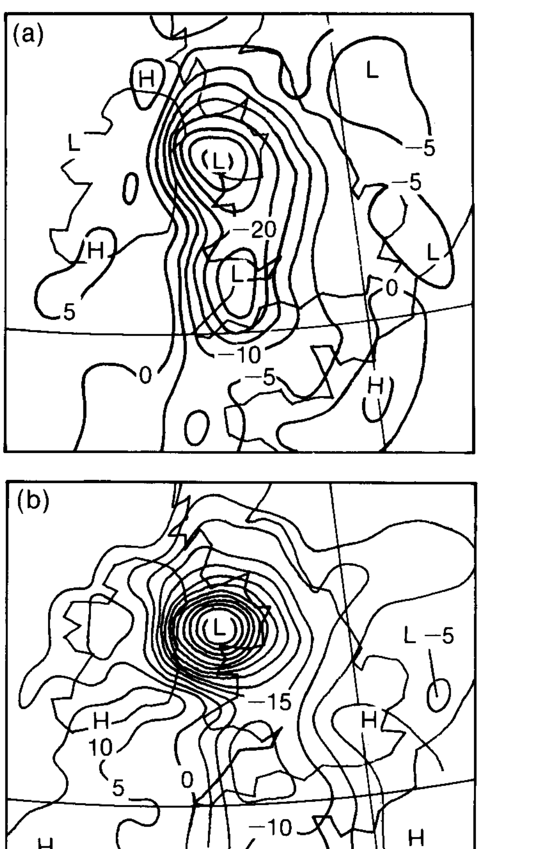

Figure 14. Vertical velocity fields (mb h^{-1}) at 700 mb valid at 12 GMT on 28 July 1988. Negative values represent upward motion and positive values downward motion. (a) and (b) are 12- and 6-hour forecasts respectively. Contours are at intervals of 5 mb h^{-1}.

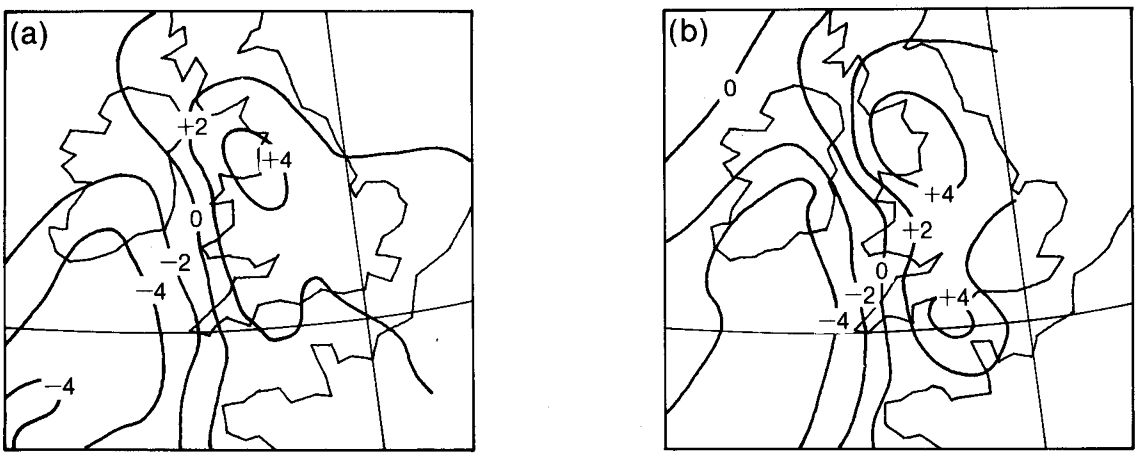

Figure 15. Thermal advection fields (°C $6h^{-1}$) averaged at 850, 700 and 500 mb valid at 12 GMT on 28 July 1988. (a) and (b) are 12- and 6-hour forecasts respectively. Negative values represent cold advection whilst positive values represent warm advection.

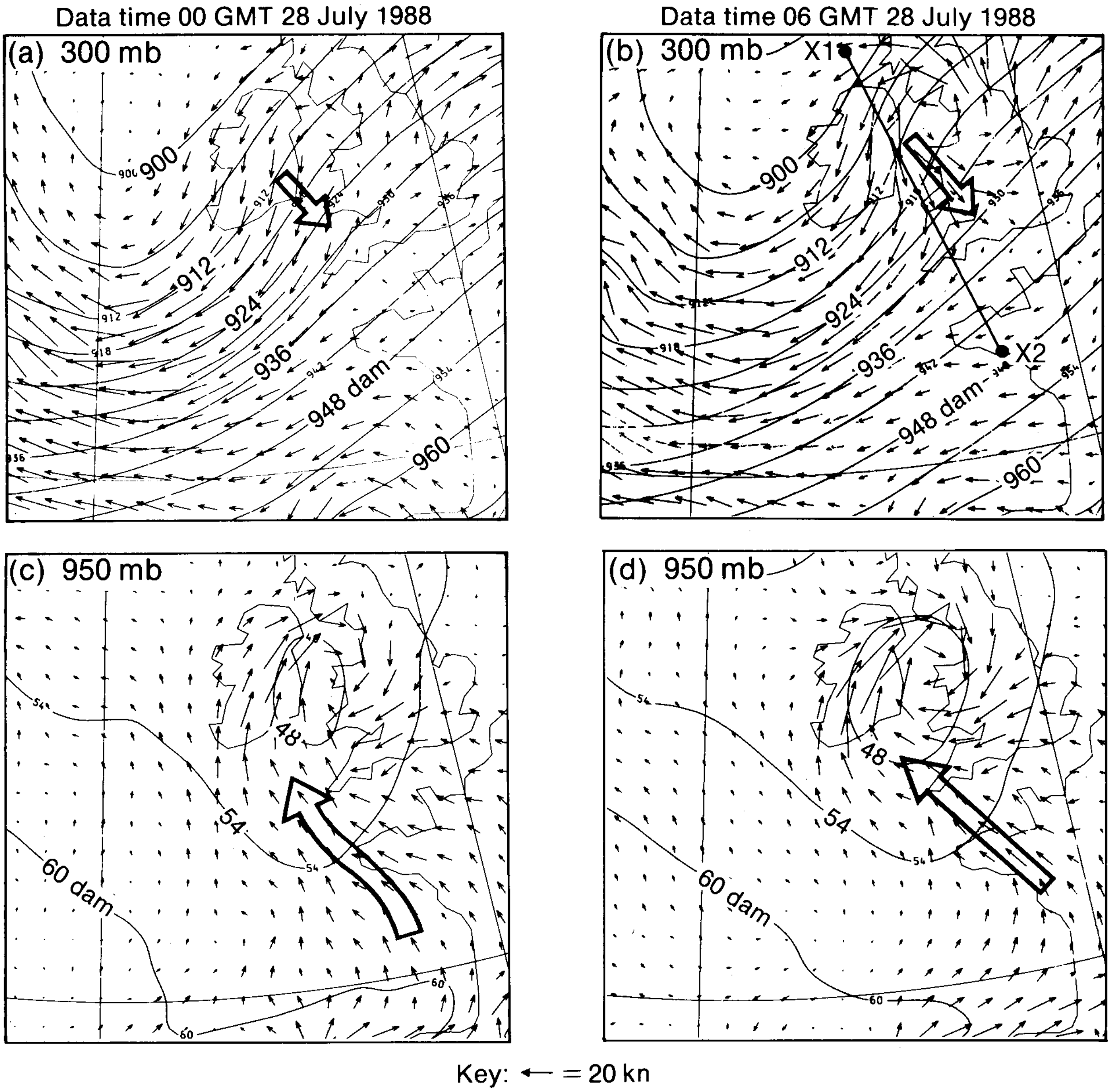

Figure 16. Forecast ageostrophic components of wind (arrows) and heights in dam (continuous lines) valid at 12 GMT on 28 July 1988 based on data for 00 GMT (a) and (c) and 06 GMT (b) and (d). (a) and (b) are for 300 mb whilst (c) and (d) are for 950 mb. The speed of the wind component is proportional to the length of the arrow. Regions in the vicinity of the British Isles with the greatest cross-contour component are indicated with a bold arrow. X1–X2 is the line of the cross-section in Fig. 17.

gradient, whereas directly below, at 950 mb, the reverse is true. This is consistent with the sense of the indirect circulation induced at a jet exit, and W2, along with its low-level jet can be perceived as constituting the lower branch of the circulation. The upper portion of the cross-contour component of the ageostrophic flow is much less marked in Fig. 16(a), consistent with a less well organized jet-exit circulation in the 00 GMT fine-mesh run. The indirect circulation is demonstrated by the fine-mesh model cross-section shown in Fig. 17, taken through the jet exit region. The lower- and upper-level branches of the circulation are coupled by a deep layer of strong ascending motion which corresponds to cloud mass F2. The lower branch transports a shallow layer of air with high wet-bulb potential temperature towards F2. Potential instability (evident, for example, between 850 and 600 mb at point P) is released from the top of this layer giving rise to heavy rain from F2. The tongue of mid-level dry air identified in Figs 8 and 9 is well reproduced in the cross-section. Coupling of upper- and lower-level jet streaks in the manner described could therefore explain the prolonged co-existence of W1 and W2 (from as early as 26 July, Fig. 2(a)), the maintenance of the corresponding double structure to the cloud on satellite imagery and the distinctive rainfall pattern over Britain. A similar coupling process has been described by Uccellini and Kocin (1987) in conjunction with heavy snow events in the eastern USA, and by Browning and Hill (1985) for a polar trough interacting with a polar-front cloud band.

4.4 The role of the dry air

Since the difference between the two forecast runs has been explained without reference to the relative humidity pattern, the role of the dry air identified in Figs. 8 and 9 must be of secondary importance. The dry air originated in a region of marked cold advection upstream (located south of Ireland in Fig. 15) and was advected into the developing system beneath, and to the left of, jet J. Model products suggest that this dry air began to ascend over southern Britain, but not sufficiently far to initiate saturation. The longevity of the mid-level dry tongue, which was essential in maintaining the separate identities of F1 and F2 on the imagery, must imply only weak upward motion in that region (due to suppression of upward motion in the descending branch of the cross-circulation). It was only after the upstream trough began to sharpen significantly after 18 GMT on 28 July that induced ascent on its forward side (due to positive vorticity advection) was sufficiently strong to initiate bands of deep convection that finally penetrated this dry region aloft (Fig. 2(f)).

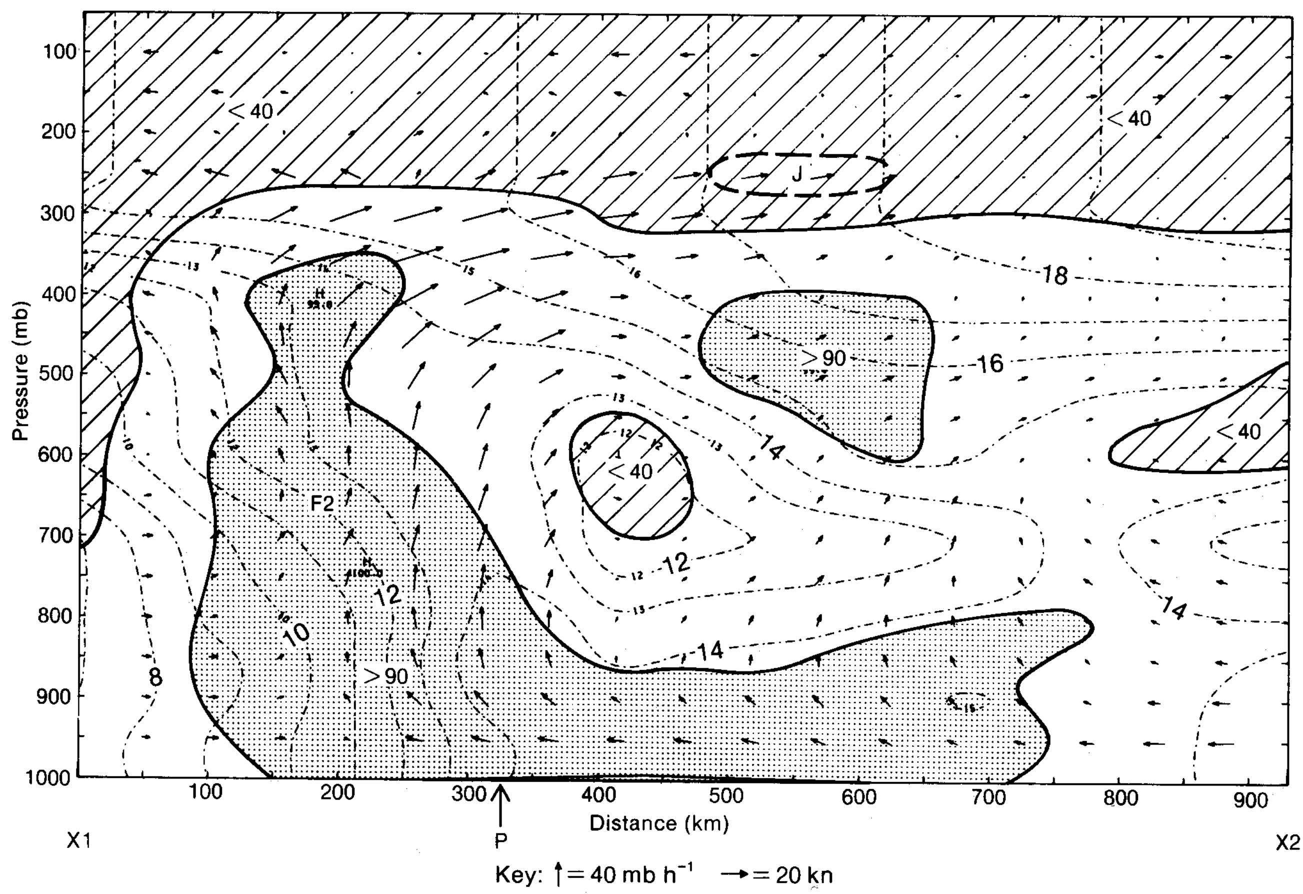

Figure 17. Fine-mesh 6-hour forecast cross-section valid at 12 GMT on 28 July 1988 along the line X1–X2 in Fig. 16(b). Arrows show the components of horizontal ageostrophic motion tangential to the plane of the section, combined with vertical velocity. Isopleths of wet-bulb potential temperature (°C) are shown as dash-dot lines. Regions of relative humidity >90% are stippled and those <40% hatched. J denotes the jet axis which is directed normal to the section. P and F2 are referred to in the text.

5. Forecasting considerations

Key questions of interest to the forecaster in this case would have been:

(a) What was the earliest stage at which the rainfall pattern over Britain could have been predicted?

(b) Would the gap between the two main rain areas persist?

With regard to (a), the existence of the double structure to the cloud signature on 27 July may have suggested a reduction in rainfall intensity between the two frontal zones. However, this hypothesis could not have been confirmed until the system was detected by the radar network. With regard to (b), the initial development of deep convection in the gap, previously occupied by dry air aloft, did not take place until after the northern cloud mass F2 had begun to rotate, by which time substantial cyclogenesis had already occurred. This observation is consistent with the forecasting guidelines presented by McGinnigle *et al.* (1988).

6. Conclusions

The main messages that emerge from this case-study are as follows.

(a) A double cloud band seen on satellite infra-red imagery existed some 36 hours before the associated depression reached the British Isles. The double structure to the cloud pattern led to two distinct areas of rain separated by a corridor of mainly dry conditions (which lay over southern England). Radar rainfall displays, in particular COST-73, provided direct evidence for this structure to the rainfall pattern early on 28 July, which was not captured by the available numerical-model guidance. In such cases it is appropriate to analyse a double frontal structure, this being consistent with the thermal field, the surface observations and the rainfall pattern. The surface depression centre lies beneath warm cloud tops on the south side of the northern cloud mass.

(b) A twin warm conveyor-belt model (similar to the instant occlusion model of McGinnigle *et al.* (1988) explained the observed cloud and rainfall distribution. The configuration appears to have arisen as part of an indirect circulation at the exit of an upper-level jet. The absence of rainfall over southern England was due to suppression of upward motion at the right exit of the jet combined with a deep tongue of dry air aloft. The dry air had originated upstream of the depression through earlier subsidence within a region of marked cold advection. Deep convection occurred within this hitherto cloud-free gap only when cyclonic rotation of the northern cloud mass had commenced.

(c) The coverage of data at 00 GMT on 28 July 1988 was clearly insufficient for the fine-mesh model to achieve the correct upper-air analysis west of the British Isles. As a result, the model's 12-hour rainfall forecast for southern Britain was misleading. Extra aircraft reports at 03 GMT which were available for the 06 GMT model run appeared to be crucial in resolving the strength of the jet and the vertical-velocity pattern necessary to produce a more useful forecast.

Acknowledgements

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The autumn of 1988 in the United Kingdom

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Summary

Autumn temperatures were just below average in most places and while rainfall in northern areas was about normal, central and south-eastern areas had a dry autumn. It was generally sunny except in north-west Scotland where it was rather dull.

1. The autumn as a whole

Although there were mild and cool spells during the autumn, they more or less cancelled one another out to give overall mean temperatures slightly lower than the normal except in northern Scotland and south-east England. Rainfall was generally about average or a little below, but many parts of the south had a relatively dry autumn. November was a dry month everywhere. Sunshine totals were just above average in most places but it was rather dull in north-west Scotland and East Anglia. One or two places in the north Midlands and north-east England were particularly sunny. Information about the temperature, rainfall and sunshine during September–November 1988 is given in Fig. 1 and Table I.

2. The individual months

September. Mean monthly temperatures were generally near normal over the United Kingdom as a whole but somewhat warmer in the east of Highland Region, reaching 0.7 °C above normal at Wick. However, Folkestone, Kent had a mean temperature of 0.8 °C below normal. Sheffield, Weston Park, South Yorkshire reported the highest September maximum temperature, 25.2 °C, since 1982 and the lowest September minimum, 1.9 °C, since 1932. Monthly rainfall totals were below normal nearly everywhere with less than half the normal in many parts of England and Wales. The wettest area was around Cape Wrath, Highland Region with 150% of normal rainfall and the driest places were in southern and eastern areas of England with less than half the normal rainfall with localized exceptions. Sunshine amounts were about normal over the United Kingdom as a whole, although it was somewhat sunnier in the north-east. Amounts ranged from 137% of normal in eastern Scotland to 73% in the Western Isles.

The month started showery in many areas, becoming dry and warm generally on the 5th. Southern areas remained dry on the 6th but there was heavy rain in the north. On the 7th it was sunny in many places and on the 8th and 9th quite warm in south-east England. However, rain in the north and west spread southwards to reach all areas by dawn on the 11th. The showery weather continued on the 13th and 14th followed by a

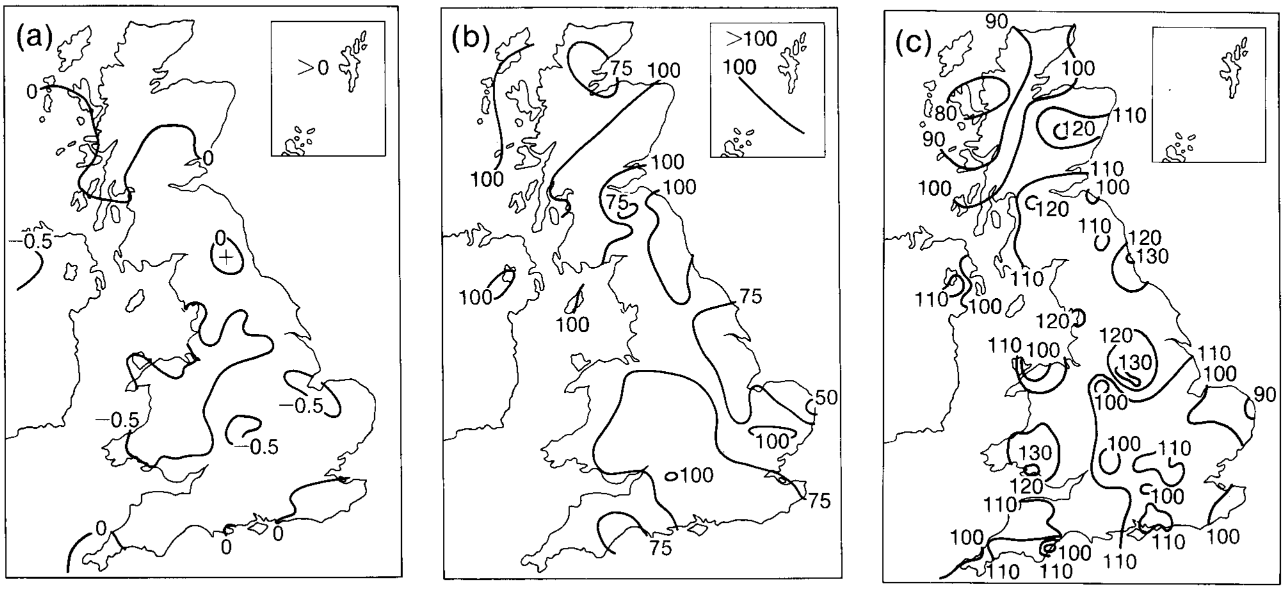

Figure 1. Values of (a) mean temperature difference (°C), (b) rainfall percentage and (c) sunshine percentage for autumn, 1988 (September–November) relative to 1951–80 averages.

Table I. District values for the period September–November 1988, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+0.1	0	93	93
Eastern Scotland	−0.1	0	107	111
Eastern and north-east England	−0.3	−2	91	121
East Anglia	−0.4	−2	81	107
Midland counties	−0.5	−3	72	117
South-east and central southern England	−0.1	−3	70	114
Western Scotland	−0.1	0	99	116
North-west England and North Wales	−0.5	−2	84	117
South-west England and South Wales	−0.2	−2	80	118
Northern Ireland	−0.3	−2	99	106
Scotland	−0.1	0	98	107
England and Wales	−0.3	−2	80	116

Highest maximum: 26.7 °C in Midland counties in September.
Lowest minimum: −11.6 °C in western Scotland in November.

period of mainly dry weather with a fair amount of sunshine. After the 22nd most places experienced some periods of wet weather with heavy rain at times. Showers occurred on the 28th, with the first snow of the season falling over the highest parts of the Grampian Mountains. Further showers occurred in the last two days, but most places became dry and sunny.

October. Mean monthly temperatures were below normal generally over Scotland, Northern Ireland and parts of northern England, but about or rather above normal over the rest of England and Wales. In parts of south-east England temperatures were about 1 °C above normal while in the Moray Firth area of Scotland they were almost 1 °C below normal. Day maxima were particularly low in Scotland and north-east England, while night minima were particularly high in the south and east and south-west. The night of the 30th was the coldest in October in Sheffield for 33 years, when temperatures dropped to −1.4 °C. Monthly rainfall totals were above normal in most of the United Kingdom, the wettest places being parts of Tayside and Grampian Regions, with around twice the normal, while Lowestoft, Suffolk had only half the normal rainfall for the month and some central areas of England and Wales were only slightly wetter. However, the thundery conditions produced marked contrasts over small areas and some parts of East Anglia recorded more than 160% of normal. On the 19th heavy rain flooded parts of Liverpool and the Wirral with flood-water 2 m deep in places; Crosby measured 82 mm of rain and Aigburth 42 mm in the day. On the 25th more than 80 mm fell in a day in the area of the Mourne Mountains, including falls of 81 mm at Bryansford and 97 mm at Trassey, Co. Down; many places across the Province had falls of more than 20 mm resulting in flooding, blocked roads and some structural damage. North-east of a line from the Isle of Lewis to the Thames Estuary, October was mainly dull and Orkney and Shetland in particular had 30% less sunshine than normal. Elsewhere, sunshine amounts were normal or slightly above normal, reaching 23% above normal at Cardiff, South Glamorgan. Parts of north-east England were particularly dull from the 15th to the 26th: Leeming, North Yorkshire recorded only 3.8 hours of sunshine during the 12 consecutive days.

Apart from the first few days, a short dry spell at mid month and a dry period at the end, the month was generally wet, with heavy rain at times. The dry spell at the end of the month was interrupted by a few showers near the east coast. Thunder occurred in many parts of England during the 6th and 12th and there was widespread hail on the 6th and 7th. A severe thunderstorm occurred in Northern Ireland on the 12th on the north side of the Mourne Mountains around Bryansford, Co. Down. On the 18th and 19th thunderstorms occurred over a wide area of England and Wales. Aughton, Lancashire reported thunderstorms, severe at times on the 19th. Lightning interrupted power supplies at Stoke-on-Trent. There were showers, sometimes of snow or hail in Scotland on the 28th and 29th. The observer at Keyworth, Nottinghamshire reported that rain-water was cloudy and there was a dust deposit on cars on the 17th. There were further reports of dust deposits in south-east England on the 28th.

November. Mean monthly temperatures were generally above normal in Scotland but below normal elsewhere in the United Kingdom, ranging from 1 °C above normal in the far north-west of Scotland to as much as 2 °C below normal on the south coast of England. Mean monthly rainfall amounts were below normal in most parts of the United Kingdom, the exception being part of north-east England where rainfall was above normal, reaching 124% at Newcastle upon Tyne. Some parts of south-west England and central southern England had less than a quarter of the normal rainfall. It was the driest November since 1956 over Wales, although only slightly drier than 1983, and over England since 1978. Northern Ireland had the second driest November since 1957. Monthly sunshine amounts were above normal nearly everywhere in the United Kingdom except for some coastal parts of north-west Scotland where it was rather dull with less than 80% of the average. The brightest areas during the month were along the Caledonian Canal, part of central England from Merseyside to The Wash and part of Cumbria and neighbouring Dumfries and Galloway where sunshine amounts were more than 160% of average. The 4th was the sunniest November day recorded at Easthampstead, Berkshire since 1965. Glasgow had its sunniest November since 1947 and at Edinburgh, Botanic Garden it was the sunniest November since records began there in 1939. Wingerworth, Derbyshire reported the sunniest November since records began at the station in 1970.

There were a few outbreaks of cold and wet weather during the month. Early on the 20th, snow over central areas of Scotland moved southwards to affect most of northern and eastern England as far south as east Kent. Snow fell at Oxford where, although snow falling in November is not unusual, the last occurrence of snow lying and covering more than half of the ground in November was in 1969. Wintry showers occurred during the next two days mainly in eastern coastal areas. There were outbreaks of thunder on the 11th in the far north of Scotland, accompanied by hail in places, and on the 20th in east Kent.

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Visit of the Meteorological Office delegation to China, 14–26 May 1989

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Summary

This article concerns a visit made by a delegation of Meteorological Office staff to the China State Meteorological Administration from 14 to 26 May 1989. Both technical and cultural aspects of the visit are described.

1. Introduction

Following an invitation from Mr Zou Jingmeng*, Head of the Chinese State Meteorological Administration (SMA), to Dr John Houghton, Director-General of the Meteorological Office, an Office delegation visited China between 14 and 26 May 1989. The delegation was led by Dr David Axford, Director of Services; the other members were Mr Chris Collier, Assistant Director of the Nowcasting and Satellite Applications Branch and Mr Roger Hunt of the Public Services Branch. Dr Axford and Mr Zou Jingmeng are shown in Fig. 1.

The main purpose of the visit was to learn about the SMA and to discuss with our Chinese colleagues as many of the issues as possible concerning the running of a National Meteorological Service. The visit took place at a time of civil unrest in China but the itinerary went ahead more or less as planned and, in addition to the technical matters, the delegates were still able to enjoy traditional Chinese hospitality and to see something of the country's culture and daily life.

*Mr Zou Jingmeng is President of the World Meteorological Organization.

2. Technical aspects

2.1 Chinese State Meteorological Administration

The SMA is a complex organization, not surprisingly in view of the size of China, with a massive outstation structure for forecasting and climatological purposes. The National Meteorological Centre is at Beijing (see section 2.2) and this includes the Chinese equivalent of the Central Forecasting Office at Bracknell. Underneath that are, or will be, seven Regional Centres — only two are in operation at present — 30 Provincial Bureaux, 300 Prefectural Meteorological Offices and 2400 County Meteorological Stations. Most of these carry out forecasting as well as observing. There are about 600 synoptic stations in China, 200 of which report hourly.

Three major educational institutions come under the SMA, together with a number of secondary technical schools, while at the Headquarters complex in Beijing there is an Academy of Meteorological Sciences and the Meteorological Satellite Centre. The total staff of the SMA is about 65 000.

Figure 1. Dr David Axford (left) and Mr Zou Jingmeng.

One of the interesting facts to emerge was that apart from employing meteorologists and the usual support staff, the SMA is responsible for housing most of its staff, educating their children and looking after their retired staff members. Some of their staff are, therefore, school teachers, doctors, accommodation managers, etc. They even run a rest centre in the south of China at which members of staff can take their holidays.

It also came to light early on that that the SMA has no responsibility whatsoever for aviation forecasting, civil or military. Both of these are run by entirely separate organizations. While conferences take place at an operational level, observations from the civil aviation network are not even passed to the SMA.

Our visit was planned and executed in a highly efficient but relaxed manner by our Chinese hosts to take in the complete range of SMA outstations as well as one of the meteorological institutes and all of the Beijing facilities.

2.1.1 Services at Shanghai Regional Centre

The first stop was Shanghai — the world's largest city and one of the Regional Centres, with 700 staff. Apart from having forecasting responsibilities for a large area of south-east China, there are also climatological and telecommunication sections and a large research section specializing in work on typhoons, storm-surge research and the development of techniques for nowcasting, making use of the good radar and satellite imagery facilities. Severe weather is a problem throughout China, with typhoons posing regular threats to the southern and eastern coastal areas, and severe storms, flash-flooding and hail distributed more widely (Shanghai's record 24-hour rainfall is 515 mm). Forecasts are issued as guidance for their outstations and also for customers, mainly the various local government sections dealing with water, agriculture, etc., but also in a small way to industry and the media.

While in Shanghai we visited a factory making meteorological instruments, and another producing radiosondes, largely for SMA operational use. Both were keen to develop further and to promote themselves internationally.

2.1.2 A Provincial Bureau — Nanjing

We then visited Nanjing in Jiangsu Province; this is one of the Provincial Bureaux and is housed in an attractive 500-year old observatory. The Provincial Bureaux are jointly managed by SMA and local

Figure 2. Old and new in the Nanjing Meteorological Institute — radar dome and satellite receiving dishes amidst traditional Chinese gardens.

government. This potentially confusing situation accounts, for example,for the large numbers of weather radars in the province. There are eight 3 cm radars, three 5 cm radars and one 10 cm radar as well as a 10 cm Doppler radar. This is more than required to cover the area effectively, but the local government divisions are keen to compete with each other. Nanjing has a range of responsibilities, including research work, not dissimilar to the Regional Centre and making use of an impressive array of microcomputers. Since 1985 they have been charging for some services; they currently earn about £85 000 per annum.

We went to the Nanjing Institute of Meteorology (NIM) (Fig. 2), which has about 1800 students including 120 post-graduates. There are basic forecaster courses, although we learned that there is no system for providing regular refresher courses. While at the Institute, Chris Collier presented lectures on 'Recent Advances in Ground Based Weather Observations' and 'Nowcasting in the UK Meteorological Office', both of great relevance to the SMA.

2.1.3 A Prefectural Office — Yang Zhou

One of the Prefectural Offices for which Nanjing has responsibility is in the ancient town of Yang Zhou. During our visit there we appreciated the general difficulties with communications in China. The office was keen to develop services, including commercial ones, and were aware they had a long way to go. However they only received a limited amount of information from their parent offices and some ECMWF and Japanese Meteorological Agency (JMA) forecasts by radio facsimile. For outward communications they had to rely almost entirely on speech using VHF radio.

2.1.4 A County Station — Miyun

While in Beijing, we travelled north to visit Miyun, one of the County Stations at the end of the administrative chain. Here facilities were fairly basic, with forecasters relying on poor copies of Beijing and JMA charts via radio facsimile, and VHF line-of-sight radio for most of their communication. In severe weather in particular (which occurred while we were there), there is radio contact with Beijing for a verbal description of the Beijing radar display.

2.2 Facilities at Beijing

At Beijing, we visited the National Meteorological Centre (Fig. 3), the Academy of Meteorological Sciences (where David Axford lectured on 'The Organization and Structure of the UK Meteorological Office' and 'Weather Services to Civil and Military Aviation in the United Kingdom' and Roger Hunt gave lectures on 'Numerical Weather Prediction in the Meteorological Office' and 'Current Research into Climatic Changes') and the Meteorological Satellite Centre. The latter was well equipped, with 400 staff. The first Chinese meteorological satellite was launched last year, although unfortunately it had an operational life of only about 1 month. At the National Meteorological Centre, forecasters use model output from JMA, ECMWF and the USA. They also run two forecast models of their own, one a 5-layer model of the northern hemisphere with a grid length of about 400 km run once every day at 0000 GMT, and a limited area model with twice the

Figure 3. Dr David Axford seated at a weather radar display with Mr Chris Collier (left) and Mr Roger Hunt (right) at the National Meteorological Centre in Beijing on 20 May 1989. Behind Dr Axford is Mr Li Zechun, Head of the National Meteorological Centre (second from right).

horizontal resolution and the same vertical resolution run daily at 1200 GMT. Forecasts are available about 8½ hours after the analysis time. They are currently developing a 15-level spectral model for use with a Cyber 990 computer which they plan to install in 1990.

3. Cultural aspects and hospitality

3.1. Background

The visit of the British Delegation from the Meteorological Office to China was made at the time of civil unrest with students and the public calling for greater freedom and democracy than they had experienced since the 'New China' was formed in 1949. Student demonstrations and hunger strikes in Tiananmen Square in Beijing began on 13 May and steadily escalated. We arrived in Beijing on Friday 19 May. On the night of Saturday 20 May the Government officially imposed martial law in Beijing, but the Army was held back outside the city by the citizens. On that first night the atmosphere on the streets of Beijing was electric. They were filled with students and citizens who created road blocks at random, and marched up and down with flags. Fortunately they were friendly to English onlookers! During the following week the situation remained tense and unresolved. While initially transport (subway, buses, taxis) stopped, and a general strike appeared to be in force, the situation gradually eased. The hunger strike ceased, but the students stayed in Tiananmen Square. All satellite transmissions from Beijing, including the American television broadcast of Cable News Network (CNN), were stopped from transmitting out of Beijing on 20/21 May, but they seemed to be back intermittently during the week. They were banned again at the end of the week. CNN broadcasts into Beijing were continuously available at our hotel, which had its own receiving dish.

Throughout this difficult period Madam Chen of the SMA continued to carry out the programme of visits as arranged. At times this was difficult. During our visit to Nanjing Institute of Meteorology (NIM) the President, Zhu Qiangen, and his senior staff sat briefing us while the students left the Institute chanting on their way to demonstrate in the city centre (outside our hotel). During the day the NIM lacked students, and Chris Collier's lecture was given to some 30–40 of the Professors and other teachers only. Our programme went close to plan — the only visit not possible was to the Forbidden City — and was arranged on a day-to-day basis as the situation allowed. At times we appeared to know more from the CNN satellite broadcasts in the hotel than did the staff of the SMA. They told us that the Voice of America and the BBC World Broadcasts were jammed at one time. On the weekend after we left Beijing the crisis seemed to have eased, and there was talk of the students giving up.

We returned to the United Kingdom on 1 June. Shortly after (2/3 June) the 27th Army troops were brought into the centre of Beijing to drive out the students. At the time of writing (8 June 1989) there are reports in the media of 7000 dead and 10 000+ injured in Beijing, and the position is totally confused. The UK delegation is saddened and distressed at this news, and most concerned with regard to the safety of the new friends we made during our visit.

3.2. Cultural visits

Our programme was arranged to allow us to make a number of cultural visits, which allowed us to see a wide range of Chinese environments, from the crowds of bicycles and people jam-packed in the narrow streets of Shanghai, and their shanty apartments, to the comfortable spaces in the countryside where farmers can build their own substantial houses for their families. The four classes in China are Party Members, Farmer, Citizens (educated) and Workers — and Farmers seem to do best!

The visits were also arranged to give us background to the New China and its history. In Shanghai we had only two nights, and there was not time to see anything but the mass of people; people crammed into buses, people on bicycles cycling impassively ignoring buses and cars, people walking amongst the cycles, dust and smells which made us cough, live chickens being plucked in a cart, and live ducks and pigs trussed on wagons on their way to slaughter. The culture shock was sudden; we were really abroad for the first time. We visited two factories, travelling through the narrow, winding bustling streets. They were at the bottom end of the range of small companies to be found in the West, located in a few rooms in a street of houses, and unkempt, yet the second factory produces 60 000–70 000 radiosondes a year, and says it could produce 250 000. We visited the Bund, the famous avenue on the banks of the Huangpu River, and the Friendship Shop. Shanghai is a city of 12 million people and is vastly over-crowded.

In Nanjing we found an attractive city with wide tree-lined boulevards and streets. Our hotel, the Jinling, was close to the centre, and the scene of demonstrations by students every day we were there. On arrival at 0830 a.m. in a British Aerospace 146 aircraft belonging to Eastern China Airlines we were first taken to be shown the Chang Jiang Bridge over the Yangtze River. This bridge, 22 000 feet long, was said to be impossible to build, and is shown to demonstrate the abilities of the 'people of the New China.' It was raining, and new young conscripts were being drilled. Our political education continued in Nanjing, notably by visits to the tomb of Dr Sun Yat-sen presented as the father of the New China's philosophy, the 1912 National Charter and Constitution of the Republic. We were then taken to Wu Liang Dau, a Buddhist temple (at which, incidentally, David Axford showed that fortune was on the side of the delegation by placing a coin to stay on a bell and floating another on water) and the Linggu Pagoda which has nine storeys and, as counted by the delegation, some 257 steps.

During Wednesday afternoon we were taken 'shopping' again, as well as to a Memorial Park (Lighthearted Lake) where we went round a Russian-style exhibit concerning the infamous wife of Mao Tse Tung (Jaing Qing) and her history. That evening, students were massed in the square, and during our walk we could feel the intensity of the crowds. They were all friendly to foreigners, however — no threats, only surprised curiosity.

Our visit to Yang Zhou Prefectural Weather Bureau on Friday 19 May further extended our education. The drivers sped at a crazy speed over the 72 km, and we saw our first views of the open countryside. It is green and cultivated, and pleasant houses (typical 4-bedroomed size in the United Kingdom) were to be seen built by farmers for themselves and their families. In the afternoon a delightful guide took us round the sights at Slender West Lake. The Angling Pavilion, the Wutung Bridge and the White Dagoba all give views which typify the 'China landscapes' we British are brought up to expect.

In Beijing we saw the wide new arterial roads of a modern city again — a lane for vehicles, another lane for bicycles, another for pedestrians. When we arrived the buses, trams and subways had been stopped, so cycles and people were everywhere. Our hotel was 10 km from the centre of Tiananmen Square, but only 100 m from the SMA complex in the west-north-west of the city, which was both convenient and fortunate. It is unlikely that we could have kept to the programme over the critical Saturday to Tuesday period if we had been further away from SMA. Thus despite demonstrations blocking the roads, and one or two nasty moments when our cars were stopped by students who wished to hijack them (I wound down my window to show a Western face, and the driver shouted that he had Englishmen on board), we still drove to and from the SMA on Saturday. On Sunday we headed out of town to the Great Wall of Mutianya, leaving the protests behind us. We took the cable car, and then climbed the steps to the north until at last we found the ancient unrenovated wall, decayed with bushes growing in the central road (Fig. 4). This is an extraordinary scenic visit — it is one of the wonders of the world — and getting there, despite all odds, the British delegation was as one in feeling that we had achieved the high point of the cultural visits. We also noted that the way we took was very steep — some of the steps were like climbing a cliff — and the sun was hot that day.

The Ming Tombs were off the agenda (closed for security purposes), and we did not get out of Beijing again until Tuesday 23 May when we were taken about 72 km north to Miyun County Weather Station. Again we had a chance to see the countryside (Fig. 5). The Forbidden City was closed (!), but on Wednesday the Summer Palace (Yiheyuan) was open. Some students were to be seen relaxing from their vigils in Tiananmen Square and we too were able to relax and take photographs amongst the various Palaces (with titles such as 'Joy and Longevity' or 'Virtue and Harmony') and to take a boat trip to see the 17-arched Bridge and the Temple of the Dragon King.

By Thursday, the situation had relaxed sufficiently for us to visit the British Embassy and (to Madam Chen's pleasure) the Friendship Store, and after confirmation from Zou Jingmeng at the dinner given by

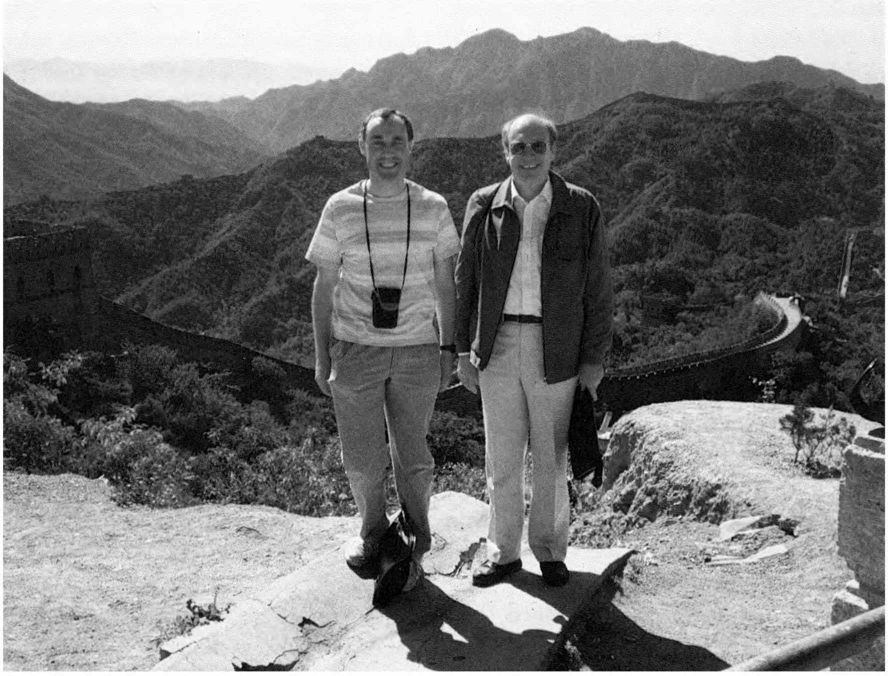

Figure 4. Roger Hunt (left) and Chris Collier standing on the Great Wall of China.

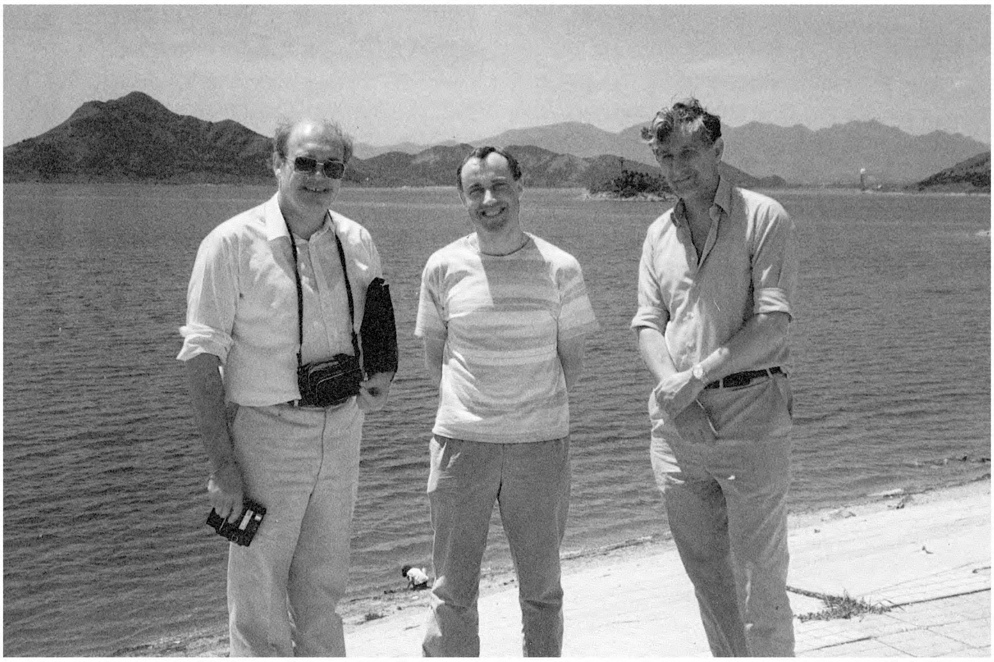

Figure 5. The delegation at Miyun — Dr David Axford (right), Messrs Roger Hunt and Chris Collier (centre and left).

the British delegation on Wednesday evening, we were allowed to stop briefly in Tiananmen Square and take some photos of the student protesters.

Overall, by the time we left on Friday 26 May, we felt that we had seen as good an overview of the eastern plain area of China as was possible in the two weeks available. We were struck most by its 'foreignness'. It is unlike anywhere any of us had been before in Europe, America or indeed the eastern bloc countries (USSR, Hungary, etc.). We had been given a brief education in the history of the New China since 1949. We have seen the people in the midst of a revolution, and they appeared mainly calm and peaceful, friendly and curious when they see an English face. The well-informed citizens we met all seemed to support the students in their desire for more freedom, but there was also a clear message that it may take a long time, and that it was necessary to tread carefully to ensure personal survival. Events since we returned have shown how true this was.

3.3 Official Entertainment

During the visit we stayed in three Western hotels — the Hilton International, Shanghai, the Jinling Hotel, Nanjing and the Olympic Hotel, Beijing. All are first class 4-star hotels which acted as oases of the Western environment and food to which we could retreat after each day in the Chinese city or countryside. We had an American breakfast each day to set us up, and on the few occasions when we were left to our own devices for dinner, we alternated between Chinese experimentation and Western pragmatism.

On arrival at any new Office Bureau or Institute, the procedure was the same. We were ushered into a formal room which contained comfortable easy chairs, and the two 'chiefs' — the Head of the Weather Bureau or Institution concerned and the Leader of the British delegation would sit side-by-side on a settee with a cup of hot china tea on a table in front of them. There would be a few minutes of courteous speeches of welcome and introduction on both sides through the interpreter and an exchange of business cards, then the Head of the Weather Bureau gave a spoken briefing on his Office and its responsibilities. We would then respond with questions and comments, and conclude by offering gifts of varying size, depending on the status of the Office, accompanied by official photographs. We had come prepared with three Meteorological Office shields (the Office crest), a good book of English scenes for Mr Zou Jingmeng and a number of other smaller objects as gifts. They were all accepted gracefully and there were responding small gifts from the higher status Chinese Offices (e.g. a scarf with the local insignia, a Chinese Meteorological Society tie, a small pot from Mr Zou Jingmeng). Then the visit around the location would proceed.

During our 12 full days in China we enjoyed ten Chinese meals, four of which were banquet dinners. We had previously practiced the use of chopsticks and did not resort to western implements at any time. We resisted maotai having sampled it at the first banquet (it is a tasteless liqueur) and thereafter we were served with wine and mineral water. The traditional procedures for formal banquets, including the initial speech and toast by the host and the response of the guest were followed. Fodor's Travel Guide on the Peoples Republic of China, with a section on business travel, proved invaluable here. We ate Cantonese-, Sichuan- and Northern-style food including shark's fin, Peking roast duck, sea cucumbers (slugs), hundred-year-old eggs, braised tendon and fungi of all descriptions. Notable dishes included squirrel salmon ('squirrel fish with a bushy tail'), steamed turtle fish and bottle gourd duck. We ate out in Yang Zhou at the Vegetarian Fragrance Restaurant in which the dishes look like duck, chicken or sausage but are in fact vegetables. We ate snow mushroom consommé of translucent silver appearance, hot peppery Sichuan bean curd, and duck gizzard. The delegation took it all as it came, and their stomachs survived — protesting mildly.

There were some temporary upsets, lasting at most a day. One was caused by a Western-style meal in which one delegation member was foolish enough to take consommé — clearly the water had not been boiled. Tap water is not potable, or even usable for cleaning teeth, and we used the boiled water in the hotel room or purchased mineral water. The meal at the NIM was notable for its number of dishes. The students were away protesting and the cooks ran amok with over 16 courses. In fact after the President had risen to his feet and we were leaving, two more courses of sweet (sago and coconut) and sour soups covered in fluffy egg white were being brought in. Chris Collier gave his lecture in the afternoon unperturbed. In Beijing we were given another very large Chinese meal at lunch time on Monday 22 May in honour of Roger Hunt's birthday. By this time we knew the scheme of things — sea slugs, antique eggs and fresh frogs legs were tasty morsels and after the customary 12–14 courses a large birthday cake was brought out. Despite a tendency for stupor to set in David Axford and Roger Hunt gave 3 hours of lectures and discussions during the afternoon.

The banquet given by Mr Zou Jingmeng was re-arranged at a nearby location, and the British delegation gave a return dinner in the Olympic Hotel. Both occasions went off well, particularly the latter in which we introduced moatai for the final two courses for Mr Zou, who gave us mandatory 'gambays' (bottoms up) to finish off the visit.

4. Conclusions

Overall, we found there were many areas where the SMA was relatively advanced. The facilities and technology available in some centres were very good and improving quickly. Some of the developments in the fields of Doppler radar, ground-based observing systems, nowcasting and the use of Model Output Statistics were particularly noteworthy. The meteorological research being undertaken throughout the country was clearly of a high standard. It would be correct to say that the research was more academic in nature and less practical in terms of user requirement than is the case in the Meteorological Office.

It was also the case that both the application of the technology in an operational sense and the forecasting services were comparatively undeveloped; there was little attempt to provide customer-orientated products for example. However this has to be seen in the context of an enormous country with big problems in communication systems. It is difficult to provide a complex service using speech via a VHF radio set. For similar reasons, the guidance, data and products provided to the smaller outstations by their parent offices, including Beijing, were lacking in substance. It was hard to see how consistency could be maintained between forecast offices.

Basically it was clear that the SMA has so far put more effort into developing technology and a strong theoretical base than into day-to-day operations and services. In the circumstances this is probably understandable.

We feel that the SMA is developing quickly and will become a major force in world meteorology in the not too distant future. We found the visit extremely useful and enjoyable and is a further step in a growing and hopefully friendly relationship between our two meteorological services.

We are very grateful to our hosts for their great hospitality and for the opportunity of seeing something of the Chinese way of life.

Conference report

The Labrador Sea Extreme Wave EXperiment (LEWEX) Symposium, Applied Physics Laboratory, The Johns Hopkins University, Baltimore, Maryland, USA, 18–20 April 1989

LEWEX was an international effort to assess and compare different methods of measuring and modelling directional ocean-wave energy spectra. From 13–19 March 1987 measurements of directional ocean-wave energy spectra were made using various instruments in the Labrador Sea area. These instruments included drifting buoys, moored buoys, ship- and aircraft-borne radar sensors.

Directional wave-spectra were collected from six numerical wind–wave models driven by four independent wind-field estimates for the same period, and also 'common' wind-fields were used to drive nine wind–wave models; these calculated spectral data were added to the LEWEX data base.

The LEWEX symposium was attended by over 100 people from widely varying backgrounds representing different institutions in Canada, the USA, Australia and six European countries. The Meteorological Office played an important role in the modelling side of the experiment and was represented by Dr P.E. Francis, and Miss K.M. Rider from the wave modelling group in the Forecasting Products Branch. The symposium was the first and probably the last time that all those who had participated in the experiment would meet together to discuss the results and their implications for measuring, modelling, predicting and applying global directional ocean-wave spectra.

Those speaking on measurements discussed the problems of using the instruments during the experiment, and then of interpreting the data and presenting them for comparison with model estimates of directional wave-spectra.

Presentations were given on the performance of each of the wave models from which spectral data had been obtained. Miss Rider described how the Meteorological Office wave model had been used to output spectral data for LEWEX and discussed some of the results.

The symposium was an ideal occasion for everyone attending to broaden their understanding of different aspects of wave measuring and modelling. The general opinion was that there is still a great deal of progress to be made in the next few years, especially in the area of satellite measurements of directional wave-spectra and the assimilation of satellite data into wave models. Hopefully it will be evident that progress has been made towards ensuring success for the next experiment which is being planned for the early 1990s.

K.M. Rider

Notes and news

1990 Watershed Management Symposium, Durango, Colorado, USA, 9–11 July 1990

The Irrigation and Drainage Division of the American Society of Civil Engineers is sponsoring the 1990 Watershed Management Symposium. The purpose of the symposium is to pursue scientific knowledge and to promote sound watershed processes, modelling of wind/water erosion, and application of planning and analysis tools in watershed management.

The symposium will be held on 9–11 July 1990 and will include technical sessions on precipitation and climatic processes, weather modification, infiltration processes, the role of vegetation, wind/water erosion processes, sediment transport/deposition by wind/water, remote sensing, data collection/management, geographic information systems and applications of planning and analysis tools. Session papers will be published in bound proceedings and distributed at the symposium.

Durango is located in the scenic San Juan Mountains of south-western Colorado. Recreational opportunities include hiking, fishing, golf, tennis and river rafting. Major attractions include the Durango and Silverton Narrow-gauge Railroad and Mesa Verde National Park. Durango is served by four airlines, with daily flights from Denver, Phoenix, and Albuquerque.

Requests for placement on the mailing list for future announcements should be sent to:

Mr Robert Riggins
USACERL
PO Box 4005
Champaign
IL 61824-4005.
USA

Modernization of the US National Weather Service

Recently the National Weather Service (NWS) of the USA (the equivalent of the Meteorological Office in the United Kingdom) has announced modernization plans, to cost $1 billion, for commencement in 1992 and completion by 1995, to equip it for the challenges and demands of the 21st century. The plans cover all the essential components of modern meteorological services — observing systems, communications, computers and forecast offices.

The USA has a population of about four times that of the United Kingdom spread over an area 40 times larger, but with a weather service which will still be only about twice as large in terms of staff and facilities. As a consequence the modernization involves a great dependence on remote automatic sensing systems and communications.Important parts of the new service will be weather satellites, a national network of weather radars and surface weather monitors, all linked to forecast offices by high-capacity communication lines.

The satellite system will use the next generation of Geostationary Orbiting Equatorial Satellites (GOES-NEXT) to replace the present GOES which are situated to the east and west of the USA to monitor the movement of approaching storms. The GOES-NEXT will have capabilities of both cloud imaging and atmospheric sounding. Upgraded NOAA polar-orbiting satellites with increased capabilities for atmospheric sounding in unfavourable cloudy conditions will also be used.

Surface observations of high quality and round-the-clock availability will be provided by 1000 Automatic Surface Observing Systems (ASOS) located mainly at airports. The ASOS observations of pressure, temperature, wind, cloud height and precipitation will be required not only for safe aircraft operations but also to provide warnings of severe storms, often leading to floods. Storms will also be monitored by 121 'Next Generation (Doppler) Weather Radars' to be run by the NWS and supplemented by a further 39 radars operated by other government departments.

The contact with customers will be through a network of 115 forecast offices with sophisticated data processing and display equipment, a reduction from approximately 300 at present using dated technology. There will be a corresponding reduction of personnel, mainly by natural wastage through retirement of World War II forecasters, from about 4700 to 3900. An interesting feature is that many forecast offices will also have hydrologists on their staff.

Finally, to facilitate the movement of data between the forecasters and the observing systems, new high-speed data lines are envisaged, along with new computers, 20 times faster and with 10 times the capacity of the present ones. These computers will be used to produce 2-, 5- and 10-day forecasts and special forecasts when there is a threat of hazardous conditions.

Review

Recent climatic change, edited by S. Gregory. 155 mm × 234 mm, pp. xvi+226, *illus.* London, New York, Belhaven Press, 1988. Price £33.00.

The book contains the proceedings of a symposium (Sheffield 1987) organized by the Study Group on Recent Climatic Change of the International Geographical Union, altogether 27 papers — of different quality as usual. Many papers contribute new data series, mainly on rainfall variability, but also on wind resources and chemical composition of rain-water. Regional aspects prevail, except for the first four papers on global problems.

Bach summarizes model results, but only regarding the expected global mean surface temperature. Using the generally accepted boundaries of warming with doubling CO_2 (1.5 and 4.5 K) and including other trace gases he extrapolates the trend until AD 2100 using three extreme scenarios and (for comparision) estimated palaeoclimatic averages back to the Miocene. Schönwiese compares the effect of different volcanic parameters on past temperature, Jones uses different techniques to obtain truly representative area-averaged data for precipitation. Parker and Folland carefully discuss quality control and corrections to homogenize the historical Sea Surface Temperature (SST) data set of the Meteorological Office; their figures show the enigmatic global cooling between about 1902 and 1912 without comment.

Eight papers deal with Europe and the Mediterranean; which include a comparison of records from the Svalbard area and the role of upper-air patterns, urbanization and cloud seeding on rainfall in Israel. From the six papers on tropical and southern Africa, three deal with relations between the drought-ridden Sahel belt and the SSTs in the tropical oceans. Owen and Folland could simulate significant changes of rainfall and of upper winds as caused by the observed SST, with only minor feedback effects of soil moisture. Using the Goddard Institute for Space Studies model, Druyan found also a strong effect of prescribed SST anomalies, overriding varying initial atmospheric conditions. On the basis of an empirical orthogonal function analysis of SST, Parker and colleagues found some skill in forecasting Sahel rainfall, at least for dry years. In central Sudan, Hulme correlated rainfall with length of rainy season, especially with its termination; a significant role of El Niño Southern Oscillation (ENSO) anomalies could only be confirmed for the Kenya coast (Farmer). Tyson gives some extensions to his recent book (1986). The final nine papers cover other regions, such as the study of rainfall anomalies of north-east Brazil as correlated with Atlantic SST, which indicated also predictive skill. Caviedas outlines the role of ENSO anomalies for South American key regions. Of special value are the collection and evaluation of the wealth of weather diaries at 18 stations in Japan since 1700, with some going back to 1650. Together with an eigenvector orthogonal function analysis of observed rainfall data for 1901–84, a historical record of rainy days during June–July at Yokohama is given for 1710–1895 which shows a distinct but questionable downward trend; significant correlations exist with regions of China and Korea.

The book presents many important empirical aspects of regional climatic change, which substantially supplement and expand our knowledge. There are many instructive illustrations, useful bibliographies and an index containing many names but only few subjects. Due to the variety of items, no comprehensive summary could be given. It is indispensable on the bookshelf of every climatologist interested primarily in facts and applications, while modelling scientists could use it for regional verification (which is only too often underrated).

H. Flohn

Satellite photograph — 5 July 1989 at 0919 GMT

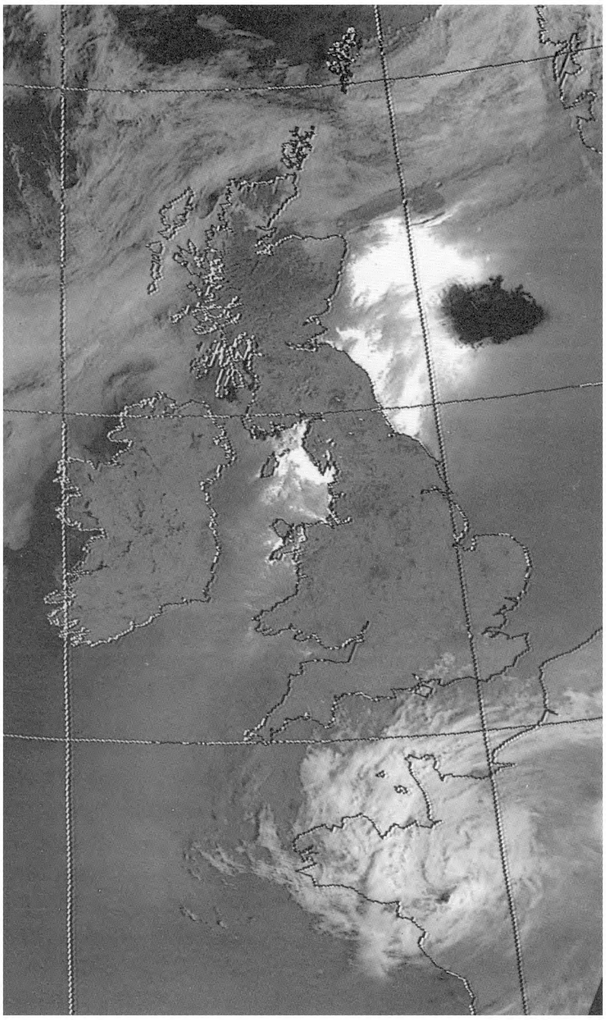

Figure 1. NOAA-10 visible image for 0919 GMT on 5 July 1989.

Photograph by courtesy of University of Dundee

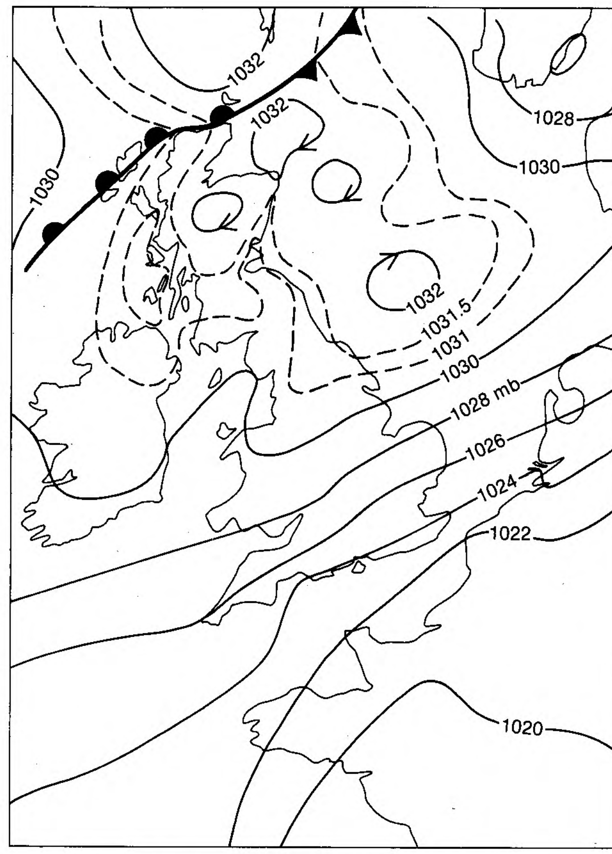

Figure 2. Surface analysis at 0600 GMT on 5 July 1989. Isobars are drawn at 2 mb intervals, but additional isobars are shown near the centre of the anticyclone. (The 0600 GMT analysis is shown rather than 0900 GMT due to there being more observations over the North Sea at the earlier time.)

This NOAA-10 visible image (Fig. 1) was taken during a period of anticyclonic weather when the British Isles was largely cloud free. There were several features of particular interest in the image.

Over the seas surrounding the British Isles, considerable sun glint is present. However, over the North Sea, there is a sharply defined 'black' region, where there is a total absence of glint. Such areas are occasionally seen when the sea is *mirror*-calm such as in the middle of an anticyclone. (If the sea were calm everywhere, then, due to the sun/earth/satellite geometry, glint would be confined to a narrow line roughly parallel to the satellite track.) On 5th July, surface observations in the area (Fig. 2) indicating both calm wind- and sea-conditions suggest this to be the case here. Further, by evening, infra-red satellite data indicated anomalously high sea-surface temperatures in the same area, almost certainly due to the lack of vertical mixing in the calm seas following solar insolation.

The meandering cloud band across the extreme north of Scotland is stratus and stratocumulus marking a weak cold front. The Scottish mainland has acted so as to partially block the southward movement of the front, and to cause dissipation of the cloud.

An upper vortex is present over western France, defined in the image by middle and upper cloud formed during earlier convection. A small but persistent clear area is seen at the vortex centre.

G.A. Monk

GUIDE TO AUTHORS

Content

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

Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (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.

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'.

Illustrations

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

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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Dines pressure-tube anemometer
Noctilucent clouds during 1988
Commercial aspects of meteorology
Analysis of humidity at Athens

HMSO

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One hundred years of the Dines pressure-tube anemometer*

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

Summary

A brief description is given of the development of the Dines pressure-tube anemometer which celebrates 100 years of use world-wide.

1. Introduction

One hundred years ago William Henry Dines (1855–1927) demonstrated his prototype pressure-tube anemometer (PTA) to the Wind Force Committee of the Meteorological Society. This instrument was the result of the combination of Dines's academic prowess, practical capabilities and experimental skills. PTAs are still in use today in many countries of the world and in desert conditions which cannot be coped with by modern electrically powered anemometers. In this article a brief description is given of Dines's early life which led to the development of the PTA, and its use and manufacture thereafter.

For readers unfamiliar with this instrument the basic components of the speed-measurement mechanism are shown in Figs 1 and 2. It operates using a vane to ensure that an open-ended horizontal tube always points into the wind creating a pressure in the tube (Fig. 1). A second, vertical, static tube is drilled with holes so that the air travelling past creates a suction. The two tubes lead to a sealed tank containing water in which floats an inverted 'bell' attached to a rod which actuates the recording mechanism (Fig. 2). The pressure tube leads to the space above the water in the bell, and the suction tube to the space above the water in the tank. As the wind speed increases, the combined action of the pressure increase in the pressure tube and its decrease in the suction tube causes the float to rise. Fig. 3 shows the

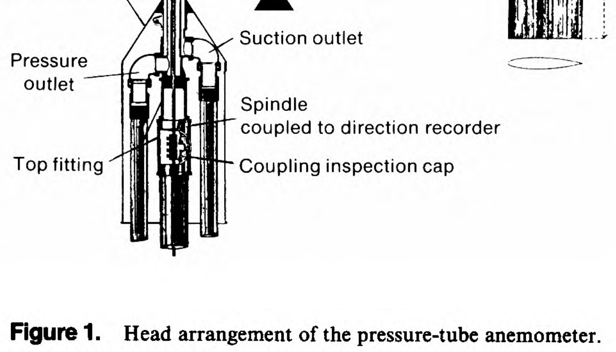


Figure 1. Head arrangement of the pressure-tube anemometer.

* This article is based on a more comprehensive article on the subject which is lodged, as a pamphlet, in the National Meteorological Library, Bracknell.

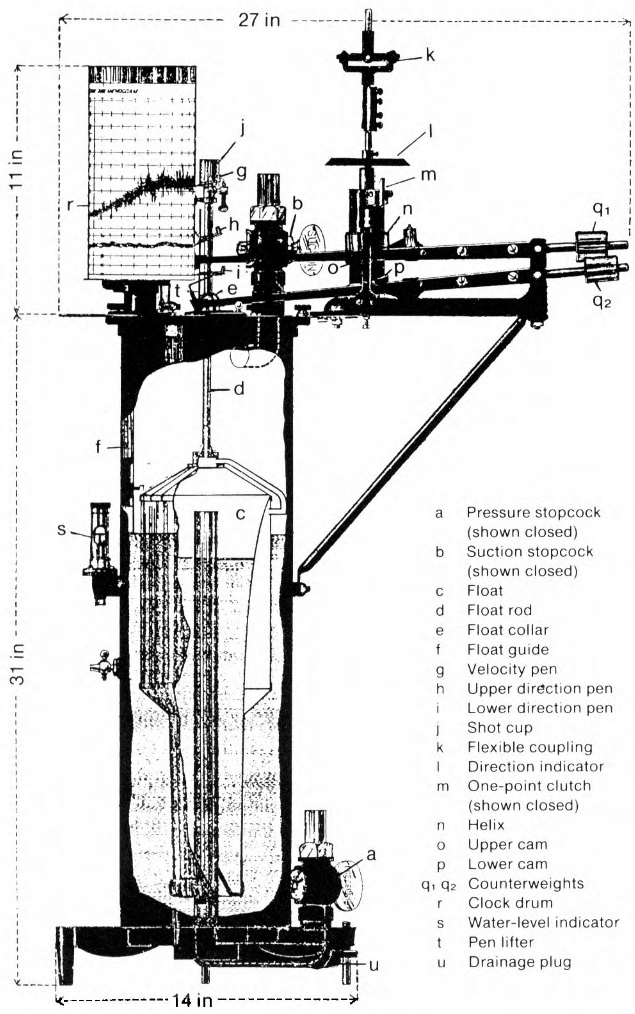
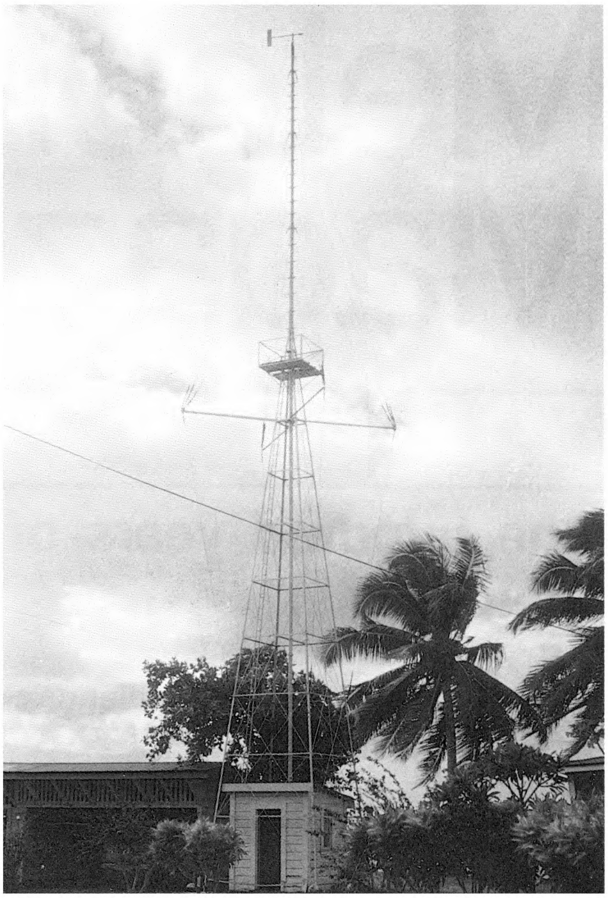


Figure 2. Recording mechanism of the pressure-tube anemometer.



Photograph by courtesy of Mr J.S. Falconer, New Zealand Meteorological Service

Figure 3. The pressure-tube anemometer mast at the Geophysical Observatory, Apia, Western Samoa.

PTA head and down-tubes installed on a lattice tower and guyed mast at Apia, Western Samoa. A Dines PTA thus exposed must rank as one of the more impressive meteorological instruments!

2. Dines's early years

Between the ages of 9 and 14 Dines attended Woodcote House School, Windlesham where he displayed an outstanding grasp of mathematics. From there he progressed to Trinity College, Eastbourne but left after a year, at the age of 16, having come into conflict with his master who disapproved of his unusual style of mathematical expression. The next four years laid the foundation of his skills in engineering and drawing during an apprenticeship at the London and South Western Railway locomotive works at Battersea. In this period his interest in wind and its measurement was awakened having observed, from the footplate, that the smoke from locomotives seldom overtook them; from which he concluded that wind velocities greater than 25–30 m.p.h. were uncommon inland. This agreed with the view of his father (G. Dines) that currently reported wind speeds were often too high such that if they were correct then buildings could not have withstood them.

At the end of 1877 Dines started his studies at the University of Cambridge, reading mathematics. During his stay, the Tay Bridge disaster occurred on 28 December 1879, which again stimulated his interest in the pressure exerted by wind on engineered structures and provided the initial motivation which led to development, 10 years later, of the prototype PTA.

At this time the Robinson cup anemometer was widely used to register wind speed but there was disagreement amongst scientists of the day about its accuracy; Dines was convinced that it under-registered gusts and over-registered mean speed because of mechanical lag associated with the cup's momentum. As a focus for discussion on wind measurement the Royal Meteorological Society formed the Wind Force Committee in 1885 to investigate and report upon 'the best mode available for... a satisfactory solution of the entire question of wind force'. Dines later became a member of this Committee. In the mid-1880s Dines started experimental work on wind speeds registered by contemporary anemometers, and air pressure exerted on plates, using a whirling test-bed installed at

Hersham. It was on this installation that Dines tested his prototype PTA head which he demonstrated to the Committee on 18 December 1889. The PTA head was found to have a large tolerance of wind direction — up to 15° — before a decrease of recorded speed occurred, so the provision of a vane to keep the open tube facing into the wind was adequate to enable high accuracy of registration even with gusts and turbulent winds.

In 1891 the Committee organized an anemometer comparison which included (along with others) the Robinson, the Kew-pattern and the PTA, the instruments being mounted on the roof of a house, designed and built to Dines's own specifications, in Oxshott. Difficulties were encountered in finding a suitable height above the roof to avoid eddies caused by the house itself; finally a height of 18 ft was used. As a result of these comparisons the PTA was recommended to the Meteorological Council and in 1892 the first production PTA was made by the Munro company (now R.W. Munro Ltd). In 1896 further comparisons were made using anemometers exposed on the training ship HMS *Worcester* at Greenhithe and on Stone Ness lighthouse about half a mile distant on the north side of the River Thames. Interesting deductions about the exposure of anemometers were made from the observations, which suggested that the influence of low hills (175 ft high) a mile away and of trees a quarter of a mile away could be detected. These results and the Oxshott findings were instrumental in defining the standard practice of measuring winds at 10 m (33 ft) height over a flat plain without obstruction, which is recommended by the Meteorological Office today.

The pitot head is only part of the complete PTA installation and several other workers contributed to the development of the very practical and reliable instrument that it has been. Munro's contribution was to redesign the float tank and recorder. A new-shape float and taller tank were provided to cope with winds up to 120 m.p.h. but the experience of even higher gusts recorded on Mauritius required a longer float which could cope with winds up to 200 m.p.h. Subsequently a gust of 174 m.p.h. was recorded on Mauritius using the 'long-float' modification — Fig. 4 depicts the winds recorded during the passage of the tropical cyclone in which this gust occurred.

In the early 1900s Baxendell designed a wind-direction finder to complement the PTA head giving rise to the Dines–Baxendell anemograph which used a common head. Initially the Baxendell direction recorder was mounted directly below the wind vane, was noisy in action and needed a separate chart drum from the PTA. Dines's son (J.S. Dines) developed a twin helix and chain combination (see Fig. 5) allowing the recording of wind speed and direction on one chart. In 1918 J.H. James, the Meteorological Office's chief mechanic, demonstrated that long levers operated the twin pens more successfully; later modifications have included the use of polythene tubing, and felt-tip pens (see Fig. 6).

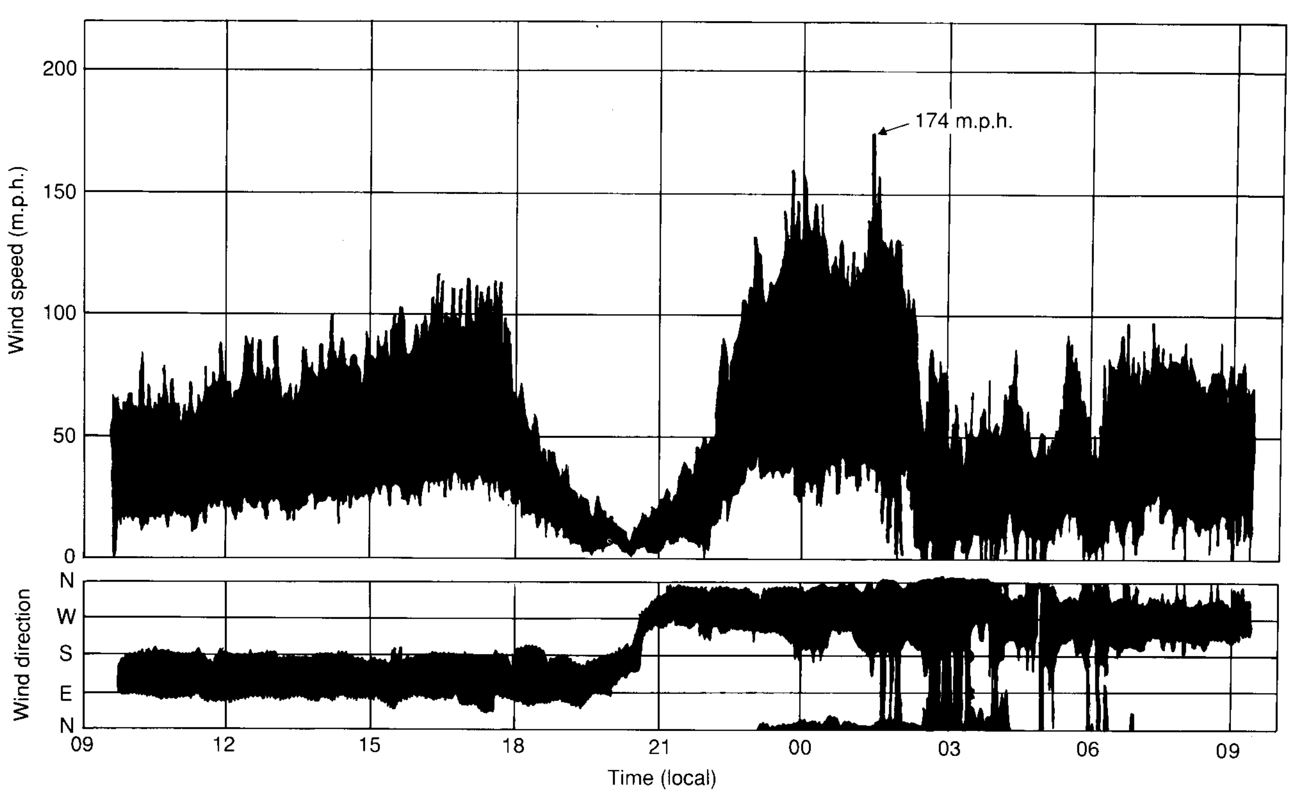
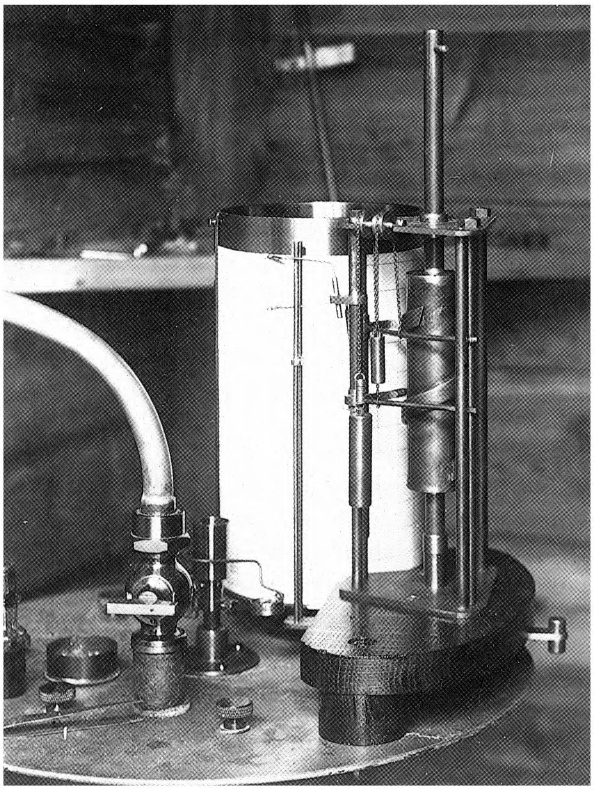
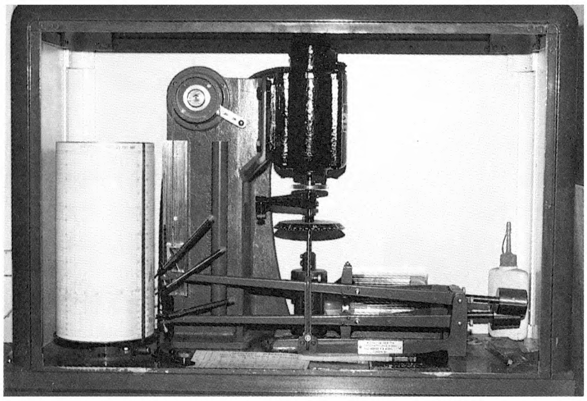


Figure 4. Pressure-tube anemometer record showing the passage of tropical cyclone Gervaise over the Mon Désert Alma Sugar Estate, Mauritius on 6/7 February 1975, during which the island's record gust of 174 m.p.h. was registered. (Reproduced from information supplied by Mr R.R. Vaghjee, Mauritius Meteorological Service.)



Photograph by courtsey of Mrs G. Poole

Figure 5. The 'chain system' for recording both wind speed and direction on one chart (*circa* 1910).



Photograph by courtesy of Mr J.S. Falconer, New Zealand Meteorological Service

Figure 6. The long-lever recording system with fine-line felt-tip pens attached.

In the 1930s some PTAs were adapted so that by electrical means their readings could be made available remotely (then known as Distant Reading Anemometers, DRAs) and this was useful particularly on airfields where the mast could now be sited some way from offices and hangars. The DRA was not popular because of the high ambient noise levels from the recorder unit's electric motors which operated continuously.

The PTA is not suited to use in cold climates because the head opening and suction holes can easily be blocked by snow, and the water in the tank could freeze, as was demonstrated by the one optimistically taken by Scott's Polar Research Expedition to Antarctica in 1910. However, in the 1940s a PTA was modified so that the exposed parts were heated electrically — requiring about 2 kW — thus enabling it to register winds up to 130 m.p.h. in temperatures down to −39° F.

3. Supply and use of the Dines PTA

In 1892 Munro began to manufacture 'speed only' instruments at a rate of five or six per year. By 1901 forty-three PTAs had been installed. Three were under test on Tower Bridge, with others equipping Kew, Holyhead, Scilly, and Southport Observatories. Exports listed by that time were: India 8, Japan 4, Mexico 3, Switzerland 2, Austria 2; also one each to Argentina, Egypt, The Netherlands, Nigeria, Norway, Spain, the US Weather Bureau and the Central Observatory, Paris. A further 21 sites had Dines PTAs installed by 1905, including Agram, Hungary; São Miguel in the Azores; Mauritius; Milan, Italy; three more in Japan; the University of Glasgow; and one on the Eiffel Tower in Paris.

Production and orders steadily increased with 54 PTAs being made during 1939, but World War II reduced this figure to 12 complete sets in 1940. With the Battle of Britain won, eventually by 1944, the 'war effort' saw Meteorological Office contracts for 165 PTAs being fulfilled at a steady rate of 8 per month.

Dines PTA production has tapered off since the instrument's 'heyday', a 25-year period, 1948–73, when export orders were being sent to Argentina, Australia, China, India, Mozambique, New Zealand and the United Arab Republic. Since the instrument does not need an electrical power supply to remain operative it was favoured in countries experiencing destructive hurricane-force winds; an order for 35 PTAs (equipped with 180 kn floats) destined for Cuba, occupied the factory over the period 1970–71. A recent peak demand saw over 40 new PTAs made and despatched during 1981–82 by Munro to various places including the Niger River Valley 7, Botswana 5, Jordan 5, Malaysia 4, and Fiji 1. In all, Munro PTAs have been despatched to 29 countries since 1982. The eight countries with the largest numbers of Munro PTAs still operating are listed in Table I. A list of stations offering researchers the possibility of a 60-year continuous record made with Munro PTAs is given in Table II.

In the United Kingdom there are only a few PTAs still continuously recording and in good repair. These are at East Malling, Fleetwood, South Shields, and at the Universities of Durham and Keele. The East Malling PTA produced an interesting record (as shown in Fig. 7) during the storm of 15/16 October 1987 at a time when there were widespread power cuts in south-east England (the break in the speed trace was caused by the pen running dry in a period of extreme gustiness; the station is not manned around the clock).

Table I. Munro's production and export figures over the past 50 years (1938–87) for Dines PTAs

Country	No. of PTAs now operating	Sets despatched directly by Munro since 1938	Sets including DRA conversions	DRAs now in service	Dines PTA first used
Australia	88	106	50	13	1927
Malaysia	32	24	3	–	1930
Sudan	23	17	–	–	1922
South Africa	18	62	37	18	1904
Syria	17	55	–	–	1959
Jordan	17*	11*	–	–	1955
Egypt	16	33	–	–	1899
Irish Republic	16	19	3	–	1924

* Uncertain figures.

Table II. Some stations where PTAs have recorded more or less continuously for over 60 years

Name and location		Duration of records	No. of years
Kew Observatory, London, United Kingdom		1896–1981	86
St. Mary's Observatory, Scilly Isles, United Kingdom		1896–1981	86
Pamplemousses, Mauritius	Royal Alfred Observatory	1903–1960	86
	Scientific and Industrial Institute	1961–present	
Dover, United Kingdom		1907–1988	82
Fernley Observatory, Southport, United Kingdom		1896–1977	82
South Shields, United Kingdom		1909–present	81
Fleetwood, United Kingdom		1914–present	76
Coats Observatory, Paisley, United Kingdom		1914–present*	76
Den Helder, The Netherlands		1897–1972	76
Shoeburyness, United Kingdom		1902–1974	73
Anglesey, United Kingdom	Holyhead	1895–1952	69
	RAF Valley	1952–1963	
Khartoum, Sudan		1922–present	68
Valentia Obervatory, Irish Republic		1924–present	66
One site, Yucatan State, Mexico		1925–present	65
Meteorological Office, Vacoas, Mauritius		1925–present	65
Central Institute for Meteorology and Geodynamics, Vienna, Austria		1911–1974	64
The Geophysical Observatory, Apia, Western Samoa		1927–present	63
Hobart, Tasmania		1927–present	63
Eskdalemuir Observatory, United Kingdom		1908–1967	60
Several stations, Malaysia		1930–present	60

* Last known operating Dines–Baxendell recorder.
Where records cease before the present time, the station has closed or the record been discontinued.

4. Other PTA designs

PTA designs remarkably similar to the original 'Dines' have been developed and marketed by Askania, Steffens–Hedde, and Fuess. During 1939–42 Fuess Universal instruments were installed at new bases in occupied Europe. In Belgium and Germany some Fuess PTAs are still in use today, and the Spanish Instituto Nacional de Meteorologica currently operates a network of 15 of these PTAs including one at the Base Aerea de Villanubla which has seen more or less continuous service since 1942.

5. Concluding remarks

Over the last century Dines PTAs have been found to provide robust and reliable service over long periods in many remote and sometimes hostile environments. In Zimbabwe, where a network of 13 instruments is maintained, recorders at Bulawayo and Harare still function well using their original tanks installed in 1936! Wherever it has operated, sensitivity combined with durability has been the hallmark of the 'Dines/Munro' PTA.

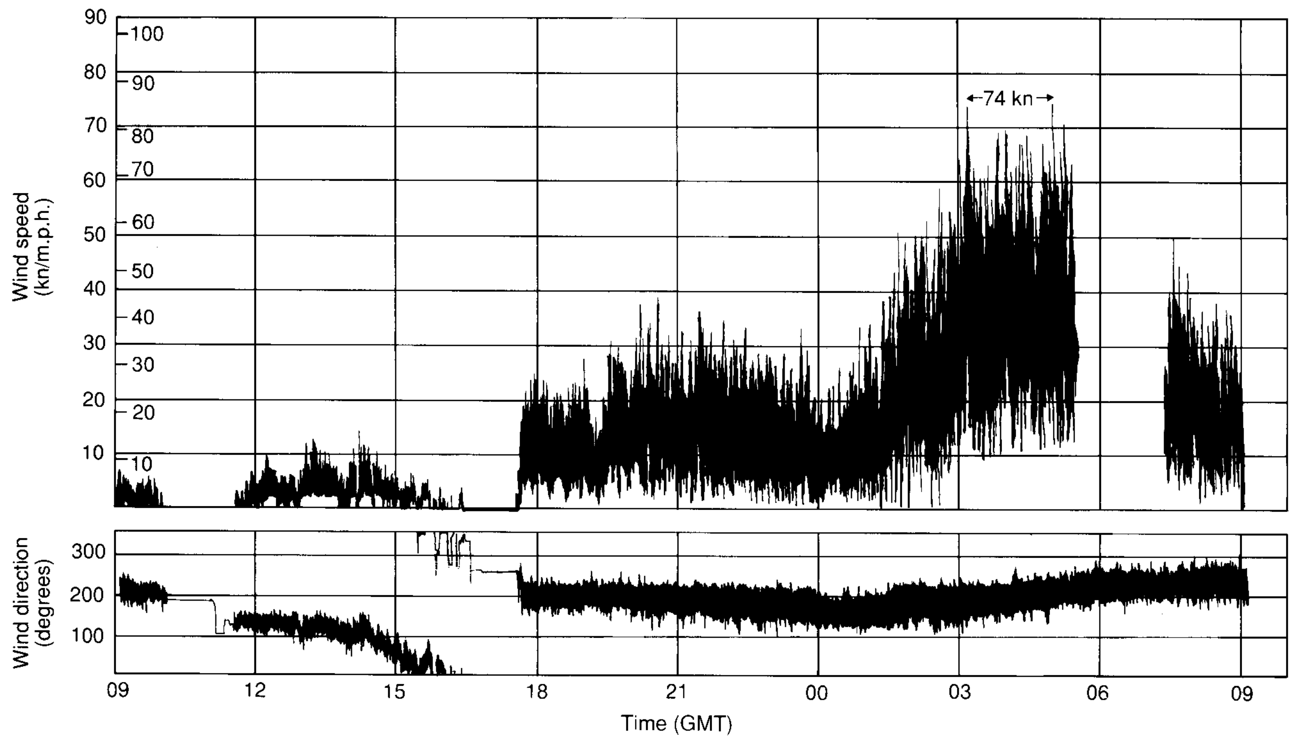


Figure 7. Pressure-tube anemograph record made at the Institute of Horticultural Research, East Malling, Kent during the 'great storm' of 15/16 October 1987 showing gusts of 74 kn at 0312 and 0501 GMT. (Reproduced from information supplied by the Institute.)

Acknowledgements

Thanks are extended to Mrs G. Poole, W.H. Dines's granddaughter, for the use of family documents to prepare this article, and to R.W. Munro Ltd, makers of the PTA, for access to their manufacturing and sales records. Thanks are also due to J.S. Falconer, New Zealand Meteorological Service and B. Bradshaw, Australian Bureau of Meteorology, for information regarding the operations of PTAs and to R.R. Vaghjee, Mauritius Meteorological Service, for supplying the anemogram of tropical cyclone Gervaise.

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Noctilucent clouds over western Europe during 1988

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Summary

Noctilucent cloud reports by voluntary and professional observers in the British Isles, Denmark, The Netherlands, Finland and Estonia suggest another year of high incidence of the phenomenon.

Table I summarizes the noctilucent cloud (NLC) reported to the Aurora Section of the British Astronomical Association (BAA) during 1988. The times (UT) are of reported sightings, not necessarily the duration of a display. 'Negative' nights (Table II) are based on the judgement of two or more experienced observers north of 54° N with clear or nearly clear sky conditions over the period of the night when NLC is likely to occur. Again, observers in British latitudes were forced to contend with bad weather and very poor skies in July, one of the worst summer months for years. Nevertheless, 38 positive sightings were made from the British Isles, Denmark and The Netherlands, 31 from Finland and Estonia.

Contributions were received from 35 voluntary observers and 9 meteorological stations in the British Isles, 5 observers in Denmark, 1 in Norway and 8 stations of the Royal Netherlands Meteorological Institute, together with a summary of the work of the excellent Finland–Estonia network. Full reports by the latter are published in the periodical *Ursa Minor* of the URSA Astronomical Association (Laivanvarustajankatu 3, SF-00140, Helsinki 14). The Canadian–USA observing network, co-ordinated at Edmonton by Mr Zalcik, is now well established but its results are not included here.

Over the last few years there has been a growing interest in NLC and mesospheric conditions with possible implications as to the state of the global environment. The intention of the BAA Aurora Section, an amateur organization with limited funding, is to provide a data bank of NLC distributions for professional workers and to maintain a continuity of observations. However, it will be apparent, from previous reports, that the 'western Europe' network is far from complete — several northern countries do not participate. The author would be interested in making contact with individuals and agencies in such lands, as it would be desirable to spread the observing network as far as possible to obtain a clearer picture of the incidence and movements of this intriguing phenomenon.

Details of individual displays and instructions for the systematic observation of NLC may be obtained from the author. All data are ultimately transferred to the Balfour Stewart Archive in the University of Aberdeen.

Thanks are due to all amateur and professional observers for their work, and to Dr M. Gadsden (Aberdeen), Mr R.J. Livesey (Director, BAA Aurora Section), Mr N. Bone (Director, Junior Astronomical Society Aurora Section), Dr B. Zwart (The Netherlands), Mr V. Mäkelä (Finland), Mr. J.Ø. Olesen (Denmark) and his colleague Mr H. Andersen whose superb photographs are regularly shown at astronomical meetings and exhibitions.

Table I. Displays of noctilucent clouds over western Europe during 1988

Date — night of	Times UT	Notes
14/15 May	2203–2240	Faint veil and bands at Milngavie near Glasgow, max. elev. 22° at 2203.
16/17	2200–0200	Faint bands at Machrihanish.
20/21	0015–0215	Suspect faint veil, bands visible only in binoculars at Morpeth. NLC at Helsinki.
23/24		Small NLC at Espoo (Finland).
25/26		Suspect NLC at Pori (Finland).
26/27		NLC to zenith at Helsinki. NLC at Tallinn.
4/5 June	2215–0045	Weak NLC to elev. 7° in NE at Milngavie.
6/7		NLC at Tallinn.
7/8	2245–0050	Billows and twisted bands to elev. 45° at Caithness, bands and whirls at Dundee, St. Andrews, Milngavie. Faint horizontal bands and complex structures photographed at Kilbirnie, Ayr, by Mr McEwan.
11/12	2110–0220	Veil, bands and billows as far south as Cambridge. NLC over ¾ sky at Caithness at 2245. Max. elev. 15° at I. of Man. Bands at Rønne. NLC at Tallinn. Bands elev. 10° at Nieuw Loosdrecht, Bussum and Rotterdam.
12/13	2130–2200	NLC at Nieuw Loosdrecht. Faint veil at Tallinn.
14/15	0100	Low bands photographed at I. of Man.
15/16	0030–0140	Faint veil, distorted bands and whirls in patchy tropospheric cloud at Kilbirnie.
16/17	2220–2305	All-sky NLC at Espoo and Jämsä (Finland). Bright billows to elev. 10° at Vildbjerg (Denmark). NLC at Tallinn.
17/18 June	2135–0215	Veil, bands and billows at Espoo, Pori, Jämsä, Helsinki. Faint veil and radiating bands to elev. 33°, horizontally widespread, at Kilbirnie. NLC at Tallinn.
18/19	2337–0200	NLC in trop. cloud gaps at Alness and Edinburgh. Bands, billows and whirls to max. elev. 28° at Morpeth and Castleford.
19/20		Faint bands and whirls, Co. Clare. Faint band at Espoo.
20/21	2145	Suspect NLC at Helsinki.
21/22	2151–0100	NLC over ⅛ sky, Orkney and N. Scotland. Veil, bands and billows in central Scotland and Netherlands. NLC in trop. cloud at Preston. Bright NLC at Espoo and Tallinn.
22/23	2120–0130	Bright display, all forms, into S. sky at Alness 2350. Max. elev. 60° at I. of Man, 25° at Cambridge; as far S. as Cardiff. Veil and bands at Rønne. Billows to elev. 15° at Rhoon, Rotterdam.
23/24	2210–0130	Faint horizontal bands, some billows, elev. 8° at Morpeth. Veil and bands at I. of Man. Bright NLC in trop. cloud in central Scotland. Veil, bands and billows, low, Co. Clare. NLC at Rhoon
24/25	2335–0118	Diffuse bands in misty sky at Milngavie. Suspect NLC in trop. cloud at Edinburgh. Veil and bands to elev. 23° at Vildbjerg.
27/28	2045–0230	Bright bands, billows, whirls in W. Scotland and I. of Man where elev. 45° at 0200. NLC extensive at Vihti, Jämsä. Bands to zenith at Helsinki. Veil and bands Jutland, Rønne, Deventer. NLC at Tallinn.

Date — night of	Times UT	Notes
28/29 June		Faint bands at Jämsä
29/30	2238–0130	Small NLC patch in trop. cloud at Alness. Faint display, all forms at Morpeth. Billows and bands in trop. cloud in central Scotland. Bands low in sky at Leeds.
1/2 July		NLC at Tallinn.
2/3	2130–0300	Extensive and bright display, all forms, seen as far south as London and Guildford. Photographed at Kilbirnie. NLC at Jutland: bright bands and billows to elev. 25° photographed at Vildbjerg. Large billows elev. 15° at Appingedam, Netherlands.
3/4	2120–0313	Moderately bright display, all forms, in Scotland and as far south as Leeds where faint veil suspected in zenith. Photographed in Skye and Kinloss where max. elev. 56°. Bright bands and billows photographed at Jutland. Billows at Appingedam. NLC throughout Finland and at Tallinn.
4/5		All-sky NLC in Finland, all forms. NLC at Tallinn.
5/6		NLC at Tallinn.
6/7	2125–0305	Veil, patches, bands and billows in central Scotland. Patches to elev. 10° in Essex. Small faint bands at Vildbjerg. Faint NLC at Jämsä.
7/8	2100–0100	Fairly bright, veil, bands and some billows in E. Scotland. Faint NLC elev. 20° at Todmorden. Bright bands and billows photographed at Jutland and Funen. NLC at Tallinn.
8/9	2145–0200	Bands and billows to elev. 30° at Alness. Bands, billows and whirls at Dundee. Small patches I. of Man. Veil, bands and billows in trop. cloud at Vildbjerg, Turku and Espoo. NLC at Tallinn.
9/10	0235–0250	Billows in NE, elev. 15° at Northolt.
10/11		Veil, bands and billows at Vammala (Finland).
11/12	2330–0125	Veil, bands and billows to elev. 25° at Alness. Patch and bands at Dundee. Moderately bright, all forms at Turku, Helsinki, Jämsä. NLC at Jutland and Tallinn.
12/13	2115–0245	Bands and billows in trop. cloud at Wick and Shetland. NLC overhead and covering ½ sky in Orkney. NLC to elev. 19°, all forms at Jutland. All-sky NLC, all forms at Espoo, Jämsä, Helsinki and Tallinn.

Date — night of	Times UT	Notes
13/14 July	2345	Band in trop. cloud gap at Sumburgh.
15/16	0200	Veil, bands and billows at Dundee.
16/17	2055–0000	NLC in trop. cloud gap NNW, Orkney. Bright bands and billows photographed at Alrö and Vildbjerg, max. elev. 28°.
20/21	2350–0005	2 bands in trop. cloud gap at Alness.
21/22		A few bands at Espoo, Raake and Vantaa. NLC at Tallinn.
22/23	2310–2320	Thin band in NW elev. 4° at Sumburgh. Faint NLC in poor sky at Turku.
24/25	2315–0100	Bright bands and billows in N. Scotland, elev. 45° in Shetland.
25/26		NLC to elev. 10° at Turku.
26/27	2305–0305	Veil, bands and whirls in N. Scotland. NLC in trop. cloud at Edinburgh. Moderately bright veil and bands up to elev. 8° at London.
27/28	0245	Bands in trop. cloud gaps at Edinburgh. Brilliant and multicoloured 'NLC' observed at Tallinn and throughout Finland, believed to have been induced by Soviet rocket exhaust. Photographs are in the URSA journal *Tähdet Ja Avaruus*, **5/88**, 172–173.
28/29	0215	Small bands and veil NNE at Dundee.
30/31		Moderately bright veil, bands and billows at Turku, Liminka and Siuntio. NLC at Tallinn.
1/2 Aug		NLC at Tallinn.
3/4	0200–0315	Faint bands and billows to elev. 10° at Morpeth. Billows above low trop. cloud at Wallsend.
4/5		Suspect faint NLC at Helsinki. NLC at Tallinn.
5/6	2050–0328	NLC patch in trop. cloud gaps at Caithness. Very faint bands at elev. 12° at Morpeth. NLC patch photographed at Frimley, Surrey at 2050.
6/7	0000	Suspect NLC in north at Kirkwall.
7/8		Veil, bands and billows at Raake (Finland). NLC all forms to elev. 60° at Kemi.
8/9	2330–0000	Moderately bright bands and billows to elev. 20° at Kustavi. Billows at Bergen. NLC at Tallinn.

Table II. Negative nights (British Isles) north of latitude 54° N

May 5/6, 6/7, 15/16, 17/18, 18/19, 19/20, 21/22, 25/26, 27/28, 28/29, 30/31; June 3/4, 5/6, 9/10, 10/11, 13/14; July 25/26, 29/30; Aug 1/2, 7/8, 9/10, 10/11, 12/13, 14/15, 16/17.

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Commercial aspects of the application of meteorology*

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Summary

The wide and developing role of meteorological services to specific users is reviewed and the need emphasized to market such services to both public and private sectors. Providers of such services are encouraged to interpret meteorological advice into industry-specific parameters so as to put the interpretation of the effects of the weather on a customer or business on to an objective rather than a subjective basis. This implies the development of close customer–contractor relationships.

1. Introduction

National Meteorological Services (NMSs) meet the needs of their countries in various ways. First and foremost they provide the primary functions of making or having observations made to the necessary standard for all meteorological purposes, secondly they provide basic weather analyses and prognoses, and thirdly they collect and validate all available meteorological data to create meteorological data archives. Thereafter NMSs differ in their modes of operation. In some countries all secondary services using the basic material of observations, analyses, prognoses and data archives are provided by, and only by, the NMS. In other countries all or most of this secondary service provision to users is carried out by independent or quasi-independent organizations for their own, usually profit-making, motives. Between these two extremes there are mixed situations, with the NMS and the independent meteorological organizations either competing directly or complementing each other in the services that they provide. In at least one World Meteorological Organization (WMO) Member State (not the United Kingdom) the NMS has indicated that it is being transformed into an independent institution outside the control of its government finance. Such a service will have to sell services sufficiently to raise all the running costs of the NMS including research and development. In a number of other countries the NMS is having to make choices between increasing revenue for services and reducing such activities as research and development.

In whichever situation exists it is vitally important that there should be sufficient funding for the NMS to provide the primary services mentioned above. This need is usually recognized by governments, and an important role of WMO is to help to ensure that governments continue to take that view. However, there has also to be sufficient funding for the provision of the secondary services to end users. Where such services are supplied by commercial organizations then the need to market and sell such services with a realistic pricing structure will be well understood. A commercial organization doing otherwise would not continue in existence. Where, however, services are mainly or entirely supplied by the NMS then, typically, an appreciation of the need to have sensible and defensible pricing structures is less likely. Similarly, the need to market or advertise services may not be understood.

* This article is based on the author's contribution to the World Meteorological Organization report, WMO-TD No.281, on 'Climate applications: on user requirements and need for development' presented to the tenth session of the Commission for Climatology, Lisbon, April 1989.

2. Application of meteorology

In recent years there have been developments in the application of meteorology to many human activities. Meteorology has been perceived as being capable of providing input to day-to-day operations such as transport by sea, air or land, to energy generation and acquisition, to water supply, to agriculture, and to many manufacturing and construction projects. Meteorological advice can be used in the planning or design stages of the same operations. Meteorology is thus entering (or has already entered in many cases) previously unforeseen applications by industrial, commercial and professional organizations. These organizations may be managed either nationally or regionally by the State or can be private sector firms varying in size from multinational companies to one-man businesses.

This widening of the application of meteorological services has been occurring at a time when governments are looking more and more at their own operating costs. Decisions at all levels of government are increasingly having to be made on cost–benefit grounds. Yet this is at a time when the techniques of management have become sufficiently sophisticated so that the efficiency and effectiveness of industry, commerce and the professions can be increased by the input of the appropriate meteorological information. This somewhat paradoxical situation is heightened by the imprecise nature of meteorology as a science, particularly in the field of forecasting, but also in the marked variabilities that can occur in weather parameters over short distances and over small time-scales. The science of meteorology is still developing at a pace often dictated by advances in technology applied to observing systems, communications and computing. The uncertainties in weather analyses, even with the most advanced observing systems available, to say nothing about uncertainties inherent in forecasting, make it difficult to convince the lay person that benefits can accrue by means of the careful application of such an imperfect tool. This problem of persuasion is enhanced by the increasing complexity of modern-day life in developed countries and by the increasing perception by meteorologists of the many and diverse ways in which their science can be applied. In developing countries, problems are also heightened but here, more often, it is because of the greater limitations of the basic database and the difficult forecasting problems in these often tropical or subtropical areas. Countries in such areas are often those in greatest need of meteorological advice and services and yet the understanding by the potential user of what may be achievable can be even less than in more developed countries with a longer history of the systematic application of meteorology to commercial and industrial problems.

3. Educating users

The above summary indicates that there is a process of education to be undertaken. It is also common experience that it is difficult to persuade lay persons to understand and use meteorological advice provided to them in terms with which they are not familiar. Therefore, it follows that meteorologists have to be able to understand the problems of potential users of weather services and have to be able to present information in terms related to the needs of the end user. There is nothing new in this concept. For example, aviation forecasters do not normally provide airline operators with detailed forecasts of wind shear and temperature lapse rate, rather they provide forecasts of the extent and severity of clear air turbulence. In entering into discussions regarding weather services, whether to organizations in the public or private sectors of national economics, the meteorologist must extend this principle. Services must be made specific as far as possible. Agriculturists do not want to know what the temperature and humidity have been over the past few days or what they are to be over the next few days, but they do want to know whether or not they should be spraying their crops for disease or pest control purposes.

4. Financial aspects

The level of services capable of being supplied by an NMS depends upon the resources available and this, as already noted, can be dependent upon the funding of the NMS. Where services are being supplied to national or state concerns, such as those engaged in power supply and generation or to transport services, then it is important that the benefits of the meteorological services provided be recognized either by transfer of funds from the user to the NMS or, more simply, in government funding to the NMS. Such arrangements necessitate an appreciation of the cost-accounted benefits of the meteorological advice to the user and, thus, to the national economy. When private sector organizations are taking meteorological advice then the discipline imposed by the need to operate with a trading profit provides a regulator of any payment made to the NMS. In the past many NMSs, particularly in the more industrialized and developed countries, have supplied meteorological advice and information to private sector organizations at charges well below the cost of providing the service if not at zero or minimal cost. In some countries legislation does not permit the NMS to charge customers or limits the charges that can be made. Increasing costs of running NMSs and greater demand upon government funds are resulting in such subsidies of private sector enterprises being reduced and there are increasing pressures upon NMSs to recover revenue for such work.

5. Communication

A technological constraint upon services provided by meteorologists whether of the NMS or from the private sector is the problem of communication with the end users. Many meteorological services are only of value if they can be made available to the end users on time-scales appropriate to their operations. When providing services to a small number of customers then this is not usually a problem — telephone or telex messages, for example, can be sufficiently effective and speedy. When providing services to, say, many thousands of farmers then effective, efficient and rapid message-dissemination is required. Here, again, cost can enter the equation and labour-intensive distribution methods may not be cost-effective.

6. User requirements

User requirements can be categorized in various general ways as follows:

Design.
Planning.
Operations.
Post mortem.

The types of user requirement will now be considered under these four general headings.

6.1 Design

The potential user of meteorological services for design can be concerned with, for example, engineering structures, the formulation of a service or the development of an operational system.

At the design stage of a structure or building there will be a need at an early stage to define criteria to ensure that the structure is capable of withstanding an acceptable range of meteorological conditions and that the probability of failure is less than some specified value. In some cases the designer will wish to ensure that the structure is able to withstand the worst possible combination of conditions. This might be, for example, in the case of an earth dam where overtopping could be catastrophic. The spillway in such a situation has to be able to withstand the probable maximum flood. In other cases it will be acceptable to design with a finite (although small) probability of failure. Similarly, when designing a system or a service then the probability of interruption or failure has to be at an acceptably low level. An example might be a land transport system in which there is a choice of vehicles. The extra cost involved in purchasing vehicles capable of operating under very adverse weather conditions might or might not be justified by the frequency with which those conditions occur. Similar considerations can enter into the design of structures. For example, the extra cost of putting wind shields on a bridge so that vehicles can cross safely when winds exceed some given speed might, or might not, be justified depending upon the frequency with which such winds occur and the penalties incurred in not being able to use the bridge in those extreme conditions.

When working with designers the meteorologists have to be aware of the characteristics of the weather sensitivities involved. A structure may react to gust speeds of a specific duration, it may be prone to loading by snow, it may have to withstand penetration of rain, it may have to be used under certain extreme conditions of temperature or sunshine. A transport system may cease to operate during spells when there is significant visibility reduction due to blowing dust or fog. The design of such systems will depend upon how often these conditions occur, what the cost is of providing equipment to clear the snow, what are the cost penalties of over-design etc.

A particularly important aspect of the advice that can be given by meteorologists to designers is in the understanding of the meteorological data, their shortcomings and, particularly, their representativeness. Weather observing networks very rarely provide all the data that might be required for a particular application. So meteorologists must be able to decide and advise upon what data can or should be used for a particular application and how these data should be interpreted. Many designers, even those of long and wide experience, do not understand sufficiently the effects on meteorological elements, particularly on extremes, of large-scale topography, local topography or seasonality. Accordingly the meteorologists must take steps to ensure that their expertise and their roles during design phases of projects are well understood.

6.2 Planning

Planning can be in the sense of a one-off problem such as a major construction project or, perhaps, a repetitive operation likely to occur during a definable period of time. The kinds of questions that planners have to answer usually relate to the cost and resources required to undertake a task. In the case of a major structure the questions will concern the various phases of construction. At certain times of the year what will be the probability of being able to complete certain operations? What is the probability of delays due to the ground being too wet, or too frozen? What is the possibility of getting weather windows for particularly critical operations such as the towing of structures out to oil rigs? Obviously, some design questions overlap or are very similar to those used for planning purposes while other questions are unique either to the design or to the planning phase. As for design, the meteorologist has to be prepared to make the user aware of the dangers of the uninformed or incorrect use of meteorological data.

6.3 Operations

Here the role of the meteorologist is better understood by the user. The interaction of the weather forecaster with aviation and marine interests has developed sufficiently over many years and the benefits of meteorological advice are quantifiable and in some cases quantified. In the case of aviation it is reasonably straightforward to calculate the effects on fuel usage of not taking a weather forecast and, indeed, the effects of taking weather forecast services with known root-mean-square errors in wind vectors can be calculated. However, there are many activities of a weather-sensitive nature for which professional meteorological advice is not universally used. A list, by no means exhaustive, could include the following as particularly weather-sensitive operations in addition to the normal aviation and general marine forecasting services.

The weather routeing of ships either to avoid damage or to minimize time of passage. Here the user will require not only forecasts of wind, sea state and visibility but also forecasts of the effects of that weather in terms of damage to the ship and its speed. However, to be able to benefit by the advice it must be sufficiently timely to allow action to be taken to avoid damage or loss of speed.

Management of energy supply systems requires weather forecast information for short periods of an hour or so, longer-period forecasts of a day or days and, ideally, even longer-period forecasts of weeks or months. Short-period forecasts of energy requirements are needed in order to decide whether a power station can be shut down or whether others should be started up, whether energy will have to be bought from a neighbouring country, etc. Forecasts of energy requirements for the next two or three days are used for decisions concerning maintenance of power stations. Still longer-period forecasts can be used for technical planning or the movement and purchase of fuel.

Manufacturers and retailers wish to be able to predict demand for their products, customer behaviour, and effects of weather on their products during storage or transport. Correlations of various lag times exist between weather and sales of such diverse products as ice-cream, soft drinks, soup, clothing, motor cars, bottled gas, etc. The weather can greatly influence customer behaviour and determine whether or not the customers will visit the nearest shop or travel some distance to a shopping centre or a supermarket. Food quality can deteriorate rapidly in adverse weather conditions in a manner which, of course, will vary from food to food.

Firms concerned with building and construction require forecasts specific to certain operations. The weather can influence significantly the ability to concrete, to use mechanical diggers, to spread bitumen on roads, to operate tall cranes, etc.

In agriculture, current and forecast meteorological information can be used to help farmers decide what should be done on a particular day. For example, if the ground is not fit for ploughing now, then when will it be fit? Is there a need to irrigate and, if so, by how much? Are conditions right for the propagation of disease and, if so, when will be a suitable time to treat for the disease or pest? At what stage is the growth of certain plants? What yield is going to be obtained from a certain crop? Will there be a need to heat glasshouses tonight? Is produce going to deteriorate in store? Is any action needed to ensure, say, that seed potatoes in store will reach a satisfactory state of development for planting in the spring?

The increasing complexity of modern life, the greater sophistication of agriculture and the tighter profit margins under which industry and commerce have to operate all lead to the need for better and more informed decisions to be made. Good and informed meteorologically based advice may make the difference between success and failure or profit and loss. Indeed, in many operational activities the sensitivity of the work to meteorological advice may be more important than the sensitivity to the weather itself. Before trying to persuade a potential user to take a meteorological service some consideration should be given to the ability of the user to respond by taking remedial or corrective action.

6.4 Post mortem

There is often a need to know what the weather was in some historical sense. This can be for the monitoring of certain operations, for example to determine whether or not a contractor on a construction project is keeping up to schedule or whether delays occurring are avoidable or not (see Fig. 1). There may be questions of assessment of design criteria. For example, is the amount of fuel being used to heat a building in accordance with that expected given the size of the heating plant, the aspect and design of the building? Specific knowledge regarding the weather can be required to answer questions on a wide range of legal and insurance matters (see Fig. 2). Many weather consultants in the USA refer to themselves as forensic meteorologists and, while this term is not used in many other countries, it does indicate that meteorologists can have a role to play in helping to reconstruct events that have occurred.

7. Provision of services

The ways in which meteorological services, whether of data, data analyses, forecasts or other advice, are disseminated depend upon the customers, their needs, the technology available at their disposal and the technology available to the providers of the meteorological service.

In the simplest case, when reports are prepared providing some specific advice, such as a design or feasibility study requiring meteorological input, the use of hard copy is the obvious and, perhaps, only sensible choice. In many other cases, depending upon the nature of the service, the interaction of the NMS with other meteorological organizations, and the degree of operational urgency to which the service relates, there can be good reason to use some automated or semi-automated methods of dissemination and production.

Under the auspices of WMO, international meteorological telecommunications are relatively advanced technologically and NMSs generally, whether in developed or developing countries, are usually fairly near the forefront of data handling and processing. Meteorologists thus tend to think of automated data transmissions, computer-to-computer links and of the transfer of data in machinable form whether off-line or on-line. There is, however, less acceptance of such techniques among many users, and traditional methods of communication by letter, word of mouth direct or on the telephone are likely to dominate for some meteorological services to many of the customers and for many meteorological services to certain customers.

In addition to methods of information dissemination there are also considerations of the form of the information to be provided. Do the customers wish to be presented with some general or specific meteorological advice or do they want to have such advice translated into terms relevant to these needs? Do farmers wish to know what the weather conditions have been for the past few days or will be for the next in terms of meteorological parameters such as temperature, rainfall, relative humidity, sunshine, etc. or do they really want to know about the quality of their grass or the necessity to spray their potatoes for blight? Does a power-generating authority require a forecast of temperature and wind for the next few days or does it really wish to know how much power will be needed and whether or not a power station can be shut down for maintenance?

Methods of data provision are likely to be determined by what the customer or user can accept or wishes to accept. However, it must be noted that users are very often concerned with costs, and a labour-intensive method of information dissemination may be very

DAILY WEATHER SUMMARY — PAGE 1 — TEMPERATURE AND HUMIDITY

GLASGOW (ABBOTSINCH AIRPORT) — FEBRUARY 1989

STATION NAT GRID REF = 2480E 6667N HEIGHT = 5M AMSL

DATE	NUMBER OF HOURS IN PERIOD 0700-1700 GMT WITH TEMPERATURE LESS THAN (DEG C) 0	1	2	3	4	5	8	15	RELATIVE HUMIDITY OVER 90%
WED 01	0	0	0	0	0	0	5	10	0
THU 02	0	0	0	0	0	0	0	10	0
FRI 03	0	0	0	0	0	0	0	10	5
SAT 04	0	0	0	0	0	0	8	10	1
SUN 05	0	0	0	0	0	2	8	10	0
MON 06	0	0	0	0	0	0	0	10	2
TUE 07	0	0	0	0	0	0	2	10	0
WED 08	0	0	1	2	2	3	4	10	2
THU 09	0	0	0	0	0	0	3	10	0
FRI 10	0	0	2	2	2	3	8	10	3
SAT 11	0	0	0	0	0	0	10	10	2
SUN 12	0	0	0	1	4	7	10	10	1
MON 13	0	0	0	0	0	0	5	10	2
TUE 14	0	0	0	0	0	1	10	10	2
WED 15	0	0	0	0	1	5	10	10	0
THU 16	2	2	3	5	7	9	10	10	0
FRI 17	0	0	1	4	4	6	10	10	0
SAT 18	0	0	0	0	0	0	3	10	0
SUN 19	0	0	1	2	3	4	10	10	1
MON 20	0	0	0	1	5	9	10	10	0
TUE 21	0	0	0	1	2	3	10	10	1
WED 22	0	0	0	0	0	7	10	10	0
THU 23	0	0	1	2	8	10	10	10	0
FRI 24	0	0	0	2	3	5	10	10	0
SAT 25	0	7	10	10	10	10	10	10	10
SUN 26	1	2	4	4	7	10	10	10	0
MON 27	0	0	0	0	1	5	10	10	0
TUE 28	0	0	0	0	0	3	10	10	0
MON-FRI TOTAL	2	2	8	19	35	69	137	200	17
LONG TERM AVERAGE	16	22	37	57	86	110	173	200	49
MON-SAT TOTAL	2	9	18	29	45	79	168	240	30
LONG TERM AVERAGE	19	26	44	69	103	132	208	240	59

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Figure 1. A page from *Metbuild*, the Meteorological Office's monthly downtime summary used by the building and construction industry.

BASICPROOF
DAILY WEATHER SUMMARY

GLASGOW (ABBOTSINCH) **FEBRUARY 1989**

STATION NAT.GRID REF. 2480E 6667N — 5 m above Mean Sea Level

	AIR TEMPERATURE High (deg C)	Low	RAINFALL (mm) 00-11 hours	12-23 hours	MAX. WIND dir	kts	hour	MAX. GUST kts	hour
Wed 01#	8.8	6.0	trace	trace	SW	17*	1600		
Thu 02	9.7	5.6	trace	16.4	SW	22*	1400	34	1400
Fri 03	10.7	9.2	4.4	2.6	SW	25*	2300	41	1500
Sat 04	10.2	3.9	8.6	8.0	W	25	2100	41	1600
Sun 05	10.7	1.9	2.2	3.4	W	24	0000	36	0100
Mon 06	11.4	10.6	1.0	4.8	SW	30*	1800	50	1800
Tue 07	11.0	6.6	2.2	trace	SW	30*	0400	46	0400
Wed 08	9.3	1.6	trace	trace	SE	11*	2300		
Thu 09	11.0	4.8	0.0	1.6	SE	15*	1400		
Fri 10	8.3	0.1	0.8	0.0	W	11	1600		
Sat 11	7.7	-0.8	5.0	9.8	S	26	1300	42	1100
Sun 12	5.4	0.8	4.0	1.8	W	24	1200	39	1200
Mon 13	9.9	3.8	8.2	4.0	W	37*	2000	64	1600
Tue 14	9.1	2.9	1.2	5.2	SW	25*	2300	39*	2300
Wed 15#	9.4	0.9	13.6	1.0	SW	30	0200	46	1600
Thu 16#	5.0	-0.8	0.0	0.0	W	17	0000		
Fri 17#	8.1	0.6	trace	4.0	S	19	2300		
Sat 18	10.8	6.2	0.2	3.8	S	25	1500	38	1600
Sun 19	7.0	1.0	5.0	0.4	SW	30	0500	55	0400
Mon 20#	5.9	1.3	1.0	5.0	SW	21	1100	35*	2300
Tue 21	7.7	2.1	6.8	3.4	S	21	2300	35	2100
Wed 22#	7.0	1.0	1.2	trace	SW	28	1500	42	2300
Thu 23#	4.1	1.8	trace	trace	SW	26*	1000	38*	0400
Fri 24	7.0	1.8	trace	0.8	S	15	0200		
Sat 25#	2.3	-0.4	0.8	trace	SW	8*	2100		
Sun 26	4.5	-2.9	0.0	0.0	NE	8	1300		
Mon 27#	6.1	-3.0	0.2	0.4	SW	13	1500		
Tue 28	7.3	2.5	1.0	0.2	SW	19	1300		

trace means <0.05mm; # missing hours; * value reached more than once.

WEATHER DIARY	DATES
STRONG WIND > 21 kts	2 3 4 5 6 7 11 12 13 14 15 18 19 20 21
RAINFALL >4mm in hour	4 15
THUNDERSTORM	
HAIL	5 15 19 20 23 25 26 27 28
SNOW	12 15 16 17 19 20 21 22 23 24 25 27
FROST < 0 deg C	11 16 25 26 27

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Figure 2. A page from *Basicproof*, a simple diary of the weather which may have a bearing on insurance claims.

expensive both in terms of costs for the meteorological service and for the customer. The use of Information Technology (IT) and the resultant long-term reduction in costs might well mean that automation can be introduced into both product generation and dissemination. IT can allow the often expensive human costs to be reduced, it can allow more services to be produced at little or no extra cost to the provider of services and it can free human effort for work where human input and judgement might be used to advantage.

In some countries, methods of service provision begin with the dissemination of basic meteorological data and forecasts from the NMS to other organizations which act as the interface with the user. These other organizations may simply pass on the NMS products as received or they may provide some added value. The ways in which the NMS is funded for such basic data provision are clearly a matter of political judgement in the country concerned. Where this use of other organizations is the way of working then the NMS, in order to keep its own costs down, will probably wish to provide either broadcast output to the separate users or, and perhaps additionally, may wish to provide access in an interactive fashion for the other organizations into the NMS databases of current data, historical data and predictive data.

8. Conclusions

From the above it can be seen that there are very few activities upon which meteorology does not have a bearing or the execution of which cannot benefit in some way by meteorological advice. What is apparent is that the variety of meteorological input is very great and unlikely to be fully understood, and often not understood at all, by non-meteorologists. This problem can be tackled in two ways. Either potential users can be educated in the application of meteorology to their problems or meteorologists can be educated to comprehend the requirements of users and their principal problems. In some cases the first approach is appropriate, for example aviators and mariners have a reasonably good appreciation of the benefits of taking meteorological advice and the penalties of not doing so. Even here there are probably some instances where operations could be undertaken more efficiently or more effectively given the application of appropriately tailored meteorological advice. In other cases, for example in the field of civil engineering, there can be considerable meteorological input particularly at the design stages of projects but often in a somewhat mechanistic way by reference to handbooks or standard formulae. There is a tendency for civil engineers working upon the design of structures to use standard meteorological input for such factors as wind loading, temperature limits, rainfall penetration, etc. In many cases this might be the best advice but there must be others where more specific advice would be of benefit. In many other walks of life the potential users have insufficient scientific background or understanding to know what informed meteorological advice could do for them or their work.

In many areas of trade or commerce the 'weather' is simply accepted as another unknown, another variable against which some money may be put as a contingency or against which there must be some slack in the system. This can be the case particularly, for example, with sales of goods and customer behaviour. Better knowledge of the weather relationships in these cases can help manufacturers, suppliers and retailers to plan their production, their distribution of goods, their tactical advertising and their sales strategy to good advantage.

In addition to the concept of weather sensitivity, some thought must also be given to the sensitivity of the customers or users to weather services. Indeed, from the point of view of the paying customers the critical question may well not be whether or not they lose money because of the weather but can they save money by using meteorological advice. The meteorologist has to give attention to this important issue and consider on a market-by-market or customer-by-customer basis just how an appropriate service can be provided to meet a specific need.

551.553.11:551.571.31:551.553.6(495)

Analysis of absolute humidity by wind speed and direction during land- and sea-breeze days at the National Observatory of Athens, Greece

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Summary

The technique of the rectangular wind-frequency isopleth diagram is used to examine the dependence of ambient air-water content on wind speed and direction on land- and sea-breeze days. The variation of absolute humidity in each direction at a monitoring site, as the wind speed varies, is shown pictorially. The absolute humidity is shown to increase when the wind blows from the sea and especially from directions between south-south-west and west-south-west. The local maxima and minima, occurring in some sectors, are discussed in detail.

1. Introduction

A data presentation technique developed by Zambakas (1982), the rectangular wind-frequency diagram, has been extended in scope. The existing technique enabled the distribution of wind by direction and speed to be analysed. However, it is possible to examine the effects of these variables acting simultaneously on other ambient air elements, as has been done previously (Zambakas 1984, Zambakas *et al.* 1985). In this study the technique is applied to the behaviour of ambient air-water content during days of nocturnal land-breezes and daytime sea-breezes. Details of the technique are discussed by Zambakas (1982, 1984).

2. Data

Sea-breeze days occur in Athens throughout the year. These days were selected from the 7-year period 1961–67 for the months of April (27 days in all), July (24 days) and October (24 days). Because of the rarity of this phenomenon during the winter period, a 30-year period, 1938–67 (26 days), had to be considered for January. Only days with pure sea-breeze conditions were selected to avoid interference by any other wind component during the period of the sea-breeze day. The nights before and after the chosen day had only a light land-breeze or were calm. Data were derived from the records of a pressure-tube anemograph situated at the National Observatory of Athens (NOA, 37° 58′N, 23° 43′E and 107 m above mean sea level) for where the land- and sea-breeze characteristics are examined here. These anemograph data were used by Zambakas (1973) to examine the times of the beginning and end of the sea-breeze at Athens (Atkinson 1981, p. 133), and hodographs were used to study the veering or backing of the wind during sea-breeze days. The NOA lies on a promontory and is about 5 km from an indented coastline. The topography of the region of the measurement site is shown in Fig. 1.

The mean hourly absolute humidities were calculated in millimetres of mercury (mm Hg) from the corresponding records of a hygrograph (Smithsonian Institution 1939, Table 81); in normal atmospheric conditions the absolute humidity measured as water vapour pressure (mm Hg) and in units of water concentration ($g\ m^{-3}$) have nearly the same numerical value.

3. Duration and speed of land- and sea-breezes

The characteristics regarding the duration and the time at which the land- and sea-breezes begin and end are shown in Fig. 2. These are known characteristics relative to the times of sunrise and sunset (Zambakas 1973). It has been assumed that diurnal variations remain reasonably constant over the month. The times of the beginning and end of the sea-breeze during July from Fig. 2 (from Zambakas (1973) and not calculated from anemograph data) are considered to be 0900 and 2300 hours local time (GMT+2 hours), respectively.

4. Variation of humidity with hourly wind speed and direction in land- and sea-breeze conditions

The ambient air absolute humidities were examined for 24 days in July, i.e. 576 hours. Results for other months have not yet been tabulated because at present these have to be calculated manually in the absence of computerized records.

Fig. 3 shows the frequency isopleth diagram of wind speed and direction. The frequency is calculated from the numbers of observations in increments of $0.2\ m\ s^{-1}$ and 10°, relative to the total of 576 observations. The frequency of the calm category (wind speed $< 0.2\ m\ s^{-1}$) is 20%. The pattern of isopleths in Fig. 3 suggests the wind flows in preferred directions with a range of speeds rather than with preferred speeds in a range of directions.

The nocturnal land-breeze is clearly seen in the sectors 0–140° and 270–360° with the maximum wind frequency isopleth (f) where $f > 4\%$ in the direction 0°. The sector of the sea-breeze (140–270°) is also shown with the maximum wind frequency where $f > 8\%$ in the direction 210–220°.

It is noteworthy that the median values are preferable to the mean in both Figs 3 and 4 because the frequency distribution is not Gaussian but highly skewed to the right. The wind speed seldom exceeds $2.5\ m\ s^{-1}$ ($f < 0.1\%$) during the nocturnal land-breeze or $6.8\ m\ s^{-1}$ during the sea-breeze (Fig. 3).

The isopleths of absolute humidity as a function of wind speed and direction in land- and sea-breeze conditions are plotted in Fig. 4 (values calculated in increments of $0.2\ m\ s^{-1}$ and 10°, the median being taken because the values are skew). During the land-breeze the absolute humidity does not exceed $15\ g\ m^{-3}$ (≈ 15 mm Hg), but during the sea-breeze it reaches about $18\ g\ m^{-3}$ (at $3\ m\ s^{-1}$, 240°). In calm conditions the absolute humidity averages $12.6\ g\ m^{-3}$.

5. Comments, bioclimatic and medical discussion

It has been noted that the highest values of absolute humidity occur when the wind blows from the Gulf of Saronikos (see Fig. 1) between 200 and 270° (Fig. 4). It

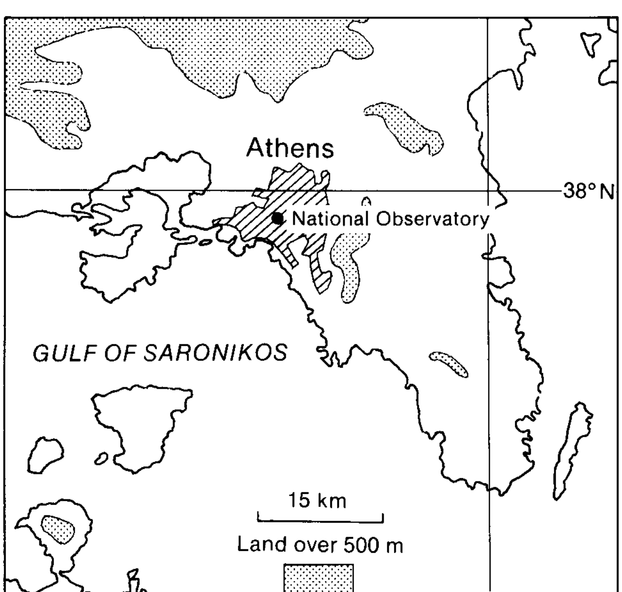

Figure 1. Location of the National Observatory of Athens, in relation to the sea and topographical features.

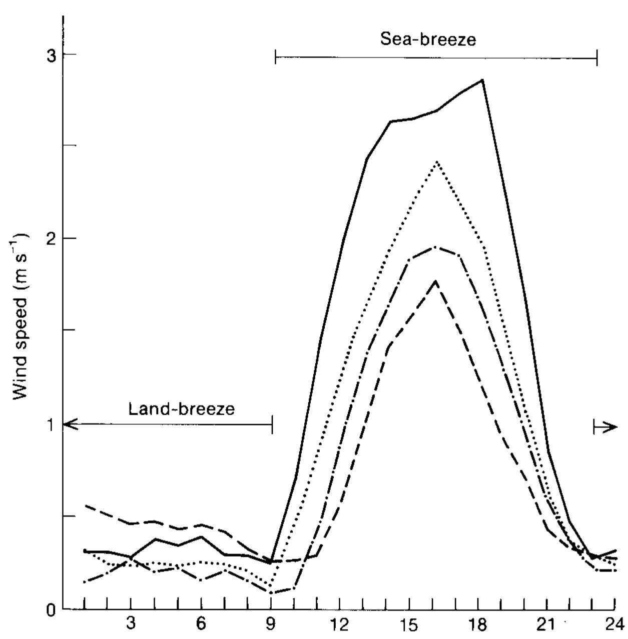

Figure 2. Mean hourly wind speeds at the National Observatory of Athens, during land- and sea-breeze days for January (dashed line), April (dotted line), July (continuous line) and October (dash-dot line).

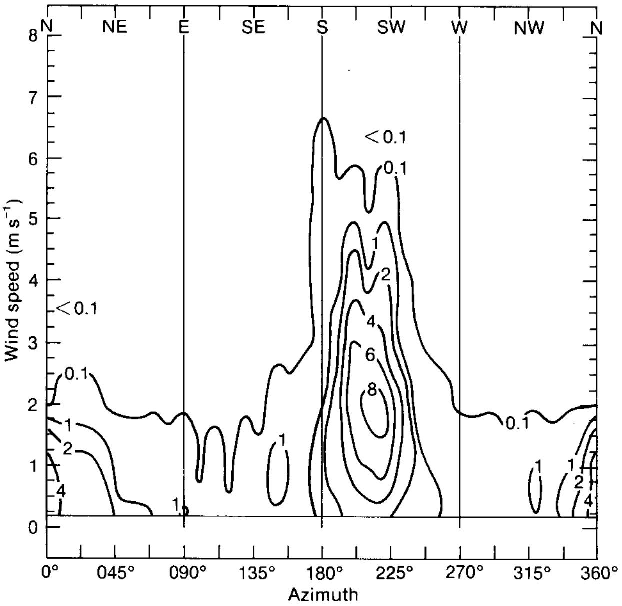

Figure 3. Frequency isopleth diagram (%) of 576 mean hourly surface wind observations at the National Observatory of Athens, during land- and sea-breeze days in July 1961–67.

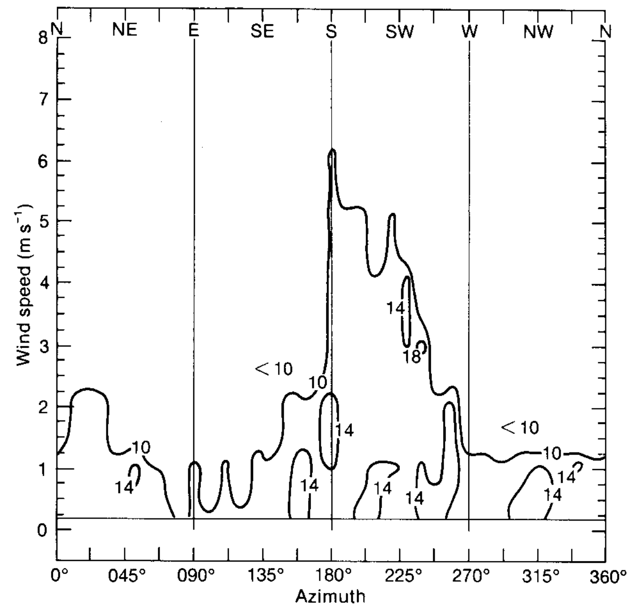

Figure 4. Rectangular isopleth diagram of 576 hourly measurements of absolute humidity (mm Hg ($\approx$ g m^{-3})) at the National Observatory, Athens, during land- and sea-breeze days in July 1961–67.

is suggested that the islands and the shallow sea facilitate greater evaporation when the sea-breeze is in this sector.

In Fig. 2 it can be seen that the sea-breeze wind speed is greatest in July, followed by April, October and January with maximum mean wind speeds of 2.9, 2.4, 2.0 and 1.8 m s^{-1}, respectively. Conversely, during the land-breeze the wind speed is greatest in January. The differences between the mean air temperature at NOA and those over the sea during July, April, October and January are 1.2, −0.8, −1.1 and −2.9 °C, respectively (Kotinis-Zambakas 1983, p. 210) — a steady increase, which corresponds to a steady decrease in wind speeds as shown in Fig. 2, although this only refers to sea-breezes.

The sea-breeze days in Athens are bioclimatically comfortable during April and October, while July is in a period favoured by tourists (Zambakas and Kotinis-Zambakas 1984). In recent decades, the Athens Basin, which is open only to the sea, has suffered from air pollution. This pollution usually prevails during sea-breeze days as the wind is light and it cannot disperse the pollutants over the mountains surrounding the Athens Basin. Previously, when the Athens Basin was not so urbanized, the sea-breeze was a refreshing light wind for the Athenians.

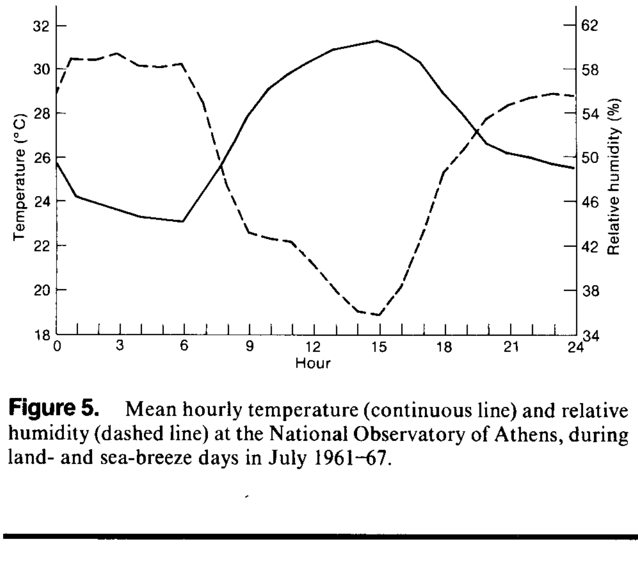

Figure 5. Mean hourly temperature (continuous line) and relative humidity (dashed line) at the National Observatory of Athens, during land- and sea-breeze days in July 1961–67.

The alternation of sea-breeze and other weather days during the winter causes bioclimatical discomfort and consequent medical disorders; influenza and viral diseases are common. During the summer sea-breeze days, the night hours are relatively comfortable with temperatures of about 24 °C, and more so with a relative humidity of 50–60% (Fig. 5).

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Workshop reports

Workshop on Artificial Intelligence Research In the Environmental Sciences (AIRIES-89), Washington DC, 2–4 May 1989

This was the third AIRIES meeting, the previous two having been held in Boulder, Colorado. It brought together upwards of 100 scientists, mainly from the USA and Canada where most of the activity in this field is centred. Meteorology was the discipline most strongly represented but with others such as forestry and pollution control well in evidence.

The first session was entitled 'Example applications' and set the tone for the meeting, which throughout was firmly anchored to the practicalities of putting Artificial Intelligence (AI) to work in real applications. Two talks were of particular interest to meteorologists. John Bullas (Atmospheric Environment Service, Canada) discussed the 'SWIFT' severe-storm forecasting system, one of the largest and most mature of the meteorological expert systems in existence, which uses local knowledge about the behaviour of weather systems, and the ability to interpret worded observations, to modify and refine predictions based on convection indices derived from numerical weather prediction (NWP) models. Encouraging results had emerged from limited operational trials in Alberta. Peter Zwack (Universitè du Québec) talked about 'OASIS', a system for producing forecasts of low cloud. He stressed the importance of building 'deep knowledge' into the system. Deep knowledge is a description of underlying governing processes (ultimately the physical laws) whereas 'shallow knowledge' consists of empirical rules about observed behaviour, without any attempt to relate them to mechanisms or principles. Systems incorporating deep knowledge are more difficult to build but are more likely to be transportable geographically and should be able to cope better with unforeseen events. However, shallow knowledge may still have a role in adding site-specific rules, to tune the system for a particular location.

The next session was on 'Tools and techniques'. This provided an opportunity for discussion of the traditionally troublesome process of knowledge acquisition — how to collect the important knowledge about a subject and then get it into an AI system. Robert Hoffman (Adelphi University, New York) discussed the psychology of eliciting knowledge from human experts. He discounted the value of trying to automate the process as this would force the experts to think in unnatural ways, with the result that much of their true expertise would not get transferred. Interest continues to be shown, however, in ways of enabling machines to learn directly from examples, without the need for a human being to understand the problem and to formulate rules and principles. One approach, exemplified in a ground-water contamination predictor described by David Jensen (Washington State University), is to induce explicit rules automatically from collections of examples and then to apply these rules in an expert system. Care is required in choosing the factors to be presented in the examples, but the working of the resulting expert system can be followed and additional rules can be formulated and added by the system designer. A machine-learning technique which is attracting growing attention is the use of a neural network to determine the association between a given set of input and output patterns. The network is presented with a series of input patterns from the set, for example profiles from sonde ascents together with, in each case, the corresponding 'correct' output pattern, such as an indication of thunderstorm likelihood. Having been shown the appropriate input/output examples, the network programs itself to compute the function which relates the input to the output. Paul Lampru (Consultant's Choice Incorporated) claimed high skill scores had been achieved using a neural network in a precipitation forecasting application, and in another session Vernon Derr (National Oceanic and Atmospheric Administration/ Environmental Research Laboratories (ERL), Boulder) reported that two neural networks were among seventeen AI projects being undertaken at ERL. Neural networks appear to hold promise, but are viewed with suspicion by many because they are 'black boxes', lacking the comforting understandability of rule-based systems.

Molly Stock (University of Idaho) chaired a session on 'Issues and perspectives' and presented the first paper, in which she described a task analysis on forestry management. The analysis had taken more than a year and sought to discover exactly where and how expert systems could be applied to maximum effect, while still leaving human beings with genuinely satisfying jobs. The design of the expert systems themselves had yet to commence. The thoroughness with which this study had been carried out was an example to us all, and will probably pay off in the end, but one wonders whether in practice many organizations would have the patience to undertake such a large and not obviously productive preparatory exercise.

Bryan Conway (Meteorological Office) described plans to apply expert system techniques to short-period thunderstorm forecasting in the United Kingdom, concentrating on the different problems to be overcome, including the optimum combination of many flawed data sources, the interaction between the system and the user and the automation of pattern-recognition tasks.

The final session of oral presentations was on 'Integrated systems' — combining AI with conventional techniques. Work recently begun at the Meteorological Office to automate very-short-period precipitation forecasts by combining radar and satellite observations with NWP model output is a good example of this and was described by Gill Sutton. Various numerical techniques can be used to generate forecast fields of precipitation but an intelligent process is needed to choose the most appropriate technique in the light of an understanding of the meteorological situation.

The meeting included two poster sessions showing a range of applications and techniques. These sessions included some demonstrations of small expert systems running on microcomputers. Though interesting, these were limited by their reliance on dialogue with the user — a severe bottle-neck for many meteorological applications. One very good thing was the absence of parallel sessions, which now seem to be a regular feature of larger meetings, so that it was possible to see the posters without missing something else.

'Shootout-89' was a panel session devoted to an experiment of that name held from May to August this year at Boulder, where several systems developed by different groups and in different places, ranging from simple statistical predictors to large systems like SWIFT, were competing to forecast severe storms in four regions of north-east Colorado.

This was a very useful meeting, uniquely focused on the intersection of two large subject areas — AI and environmental science. There was a refreshing openness of discussion — for the most part we have not reached the stage of people defending entrenched positions at all costs, though there was lively debate about many of the issues raised. The meeting showed what is being achieved in this field and what the current preoccupations are in a way that does not fully emerge from studying published papers. Some participants thought that papers should be submitted and proceedings published (this has not been the case with AIRIES so far), but others felt that it was more important to keep the cost down, the meetings informal, and let people present their latest work. There was general agreement that the meeting was well organized and run — perhaps its relatively small size helped here.

There was strong support for AIRIES continuing as an independent event, although the American Meteorological Society (AMS) has now established an AI committee and the subject should start appearing more strongly at AMS-sponsored meetings. Further AIRIES workshops are envisaged at intervals of about 18 months.

B.J. Conway and G. Sutton

International Workshop on Satellite and Radar Imagery Interpretation, Shinfield Park, Reading, 24–28 July 1989

An International Workshop on Satellite and Radar Imagery Interpretation was held at the Meteorological Office College, Shinfield Park, Reading, England, from 24 to 28 July 1989. It was organized by the Meteorological Office as a follow-up to an international workshop on this subject at the same venue in 1987*. At this earlier meeting it had been agreed to reconvene in 1989 under the joint chairmanship of Dr Greg Forbes (Pennsylvania State University, USA) and Mike Bader (Meteorological Office), with a view to providing material which could be used directly in the production of a reference manual on satellite and radar imagery, explaining the use of conceptual models and other interpretation methods for forecasters working principally in middle latitudes.

The workshop was opened on 24 July by Dr Keith Browning, Director of Research, Meteorological Office, who welcomed delegates from the fields of research and operational forecasting in Austria, Canada, Denmark, the Federal Republic of Germany, France, Switzerland, the United States of America and the United Kingdom. EUMETSAT, the main sponsor, was represented; the World Meteorological Organization are also supporting the project. Dr Browning thanked the sponsors for their support and reminded delegates that the manual was to meet an operational as well as a training need. A large amount of material had been submitted for discussion and consideration at the workshop. Dr Browning acknowledged the work done by all authors (including those not present) and by those who reviewed the contributions prior to the workshop, and reminded participants that there was a lot of material now available which needed to be reviewed for the planned reference manual. He said that the consolidated result would provide forecasters from many nations with some very effective guidance especially where forecasting rules were clearly identifiable.

After the opening plenary session, the workshop broke up into four specialized working groups. In addition, an Editing Committee group, with the task of integrating the selected material, met daily with the chairmen of the specialist groups to review progress and identify areas of common concern between the groups. The specialist groups were as follows:

(a) Working Group A, chaired by Peter Wickham (United Kingdom), dealt with the introduction and general characteristics of satellite and radar imagery. The group of papers in this area, which will form the first two chapters of the manual, covered the principles of remote sensing by satellite, information about satellite orbits and the characteristics of sensing channels. Basic principles of interpretation, cloud types and topographical features detectable were identified and agreed upon. An overview of how satellite pictures can provide an invaluable source of information to forecasters and how it could be applied was agreed. The basic principles of weather radar and radar types were also noted. Problems in interpretation brought about by, for example, anomalous propagation, occultation and the bright band were covered well by submitted material. This material would enable the uninitiated forecaster to be better prepared to handle the common, and not so common, precipitation patterns included in the manual.

(b) Working Group B, chaired by Martin Morris (Assistant Director (Central Forecasting) Meteor-

* Preprints of the 1987 workshop are still available from EUMETSAT headquarters.

ological Office), was concerned with three chapters dealing with the weighty subjects of using imagery in synoptic-scale analysis and identifying the principal air flows within waves, warm and cold fronts, occlusions, and ex-tropical storms reacting with the polar front. The group comprised experts from six nations, and not surprisingly there was intense debate, at times with cherished ideas being challenged and tested, in this forum. Nevertheless the group managed to identify and agree on the key issues of highlighting and interpreting the signatures commonly seen on satellite pictures, and where appropriate on radar images too, together with appropriate diagnostics so that the resultant weather can be better understood and predicted by the forecasters.

(c) Working Group C, chaired by Dr Jim Purdom (USA), dealt with papers submitted for inclusion on the section concerning convection. The group recognized the need to cover the whole range of convection from sea-breeze/land-breeze systems, mesoscale convection and circular systems through to supercells both in Europe and North America, together with the associated weather. The nature of the forcing mechanisms and instability was agreed as crucial for identifying different convective systems that challenge regional forecasters. The case-studies used have clearly demonstrated the different signatures from satellite and radar imagery commonly observed, so that forecasters should find this area of guidance most valuable.

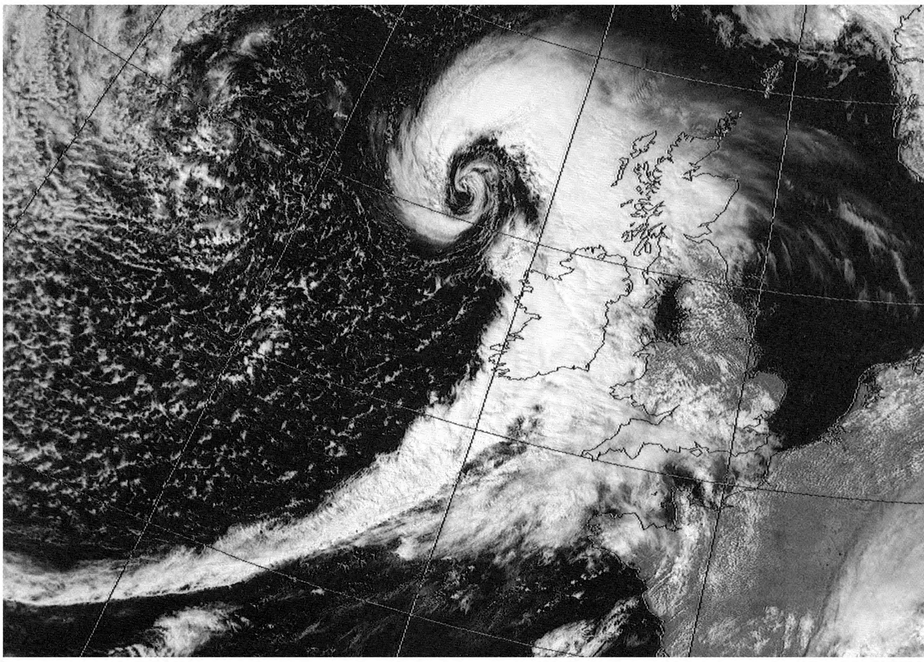
(d) Working Group D, chaired by Dr Jim Gurka (USA), determined the most suitable material for the last two chapters of the manual. These chapters concern the problem areas of forecasting fog and low cloud, topographical effects and polar phenomena. Members identified some very useful material to illustrate clues for the forecaster wrestling with the problems of fog and the ever-difficult stratus and stratocumulus. Topographical effects such as lee waves, föhn and rain-shadow events were included and material agreed for publication. Polar phenomena, and not only the polar low, are of concern to many forecasters working in middle latitudes, and a substantial amount of excellent guidance has been identified including how to use the 3.7 μm channel in addition to the more familiar ones.

Participants have returned to their respective organizations to fine-tune some of the material to be included for the publication. The Editing Committee has a lot of work to do to put it together but it is hoped to publish the manual next year. In addition the Office plans to produce, on the same time-scale, a pocket edition of the reference manual. The organizing committee, headed by Mike Bader and Tony Waters (Meteorological Office) are to be congratulated on such a productive week, and also the Meteorological Office College for ensuring the hosting arrangements worked well and thus allowed the week to pass so smoothly.

Finally, despite the hard work indoors, time was made available for the USA to take on the rest of the world in a serious cricket match one evening. The scores did not matter but teamwork of the highest order prevailed on the field!

P.R.S. Salter

Satellite photograph — 14 August 1989 at 1342 GMT



Photograph by courtesy of University of Dundee

Figure 1. NOAA-11 visible image for 1342 GMT on 14 August 1989.

The NOAA-11 visible image shown here (Fig. 1) illustrates the cloud pattern associated with an intense surface low at the end of a period of explosive deepening. A well marked cold frontal cloud band terminates within the cloud spiral near the centre of the low. There is little evidence either in the image or from surface observations of a distinct warm front (Fig. 2). Right at the leading edge of the frontal cloud band, a narrow 'rope cloud' can be seen. Images from the radar at Shannon (western Ireland) near the time of the picture confirmed that near the south coast of Ireland this rope cloud was coincident with a narrow band of heavy rain (exceeding 60 mm h^{-1}) caused by line convection. As the band continued eastwards, several thunderstorms were reported and gusts of wind exceeded 50 kn in places. Near Pwllheli in North Wales a tornado caused considerable property damage at a holiday camp.

The occurrence of a rope cloud and/or line convection together with strong gusts (occasionally tornadoes) and thunderstorms at strong cold fronts is not unknown. Indeed, analysis of radar data on occasions of tornado reports at cold fronts over the United Kingdom* suggests that intense line convection is a common feature. When thunderstorms also occur they are often characterized by relatively warm cloud tops, in this case typically −20 to −30 °C.

G.A. Monk

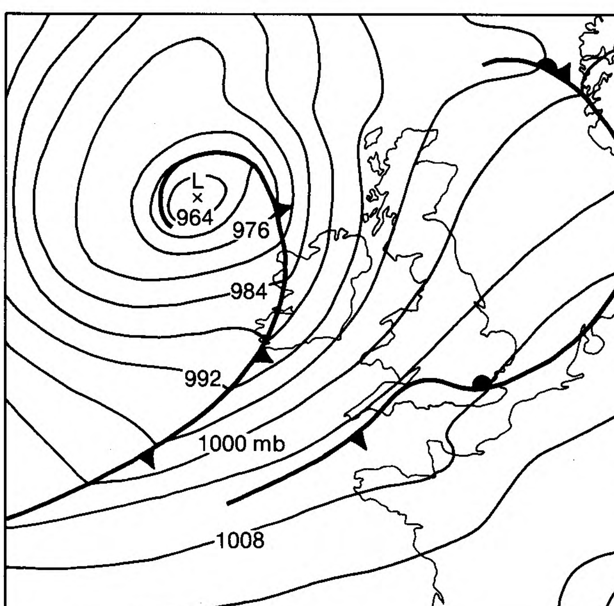


Figure 2. Surface analysis at 1200 GMT on 14 August 1989.

* Information on tornado outbreaks from: Meaden, G.T.; The classification of whirlwind types and a discussion of their physical origins, *J Meteorol UK*, **10**, 194–202.

GUIDE TO AUTHORS

Content

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

Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (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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Heavy rainfall at Khartoum
Meteorological support during pollution incidents
Ceilometer comparison

HMSO

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Heavy rainfall at Khartoum on 4–5 August 1988: A case-study

A.M.A. Ali
Meteorological Department, Khartoum, The Republic of Sudan

Summary

Surface and upper-air observations, and satellite imagery have been used to study the development of a rare event of large rainfall over parts of the Sudan on 4–5 August 1988.

1. Introduction

The intertropical convergence zone (ITCZ) is a narrow region where northerly and southerly tropospheric winds meet. It shows a discontinuity of moisture which in the Sudan (Fig. 1) is usually indicated at the surface by the location of the 15 °C dew-point isopleth.

The moist southerly to south-westerly air to the south of the ITCZ which affects the Sudan has two sources:

(a) an air mass which passes over equatorial Africa from the Atlantic and is moist and unstable to a great depth (the main source), and

(b) an air mass which comes from the Indian Ocean meeting the one in (a) over the Congo.

In addition to a seasonal movement of the ITCZ, which in eastern Africa follows closely the solar latitude, there are periodical movements lasting several days consisting of a southward displacement followed by a northward one. These periodical movements are associated with the oscillation of subtropical anticyclones and their interactions with mid-latitude troughs, cyclones and fronts. In addition to the convective precipitation caused by convergence at the ITCZ, steady widespread rain, not thundery in character, occurs during mornings and evenings in the moist southerly air masses.

Daily rainfall totals of a few (or a few tens of) millimetres are common in this area as in Fig. 2(a) which shows the totals for 3 August (i.e. for 0600 UTC on 3 August to 0600 UTC on 4 August). On this day the rainfall was confined to an area across central Sudan. On 4 August, rainfalls in the range 0–20 mm were recorded across central Sudan but in addition heavy rainfall was registered to the north at Atbara (64 mm) and especially Khartoum (210 mm) (Fig. 2(b)). The rainfall had a well defined southern edge with no rain being recorded at Edduiem and Wadi Medani about 160 km to the south of Khartoum. At Khartoum the rain fell in two storms, one lasting from about 1800 UTC to 2000 UTC on 4 August and the second from 2200 UTC on 4 August to 0800 UTC on 5 August.

This is clearly a rare event and the aim of this case-study is to demonstrate the meteorological factors involved in this rain storm using all surface and upper-air data available. The result can be regarded as a contribution to the development of forecasting techniques for such events when similar pre-conditions are observed.

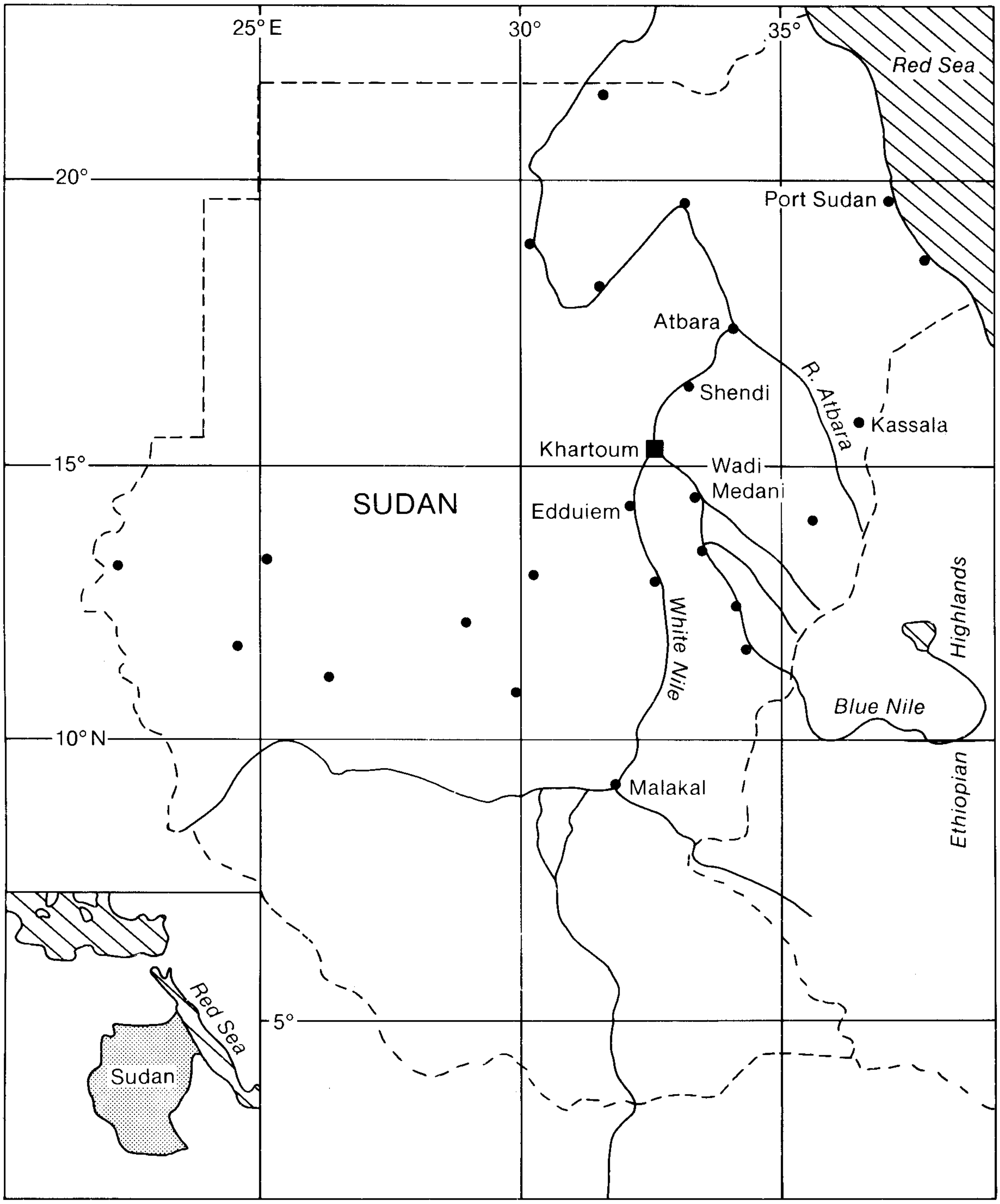


Figure 1. The Sudan, showing the location of places mentioned in the text. In this, and other figures, the location of Khartoum is denoted by a black square, and the black dots are stations in the observing network.

2. The synoptic situation

2.1 General

The surface pressure chart for 1200 UTC on 3 August (Fig. 3(a)) shows a low pressure area over the Arabian Gulf from which a trough extended westward to link with the low centred over the north of the Sudan. An anticyclone over the Sahara desert extends northward over eastern Europe.

By 1200 UTC on 4 August (Fig. 3(b)) the anticyclone over the Sahara desert has collapsed allowing the low pressure area to extend south-westwards. A ridge of high pressure over north-east Sudan with its axis approximately along the line of the Atbara river led to a wave development at the eastern end of the ITCZ.

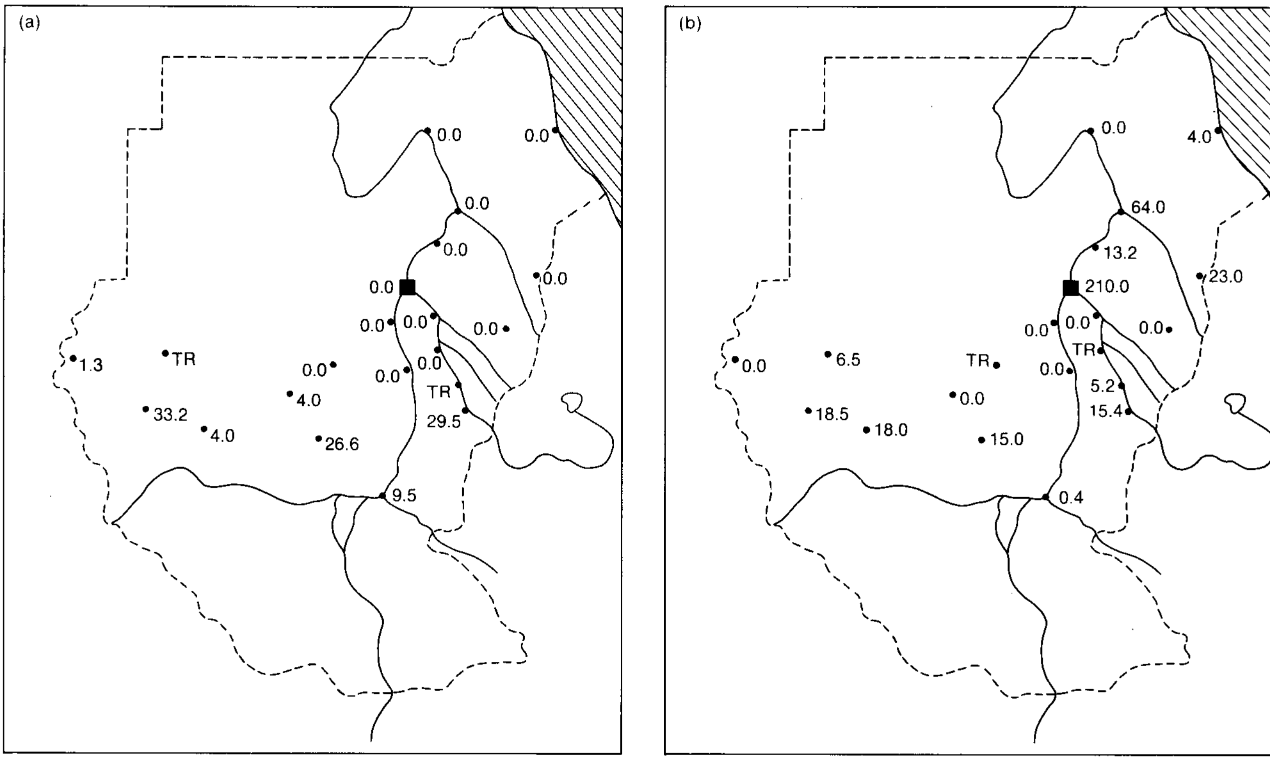


Figure 2. (a) Daily rainfall totals (mm) for the period from 0600 UTC on 3 August to 0600 UTC on 4 August. (b) As in (a) but for 0600 UTC on 4 August to 0600 UTC on 5 August.

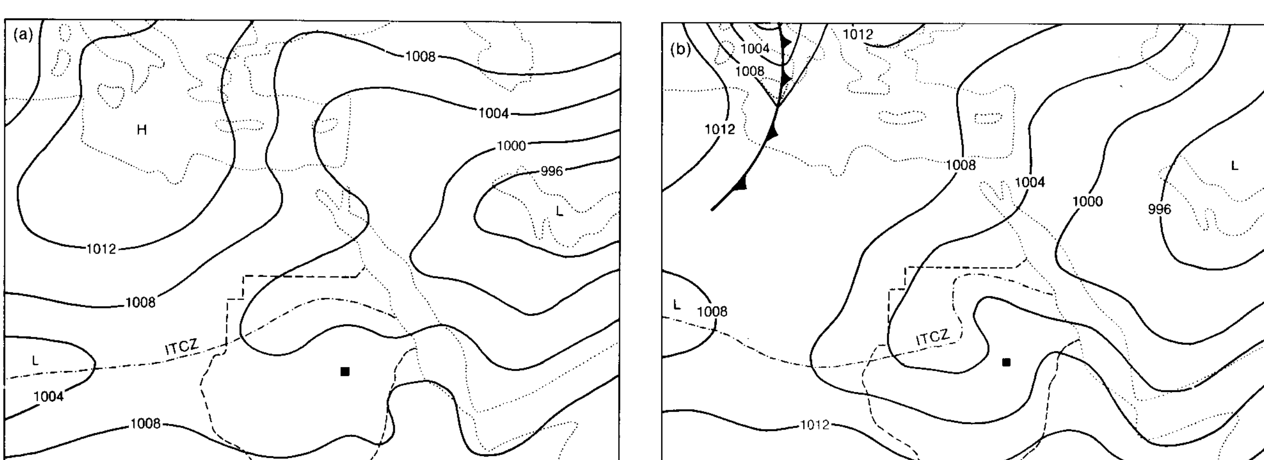


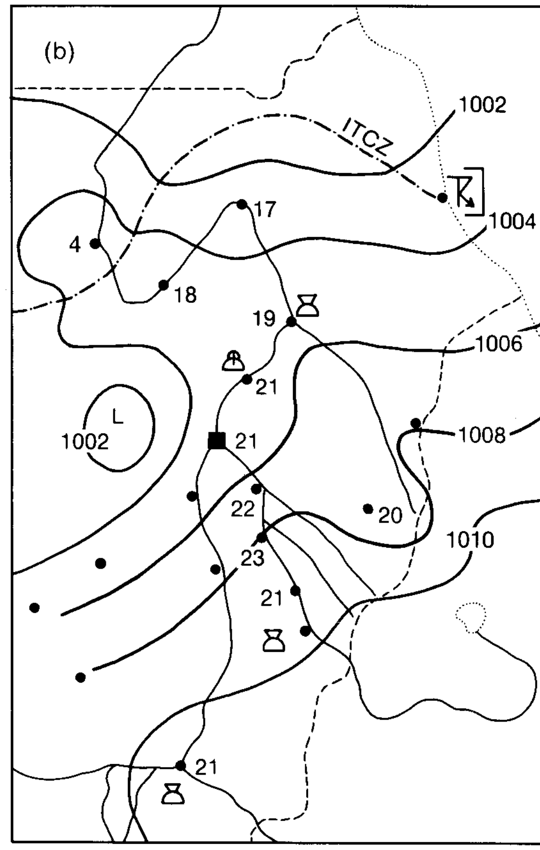
Figure 3. (a) Surface pressure (hPa) over the Sudan and neighbouring areas at 1200 UTC on 3 August. (b) As in (a) but for 1200 UTC on 4 August.

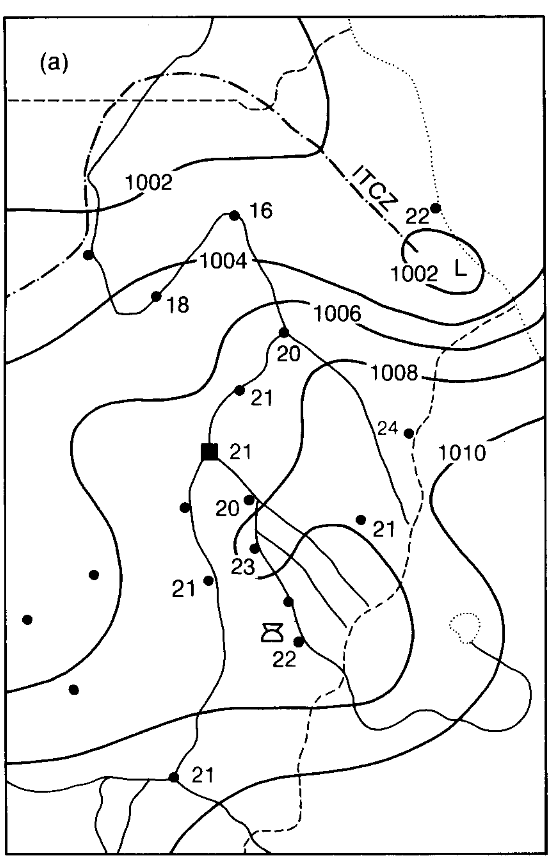
2.2 The Sudan area

At 1200 UTC on 3 August (Fig. 4(a)) a small area of low pressure lay to the south of Port Sudan. Most of the area south of the ITCZ was under the influence of moist southerly winds with dew-point temperatures in the range 16–24 °C; only one station, to the south of Khartoum, reported cumulonimbus clouds. Twenty-four hours later (Fig. 4(b)) there was a low pressure centre to the west of Khartoum, the dew-points were not changed significantly but now cumulonimbus cloud was being reported in the elongated area from Malakal to Atbara and lightning further north-westwards at Port Sudan. Six hours later (Fig. 4(c)), again the low pressure was centred nearly over Khartoum and now the cumulonimbus clouds and lightning were observed there and to the north and east. The dew-points remained high.

2.3 Upper-air analyses

The 850 hPa height for 1200 UTC on 4 August (Fig. 5(a)) shows a trough aligned north-east to south-west, approximately coincident with the main trough in the surface pressure. This trough extends up to the 500 hPa level (Fig. 5(c)); at 700 hPa (Fig. 5(b)) the trough axis passes over Khartoum.





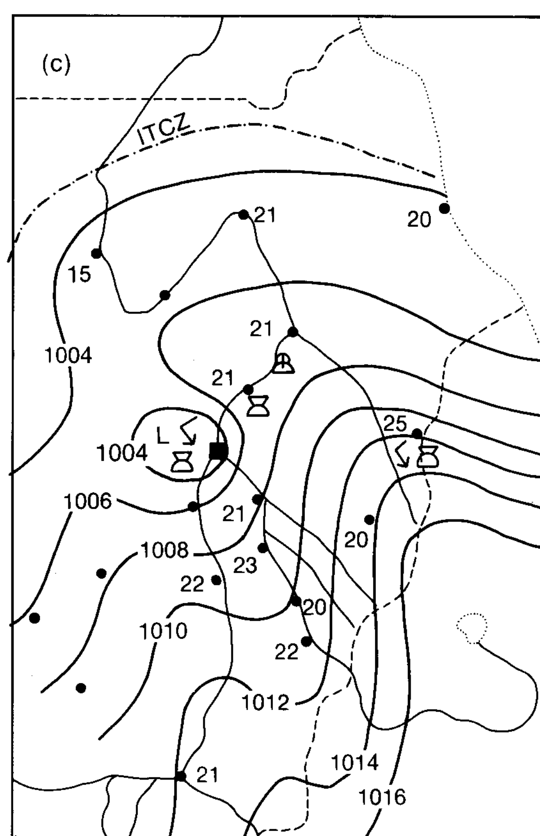


Figure 4. (a) Surface pressure (hPa) at 1200 UTC on 3 August. Also shown are station values of dew-point temperature (°C). Cumulonimbus clouds and lightning are denoted by conventional symbols. (b) and (c) As in (a) but for 1200 UTC on 4 August and 1800 UTC on 4 August respectively.

2.4 Additional information

The percentage changes in the surface relative humidity in the 24-hour period from 1500 UTC on 3 August to 1500 UTC on 4 August for the Khartoum area are shown in Fig. 6. The changes in daytime maximum temperature from 3 to 4 August are shown in Fig. 7.

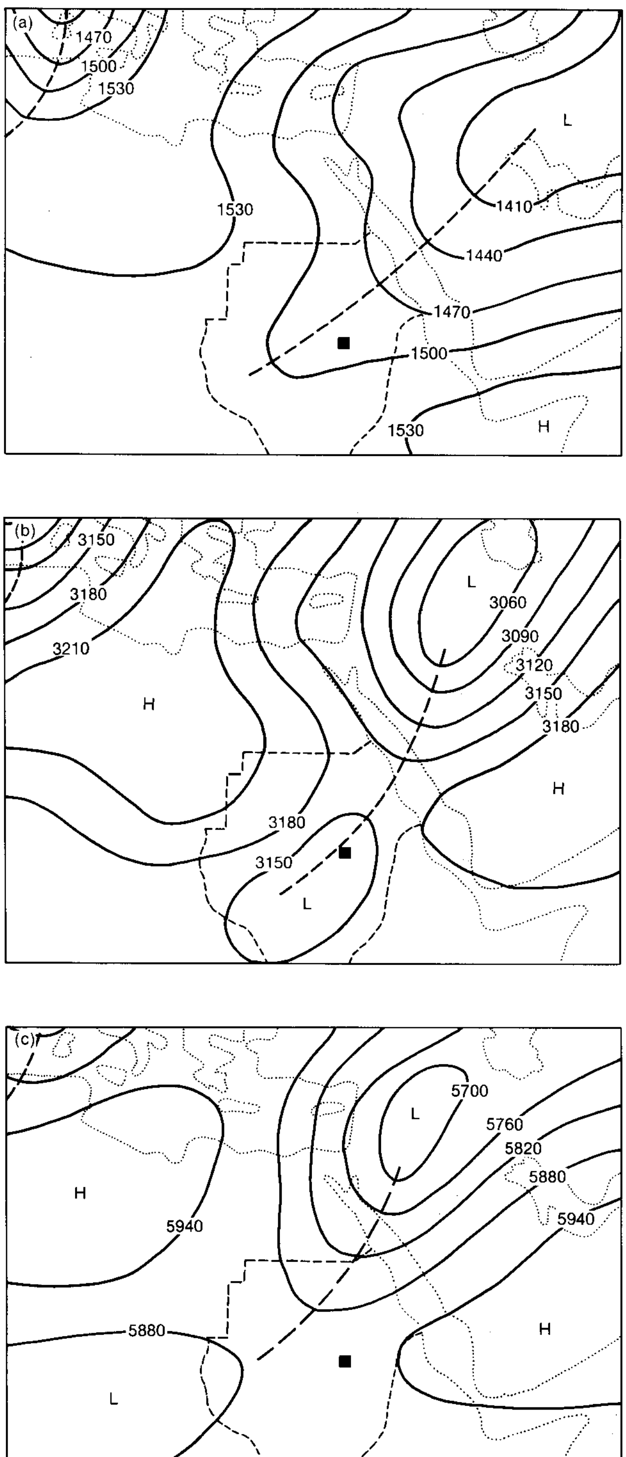


Figure 5. (a) 850 hPa level height (gpm) over the Sudan and surrounding areas at 1200 UTC on 4 August. (b) and (c) As in (a) but for 700 and 500 hPa levels.

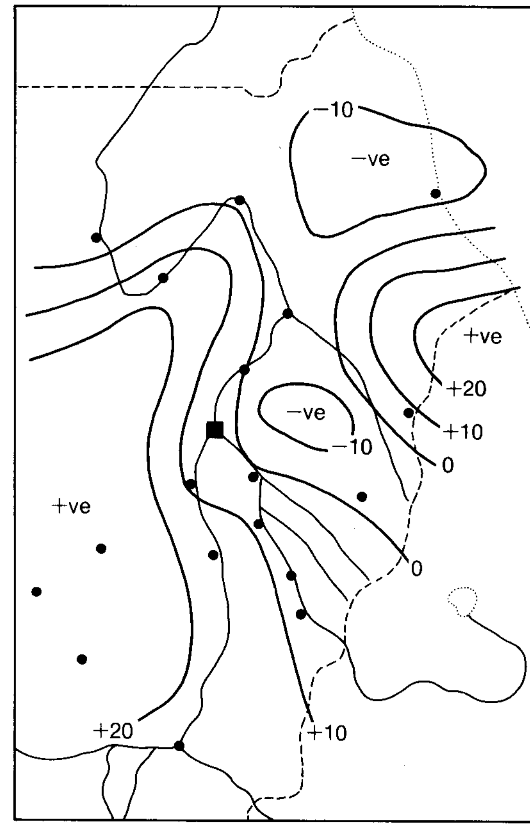


Figure 6. Percentage changes in relative humidity in the 24-hour period from 1500 UTC on 3 August to 1500 UTC on 4 August.

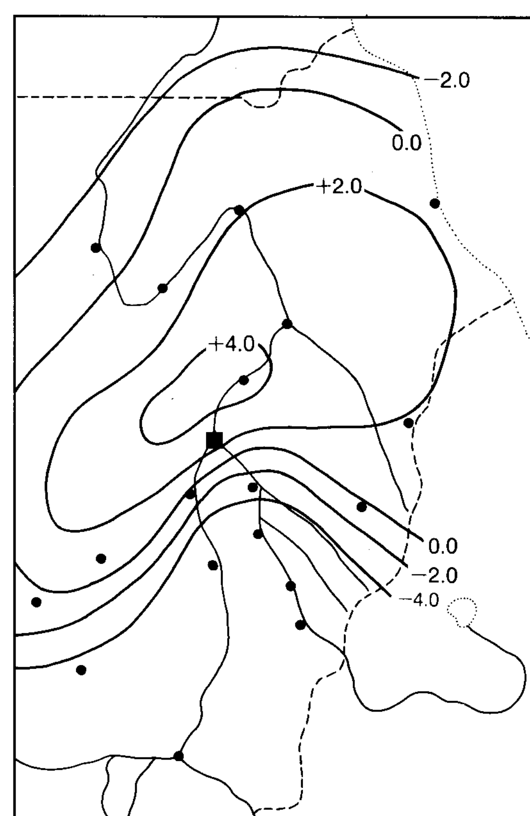


Figure 7. Changes in daytime maximum temperatures (°C) from 3 to 4 August.

The divergence/convergence was calculated using streamline and isotach analysis for the area bounded by latitudes 10–22° N and 30–40° E for a time of 1200 UTC on 4 August. The wind data were interpolated on a mesh of size 2° × 2°. The divergence/convergence at 850, 700 and 500 hPa are shown in Figs 8(a), 8(b) and 8(c) respectively and the 850 hPa streamlines and isotachs for 1200 UTC on 4 August are shown in Fig. 9.

Meteosat infra-red images are available during the event. Figs 10(a), 10(b) and 10(c) are sketches of images for 1450 UTC on 4 August — about 4 hours before the first storm over Khartoum, 1818 UTC on 4 August — at its commencement, and at 2218 UTC on 4 August — at the start of the second and longer storm.

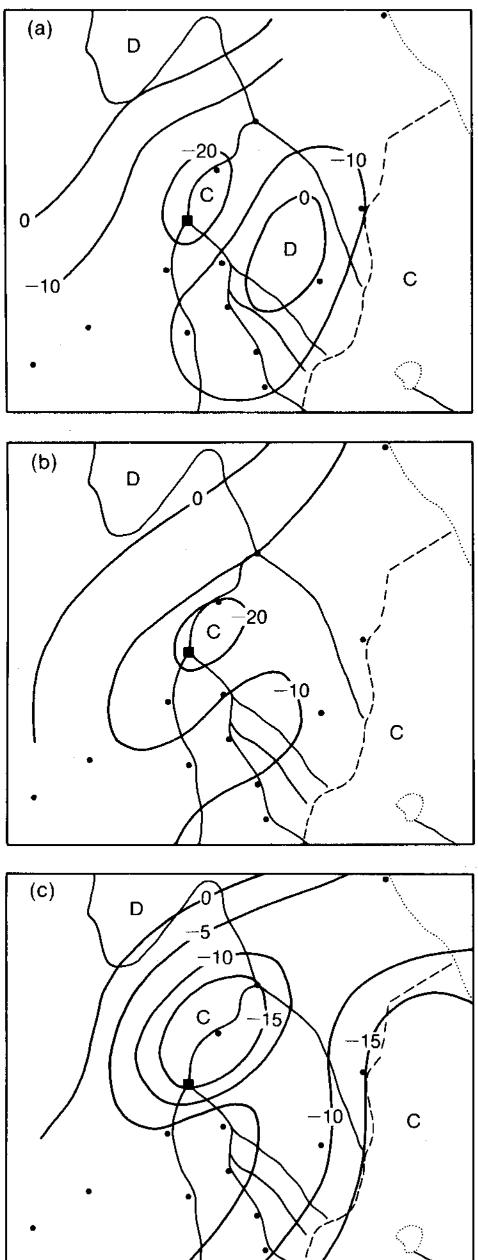


Figure 8. (a) Divergence (D)/convergence (C) at the 850 hPa level at 1200 UTC on 4 August. Numbers are in units of 10^{-6} s^{-1}. (b) and (c) As in (a) but for 700 and 500 hPa levels.

3. Discussion

The surface and upper-air charts as described in section 2 show that on the day of the event the area was under the influence of a very deep layer of unstable moist monsoon air. The presence of a trough line, at least up to the 500 hPa level (Figs 3(a), 3(b), 5(a), 5(b) and 5(c)) triggered the mechanism of development. The relative humidity anomaly charts in Fig. 6 and the isotachs in Fig. 9 show that moisture was injected into the Khartoum area by two mechanisms:

(a) the north-easterly surface flow from the south-west of Khartoum where widespread rainfall took place on 3 August (Fig. 2(a)), and

(b) the westerly flow from an area north-east of Kassala, and at the northern end of the Ethiopian Highlands. This flow is revealed by a line squall which can be seen as an extensive band of clouds with cloud-top temperatures of lower than −70 °C on the extreme right-hand side of Fig. 10(a). This band of cloud moved steadily westward on successive Meteosat images as in Fig. 10(b). The formation and movement of line squalls in this part of the world have been described by Ali (1986).

In Fig. 7 it can be seen that in the Khartoum–Shendi area there was a increase of about 4 °C in surface temperature from 3 to 4 August, but in the same period the temperature to the south of Khartoum decreased by the same amount. This steepening of temperature gradient made a thermal contribution to reinforce the dynamical instability which caused the storms.

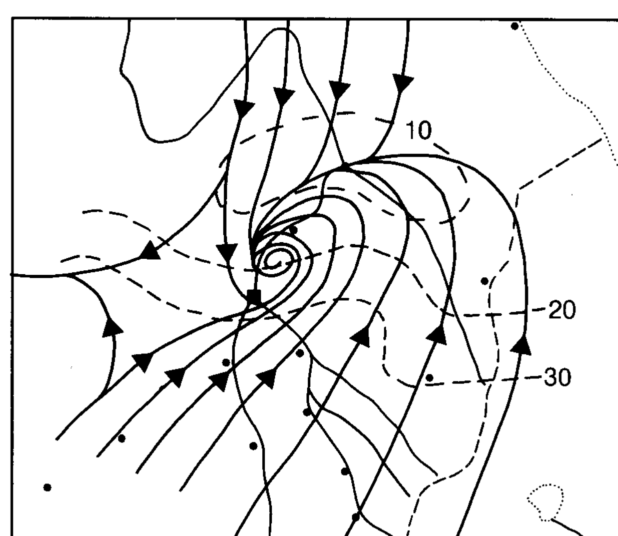


Figure 9. Streamlines (solid lines) and isotachs (dashed lines) at the 850 hPa level at 1200 UTC on 4 August. Units of wind speed are knots.

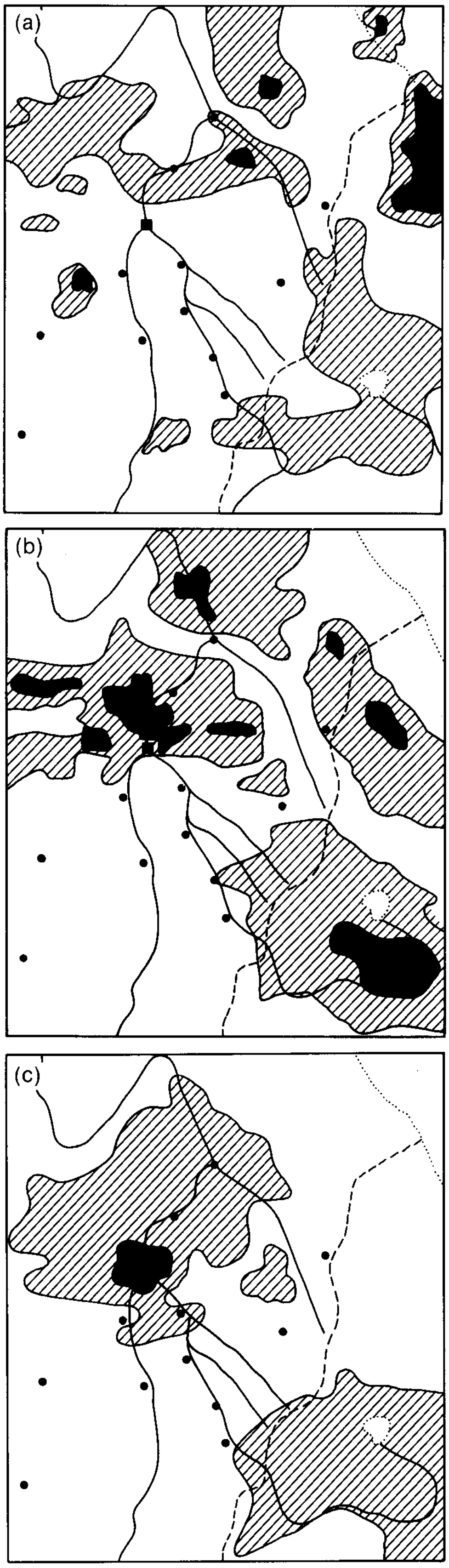


Figure 10. (a) Sketch of Meteosat infra-red channel image for 1450 UTC on 4 August. The shading denotes cloud-top temperatures in the range −40 to −69 °C and the black areas temperatures less than −70 °C. (b) and (c) As (a) but for 1818 UTC and 2218 UTC on 4 August.

The convergence/divergence fields at 850, 700 and 500 hPa at 1200 UTC on 4 August (Fig. 8) all show a centre of convergence situated over the Khartoum–Shendi area. The large vertical extent of convergence right up to the usual level of non-divergence — about 500 hPa — concentrated over a small ground area promoted vigorous uplift. The streamlines and isotachs (Fig. 9) confirm that a vortex formed just to the north of Khartoum which was on the cyclonic-shear side of the low-level winds. The region of confluence is between the drier air advected from the Sahara and the more humid air from the south-west.

A large area of cloud with cloud-top temperature lower than −70 °C formed over and just to the north of Khartoum at about 1800 UTC (Fig. 10(b)) and heavy rain fell for the next 2 hours. Leading up to this time there was considerable cloud development well to the north of Khartoum due to the advanced northerly position reached by the ITCZ; for instance, Port Sudan registered 4.0 mm of rain on 4 August, an unusual amount of rainfall in that area and at that time of year.

At about 2200 UTC on 4 August the second period of heavy rainfall commenced with the formation of another area of cold cloud-top temperature, this time centred right over Khartoum, and this lasted until about 0400 UTC on 5 August. The rain ceased at about 0800 UTC on 5 August.

The joint effect of this line squall and the local development of clouds which acted as a feeding mechanism to the squall, were the main causes of the second storm.

4. Conclusions

The large rainfall (210 mm in 12 hours) at Khartoum on 4 and 5 August was caused by the following factors:

(a) The ITCZ had moved to an advanced northerly position on 4 August.

(b) A deep vortex developed just to the north of Khartoum as a result of intense surface heating coupled with an approaching trough at upper levels.

(c) There was a deep layer of vertical motion over the Khartoum area leading to the formation of massive cumulonimbus clouds.

(d) Moisture injection into the area which came from:

(i) Widespread rainfall to the south and south-west on 3 August combined with a deep layer of strong south-westerly winds which continued until 4 August.

(ii) The arrival of a line squall from the east into the area 2 hours before 0000 UTC on 5 August.

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Meteorological aspects of nuclear and chemical incidents

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Summary

This paper summarizes the meteorological support available to the emergency services in the event of nuclear and chemical accidents.

1. Introduction

As soon as either radioactive materials or toxic chemicals have been released into the atmosphere, the area in which the population, livestock and crops are at risk is strongly influenced by the prevailing weather conditions. For those managing the response to incidents of this kind, meteorological advice is probably of most value:

(a) at a very early stage, when it is important to know where the plume is liable to spread, so that the emergency services can deploy their resources in the safest and most effective manner, and

(b) after the emergency is under control, when the scientific advisors are trying to ascertain where significant amounts of material may have been deposited on the ground.

This paper outlines what advice the Meteorological Office can offer and how quickly that advice can be made available for scenarios ranging from short duration local chemical accidents to major nuclear accidents such as Chernobyl. The arrangements for the provision of this advice is the responsibility of the Defence Services Branch of the Office (Turton and Caughey 1989).

2. Background

Following the release of a toxic substance into the atmosphere the subsequent path of the material is mainly determined by the prevailing wind. In a 'steady' wind the material would move downwind in a straight line, slowly spreading out as it went through the effects of turbulent diffusion. However the wind is rarely 'steady' and there are nearly always changes in both speed and direction over short periods of time (of the order of 5–10 minutes). The plume of material therefore meanders as it drifts, as shown in Fig. 1. The track of the meandering plume continually changes so that sometimes a given point on the ground is affected by the pollution and at other times it is in clear air. What is required for emergency planning is an indication of the total area which could be affected by the plume at some time during the course of an incident. This area is called the 'Area at Risk'. Its size varies as meteorological conditions change, but, with a knowledge of the local conditions near the accident site, it can be calculated to a useful degree of accuracy in any particular instance.

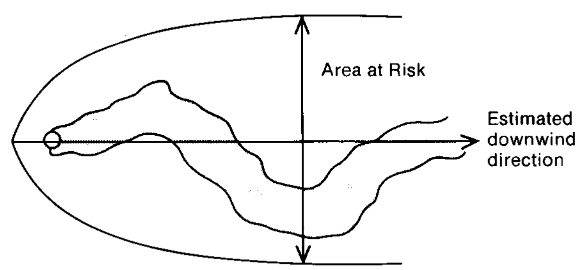


Figure 1. The Area at Risk after the release of a toxic substance.

A second aspect, which is particularly relevant to the longer range transport of pollutants, is the effect of rain. For example, as rain falls through a cloud of nuclear material, it collects the particles and deposits them on the ground. This process is referred to as 'wet deposition', or more colloquially 'wash-out', and was largely responsible for the high radioactive levels in the Lake District and surrounding areas following the Chernobyl accident (Smith 1988).

Meteorological advice must be made available to the emergency services both quickly and in a form that they can readily assimilate. The remainder of the paper discusses how that is achieved. Important aspects for consideration are:

(a) the nature of nuclear and chemical accidents and how that affects the requirements for an emergency response,

(b) the organization of the authority responsible for leading the emergency response and the communications lines to that authority,

(c) Meteorological Office procedures for internal (i.e. at sites within the United Kingdom) nuclear and chemical incidents, and

(d) international aspects and how meteorological advice is made available to deal with overseas accidents which may affect the United Kingdom.

3. Nature of an emergency

From a meteorological point of view there are differences between chemical and nuclear accidents. With chemical accidents there is, broadly speaking, an instantaneous release, followed by a gradual reduction in the amount of material released as the accident is brought under control. Typically this occurs over a period of hours. The amount of released material is usually relatively small and in consequence the area in which there is a requirement for special precautions is typically a few kilometres long by 1 or 2 kilometres wide.

While the above scenario is also applicable to many nuclear accidents, it is possible for nuclear accidents to continue to release significant quantities of material for several days, as was the case at Chernobyl. This, combined with the fact that radioactive material can be measured in very low concentrations, means that the released material can be detected over very large areas; less than 3% of the core of Chernobyl was released to the atmosphere and that accident caused concern over a region many thousands of square kilometres in extent.

Thus, in meteorological terms, most chemical and many nuclear accidents require a good knowledge of the local conditions and are therefore best dealt with by regional Meteorological Offices. However, for large nuclear accidents, in which the radioactive material travels for several thousands of kilometres, global-scale numerical forecast models are required to predict the movement of the plume, and meteorological advice can best be provided by the Central Forecasting Office (CFO) at Bracknell.

Because of this, and because there are different authorities responsible for handling chemical and nuclear accidents within the United Kindom, it is necessary to have different procedures for supplying meteorological advice for the different types of incident. These are:

CHEMET — CHEmical METeorology — for UK-based chemical accidents.

PACRAM — Procedures And Communications in the event of an accidental release of RadioActive Material — for UK nuclear sites.

INTERNATIONAL PROCEDURES — for overseas nuclear accidents and chemical incidents which may affect the United Kingdom.

4. CHEMET

Under the Control of Industrial Major Accident Hazard (CIMAH) regulations, a firm is required to register any site at which large amounts of hazardous chemicals are stored. However, the large number of such sites precludes the Meteorological Office making special arrangements with each, and it is more practical to make meteorological advice available to the Police and Fire Brigades, who will always be at the scene of any major incident.

The initial response to any request from the Police or Fire Brigade for meteorological advice must be handled quickly, and, within 2–3 minutes of notification, the appropriate meteorological office will provide:

(a) Surface wind speed and direction.

(b) An indication of the plume behaviour — whether it will disperse quickly or remain trapped near the incident site.

Such information allows those in charge of the response to the incident to deploy their resources both safely and in the most efficient manner.

Following the initial contact, the Meteorological Office will then prepare more detailed information which includes:

(a) Definition of the Area at Risk.

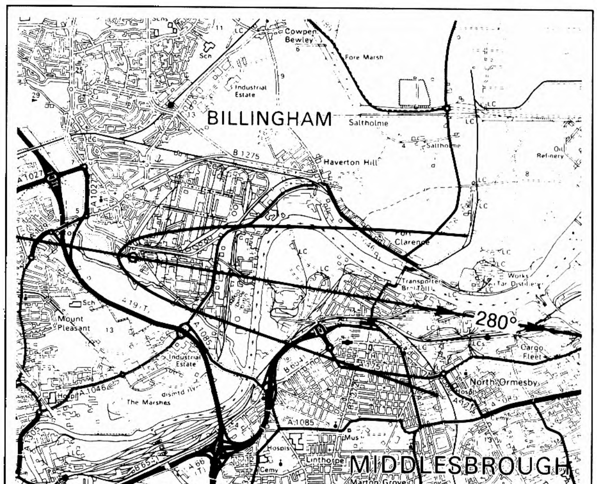
(b) Information on any likely significant changes in wind direction.

(c) Details of any rain, snow, etc.

(d) Special parameters for scientific advisors.

This will be available some 20–30 minutes later and will be sent automatically to both the Police and Fire Brigade Incident rooms. An example of an Area at Risk diagram is shown in Fig. 2. There are some 15 different templates (outlines of the areas) which can be used depending on the prevailing weather conditions.

Other organizations who are likely to become involved are expected to be informed of the incident by the Police, or come to the Police for initial briefing. Consequently, in the first instance, they will be able to obtain meteorological information from the Police. At a later stage, when more detailed information is required, or there is a need to clarify any information that has already been provided by the Meteorological Office, organizations such as Emergency Planning Authorities, Ministry of Agriculture Fisheries and Food (MAFF), etc. may contact the appropriate Meteorological Office directly.



Reproduced from the Ordnance Survey 1:50 000 Landranger Map with the permission of the Controller of Her Majesty's Stationery Office.

Figure 2. An illustration of the Area at Risk map that is sent to the Police and Fire Brigades as part of a CHEMET response. In this example the prevailing surface wind direction is from 280°.

Fig. 3 shows the regional areas of responsibility of Main Meteorological Offices (MMOs) for CHEMET purposes. The appropriate emergency telephone numbers are promulgated to central organizations for distribution to Police Authorities, Fire Brigades, Emergency Planning Offices, MAFF, etc. It is important that these Meteorological Offices are used for emergency advice, in preference to any of the more local Offices, since only at these MMOs is there 24-hour cover by an experienced forecaster. Significant delays could occur if the request had to be transferred from a smaller office to the appropriate MMO.

5. PACRAM

The structure for providing meteorological advice in the event of a nuclear accident within the United Kingdom is slightly different from that for chemical incidents. Each nuclear site, and its accompanying Offsite Support Centre (OSC) (a building situated some distance from the nuclear installation), is linked with a designated MMO, as shown in Fig. 4. Sites are generally grouped geographically, for example Hunterston, Torness and Chapelcross are linked to Glasgow Weather Centre, but there are a few exceptions where an operator wishes to have all his sites linked to one source for meteorological advice, e.g. the site marked with an 'asterisk', close to Cardiff, which obtains meteorological advice from Brize Norton. The solid lines round the outside of the United Kingdom delineate regional responsibility amongst the MMOs and CFO for nuclear material in ports and harbours.

Defence related nuclear installations (e.g. Harwell and Aldermaston (see Fig. 4)) have access to meteorological advice in the same way as civil installations, but special arrangements are necessary to deal with military material in transit and the Ministry of Defence (MOD) has its own internal organization for responding to incidents of this nature. Civil nuclear material is also transported by both air and land, but since the material generally remains the responsibility of the despatching organization, meteorological advice is available to an operator through the same source as in the event of an accident at his main site.

In contrast to chemical incidents, where the Police and Fire Brigades have the responsibility for responding to the incident, the co-ordination of the initial response to a nuclear accident is the responsibility of the site

Figure 3. The areas of responsibilities of the MMOs involved with CHEMET.

Figure 4. Division of responsibility for nuclear sites. In the diagram each MMO involved in PACRAM is designated with a different symbol. That MMO is responsible for the provision of meteorological advice to all the nuclear sites marked with the same symbol. For example, the MMO covering the south-east region is Bracknell (CFO) (marked with a black square) and it provides PACRAM support to Sizewell, Bradwell and Dungeness. The line round the coast designates responsibility for ports and harbours along the indicated sections of coast.

operator. There are only a small number of these and therefore meteorological advice can be provided to them in a mutually agreed format, and transmitted to the site and/or OSC via nominated telephone lines. The procedures are practised regularly by the operators and the Meteorological Office is involved in many of the exercises.

In the event that a nuclear incident becomes too large to be handled at local level, dedicated incident control rooms are available in London, and in the regions (Scotland, Wales and Northern Ireland), to co-ordinate the national response. The Department of Energy have the main responsibility for responding to accidents at civil nuclear sites and, if necessary, they will open their Nuclear Emergency Briefing Room. There is a similar room in the MOD for military accidents. When either room is opened, the Meteorological Office provides an advisor who liaises between the incident controller and CFO. The role of these government department co-ordination rooms is discussed further in the next section.

6. International nuclear accidents

Following Chernobyl, the Government appointed the Department of the Environment (DOE) as the lead department to co-ordinate the national response in the event of an overseas accident in which released radioactive material might affect the United Kingdom. One of their first actions was to set up a gamma-radiation monitoring network (RIMNET) at 46 Meteorological Office sites throughout the United Kingdom (Fig. 5) — including the Isle of Man and Jersey. The instruments are read once per hour, 24 hours per day, and the information passed via the Meteorological Office Telecommunications Centre at Bracknell to the Central Data Facility at DOE Headquarters in London and Lancaster.

However, from a meteorological point of view, RIMNET only provides confirmation that the cloud has arrived; it gives no indication of the spread and concentrations within an approaching cloud, and this information is vital if the Meteorological Office is to provide forecasts of the cloud movement. Consequently, through international agreements, radiological and special meteorological data will be passed via the Global Telecommunication System (GTS) in the event of major international incidents.

Once there is a report of an international accident, the Meteorological Office has two numerical models available to predict both where the plume will go, and where it has come from. The first is a fairly basic model which can backtrack the plume for about 2 days and forecast its approximate movement for up to 5 days ahead. The output from this model is available within about 30 minutes of notification, and an illustration of the output is shown in Fig. 6. In November 1988 there was a report that radiation had been detected in the air at a village in Poland — this was later found to be a false

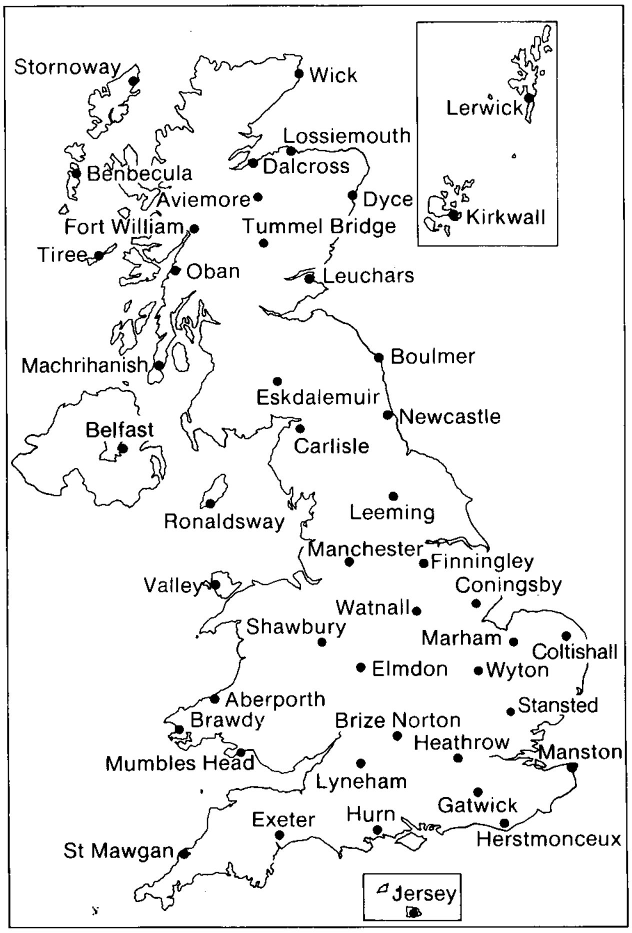


Figure 5. Radioactive Incident Monitoring Network (RIMNET) Phase 1.

alarm. However, in Fig. 6 it is well demonstrated that in this incident there would have been no serious threat to the United Kingdom; the forecast section of the trajectory showed that the plume would have been advected over the USSR while the hindcast section suggested that its origin was over Northern Poland, Scandinavia or the Norwegian Sea.

If this incident had developed into a serious threat then the more sophisticated trajectory model, developed by the Boundary Layer and Atmospheric Chemistry Branch of the Meteorological Office (Met O 14), would have been run to determine accurately the path of the material, and the likely level of air concentrations and surface deposition (Maryon 1989). This model simulates the spread of material due to wind shears and atmospheric turbulence. In addition to air concentrations it computes the radioactive decay and deposition to the surface of radio-nuclides, including material washed out of the air by rain — a process of critical importance. An illustration of this is shown in Fig. 7 which depicts a fictitious incident at 50° N, 00° W. If it had been a real incident then, as data from RIMNET and other countries' equivalent monitoring networks became available, the forecasts would have been continuously updated and refined. The different levels of shading

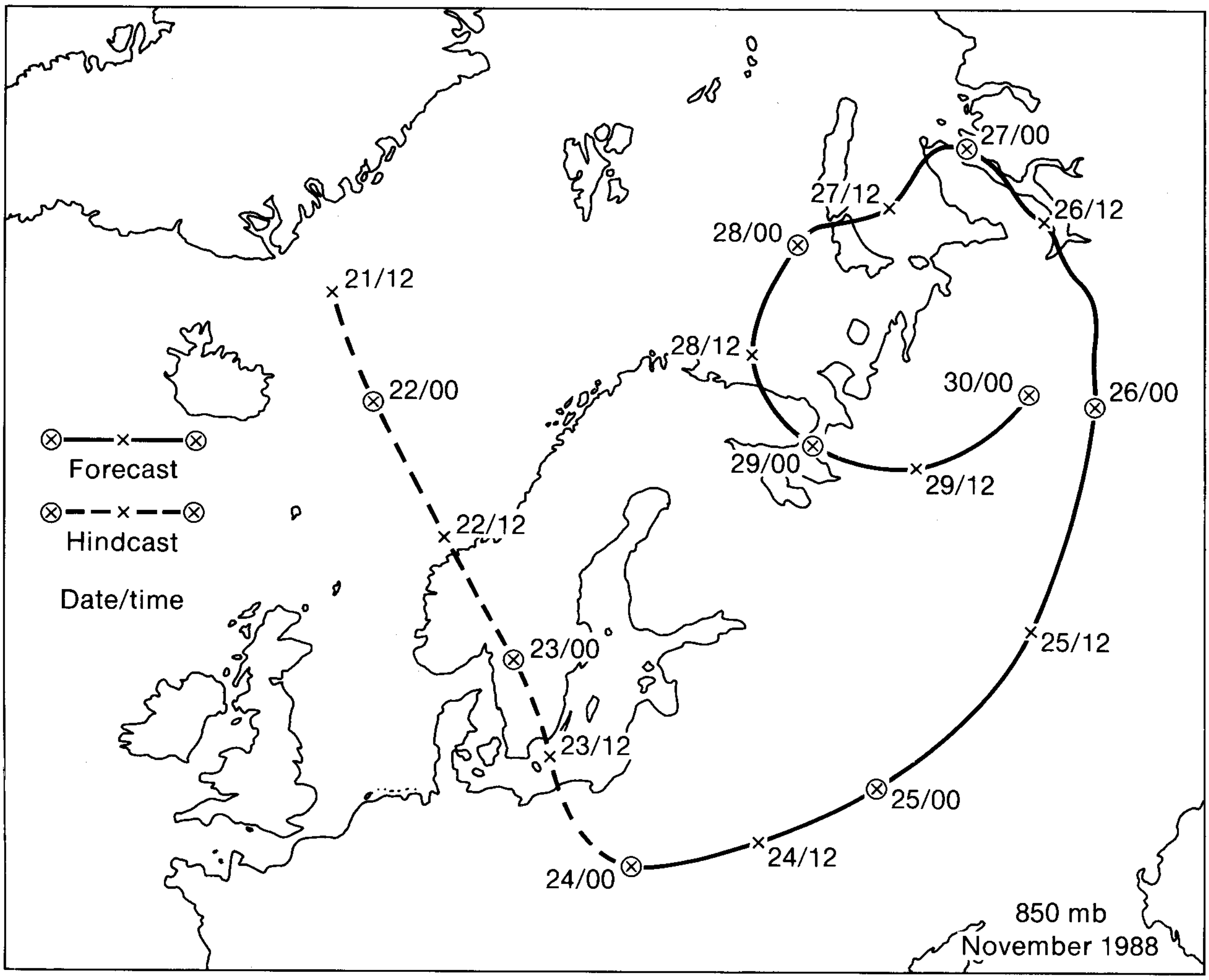


Figure 6. An example of hindcast and forecast trajectories.

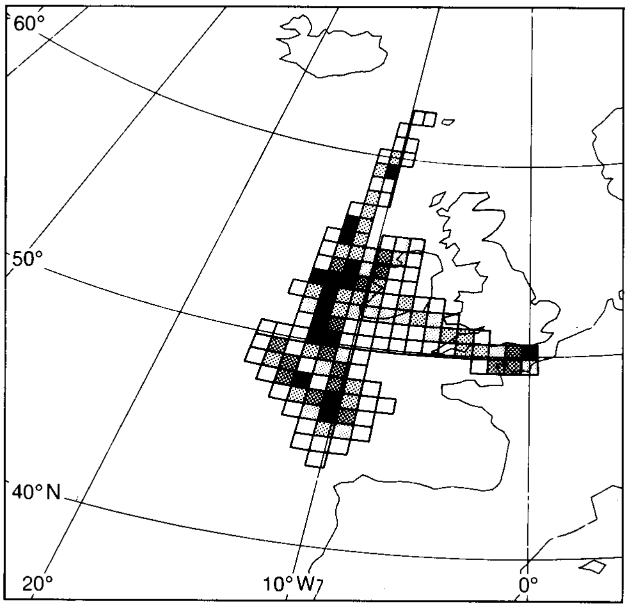


Figure 7. An example of trajectory information available from the Met O 14 model. Illustrated is the air concentration (larger shown by heavier shading) expected 3 days after a fictitious radioactive release accident at 50°N, 00°W. Note how material can be dispersed at different rates and in various directions by the differential motion within weather systems.

indicate different levels of air concentration and shows how material can be dispersed at different rates and in various directions by the differential motion within weather systems. Air concentrations need not decrease uniformly with distance from source.

In the event of an incident, data from both models is made available to the DOE. If there is a threat to the United Kingdom then the Technical Co-ordination Centre (TCC) is opened and from there the DOE co-ordinate the national response. (The TCC has a similar function to the Department of Energy and MOD co-ordination rooms discussed in the previous section. It differs in that those rooms are concerned with accidents at sites within the United Kingdom while the TCC is for accidents abroad.) Many Government Departments are represented at the TCC and meteorological advice is made available from CFO via the Meteorological Office representative.

7. International chemical incidents

For completeness there is one further type of accident that must be considered — the chemical accident which occurs abroad but where the plume of material is blown towards the United Kingdom. Essentially this reduces to the possibility of a very large amount of material being accidentally released in a nearby European factory (e.g. at a fertilizer factory). It requires a considerable amount of material, released reasonably near to the United Kingdom, for the toxic fumes to cross the English Channel and arrive in sufficient concentration to pose a threat to the population. Consequently the risk of this type of incident is considered to be very low.

In 1988 a possible example of such an incident did occur at a large factory in Nantes in north-west France. The prevailing southerly winds advected the plume towards the United Kingdom and there was initially some concern in the south-west peninsula. In the event the plume was not detected, having dispersed sufficiently during the intervening 200 miles for the air concentration to be very low, by the time it reached the United Kingdom.

Fortunately the long-range trajectory models developed by Met O 14 (Maryon 1989) in response to the Chernobyl incident, are a good basis for tracking plumes of toxic chemicals, and therefore appropriate advice is available to whichever Government Department takes the lead in the UK emergency response to such international chemical accidents.

8. Future developments

There is still considerable national and international activity in this area. The World Meteorological Organization (WMO) and the International Atomic Energy Authority are currently developing codes for the exchange of both radiological and special meteorological data via the GTS in the event of future international nuclear accidents. Such codes are particularly important; the amount of available radiological data is increasing rapidly in the wake of Chernobyl, as nations install and expand their radiological networks.

In the United Kingdom, RIMNET Phase 1 (Fig. 5) is complete and work has now begun on expanding the network to some 80 stations, at the same time automating the data collection procedures from both the new and existing sites.

There are also initiatives within WMO to formalize the exchange of information in the event of large chemical accidents in which there is a possibility that the toxic plume may cross national boundaries. As discussed above, the risk to the United Kingdom is not particularly great, but other countries are not as geographically isolated, and there is growing concern on the continent.

On the meteorological aspects of the subject, work continues on the development of the long-range dispersion model (Maryon 1989). However, this model is of use only for major incidents. In the majority of cases the plume poses a threat for at most a few kilometres downwind. Because of the necessity for speed of response, and due to the limitations both of observational data and in our knowledge of the effects of topography on air flow, the current models defining the Area at Risk are relatively crude, and it is left to the subjective assessment of the forecaster to determine the effects of terrain and other local features. This is a topic that requires further research and it is hoped that, in a few years time, it will be possible to give better guidance in this aspect of the problem.

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The WMO International Ceilometer Intercomparison, Beaufort Park 1986

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Summary

This paper describes the instruments, data recording, analyses and results for the WMO International Ceilometer Intercomparison hosted by the Meteorological Office in 1986.

1. Introduction

The first WMO International Ceilometer Intercomparison was conducted under the auspices of the Commission for Instruments and Methods of Observation, and held from February to July 1986 at the Meteorological Office experimental site at Beaufort Park, near Bracknell, England.

The objectives of the intercomparison were:

(a) To record cloud-height data from production ceilometers together with simultaneous measurements and observations of relevant meteorological variables, and when feasible to make independent estimates of cloud base using alternative techniques.

(b) To publish analyses of recorded ceilometer data, classified according to related meteorological variables, and comparisons against independent (or reference) measurements.

(c) To make recommendations concerning definitions for cloud-base measurement identifying, as appropriate, the needs for further studies and further practical experiments.

(d) To assemble information on the operational aspects of the ceilometers used in the intercomparison.

The present paper is a summary of the conduct and results of the intercomparison, and is therefore concerned mainly with the first two objectives.

2. Description of instruments studied

A total of eleven ceilometers, comprising seven different models, were eventually investigated. A list of their characteristics appears in Table I. Five of the instrument models were laser ceilometers, using the LIDAR technique based on the time for return of a pulse of infra-red laser light. The other two worked on the triangulation principle, measuring the angle of elevation of a patch of cloud illuminated by visible light.

Four of the five laser models were represented by two instruments each, which enabled conclusions to be drawn not only about the consistency of manufacture, but also about the degree to which the ceilometer performance varied according to exposure. The instrument sponsored by The Netherlands was an old design, producing analogue chart output, which had been modified for the intercomparison to produce, in addition, digital messages via a microcomputer. The remaining systems were all in production or under development at the time of the intercomparison. Several of the instruments were capable of reporting more than one cloud-base height on a given sounding; the maximum number for each is given in Table I under 'Levels per sounding'. The final column of Table I lists the abbreviations used to identify individual instruments in the remainder of the paper.

The intercomparison commenced on 3 February 1986, although the Belfort instruments (B1/B2) were not available until 22 May. The Netherlands instrument (K1) failed for periods in February and April, the Impulsphysik Ceilograph II (I4) was not repaired following a failure early in June, and B1 and B2 both developed hardware faults causing 26% and 17% loss of data, respectively. The remaining seven systems had lost little data when the intercomparison was terminated on 17 July 1986.

3. Ceilometer deployment

The laser instruments were deployed approximately 20 m apart around a circle of about 60 m diameter. The two triangulation devices were about 100 m (I4) and 350 m (K1) from the centre of the circle. No discernible bias was noted as a result of these separations.

4. Measurements and data recording

Data from the ceilometers were logged every minute. Also, measurements of temperature, humidity, horizontal visibility, global irradiance, presence and rate of rainfall, wind speed and direction were made automatically at 1-minute intervals throughout the intercomparison, with daily manual checks. In addition, special hourly observations were made between 0600 and 2100 UTC daily by experienced staff. Alternative estimates of cloud-base height were obtained on an opportunity basis by double-theodolite tracking of pilot balloons. Effort was concentrated on occasions of relatively rare weather phenomena, and was confined to daylight.

Table I. Characteristics of the ceilometers deployed in the intercomparison

Member	Manufacturer	Model	Type	Number entered	Maximum range (m)	Soundings per min.	Levels per sounding	Vertical vis?	Abbrev.
Finland	Vaisala	CT12K	Laser	2	3600	2	2	Yes	V1/V2
Federal Republic	Impulsphysik	LD-WHX	Laser	2	3600	2	3	No	I1/I2
of Germany	Impulsphysik	LD-WHL	Laser	1	1500	4	2	No	I3
	Impulsphysik	Ceilograph II	Triangulation	1	900	2	1	No	I4
Netherlands	Crouse/Hinds	TXJ-2	Triangulation	1	1500	1	1	No	K1
Sweden	ASEA	QL1212	Laser	2	3000	1	2	Yes	A1/A2
USA	Belfort	7013	Laser	2	5000	1	1	Yes	B1/B2

5. Principles and methods of analysis

The principles for analysis of the data were agreed by the International Organizing Committee; the most important of these was that no single instrument would be used or appear to be used as a standard against which others were judged. Thus, in the analysis, the median of the heights from the seven models of ceilometer were selected for each minute as representative values of cloud-base height. Where two instruments of the same type were available, only one of them was used in the calculation; a median was not defined when fewer than five had reported cloud within range. It was also agreed that analyses would be performed at the shortest common time-interval, namely one minute, and on the lowest cloud base reported by a given instrument.

Cloud-base height is very variable in space and time, and often clouds of widely differing height are present simultaneously. Minute-by-minute comparisons of reported heights therefore reveal little useful information, and much more may be obtained from comparisons of height distributions. The main tool chosen for the assessment of reported heights is the Empirical Quantile–Quantile (EQQ) plot (Murphy and Katz 1985) in which two cumulative distributions are compared directly in a compact format. Each point on the plot defines a pair of heights corresponding to a common cumulative frequency of the two height distributions. Interpretation of the resulting plot is not always straightforward, but in general if the curve lies predominantly above the line of equality, then the instrument featured on the ordinate produces heights which are on average greater than those from the instrument on the abscissa, and vice versa. (Interpretation of the EQQ plot has been discussed more fully in Jones *et al.* 1988.)

Each EQQ plot compares data at 1-minute resolution, either from two ceilometers, or from one ceilometer and the median height (MEDIAN). In either case, data were included in the distributions only if the two sources agreed that cloud was present simultaneously within range of both, thus ensuring that both distributions resulted from the same underlying meteorological conditions. No numerical analysis was performed on reported heights of higher cloud layers, penetration distances or vertical visibilities, although it was noted that vertical visibility reports were frequently misleading.

6. Results of analysis

For those ceilometers where two examples had been submitted, direct comparisons were made between instruments of the same model. The results showed that the distributions of reported heights were identical within the resolutions of the instruments, indicating that the individual modern LIDAR systems are manufactured to a high degree of consistency of performance. This result also confirmed that there was no effect due to the spatial separation of the ceilometers.

Fig. 1 shows data from a representative of each ceilometer model displayed in an EQQ plot. Each plot is derived from all qualifying available data, and compares the individual cumulative distributions with the distribution of the MEDIAN. The curves are plotted at 1% resolution and symbols appear at 5% intervals; the digits 1–9 mark the 10% intervals. Note that the curves for all but I3 are offset for clarity. Fig. 1 illustrates many of the features characteristic of each model. For heights up to about 600 m, the I4 triangulation system produced results very much in agreement with those from the laser types, although it did display a slight tendency to over-read relative to the others at the upper end of its distribution. This problem was even more pronounced in the reports from the other triangulation system (K1) above about 600 m. It is possible that a misalignment of the sensitive triangulation system could have contributed to this effect. B2 and A1 reports agreed closely with the MEDIAN, whereas I1 appeared to be systematically about 25 m lower. V1 reports exhibited an anomalous excess in the height range 500–600 m, indicated by the slight change of slope in the EQQ plot in that region.

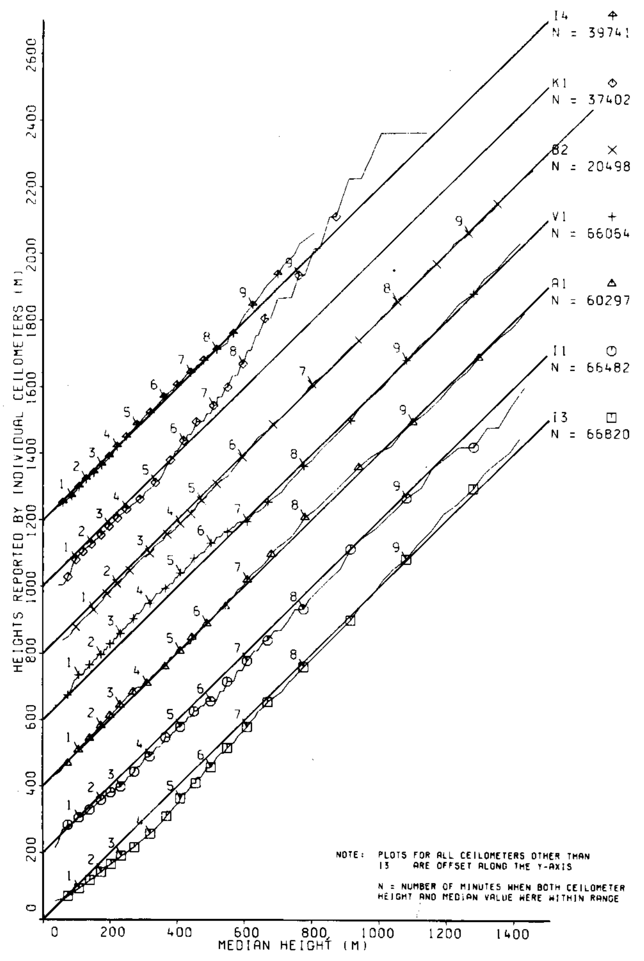

Figure 1. Empirical quantile–quantile plots of heights against median recorded by a representative from each ceilometer model for all available data. See text for further explanation.

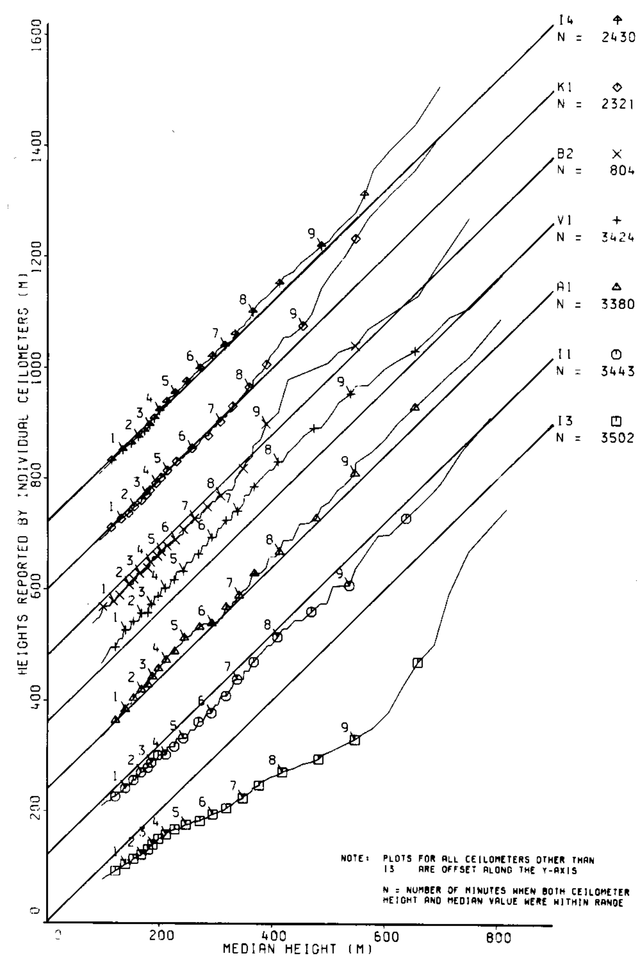

Figure 2. As Fig. 1 but for conditions of any liquid precipitation and visibilities ⩾ 1000 m.

The departure from the line of equality shown in Fig. 1 by the I3 reports is due to its response to precipitation, and is one of the more dramatic results of the intercomparison. The effect may be seen more clearly in Fig. 2, which shows only those results obtained during liquid precipitation. The I3 reports form a curve which is quasi-linear up to the 90% point. This implies a systematic difference from the MEDIAN by a factor equal to the slope of the line (i.e. about 0.6). This effect was observed to increase with increasing intensity of precipitation, such that at rainfall rates exceeding 4 mm h^{-1} reported heights were only about 15% of the MEDIAN. The large departures apparent in the tails of many of the other curves in Fig. 2 are not thought to be significant; the EQQ plot is not appropriate for deriving information from the upper limits of the distributions.

Fig. 3 shows a time–height plot of results from the hour 0800 to 0859 UTC on 21 May 1986. Precipitation was detected at the surface from 0822 onwards and the independent observation at 0845 UTC reported intermittent slight rain with a cloud base (marked 'O') at 420 m. Four pilot balloons ('S') were tracked by theodolites, and were judged to have entered cloud at heights of 400–450 m. Most of the ceilometer reports lay between 400 and 700 m, with large minute-to-minute fluctuations; however, I3 consistently reported cloud around 200 m with only occasional heights agreeing with those from the other instruments.

Results in snow were broadly similar to those in rain, with the exception that both triangulation-based instruments occasionally reported extremely low cloud bases. All ceilometers except K1 consistently responded to fog, although most reported cloud-base heights which were much lower than estimates of vertical visibility made by timing pilot balloons to the point of disappearance.

7. Cloud-strike statistics

The EQQ plot compares distributions of reported cloud-base heights but contains no information on the reliability with which clouds were detected. An assessment of relative reliability may be obtained from Table II, which shows the proportion of minutes in various weather categories for which each ceilometer type reported cloud below 900 m.

It was important to compare instruments under the same set of meteorological conditions, and therefore to select for analysis only those minutes for which correctly formatted data were received from all ceilometers.

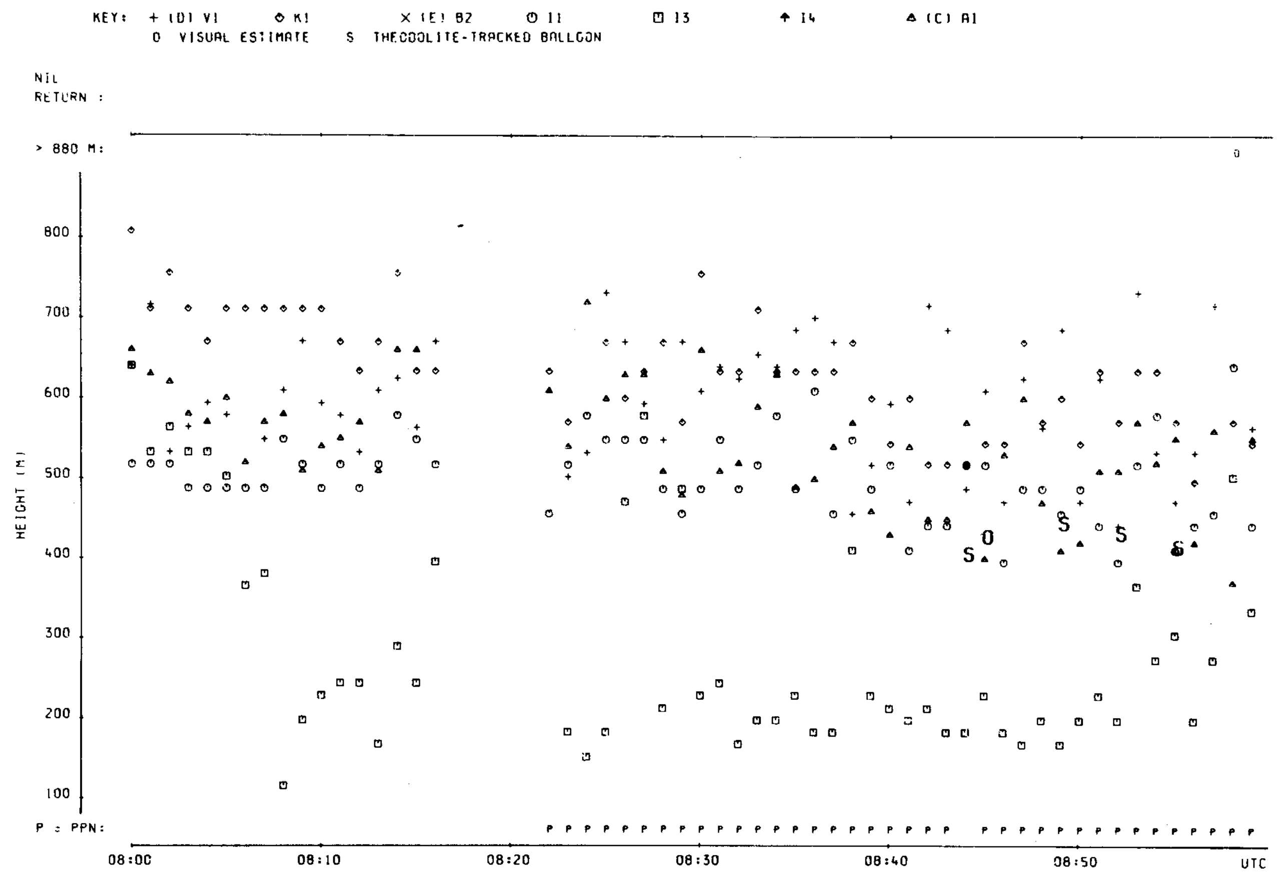

Figure 3. Plot of height against time for the period shown for the ceilometers featured in Fig. 1.

Table II. Percentage of minutes in each weather category for which each ceilometer model reported cloud below 900 m. See Table I for explanation of model.

Model	Vis. ⩾ 5000 m No ppn	Slight ppn ⩽ 0.5 mm h^{-1}	Mod.–hvy ppn > 0.5 mm h^{-1}	8/8 cloud ⩽ 1700 ft	Snow	Fog
B1/B2	17	61	60	89	—	—
V1/V2	23	83	71	98	65	100
I1/I2	23	83	80	98	61	100
A1/A2	21	80	76	90	24	90
I3	22	90	95	99	71	87
K1	14	64	62	89	41	44
I4	16	66	52	87	27	100

However, owing to the late arrival of B1 and B2, and the almost simultaneous failure of I4, this proved impossible. Entries in Table II were therefore derived from the period up to 1 June only, and the figures for B1 and B2 were estimated from the relationships observed in the periods when all the laser ceilometers were operational. The percentages in Table II are dependent on meteorological conditions as well as instrument imperfections, and indicate the relative performance of each instrument in the same weather conditions. Note that the consistency of results from examples of the same instrument model was very high, and therefore they have been combined in Table II.

In general, the two triangulation systems exhibited lower reporting rates than did the laser-based instruments, and in fact behaved similarly to each other in all situations except fog. B1 and B2 consistently reported less cloud than the other laser devices, producing many 'nil returns' instead. The Vaisala and ASEA instruments all tended to report vertical visibility estimates in precipitation; the Vaisalas particularly in heavy rain, and the ASEAs particularly in snow. The values given were usually much too great, and in fact both ASEA ceilometers always produced the value 4200 ft (1280 m) for vertical visibility. Of all the instruments capable of reporting vertical visibility, only the ASEAs did so in fog (on 2–3% of soundings). None of the Impulsphysik instruments had the option to report vertical visibility, and the laser systems, particularly I3, maintained very high cloud-reporting rates in most conditions.

8. Conclusions

(a) V1 and V2 lost a negligible amount of data through faults, and maintained a high cloud-detection rate in all conditions except moderate-to-heavy rain. Cloud heights were greater than the MEDIAN, but corresponded well with estimates using pilot balloons.

(b) I1 and I2 were also very reliable, with a high cloud-detection rate in all conditions. Reported heights were on average slightly lower than the MEDIAN. I3 was very reliable mechanically and exhibited the highest detection-rate in many situations. However, it consistently reported anomalously low cloud bases in precipitation.

(c) A1 and A2 suffered minor hardware faults resulting in the loss of a few data. Cloud detection was mainly good, except in snow; reported heights were close to the MEDIAN.

(d) B1 and B2 were still under development at the time and suffered from hardware faults which contributed to lower cloud-detection rates. Cloud heights, when reported, were close to the MEDIAN.

(e) The K1 system suffered greatly from hardware faults, and the software written to digitize the output proved inadequate in some situations.

(f) I4 had worked without loss of data until its failure late in the intercomparison. Its height reports compared well with the MEDIAN, but detection rates were modest, particularly in snow.

The intercomparison has shown that modern laser-based ceilometers are technically reliable, and perform significantly better than earlier designs. However, problems remain with the performance of all systems in some situations, particularly in adverse weather conditions which can have a significant impact on aviation.

References

Murphy, A.H. and Katz, R.W., 1985: Probability, statistics and decision making in the atmospheric sciences. Boulder, Colorado, Westview Press.

Jones, D.W., Ouldridge, M. and Painting, D.J., 1988: WMO International Ceilometer Intercomparison (United Kingdom, 1986). Instruments and Observing Methods Report No. 32. Geneva, WMO.

Notes and news

European conference on the Landscape Ecological Impact of Climatic Change, Lunteren, The Netherlands, 3–7 December 1989

As a contribution to the UNEP–WMO–ICSU World Climate Assessment Programme and within the framework of the ICSU International Geosphere–Biosphere Programme (IGBP) and the Climatology and Natural Hazards Research Programme (EPOCH) of the European Community, a European conference will be held in Lunteren (near Wageningen), The Netherlands on the Landscape Ecological Impact of Climatic Change (LICC). The scientific preparations for the conference are taking place within six international case-study groups concentrating on: Alpine regions, the Fenno-scandian region, the Mediterranean region, fluvial systems, wetlands, and coastal dunes.

During the first half of the conference, the results of the six case-studies will be discussed in parallel workshop sessions. In the second half, the final findings of the sessions will be presented and will be set in broader context through plenary presentations on various related topics.

The LICC conference is organized in The Netherlands by the Physical Geography Departments of the Universities of Amsterdam and Utrecht, and the Nature Conservation Department of the Agricultural University of Wageningen. For more information/registration, please contact the LICC conference secretariat:

Rudolf S. De Groot or Matthias M. Boer
Department of Nature Conservation
Agricultural University of Wageningen
Ritzema Bosweg 32a
6703 AZ Wageningen
The Netherlands
Tel: 31-8370-82247, Fax: 31-8370-84731,
Telex: 45015 bluwg.

Also, the Editor, *Meteorological Magazine*, has a copy of the conference programme.

Dr D.N. Axford moves to Geneva

Dr David N. Axford, Director of Services at the Meteorological Office up to September 1989, has left Bracknell to fill the post of Deputy Secretary-General of the World Meteorological Organization (WMO) in Geneva, initially for a period of two years. Before becoming the Director of Services, a post he held for nearly six years, he was Assistant Director in charge of Operational Instrumentation and then Deputy Director in charge of Observational Services.

At WMO Dr Axford will be one of the Directing Team whose duties include liaising and negotiating with other Agencies of the United Nations, such as the United Nations Environment Programme, the United Nations Development Programme, and the World Health Organization. He will take a specific interest in technical aspects of the World Weather Watch, the World Climate Progamme and the Technical Co-operation Programme.

Meteorological Office participation in IAMAP 89

As announced, with some details, in Notes and news in the April 1989 issue of the *Meteorological Magazine*, the 5th Scientific Assembly of IAMAP (International Association of Meteorology and Atmospheric Physics) was held at the University of Reading, United Kingdom, from 31 July to 12 August 1989. These assemblies are held at 4-yearly intervals.

The Assembly had four components: invited overview lectures, four major Association symposia, thirteen topical symposia organized by the individual IAMAP Commissions, and two workshops. Altogether 885 papers were scheduled to be presented of which 66 were invited review papers.

The Meteorological Office was well represented, with many of its staff being involved in planning, organization and presenting papers.

Dr K.A. Browning (Director of Research at the Meteorological Office) and Dr R.W. Riddaway (Meteorological Office) were on the Local Organizing Committee. Dr Browning chaired the Scientific Programme Committee and five other senior staff of the Meteorological Office were members and acted as convenors of the symposia. This time as President of the Royal Meteorological Society, Dr Browning also chaired the afternoon session of the opening plenary, introducing his invited lecturers, all well known in their particular subjects: Dr L. Bengtsson (ECMWF) on advances and prospects in numerical weather prediction, Dr F.P. Bretherton (University of Wisconsin, USA) on interactions within the global climate system, Dr V. Suomi (University of Wisconsin) on the global water-cycle observational needs and opportunities.

The morning session of the opening plenary was chaired by Dr G.B. Tucker (President of IAMAP) who presided over the opening address and introduced his invited lecturer: Dr F.B. Smith (Meteorological Office) on regional pollution — field and theoretical studies.

Meteorological Office staff were authors or co-authors (with workers from other organizations) of 48 papers — about 5% of the total, with strong representation in the symposia on mesoscale phenomena: analysis and forecasting (11 out of 101 papers), boundary-layer parametrization and larger-scale models (4 out of 28) and mesoscale processes in extratropical cyclones (10 out of 81).

Meteorological Office staff also contributed several poster displays — particularly on mesoscale meteorology, satellite sounding and climate-change modelling. The Central Forecasting Office also maintained a sequence of forecast charts up to 5 days ahead (updated daily) and the sequence of UK weather radar pictures of rainfall was also displayed.

On the middle Saturday of the 2-week meeting, the Office played host to about 100 IAMAP delegates, who were given a guided tour of the Office and shown the work of the Operational Instrumentation Branch and the services offered by the Advisory Services, Public Services and Marine Branches.

Books received

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

The human impact of climate uncertainty, by W.J. Maunder (London, New York, Routledge, 1989. £10.95 (paperback), £25.00 (hardback)) provides an overview of the economic dimensions of climate and human activities. It is intended to be of particular interest to decision-makers and students concerned with associated subjects.

Applications of weather radar systems, by C.G. Collier (New York, Chichester, Brisbane, Toronto, John Wiley and Sons, 1989. £44.50) records and elucidates the contribution made by weather radar data to a variety of sciences. The main emphasis is on operationally based systems, with examples drawn from a world-wide range of sources.

Spacious skies, by R. Scorer and A. Verkaik (Newton Abbot, London, David and Charles, 1989. £20.00) contains many photographs and satellite pictures of the sky from all parts of the world. The many facets of the subject are grouped into separate sections, with theoretical discussion and explanation as to why a particular picture looks the way it does.

Correction

Meteorological Magazine, August 1989, p. 164, Fig. 4. Mr S.P. Peters and others have pointed out additions and errors to the names of the people present; the photograph in the pamphlet lodged in the National Meteorological Library, Bracknell will be amended.

Satellite photograph — 21 September 1989 at 0930 GMT

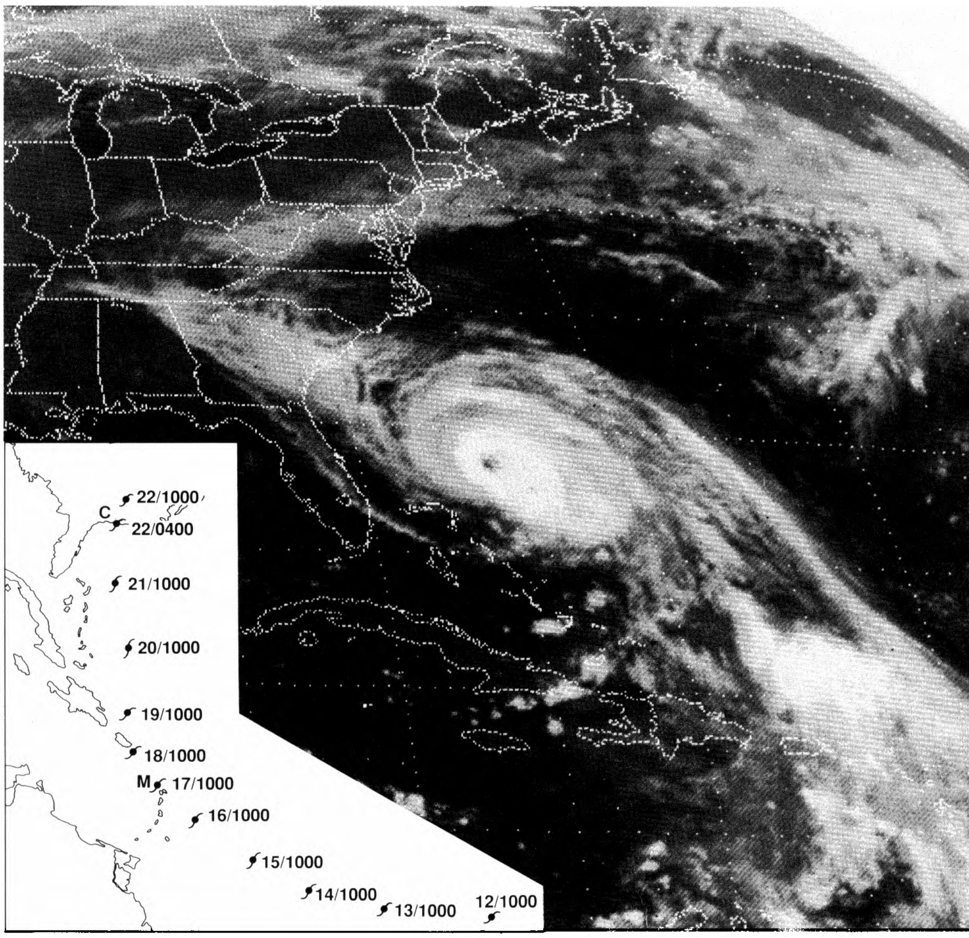

Figure 1. Hurricane Hugo as it approached the USA. The inset shows the track of the hurricane from 12 to 22 September.

This GOES infra-red image (Fig. 1), processed by the Meteorological Office's HERMES system, shows hurricane Hugo as it approached the USA, where it made landfall at Charleston (labelled C in inset), South Carolina. The picture shows a clearly defined cloud-free 'eye' near the centre of an upper-cloud shield some 600 n mile across. Within the shield, cloud tops are progressively colder toward the eye. An aircraft reconnaissance flight that traversed the storm at the time of the picture measured the eye to be 50 n mile across — the largest during the storm's life cycle.

Hugo evolved from a tropical cumulonimbus cluster that developed off the coast of west Africa, south of the Cape Verde Islands early on 11 September. Satellite imagery gave clear indication of Hugo's track (inset). Hugo was upgraded to a hurricane on the evening of 13 September. The eye was observed from early on the 15th until soon after landfall on the 22nd.

Although wind strengths were not as extreme as those associated with hurricane Gilbert in September 1988, at its peak maximum sustained winds (measured by aircraft reconnaissance) did reach 130 kn with gusts to 150 kn. The storm was almost at full strength as it crossed Montserrat (labelled M) causing extensive damage to almost all property) and Puerto Rico. Hugo temporarily weakened as it turned north-west, but reintensified as it approached the South Carolina coast. Severe wind damage was apparently restricted to coastal areas. After landfall, observations showed rapid weakening of surface winds to below hurricane force, and by late on the 22nd Hugo had been downgraded to an 'ex-tropical depression'. This moved quickly and recurved north-eastwards; its remnants becoming involved in an intense cyclogenesis on the 25th south of Greenland, with the central pressure down to 950 mb.

G.A. Monk and A.J.Waters

GUIDE TO AUTHORS

Content

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

Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (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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November 1989

Editor: B.R. May Vol. 118
Editorial Board: R.J. Allam, R. Kershaw, W.H. Moores, P.R.S. Salter No. 1408

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Night-time illumination
The aurora
Forecasting grass minimum temperatures
The winter of 1988/89

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Forecasting night-time illumination

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Royal Air Force, High Wycombe

Summary

With the increasing use of night vision goggles to aid night flying, there is a requirement for predictions of night-time illumination. The factors that affect the night-time illumination level are discussed and a model for determining the illumination presented. Estimates from the model are compared with those from other models and an example illustrating its use is given. The example highlights the effect that cloud can have on the illumination levels.

1. Introduction

There is currently an increase in the use of night vision aids for both fixed-wing and helicopter flying by all three Services. Night vision goggles (NVGs) are image-intensifying devices that collect and electronically enhance the available light at visible and near infra-red wavelengths. They are lightweight devices which are mounted on, or incorporated into, a pilot's helmet and they present the user with an image which is similar to that which he would see by daylight. (The use of such equipment is discussed in a recent article by Jones 1986.) Although NVGs are under continual development and their sensitivity is being increased, there is still a lower limit to the ambient light level below which they are ineffective. Consequently there is a requirement to forecast night illumination levels, both for operational sorties and for longer-term planning, particularly in respect of booking training areas for helicopter pilot training. Light levels and the times of astronomical events, e.g. sunrise/sunset, moonrise/moonset and the times of twilight, are also often required for land operations.

2. Background

The techniques for calculating light levels are conceptually straightforward and involve two aspects, astronomical and atmospheric. The light (sunlight and moonlight) incident at the top of the atmosphere is determined by the position of the Earth relative to the Sun and the Moon. However, the amount of light that actually reaches the surface is reduced because of scattering and absorption due to aerosol and water particles in the atmosphere.

An additional aspect that effects the illumination is 'cultural lighting'. This is the light which originates from towns and cities and is reflected back by cloud layers. It can significantly increase the ambient light level.

2.1 Astronomical considerations

The position of the Sun relative to an observer on the Earth defines the periods of daylight, twilight and night. These are defined by the solar zenith angle. The various phenomena are given in Table I.

Table I. Criteria for sunrise/sunset and twilight

Phenomenon	Zenith angle of centre of Sun
Sunrise, sunset	90° 50′
Civil twilight	96°
Nautical twilight	102°
Astronomical twilight	108°

Similarly, moonrise and moonset are when the lunar zenith angle has a value of $90° \; 34' + S - \alpha$ where S and α are the Moon's angular semi-diameter and parallax, respectively.

2.2 Meteorological considerations

As noted earlier NVGs are sensitive to light at visible and near infra-red wavelengths. The visible part of the spectrum is that between the dark blue and dark red limits at 0.39 μm and 0.76 μm wavelengths respectively. NVGs respond to light at wavelengths from about 0.6 μm (in the red) to 0.9 μm (in the near infra-red), a range which is sensitive to starlight.

Electromagnetic radiation at these wavelengths is scattered by particles within the atmosphere. Depending upon the particle sizes there are two mechanisms; aerosol particles, which are typically the same size as the wavelengths of interest, lead to Mie scattering, whilst the larger cloud and precipitation particles cause geometric scattering. The concentration of particles is important since the attenuation increases with concentration. Absorption effects are negligible in comparison.

A consequence of these effects is that in hazy but cloud-free conditions, the illumination is slightly reduced and due to diffuse sun/moon light; the sun/moon may be indistinct. However, the most significant effects occur in cloudy conditions, when the illumination can be much reduced, particularly if the cloud is sufficiently thick to produce rain.

2.3 Units of illuminance and typical values

The typical light levels resulting from natural illumination for clear sky conditions are illustrated in Fig. 1, where the lines refer to the illumination from the sun and the moon (for various phases) as a function of the solar/lunar altitude (90° − the zenith angle). The figure shows how, at night, the light level depends upon both the altitude and phase of the moon. Some typical night-time illumination values are given in Table II.

Note that the sensitivity of the human eye varies in proportion to the logarithm of the illumination.

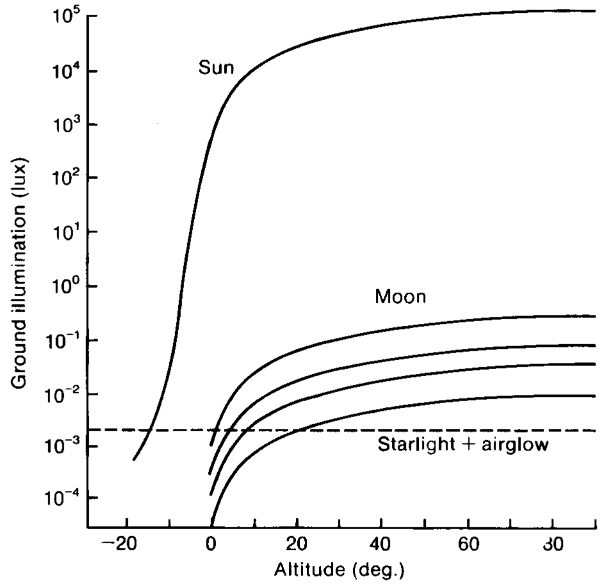

Figure 1. Illumination levels on the surface of the Earth, under clear-sky conditions, from the Sun and the Moon at various altitudes and from starlight and airglow. Phases of the Moon are 180° (line 1) (full moon), 120° (line 2), 90° (line 3) (first/last quarter) and 60° (line 4), these being the angles between the Sun and Moon. (Taken from Yallop 1986.)

Table II. Typical natural night-time light levels

Phenomenon	Light level (mlx)*
Full moon overhead	270
Full moon at 45° altitude	160
First (or last) quarter moon at 45° altitude	20
Nautical twilight	10
Astronomical twilight	3
Airglow plus starlight	2

* For a source of unit spherical candlepower, the total flux emitted is 4π lumens. 1 lx (lux) is 1 lumen incident per square metre, 1000 mlx (millilux) equals 1 lx.

3. Night illumination models

Given the astronomical and atmospheric considerations described, it is possible to estimate the level of natural illumination for a prescribed place and time. However, there is as yet no means of formalizing the effects of cultural lighting.

A model to determine the ambient light levels has been developed by the Computer and Information Systems Branch (CISB) of Royal Air Force High Wycombe, and a version of the model has been adapted to run on the Meteorological Office computer system. The model calculates the lunar and solar geometry following methods described by Duffet-Smith (1988), which use the basic orbital characteristics of the Earth and the Moon. The actual light levels are then determined using algorithms given by Yallop (1986). Results from the model are available on the RAF ASMA (Air Staff Management Aid) system, on the

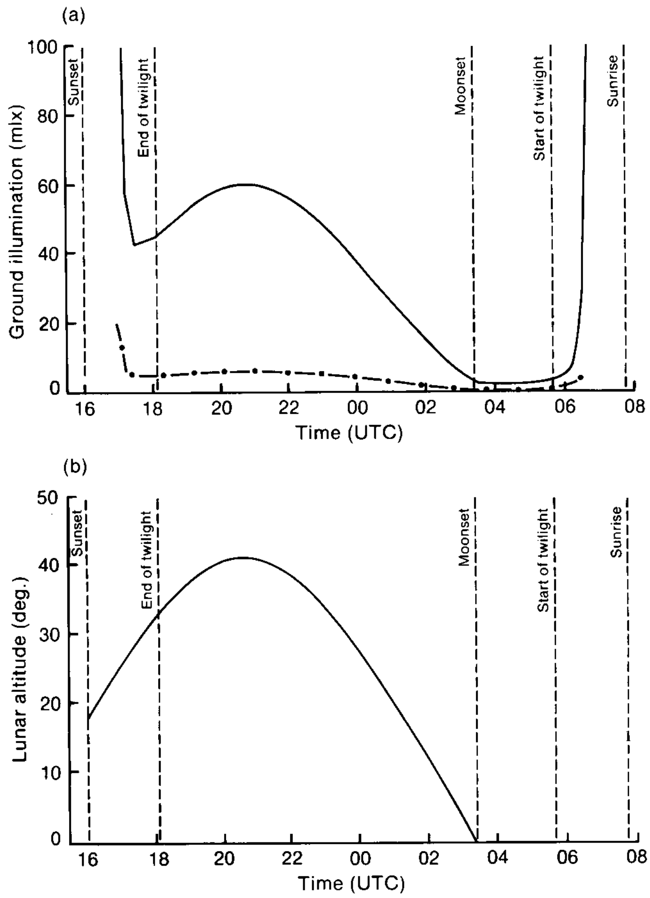

Figure 2. (a) Ground illumination for the night of 19/20 November 1988 for a location near 54°N, 1°W. The solid line shows the illumination under clear-sky conditions, the dot-dashed line for overcast conditions. (b) Lunar altitude during the night. The times of sunrise and sunset, the end and start of the twilight periods and of moonset are indicated.

Meteorological Office computer system, and micro-computer versions of the program are available at Meteorological Office outstations. A version of the model should also soon become available on the Meteorological Office Outstation Display System (Cluley and Hills 1988).

Fig. 2(a) shows an example of the night-time ground illumination for 19–20 November 1988, near 54°N, 01°W. Sunset was at 1600 UTC and the twilight periods ended at 1640 UTC (civil), 1724 UTC (nautical) and 1806 UTC (astronomical). As illustrated in Fig. 2(b) the moon rose during the early part of the night, reached a maximum elevation of 41° around 2100 and thereafter fell, setting at 0329. The estimated light level increased and fell accordingly. After moonset there was only the background starlight and airglow until the morning twilight, which began at 0537 UTC (astronomical), 0619 UTC (nautical) and 0703 UTC (civil) and ended at 0744 UTC (sunrise). The phase of the moon increased from 80% to 85% during the night.

The effect of cloud cover on attenuating the light level is simulated in the model by multiplying the clear-sky light level by a reduction factor. For thin cloud the light level is multiplied by 0.4, for medium cloud by 0.15 and for heavy overcast cloud by 0.1. As a guideline thin cloud can be taken for situations when there is a single cloud layer (e.g. stratus/stratocumulus or thick cirrus/cirrostratus) and medium cloud when there may be more than one layer and/or precipitation. Heavy cloud refers to the worst case conditions, overcast precipitating nimbostratus or cumulonimbus.

Also shown in Fig. 2(a), for comparison, are the estimated light levels for thick, overcast cloud. For NVG usage a minimum light level of 2–5 mlx is required (depending on the type of goggle) and, as illustrated in Fig. 2(a), thick cloud can bring the ambient light level down below this threshold. Consequently the ability to predict the cloud cover is of prime importance in forecasting light levels for the use of NVGs.

3.1 Comparison with other models

Night-time illumination models have also been developed by the German Military Geophysical Office (GMGO) and the US forces; the Air Force Geophysical Laboratory (AFGL) and the Army Atmospheric Sciences Laboratory (ASL). The AFGL model forms part of a Tactical Decision Aid (TDA) to support the use of NVGs and TV sights; this TDA is known as the TV TDA (Higgins *et al.* 1987). The ASL model (Duncan and Sauter 1987) is essentially the same as the AFGL model but can be run in a stand-alone mode to produce illumination estimates.

The results from the RAF/Meteorological Office model (hereafter referred to as the METO model) have been compared to those from the AFGL (Mk. II TV TDA) and GMGO models. A comparison for the night shown previously (in Fig. 2), for clear skies, is shown in Fig. 3(a). The METO and AFGL models give similar values, but the GMGO model estimates are slightly lower. Similar agreement for clear skies was also observed in a number of other direct comparisons. The close agreement between the METO and the AFGL models is not surprising since both models utilize the twilight and moonlight data of Brown (1952). The AFGL model follows the methods of van Bochove (1982) in calculating the lunar and solar geometry, which gives values virtually identical to those calculated in the METO model. No details of the methods used in the GMGO model are currently known.

As noted earlier, the effect of cloud is introduced rather simply in the METO model. However, in the AFGL model the illumination is determined from polynomial fits to calculations made using a simple two-stream broad-band (over the entire solar spectrum) radiative transfer model for a three-layer atmosphere and requires details of the cloud cover to be input. In the AFGL (and ASL) model the atmospheric transmittance also depends upon the surface albedo and the lunar zenith angle — the transmittance being greatest over surfaces with a high albedo (such as snow) and when the moon is high. The GMGO model gives three different estimates for clear, cloudy and overcast conditions.

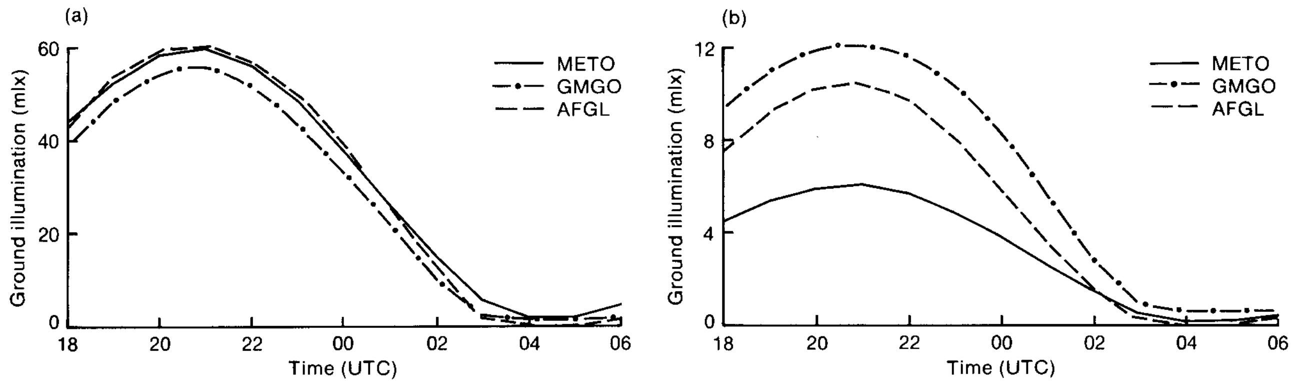

Figure 3. Comparison of estimates from different illumination models for the night of 19/20 November 1988 for a location near 54° N, 1° W. The models used are indicated, results are shown for (a) clear-sky and (b) overcast conditions.

A further comparison for 'worst light' conditions is shown in Fig. 3(b). The METO model clear-sky values are multiplied by a factor of 0.1 as appropriate for heavy cloud; the TV TDA was run with precipitation and thick overcast cloud specified and the GMGO model values were for 'overcast' conditions. The results show that the METO model values are typically half as large as the GMGO model estimates, and are also less than the values from the TV TDA (AFGL), which were closer to the GMGO estimates. Similar differences were seen in other examples.

However, whilst these differences can be marked, they should be viewed against the variability that can occur over the range of cloud conditions. Also, if the cloud is broken, then some areas will be in direct moonlight (at up to nearly clear-sky levels) and other areas will be in cloud shadows. The TV TDA actually calculates illumination levels for both direct and shadow regions, and the fraction of each. This detail is not, however, produced by either the METO or GMGO models.

3.2 Example of use

An example illustrating the use of the model is given below. Fig. 4(a) shows the synoptic chart for 0000 UTC on 17 December 1988. A frontal system had moved steadily across southern England during the afternoon and early part of the night. The position of Lyneham (51° 30′N, 1° 59′W) is marked on the chart. The change in the cloud cover at Lyneham, with the frontal cloud (only low-level stratiform cloud was visible from the ground) clearing after 2100 UTC and altocumulus then developing, is shown in Fig. 4(b). The estimated light levels (from the METO model) for Lyneham are shown in Fig. 4(c), and illustrate how the light level increased after 2100 as the frontal cloud passed. The light levels then fell as the moon sank in the night sky. Fig. 4(c) shows the existence of a window between 2100 and 0000 where the light levels were sufficient for NVG use. The existence of illumination windows such as this can be forecast using an illumination model and then overlaying the effects of the predicted cloud cover.

The effect of cultural lighting also needs to be considered. Near to towns and cities there can be a significant increase in the light level, especially when there is low-cloud cover. However, this effect can still be detectable many miles from the nearest town/city.

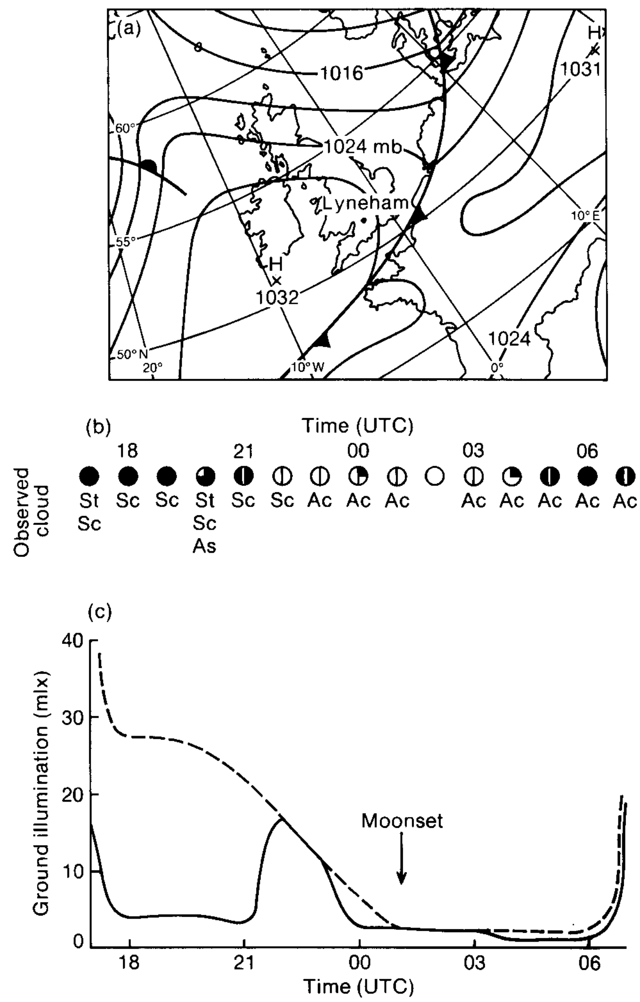

Figure 4. (a) Synoptic chart for 0000 UTC on 17 December 1988, the location of Lyneham is marked, (b) cloud observations at hourly intervals for Lyneham on this night, and (c) estimated illumination levels (continuous line) during the night (for comparison the clear-sky values are shown by the dashed line).

It should also be mentioned that the available light is not the only factor that needs to be considered when forecasting for NVGs. The range and clarity with which a particular object can be seen is determined by the contrast of the object against its background, which depends upon their relative reflectivities and the illumination, and on the atmospheric visibility.

4. Concluding remarks

This article has discussed how it is possible to make estimates of the clear-sky night-time illumination levels for a given time and place using algorithms which consider the lunar and solar geometry. The amount of light reaching the surface can be significantly reduced by the presence of cloud, and at present this is taken into account by applying simple reduction factors appropriate to the cloud cover. The examples presented have demonstrated that, in order to produce useful estimates of illumination, it is necessary to have an accurate forecast of cloud cover and type. Despite its simplicity, the method used to include cloud into the model does permit the forecaster to make reasonable estimates of the night illumination level. In the future there may be some benefit from including a more sophisticated treatment of the effect of cloud, utilizing numerical model predictions of the various cloud types and amounts which are becoming available to the forecaster.

The model is used to provide estimates of the night-time illumination, which are required to support the use of NVGs in operations and training. However, models of this sort (generally referred to as TDAs), which are used to give advice to the military, are of necessity evolutionary; enhancements and improvements being made as the needs and requirements develop.

It is anticipated that various TDAs, such as this model, may be linked to, or incorporated within, some of the computerized mission planning systems which are currently being developed by the Armed Forces. Meteorological information, and the effects of meteorology on particular military equipment, forms an integral part of these planning systems. These systems will require the forecaster to input the meteorological information and interpret the TDA predictions, and they will need improved links between Meteorological Office and military ADP equipment.

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The aurora

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Summary

A brief description is given of the main features and cause of aurorae.

1. Introduction

The aurora is one of the most striking solar-geographical phenomena and one which is frequently seen by meteorologists making conventional weather observations particularly at high latitudes.

The Northern Lights (as aurora in the northern hemisphere are also known) have fascinated mankind for many centuries. References to their apparition may be traced in the written word back to the times of ancient Greece and in the old records of China, Japan and Korea. The Norsemen related the Merry Dancers or flaming aurora as we now know them, to revelry among their gods while in medieval Europe the blood-red aurora in particular was considered to be a portent from heaven of forthcoming worldly disasters. Did not Otto the Great die in 973 after the appearance of a fiery heavenly sign?

It was Gassendi in 1621 who is said to have christened it the Aurora Borealis, the Latin for northern dawn, an appropriate name for the twilight-like auroral glow when seen low down on the northern horizon. After observing the great aurora of 5 March 1616 from London, Edmond Halley was the first person to suggest that the aurora had an electrical origin by proposing the existence of a 'luminous magnetic vapour'. Captain James Cook was the first European known to have recorded a sighting of the Aurora Australis that took place on 17 February 1773 when his vessel the *Resolution* was sailing in the southern auroral zone.

From about the mid eighteenth century the scientific investigation into the nature and cause of the aurora began. Cavendish attempted height measurements in 1784 while Biot examined the polarization of the aurora from Shetland in 1817. Spectroscopy was attempted by Angström in 1866 and by 1874 Fritz had published his monumental investigations into the frequency and distribution of the northern hemisphere aurora. The International Polar Year of 1882–83 brought in much observational data.

In 1901 Birkeland commenced laboratory experiments to simulate the effects of incoming electrified particles upon the magnetized planet and by 1911 Størmer and others were carrying out an intense stereo-photographic programme to determine heights of the auroral forms. Since then many investigators, using an increasing variety of equipment from radio to artificial earth satellites, have probed the depths of space to determine the solar origins of particles and their eventual effects upon the Earth's magnetic field and the atmosphere that cause the aurora.

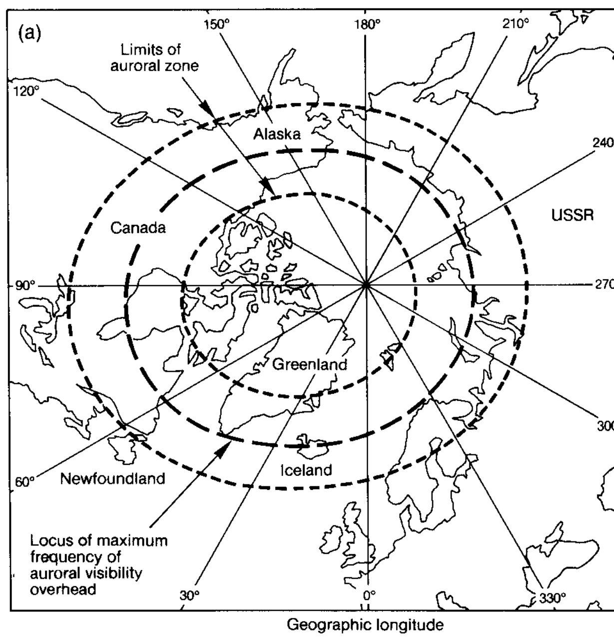
At present solar activity is approaching the next maximum in its 11-year cycle (estimated to occur in the period late 1989 to end of 1990) and has been predicted to reach greater levels than ever observed before. It is to be expected that the frequency of sightings of aurora will reach a maximum in the next year.

2. The effect of the geomagnetic field on charged particles

The aurora is the result of bombardment of the atoms and molecules of the Earth's atmosphere by charged particles. In a magnetic field the charges constrain the particles to move in directions parallel with the magnetic field lines of force; in effect the magnetic field guides the particles while the associated electric fields in the atmosphere determine the particle velocities.

To a first approximation the geomagnetic field is like that of a bar magnet (a dipole) at the centre of the Earth with its axis in line with the two magnetic poles (the north magnetic pole is located at approximately 79° N, 70° W). Close to the Earth the magnetic field lines would be expected to curve out in space and link the two hemispheres symmetrically. Close to the geomagnetic poles the field lines are nearly vertical and so it is into these regions that charged particles are preferentially guided down to Earth. The regions are two oval rings surrounding the north and south magnetic poles.

The Sun emits a steady stream of charged particles called the solar wind (described in greater detail later) which carries along with it its own magnetic field. This impinges on the geomagnetic dipole field and produces a distortion which remains roughly aligned with the Sun. As a consequence the instantaneous oval ring is displaced from symmetry about the poles, away from the Sun, and is narrower on the sunward side. The ring increases in diameter with solar activity and is up to 500 km in width. Averaged over all conditions the ovals define the regions call the auroral zones, as in Figs 1(a) and 1(b), where aurora is most frequently seen. An example of the relative frequency of the visibility of the aurorae with respect to geomagnetic latitude is given in Fig. 2.



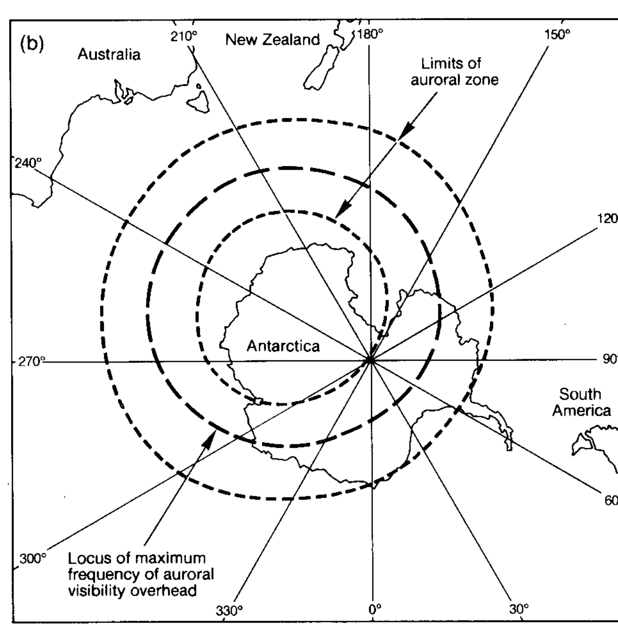


Figure 1. Approximate positions of (a) the northern and (b) southern auroral zones with the locus of maximum frequency of aurora overhead indicated by long dashed lines and the limits by short dashed lines.

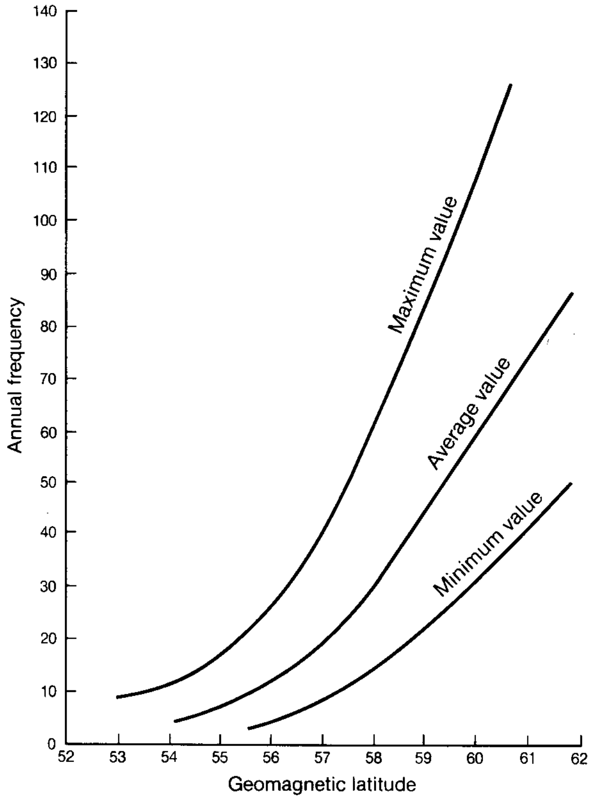


Figure 2. Comparison of frequency of occurrence per annum of aurora as a function of geomagnetic latitude and for years of maximum, average and minimum frequency (corresponding to different degrees of solar activity) in western Europe and the Atlantic area from 1962 to 1988.

3. The appearance and occurrence of aurora

The particles emitted by the Sun are mainly electrons and protons and the altitudes to which they can penetrate down into the Earth's atmosphere as a function of their energy are given in Table I. Auroral light is generated by the conversion of bombarding electron and proton kinetic energy into discrete wavelength emissions by impacting atoms and molecules in the atmosphere which become excited and then shed their energy in radiant form. A selection of auroral emissions is given in Table II, including one which is partly produced by solar ultraviolet radiation.

Table I. Penetration of particles from the Sun into the Earth's upper atmosphere

Particle	Energy (kev)	Altitude of penetration into atmosphere (km)
Electron	1	150–200
	10	100
	30	90
Proton	30 000	50
	500 000	Ground level during severe polar cap event

An auroral storm might begin with a twilight-like glow seen in the direction of the magnetic pole followed by the development of one or more homogeneous arcs slowly rising in altitude from the horizon. Rayed structures would then develop and the arcs dissolve into rayed bands. If the storm extends overhead, the rays form into a spoke-like structure with the centre of convergence situated at the observer's magnetic zenith due to the perspective effect of looking into the distance along parallel ray systems. The aurora may then break up into flickering and flaming structures which, on dying down, leave luminous patches in the sky. The whole performance may repeat itself an hour or so later.

A discrete aurora is like a curtain approximately 1 km thick and several thousand kilometres in length often accompanied by diffuse aurora on the nightward side. There is also aurora on the daylight side of the oval, seen during the polar night and mainly consisting of diffuse red emissions. These are shown diagramatically in Fig. 3 on a plot of geomagnetic latitude and local time. Figs 4, 5 and 6 show some of the banded auroral forms detailed in Table II.

During quiet periods the auroral oval remains stable, but with the onset of an auroral substorm a surge of activity passes westwards along the oval and the oval may move polewards. During great auroral storms the energy of the particles increases so that they can more readily travel down magnetic field lines and enter the Earth's atmosphere to lower latitudes. On 13/14 March 1989 a large storm occurred with aurora being seen in the tropics.

4. The solar emission of charged particles

The Sun is the ultimate source of auroral energy. It has a complicated magnetic field that controls the tenuous high temperature coronal atmosphere that surrounds it, together with the protons, electrons and other particles which escape into outer space. The field activity is related to the rise and fall of the sunspot cycle. There are points of weakness in the Sun's magnetic field that generate what are called coronal holes through which material may leave the Sun in a steady high-speed stream. Coronal holes are most active during the declining years of the sunspot cycle. There is also a steady evaporation of particles from the Sun at lower velocities called the solar wind. The Sun's magnetic field pervades the solar system as the interplanetary magnetic field which contains variations in polarity.

Associated with the sunspot cycle are eruptive events that can cause clouds of high-speed particles and magnetic bubbles to leave the Sun and encounter the Earth. Proton events can cause effects in the Earth's polar regions that appear to correlate with solar flares. These are eruptive disturbances associated with individual sunspots. The classical storm aurora is not now thought to be necessarily the result of flare activity but the result of some process in the inner corona of which the flare phenomenon is but an adjunct and not an origin.

Table II. A selection of auroral spectral emission lines

Type and emission (nm)	Target particle	Bombarding particle	Auroral height (km)	Colour	Comment
Type A					
630.0 636.4	Oxygen*	Electron Low energy	> 150	Blood-red	High altitude aurora. Above green aurora.
Type B					
666.1 669.6 686.1	Nitrogen*	Electron High energy	65–80	Red	Lower border of arcs and bands.
Type C					
557.7	Oxygen*	Electron	90–150	Green	Glows, arcs, bands, rays, patches. Normal aurora.
Type D					
630.0 636.4	Oxygen*	Electron	> 105	Red and green alternate	Associated with rapid horizontal auroral movement up to 10 km s^{-1}.
Polar cap					
656.3	Hydrogen alpha	Proton	20–60	Red	Diffuse.
Sunlit					
630.0 391.4 427.8	Oxygen* Nitrogen† Nitrogen†	Electron plus UV rays	110 to 1100	Red Blue Blue	Tops of rays.
427.8	Nitrogen†	Electron	< 90	Blue-purple	Base of bright arcs.

* Atomic
† Molecular

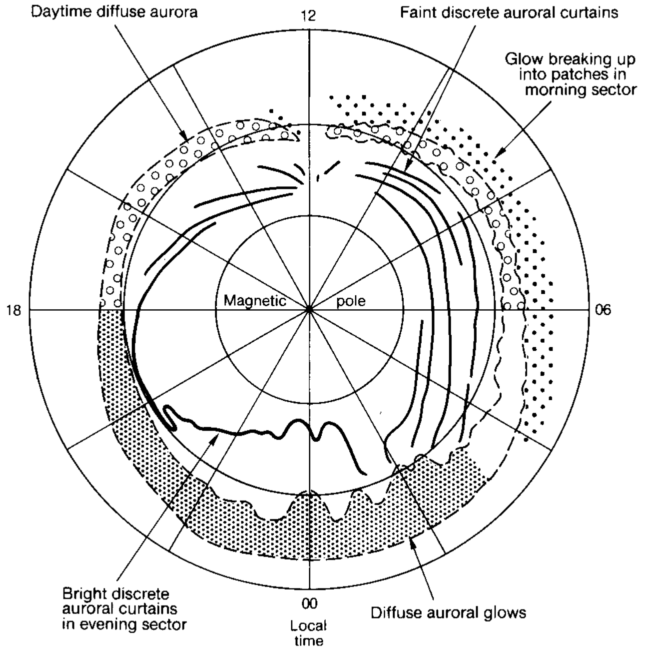


Figure 3. Approximate positions of different auroral types within the auroral oval (after S.-I Akasofu).

Figure 4. Aurora of type C (green, 557.7 nm) partially obscured by cloud.

Figure 5. Aurora of types A and B (red, 630.0 to 686.1 nm).

Figure 6. Aurora of type C (green 557.7 nm) overlying type B (red, 666.1, 669.6 and 686.1 nm).

Multiple flares in quick succession often correlate with active auroral storms. The interplanetary situation is shown schematically in Fig. 7.

The solar wind alters the shape of the quasi-dipole geomagnetic field considerably and it takes up a shape similar to the head and tail of a comet. A bow shock wave forms on the sunward side, like that of a ship cutting through the water, where the geomagnetic field and the solar wind magnetic field collide. The magnetosphere forms the head of this structure and within it are found the Van Allen radiation belts of trapped particles, the equatorial ring current and the plasmasphere that stretches down inside the magnetotail to form the plasmatail. There is a region of open magnetic field lines related to the poles that enables the interplanetary magnetic field to connect with the geomagnetic field and there is another region of closed field lines linking the two magnetic poles. The whole system of magnetic fields and plasmas forms a huge natural dynamo and large electric currents can be generated in the outer atmosphere. A representation of the magnetospheric structure is given in Fig. 8.

Active conditions on the Sun influence the stability of the magnetosphere and magnetotail to cause magnetic storms and substorms that in turn generate the storm aurora. The quieter aurorae associated with the wind streams emanating from coronal holes tend to peak in frequency in the declining years of the sunspot cycle. The transient explosive type of activity tends to intensify and decline with the cycle. Coronal hole aurorae can repeat themselves every 27 days for several rotations of the Sun each time the high-speed stream of particles encounters the Earth. Transient events may repeat themselves only if the disturbed area of the Sun remains active for more than a solar rotation. In Fig. 9 a comparison is given between sunspot, magnetic and auroral activities as measured in recent years by the Aurora Section of the British Astronomical Association.

A high-speed stream of particles forms a shock wave by driving into the slower-moving solar-wind particles. When this shock encounters the magnetosphere the field structure is compressed and the field strength is intensified to show up on ground-based magnetometers as a storm sudden commencement (SSC). This may or may not be followed by a main-stage magnetic storm in which the intensity of the field quickly falls and then slowly recovers to normal. The cause is due to the intensification of the equatorial-ring currents in the upper atmosphere that effectively act as a 'degaussing' device to reduce the field strength. Main-phase storms

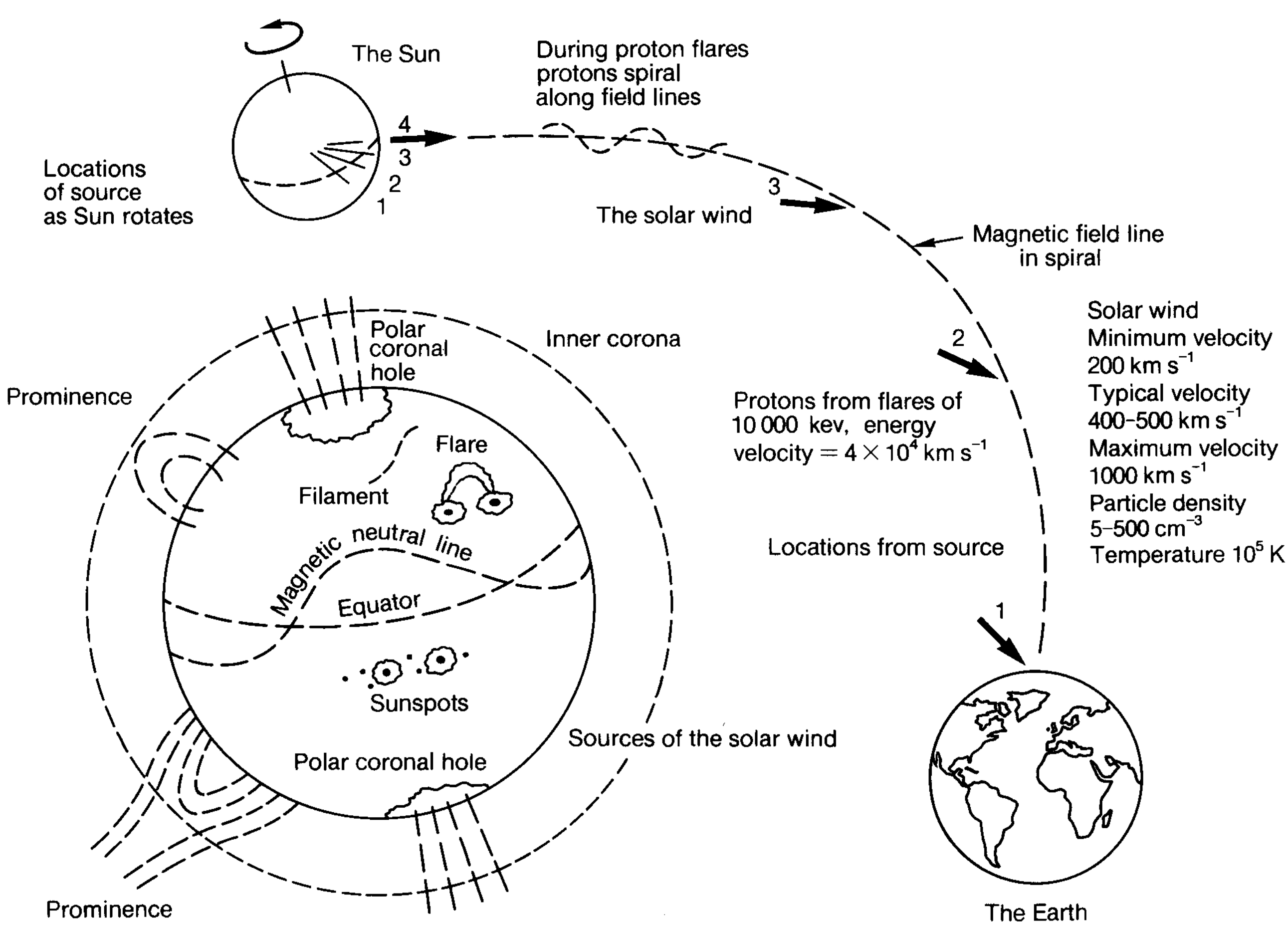


Figure 7. Solar features and the solar wind.

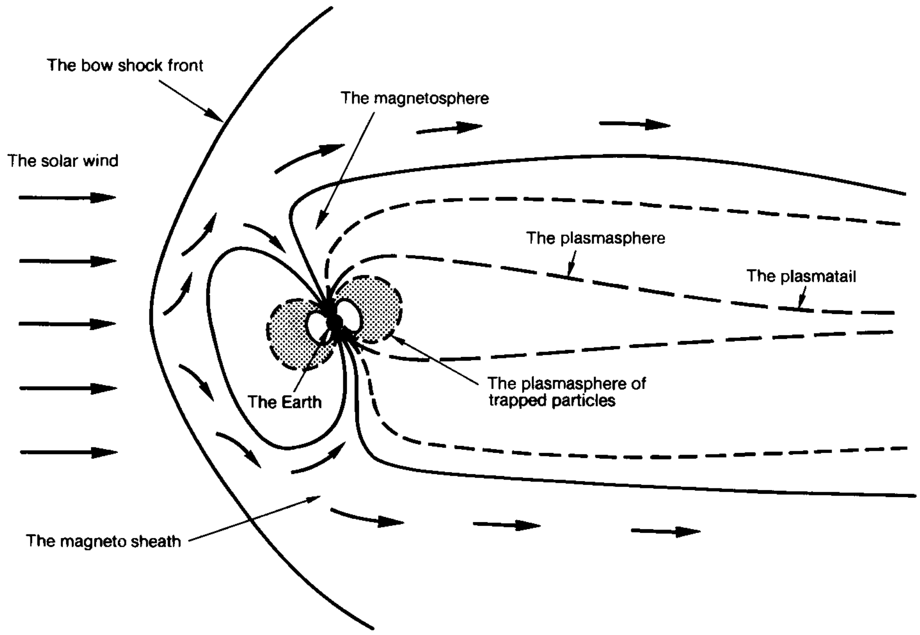


Figure 8. Diagrammatic representation of the magnetosphere.

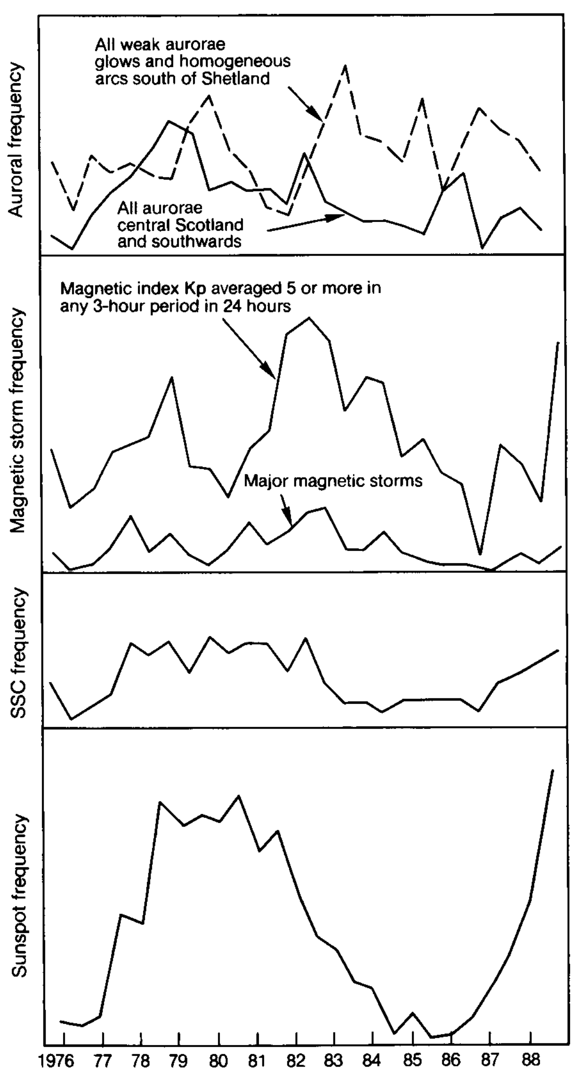


Figure 9. Schematic comparison of sunspot, magnetic, auroral and storm sudden commencement (SSC) activity 1976–88.

may occur without SSC or may slowly, rather than quickly, evolve. Idealized examples of magnetograms giving various types of storm are shown in Fig. 10.

The interplanetary magnetic field (IMF) is very variable and it is thought that the vector direction of the north–south component parallel with the Earth's magnetic axis is the key to the aurora. If the component points north then the IMF does not interlink with the Earth's field. If the component progressively turns south then the IMF lines can interlink with the Earth's field to cause magnetic and auroral activity. The direction of the IMF component appears to set the level of the dynamo generation irrespective of the speed of the solar wind. Although a major storm involves both the velocity of the high-speed solar wind and the IMF component direction the auroral substorm is triggered by the field direction on its own.

It would appear that low energy particles from the solar wind may enter the polar atmosphere by travelling down the connected field lines. The high particle-energy substorm aurora derives its material from the magnetotail, the particles being driven out of the tail into the polar and mid latitudes via the plasmasphere regions as the plasmatail collapses, rather like toothpaste coming out of a tube. The magnetosphere can bounce like a soap bubble and these variations in shape and other instabilities can cause particles to dribble into the atmosphere to form isolated arcs and other aurora. There are a number of observations on record of mid-latitude overhead aurorae suddenly appearing with lives of only 5–10 seconds.

5. Terrestrial effects associated with magnetic storms and aurora

The magnetic storm and its associated aurora can have far reaching consequences to the human race as the

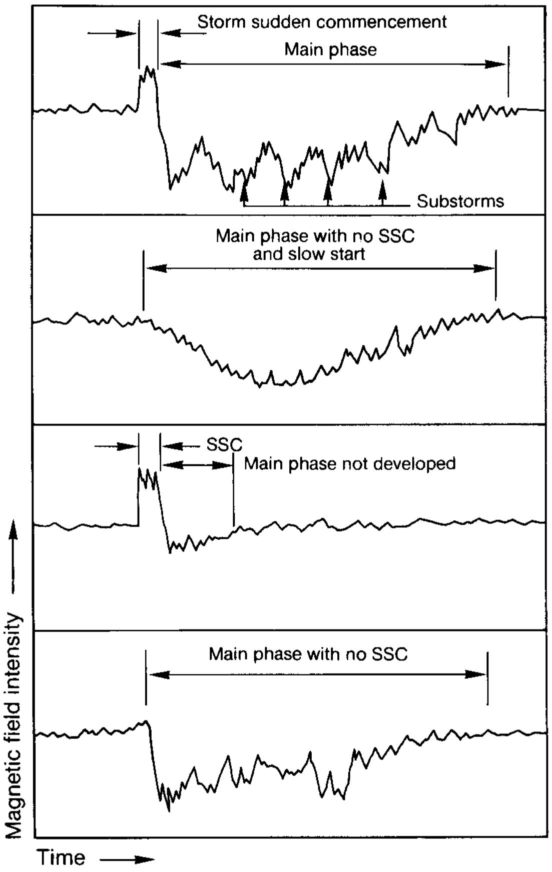


Figure 10. Idealized magnetograms of typical magnetic storms.

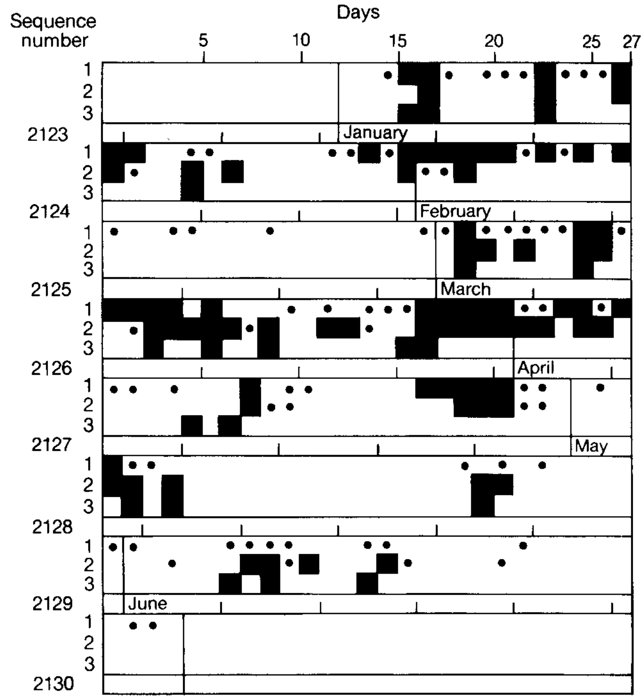


Figure 11. Bartels diagram for January to June 1989. In each sequence line 1 indicates an evening of auroral activity, line 2 is magnetic activity (K_p index averaged five or more for any 3-hour period in 24 hours) and line 3 indicates dates of sudden storm commencement. Dots denote weak activity and solid squares denote strong activity.

result of the atmospheric ionization and electrical ground potentials generated. The aurora can blot out HF radio communications but on the other hand can be used to increase the transmission path for VHF radio, a technique commonly used by amateur operators. Ground potentials can induce overloads in electricity transmission lines and on 13/14 March 1989 sections of Quebec Hydro in Canada were without electricity as the circuit breakers responded to excessive currents. New York was blacked out by the same process in 1969 and 1972. Auroral potentials can also induce electrical currents in long distance conduits such as the Alaska oil pipeline with the possibility of reversing polarity in the anti-corrosion protection systems. Magnetic surveys for mineral prospecting and other purposes, including oilwell drilling instruments, can be disrupted by magnetic activity.

The forecasting of magnetic and ionospheric disturbances is carried out by various institutions such as the National Oceanic and Atmospheric Administration in Boulder, USA, which issues weekly a bulletin *Preliminary report and forecast of solar-geophysical activity.* Information can also be provided by teleprinter and by radio. The work involves observing the Sun and assessing solar activity as it develops and then estimating the next move in the poker game, rather like weather forecasting, but with the Sun holding the aces and jokers to surprise us. Forecasting can also be based upon the plotting of past geomagnetic and auroral activity as on a Bartels diagram and looking for the repetitive patterns. An example for the first half of 1989 is shown in Fig. 11. Short-range forecasting is possible from the behaviour of magnetometers and by listening for radio aurora conditions. Radio waves from the sun may also be monitored. However, experience shows that correlation with aurora may not be high while the geomagnetic latitude of the observer comes into play.

The Aurora Section of the British Astronomical Association (of which the author is the Director) acts as a collecting centre for auroral observations, and summaries of auroral and geomagnetic activity are included in the Association's bi-monthly journal.

The story of the aurora is not yet concluded and is subject to updating and rewriting. What causes the electrons to accelerate during a substorm is not completely understood while recent research is tending to alter the earlier view that solar flares were the direct cause of the high-speed particle streams of the great magnetic storms. Although artificial Earth satellites have almost taken over from ground-based observations in the surveillance of the aurora, further studies are being planned to enable satellites to unravel the complex structures of magnetic and electric fields associated with the aurora.

In spite of the technology of modern science, the aurora remains one of the most beautiful and awe inspiring of nature's phenomena, to be enjoyed on a clear dark night in open country away from the lights of civilization.

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Estimating grass minimum temperature and probability of ground frost at Eelde (Netherlands)

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Summary

Forecasts of ground frost have been issued for many years in The Netherlands; a practical forecasting tool, however, was not available for the forecaster on the bench. In this study a set of forecasting diagrams is given for use at Eelde airport, situated in the north-east of the country; separate diagrams are constructed for use in April/May and October/November. The probability of ground frost at Eelde can be estimated from the tables given in this paper. Given the appropriate data, similar tables could be constructed for use at other sites.

1. The data

The data used are observations of wind speed and total cloud amount at 03 UTC, state of ground at 06 UTC and minimum temperature and grass minimum temperature both observed in the period 00–06 UTC. Eelde (WMO number 06280, ICAO letter code EHGG, 35° 08′N, 06° 35′E, station height 4 m) was chosen because it is in an area where ground frost often damages crops. The observations were taken in April, May, October and November of the years 1983 to 1988 inclusive; this selection was made because in these months the most damage is done to growing fruit and potato plants (spring) and harvested sugar beet (autumn). Only the period 00–06 UTC was studied, as this is the most important part of the night for the occurrence of ground frost. Wind speed and cloud amount at 03 UTC were taken as estimates of the mean value during the second part of the period. Unfortunately the amount of low cloud only was not available, so total cloud cover was used; for the forecaster this is an advantage, because the method used in determining the screen minimum temperature (Roodenburg 1983) needs the same predictors. The total number of cases was 732; there were 76 (roughly 10%) nights with air frost and 145 (roughly 20%) nights with ground frost. These numbers are small when compared with the climatological mean for 1951–80 for days with air frost and for 1971–80 for days with ground frost (see Table I). The anomalies are probably a symptom of the relatively high mean surface temperatures in the 1980s observed in The Netherlands as well as in many other places.

2. Grass minimum depression

The parameter under examination was the grass minimum depression, rather than the actual grass minimum temperature itself. The grass minimum depression is the departure of grass minimum temperature from screen minimum temperature; it depends on wind speed, cloud amount (Steele *et al.* 1969), state and properties of the soil (Lawrence 1960), and during winter possibly also on the value of the minimum temperature (Saunders 1952).

In accordance with Steele *et al.* (1969), the grass minimum depression was determined from the data as a function of cloud amount and geostrophic wind speed. As in their study, three categories of cloudiness have been distinguished: little or no cloud (0–2 oktas), cloudy (6–8 oktas) and an intermediate category (3–5 oktas). However, instead of geostrophic wind, the actual wind speed has been used, as geostrophic wind and actual wind might be only weakly related in cases with highest probability of (ground) frost. Four wind speed categories were defined: Beaufort force 0 and 1, 2, 3, and 4 or more; amounting to a total number of 12 weather categories. The results (not shown here, see Floor 1989) were subjected to a statistical test (Student's *t*-test); weather categories that did not show significantly different results were taken together as one new category. This happened to be the case for weather categories with 0–2 oktas and 3–5 oktas of cloud, regardless of wind speed and for the weather categories with 6–8 oktas of cloud and wind speeds of Beaufort force 3, and 4 or more. For the situation most prone to ground frost — little or no cloud and low wind speeds — the importance of the state of the ground was examined; dry soil showed grass minimum depressions that are 1 °C lower than moist or wet soils, the difference being significant at the 0.1% level. The definitive results for the 24 months that have been investigated are shown in Table II.

3. Grass minimum depression in spring and autumn

When Table II was constructed, no distinction was made between different seasons. However, Saunders (1952) found higher values for grass minimum depression in summer than in winter (air temperatures near or slightly below 0 °C). Steele *et al.* (1969) also mention that there is evidence that grass minimum depressions on radiation nights are greater in spring and summer

Table I. Average number of days per year with air frost or ground frost at Eelde for the months and periods shown

Month	1951–80 Air frost	1971–80 Ground frost	1983–1988 Air frost	1983–1988 Ground frost
April/May	7	21	5.5	12.7
October/November	9	18	7.2	11.5
Total	16	39	12.7	24.2

Table II. Grass minimum depression (°C) at Eelde for April/May and October/November combined, for 1983–88

Oktas	Soil	Beaufort force	Number of nights	Grass minimum depression	Standard deviation
0–5	dry	0, 1	37	3.69	1.18
	moist		50	2.67	1.35
		2	114	1.99	1.21
		3	93	1.13	0.57
		>3	34	0.86	0.44
6–8		0, 1	62	1.41	1.52
		2	102	0.83	1.04
		>2	240	0.55	0.52

than in autumn and winter. Therefore the data have been split up into April/May data and October/November data. The results show a mean value in April/May that was 0.6 °C higher than in October/November, the difference being significant at the 0.1% level. The reason for the difference probably is the continuously wet grass in the winter time, counteracting the cooling of the soil and the nearby air. Soil temperatures of Eelde are not available; values for De Bilt (WMO number 06260, 52° 06′N, 05° 11′E, station height 2 m) were looked at instead. These soil temperatures (September 1962–August 1972) are higher on average in April/May (8.7 and 13.0 °C respectively) than in October/November (11.8 and 7.1 °C respectively) (Van der Hoeven 1974); consequently the observed difference in grass minimum depression cannot be explained in this way. The seasonal difference found made necessary the construction of new Tables III and IV, like Table II but valid for April/May or for October/November only. As was the case with the construction of Table II, weather categories in Tables III and IV that did not depart significantly from another category were taken together as one new category. Distinction between dry and moist soil is not meaningful in autumn; the number of wind categories can be reduced in most cases.

4. A simple forecasting tool

From the results, given in Tables III and IV, diagrams have been constructed for use by the forecaster on the bench (Tables V and VI). Given the expected amount of cloud and the expected wind speed, the grass minimum depression can be taken from the appropriate diagram. The difference between grass minimum depressions in situations with a wind speed of Beaufort force 3 and greater than 3 with 0–6 oktas of cloud in October and November was significant, but nevertheless too small to be of practical use; therefore all cases with a Beaufort force of 2 or more have been taken together. The forecaster not only wants to obtain a spot value, but also the interval between the extreme values that have occurred in analogous weather situations; these are taken from the data set and shown in Tables VII and VIII.

5. Probability of ground frost at Eelde

The data used for the construction of the forecasting tool for grass minimum depression, consisting of Tables V to VIII, can also be used for estimating the probability of ground frost. Table IX provides the probability of ground frost for April/May, given an observed minimum temperature. A similar table, valid for October/November, is not given here but shown in Floor (1989). The table can be rewritten, taking into account the error in the forecast value of the minimum temperature. Steele *et al.* (1969) elaborate such a case for a minimum temperature forecast with a systematic error of −0.3 °C and a standard deviation of 1.89 °C. Using these values and their method, the same was done for the Eelde data; the results are shown as Table X for April/May and give more realistic values for the

Table III. Grass minimum depression (°C) at Eelde for April/May, for 1983–88

Oktas	Soil	Beaufort force	Number of nights	Grass minimum depression	Standard deviation
0–5	dry	0, 1	26	4.03	1.09
	moist		28	2.94	1.49
		2	58	2.38	1.34
		>2	67	1.13	0.62
6–8		0, 1	33	1.83	1.64
		2	55	1.16	1.25
		>2	99	0.56	0.56
	All cases		366	1.58	1.48

Table IV. Grass minimum depression (°C) at Eelde for October/November, for 1983–88

Oktas	Beaufort force	Number of nights	Grass minimum depression	Standard deviation
0–5	0, 1	33	2.52	1.05
	2	56	1.58	0.89
	3	40	1.06	0.46
	>3	20	0.81	0.39
6–8	0, 1	29	0.94	1.20
	>1	188	0.52	0.48
All cases		366	0.97	0.93

Table V. Forecasting diagram for grass minimum depression (°C) at Eelde for April/May

Cloud amount		Wind speed (Beaufort force) <2	2	>2
0–5 oktas	dry soil	4	2.5	1
	wet soil	3		
6–8 oktas		2	1	0.5

Table VI. Forecasting diagram for grass minimum depression (°C) at Eelde for October/November

Cloud amount	Wind speed (Beaufort force) <2	2	>2
0–5 oktas	2.5	1.5	1
6–8 oktas	1	0.5	0.5

Table VII. Extreme values of grass minimum depression (°C) at Eelde for April/May

Cloud amount		Wind speed (Beaufort force) <2	2	>2
0–5 oktas	dry soil	1.9/6.0	−1.0/5.7	0.0/4.0
	wet soil	0.8/6.0		
6–8 oktas		−0.3/5.2	−0.4/5.2	−0.2/3.7

Table VIII. Extreme values of grass minimum depression (°C) at Eelde for October/November

Cloud amount	Wind speed (Beaufort force) <2	2	>2
0–5 oktas	0.0/4.5	0.0/4.2	0.1/2.5
6–8 oktas	−0.2/5.2	−0.6/2.4	

Table IX. Probability (%) of ground frost at Eelde as a function of observed minimum temperature and weather situation

Cloud amount (*oktas*)	Beaufort force	Soil	Forecast minimum (°C) 0	1	2	3	4	5	6
0–5	<2	dry	100	100	100	88	77	35	11
		moist	100	100	79	64	38	14	7
	2		98	94	70	48	20	6	1
	>2		100	97	13	3	3	—	—
6–8	<2		100	79	42	27	18	12	—
	2		100	43	7	3	1	—	—
	>2		100	73	27	15	7	2	—

Table X. Estimated probability (%) of ground frost at Eelde as a function of forecast minimum temperature and weather situation for April/May

Cloud amount (*oktas*)	Beaufort force	Soil	Forecast minimum temperature (°C) −4	−3	−2	−1	0	1	2	3	4	5	6	7	8	9
0–5	<2	dry	100	100	>99	99	97	93	85	72	56	38	22	11	5	2
		moist	100	>99	99	96	91	82	69	53	37	23	12	6	2	1
	2		100	99	98	94	86	75	59	42	27	15	7	3	1	—
	>2		100	98	96	88	75	57	37	20	9	4	1	—	—	—
6–8	<2		100	98	95	89	78	63	47	33	21	12	6	3	1	—
	2		99	97	91	80	64	44	26	13	6	2	1	—	—	—
	>2		100	98	94	87	74	56	39	23	13	6	3	1	—	—

Table XI. Estimated probability (%) of ground frost at Eelde as a function of forecast minimum temperature and weather situation for October/November

Cloud amount (*oktas*)	Beaufort force	Forecast minimum temperature (°C) −4	−3	−2	−1	0	1	2	3	4	5	6	7	8	9
0–5	<2	100	>99	98	95	89	78	62	44	28	15	7	3	1	—
	2	100	99	97	91	81	65	46	28	15	7	2	1	—	—
	>2	>99	98	95	88	74	56	36	19	8	3	1	—	—	—
6–8	<2	99	97	93	83	69	50	33	19	10	5	2	1	—	—
	>1	99	97	92	81	64	45	26	13	5	2	—	—	—	—

probability of ground frost than Table IX. Table XI contains realistic estimates for the probability of ground frost in October/November. As in Table X the values for the forecast screen minimum temperature are shown in the top line.

6. Conclusion

The grass minimum depression in spring is different from that in autumn, therefore different diagrams have been constructed for April/May and for October/November, to be used in forecasting the grass minimum depression, at Eelde, starting from the forecast screen minimum temperature and weather type. Separate diagrams show the extreme values taken by the grass minimum depression in the period examined. Using the available data and following a method described by Steele *et al.* (1969) tables are presented that give a realistic estimate for the probability of ground frost.

Acknowledgements

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The winter of 1988/89 in the United Kingdom

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Summary

The winter appears to have been the rare combination of the mildest and driest in England and Wales during the last 260 years while in Scotland it was the mildest winter since 1932/33; although very wet in western areas of Scotland, it was exceptionally dry in some parts of eastern Scotland.

1. The winter as a whole

Mean temperatures were over 2 °C above normal in most parts of the United Kingdom and over parts of northern England and southern and eastern Scotland they were 3 °C above normal. The mean temperature in central England, 6.6 °C, made it the warmest winter since records began in 1659. In Scotland, December and January combined were the mildest on record. At Braemar, Grampian Region the departure from average of +4.0 °C may be compared with the previous highest value of +3.2 °C recorded in 1857/58.

After a generally dry December and a dry January except in Scotland, followed by rainfall amounts just above normal over England and Wales but well above normal over Scotland during February, seasonal amounts were well below normal in England, Wales and eastern Scotland but well above normal in western Scotland. Over England and Wales general rainfall for the period November 1988–January 1989 was 136 mm (50% of average), the driest November–January period since 1879. From the general values for England and Wales, 197 mm was recorded between November 1988 and February 1989 inclusive. This is the second driest November–February period this century, only November 1933 to February 1934 having been drier with only 175 mm.

Sunshine totals were above average for most of the United Kingdom, apart from western and extreme northern parts of Scotland where the amount of sunshine was below normal.

Information about the temperature, rainfall and sunshine during the period from December 1988 to February 1989 is given in Table I and Fig. 1.

2. The individual months

December. Mean monthly temperatures were well above normal everywhere in the United Kingdom ranging from 1.6 °C above normal at Lerwick, Shetland to 3.7 °C above normal at Lyneham, Wiltshire. Hampstead and Northwood, Greater London reported the mildest December since 1974. Halesowen, West Midlands reported the second warmest December in 33 years of record, bettered only by 1974; Lyonshall, Hereford and Worcester also reported the mildest since 1974. At Sheffield, Weston Park, South Yorkshire it was as mild as December 1934 in a record going back to 1882. Many places had a frost-free December, including Sheffield, where the last frost-free December occurred in 1972.

Monthly rainfall totals were well below normal everywhere except western Scotland, where 147% of average was reached at Kinlochewe, Highland Region, and a few places in North Wales and north-west England. The east coast of Scotland was very dry, with as little as 15% at Montrose, Tayside Region. In general

Table I. District values for the period December 1988–February 1989, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+2.4	+4	202	87
Eastern Scotland	+3.0	−2	101	117
Eastern and north-east England	+2.9	−5	68	134
East Anglia	+2.2	−4	66	128
Midland counties	+2.7	−4	68	132
South-east and central southern England	+2.5	−3	64	117
Western Scotland	+2.8	+3	149	81
North-west England and North Wales	+2.7	−1	108	109
South-west England and South Wales	+2.3	−2	83	99
Northern Ireland	+2.4	+2	95	105
Scotland	+2.7	+2	162	95
England and Wales	+2.5	−3	80	120

Highest maximum: 15.5 °C in eastern Scotland in December.
Lowest minimum: −10.6 °C in western Scotland in February.

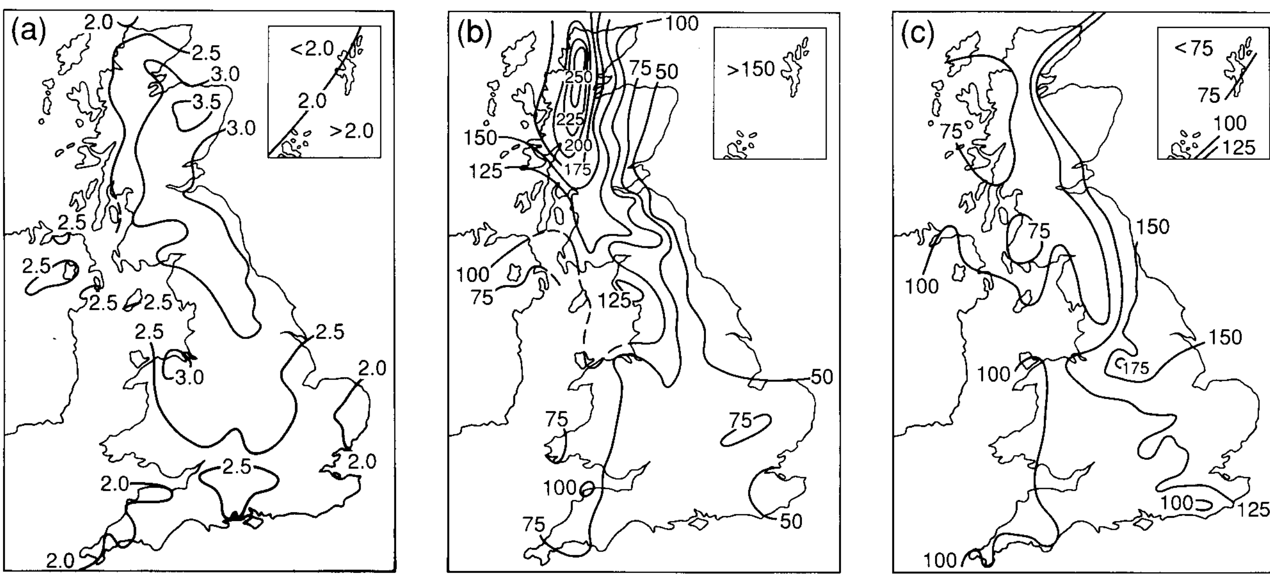

Figure 1. Values of (a) mean temperature difference (°C), (b) rainfall percentage and (c) sunshine percentage for winter, 1988/89 (December–February) relative to 1951–80 averages.

most of the month's rain fell in the first 5 days. Much of the Thames Valley, and the area just south of it, received less than 4 mm of rain after the 4th, including Benson, Oxfordshire 2.2 mm and Heathrow, Greater London 2.8 mm. Exeter, Devon had only 3.3 mm after the 5th. Hampstead reported the driest December since 1933, Lyonshall the driest since before 1947 and Northwood the driest for 30 years. Sheffield, Weston Park, had the driest December since 1971. After the 18th several places in the north had heavy falls; on the 26th Bidston, Merseyside reported very heavy rain between 1715 and 2225 UTC, with some roads in the area being flooded.

Monthly sunshine totals were kept below average in many places by persistent cloud with less than half the average in Orkney, however, sunshine was well above average in eastern areas of England and Scotland and in parts of the west Highlands, reaching more than 150% of average on the east coast. Bradford, West Yorkshire reported the sunniest December on record with 47 hours — the previous record was in 1926 (46 hours).

January. Mean monthly temperatures were well above normal everywhere ranging from just under 2 °C above normal at some places in southern England to just over 5 °C above normal in northern Scotland.

In western Scotland it was one of the wettest Januarys on record: the persistence of moist south-westerly winds created strong contrasts in rainfall across Scotland, with up to three times the average over the western Highlands and less than 10% of normal near Aberdeen. In Glen Shiel, on the road to Kyle of Lochalsh, one gauge recorded 855 mm while, in contrast, at Insch, north-west of Aberdeen, only 6 mm was recorded. At Cape Wrath, Highland Region it was the wettest January since records began there in 1941 while at Craibstone, Grampian Region it was the driest since observations started in 1925. January 1989 was the third successive month to have only about 50% of average rainfall over England and Wales, although the month itself was not exceptionally dry, January 1987 having been drier. Bradford had the driest January since 1953 and Ashover, Derbyshire the driest since records began in 1966.

Monthly sunshine totals were above normal nearly everywhere and ranged from almost half the normal in south-west Scotland to nearly twice the average in north-east Scotland. However, in western Scotland it was very dull. Wick reported its sunniest January since 1946. Bradford, West Yorkshire had the sunniest January on record.

February. Mean monthly temperatures were above normal everywhere, ranging from 3 °C above normal at Lyneham, Wiltshire and Bramham, West Yorkshire to just over 0.5 °C at Cape Wrath. Ashover reported its highest minimum temperature since records began there in 1967, 9.5 °C, and the warmest February on record, with a mean of 5.1 °C. Hampstead reported the highest mean temperature since 1966 and the highest mean maximum temperature, equal with that of 1961.

Monthly rainfall amounts were above normal nearly everywhere west of a line from Banff, Grampian Region to Beachy Head, East Sussex reaching as much as 450% of normal in the vicinity of Fort Augustus, Highland Region. In contrast, parts of Lincolnshire had less than 50% of normal rainfall. The 5th and 6th were days of contrasting weather in Scotland, when the easternmost parts of Scotland had little or no rain, while the rest of Scotland had a large amount of rain, heavy in places. As a result of the very wet January, rivers, lochs and reservoirs were already full to overflowing when exceptionally heavy rainfall occurred on 4 and 5 February. Over the western Highlands rainfall was torrential and prolonged on both days, causing flooding and landslides. Bridges, roads, housing estates and farmland were affected over a wide area and the 127-year old railway bridge over the River Ness at Inverness was swept away by flood-water on the 7th. The 2-day total of 215 mm (83.7 mm on the 5th and 131.7 mm on the 6th) at Fort William has an estimated return period of several hundred years, as does the 5-day total of 299 mm measured from the 2nd to 6th.

Monthly sunshine amounts were above average nearly everywhere and reached almost twice the average at Tynemouth, Tyne and Wear; the exception was the western side of Scotland where it was rather dull and the percentage of average was as little as 75% at Eskdalemuir, Dumfries and Galloway. Bradford had the sunniest February on record at the station.

At Fraserburgh, Grampian Region the mean wind speed increased very rapidly on the 13th from 15 kn at 1730 UTC to 60 kn at 1900 UTC as the wind direction veered from south-westerly to north-westerly, a record gust for a low-level station of 123 kn was measured; the hourly mean speed was 66 kn. The high winds disrupted traffic, brought down trees as far south as Leicestershire and North Wales, and toppled buses and high-sided lorries. In Dunfermline nine people were injured when the roof of a hospital ward was blown off.

Notes and news

The Meteorological Office to become an Executive Agency

Recently, the Director-General of the Meteorological Office, Dr J.T. Houghton, announced that the Office will be an Executive Agency within the Ministry of Defence, as from April 1990. In a letter to Office staff he stressed that in many ways there will be no change to the Office's functions; it will continue as the State Meteorological Service to meet the needs of defence, civil aviation and the general public. However, the Executive Agency status proposed will give the Office greater autonomy over its manpower and financial resources, and will thus be able to work more efficiently, to react to circumstances more quickly and, in particular, benefit from commercial opportunities.

To oversee the new Agency, the Director-General will become the Chief Executive leading a Management Team consisting of Directors of Operations, Research, Finance and Administration, and Commercial Services. Changes to the structure of the Office in the lower echelons are also envisaged to enable it to meet its new challenges most effectively.

Dr P. Ryder promoted to Director of Services

Following the move of Dr David Axford to Geneva, Dr Peter Ryder has been promoted into the post of Director of Services of the Meteorological Office.

Prior to this move, Dr Ryder occupied the posts of Deputy Director in charge of Forecasting Services and Observational Services, previously having been Assistant Director in charge of the Cloud Physics and Systems Development Branches.

The European Geophysical Society 15th General Assembly

The programme for the next General Assembly of the European Geophysical Society (EGS), to be held from 23 to 27 April 1990 in Copenhagen, is now available.

The following open sessions, workshops and symposia are on topics of interest to atmospheric physicists and climatologists.

Open sessions

Hydrology.
Meteorology and climatology.
Ocean circulation and the heat budget.
Dynamics and chemistry of the middle and upper atmosphere.
Origin and evolution of planets, atmospheres and hydrospheres.

Workshops

Scientific results of the European frontal experiments.
Usage and application of the ECMWF atmospheric general circulation model.
Physical, chemical and biological processes in the atmospheric boundary layer.
Recent campaigns on polar ozone.

Symposia

Measurement, modelling and forecasting of rainfall in space and time.
Land surface–atmospheric processes.
Verification of numerical prediction of atmospheric variables, processes and circulation.
Modelling and observation of the global thermal energy and water cycle of the atmosphere.
Polar meteorology.
Wind-generated sea-surface waves.
The global change programme: the European potential (including panel discussion on 'different scientific points of view on global change').
Chaos, turbulence and long-term predictability in geophysics.

In addition there will be Society lectures on inversion theory in geophysics, and ice and climate.

The deadline for the receipt of abstracts by the EGS office is 31 January 1990.

The aims and organization of the EGS and the scheme for assisting young scientists were described in Notes and News in the February 1989 edition of *Meteorological Magazine*, which also gives the address of the EGS office from which full details of the Assembly can be obtained.

The 16th and 17th General Assemblies are to be held in Wiesbaden, Federal Republic of Germany on 22–26 April 1991 and in Edinburgh, United Kingdom on 6–10 April 1992.

Japan to maintain World Data Centre for Greenhouse Gases

The World Meteorological Organization (WMO) has announced that the Japan Meteorological Agency will run the newly created World Data Centre for Greenhouse Gases. As such, the Centre will collect data from all parts of the world on the concentration of greenhouse gases in the atmosphere, particularly carbon dioxide, methane, chlorofluorocarbons and nitrous oxide. These gases affect the radiation balance of the earth's atmosphere and are predicted to bring about a major climate warming over the globe by the middle of the next century. The concentrations of these gases have been rapidly increasing in the past few decades due to human activites — especially the burning of fossil fuels.

These atmospheric trace gases are measured at a number of observation stations around the world as part of the background air-pollution monitoring component of WMO's Global Atmosphere Watch. However, no systematic collection and distribution of data on the greenhouse gas concentrations from all observing stations has been undertaken until now. The growing importance of these data for research and policy development on climate change now requires a much more formal approach.

The WMO works through its member countries to provide authoritative scientific information and advice on the world's atmosphere and climate. Several countries operate World Data Centres for other types of atmospheric and hydrological data: Canada for the ozone layer, the USA for chemistry of precipitation and atmospheric turbidity, the USSR for radiation data and the Federal Republic of Germany for river flow.

The new Centre will gradually develop over the next few months before its formal opening during 1990.

Reviews

Synoptic meteorology in China edited by Bao Cheng Lan. 188 mm × 263 mm, pp. vi+269, *illus.* Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag 1988. Price DM 128.00.

The first impressions given by this book are good. Most of us in Europe must be conscious of how little we know about Chinese meteorology, and the appearance of a well produced book with this title certainly whets the appetite. A quick first flip through the book is promising. It is a substantial volume and the contents page shows an orderly arrangement of the material in ten chapters, based largely on a climatological framework. There are chapters on the cold winter season, the rainy seasons, the typhoons and other tropical weather systems. There is also a chapter on the weather systems on the Tibetan plateau. Altogether, the menu is a most attractive one. The quoted references are dated up to about 1984 and there are a large number of satellite images in a block at the end of the book. Most of these date from the period 1978–81 and are not of very good quality, but at least one looks forward to a fairly up-to-date account.

However, as soon as one tries to penetrate the book in detail one's views swing to the opposite extreme. Three features are immediately and frustratingly obvious. One, there is no index. Two, the book is packed with detail, particularly of a minor geographical nature which neither the book itself nor other easily accessible sources do much to illuminate. Three, the translation into English is often of a poor standard.

Because it has a clear structure of chapter topics, it is easy to forget that the book is not quite what it seems. It is in fact a compilation of individual research papers, edited by Bao into a coherent framework. That framework is such that a better title for the book might have been *Synoptic climatology of China*. There is nothing wrong with the framework, but it is as well to note that this is not a textbook on synoptic meteorology as such. It does not, in general, describe the tools of the trade of a synoptic meteorologist. What it does is to show how the already well known tools are applied in China.

And herein, to a Westerner, lies one of the big disappointments of the book. There is nothing very new in it. The synoptic models and concepts that are used are the same as in other temperate and tropical latitudes. The practical techniques are strongly redolent of the age of synoptic charts and pencils, with some overtones of satellite imagery, and a faint whisper of numerical experimentation. The approach is kinematic rather than dynamic; synoptic patterns 'evolve' and 'interact', and the evolutions are catalogued in categories, and sub-categories, which would be easier to comprehend if the printed layout and titling were better. In short, it gives a picture of old-fashioned synoptic meteorology — what happens is documented with a mass of detail, but why it happens is less easy to discover.

But for those who have patience to find their bearings in the detailed text, and who have the foresight to construct their own index as they go along, there are many interesting topics to be found. Among the less familiar ideas to those of us who work in an oceanic climate are those which derive from conditions in a vast continental area. As well as air masses, fronts and upper-level troughs, cold and warm air 'shear lines' are prominent. Dew-point fronts, the equivalent to 'dry lines' in the USA, and 'low-level jets' are important. In the tropical area, typhoons are covered in detail, most of which is standard, but slightly fresh emphases are introduced by the mention of 'ventilation' and the 'prosperity period' of storms.

There is little or nothing on mesoscale weather systems, except the statement that 'they are the key to heavy-rain forecasting'. The accent of the book is almost entirely synoptic scale, or larger. Only one diagram seems to be derived from a radar display.

This is certainly a fascinating book, but it is not easy to read or use as a casual reference book. Anybody less knowledgeable than an experienced professional could be misled by some of the many printing errors even if they have the stamina to penetrate the detail of the text. Sadly, only the most committed China lover will find this a worthwhile buy.

P.G. Wickham

Solitons: an introduction, by P.G. Drazin and R.S. Johnson. 150 mm × 226 mm, pp. xii+226, *illus.* Cambridge University Press, 1989. Price £32.50, US$59.50 (hardback), £11.95, US$19.95 (paperback).

The Edinburgh to Glasgow canal was the scene in 1834 of the first recorded scientific observation of a soliton. J. Scott Russell noted the formation of a 'great wave of translation' when a barge was brought suddenly to rest (by some agency now forgotten). This solitary water wave continued in motion for some miles with little change of shape — and with Scott Russell in pursuit on horseback. The constancy of the wave's shape showed that the motion was dominated neither by linear, dispersive effects nor by non-linear transfers of energy between different spatial scales. Applied mathematicians now know that a balance between non-linear and dispersive (or dissipative) effects can occur in many systems, thus allowing the existence of isolated, coherent disturbances of which the water-wave soliton is the prototype. Soliton theory is widely considered to be one of the major achievements of applied mathematics since 1950.

Writers of review papers and books on solitons — and even reviewers of books on solitons — rarely find themselves able to omit mention of the famous Scott Russell story. In this respect this book is not exceptional. In a much more important respect, however, it is outstanding; it achieves a brief, clear and comprehensive introduction to the non-linear mathematical theory, including the difficult and wonderful technique known as the inverse scattering transform. These seemingly incompatible objectives are achieved by adept use of fairly short chapters, clear notation, numerous worked examples and a wealth of exercises for the reader. The main text and worked examples introduce the essential theory. The exercises (146 in number) take the adventurous reader much further and introduce or illustrate the more sophisticated concepts.

Most of the analysis concerns the equation which arises in the solitary water-wave problem, namely the Korteweg–de Vries equation in one spatial dimension. A dozen or so other non-linear equations are also discussed, the stimulus for their study being drawn from a wide range of problems in science and engineering.

The authors have taken great pains to ease the task of the serious reader as he tries to assimilate soliton theory. Most chapters have useful introductory summaries, and each concludes with well chosen suggestions for further reading. Italic headlines summarize the content of most of the exercises, and answers or hints are given in a separate section. The more difficult exercises and sections of text — including two whole chapters — are marked with asterisks. The text is well presented, misprints are few (three detected during review!) and there is a good index. A comprehensive bibliography is supplemented by a list of motion pictures of solitons.

The book is one of a new series 'Cambridge texts in applied mathematics', edited by H. Aref and D.G. Crighton. It will be of particular interest to students of applied mathematics, and there are good reasons why it should appeal to many meteorologists too. The theory of solitons is of sufficient general scientific importance to prompt interest, and soliton solutions exist in many limiting cases of equations which arise in meteorological contexts. Also, the book contains several lucid summaries of various mathematical concepts and techniques which are of wide application: elementary wave theory, elliptic functions, Lie groups, similarity theory, solutions of Schrödinger's equation, discrete and continuous spectra, movable singularities and critical points, Noether's theorem, Fréchet derivatives and Bäcklund transformations.

Solitons: an introduction is a splendid book. In less skilled hands it could have grown to at least twice its present length and have become dauntingly esoteric. As it is, the clear notation and concise presentation enable the reader to follow the basic arguments easily and to believe that even the asterisked sections would be understandable with reasonable effort!

A.A. White

Glacier fluctuations and climatic change,

edited by J. Oerlemans. 163 mm × 246 mm, pp. ix+417, *illus.* Dordrecht, Boston, London, Kluwer Academic Publishers, 1989. Price Dfl.195.00, US$109.00, £64.00.

In 1890 Prince Roland Bonaparte attempted, vainly as it turned out, to initiate a programme of regular measurement of French glaciers with a view to identifying links with meteorological conditions, and so deducing a law. International monitoring of glacier fluctuations began 4 years later and gradually gathered momentum, expanding out of Europe and, especially in the last few decades, increasing in accuracy and sophistication. The quantity and quality of data now available make identification of the complex interrelations between glacial and climatic changes a much more possible objective than it was a century ago, but it is still necessary for modellers and those primarily concerned with field investigations to understand each other's problems and preoccupations, which are not always identical.

This book is the outcome of a meeting on 'Glacier Fluctuations and Climatic Change' held in Amsterdam in June 1987, and is one of a series on glaciology and Quaternary geology. The location was perhaps not altogether fortuitous, The Netherlands being acutely aware of the possible effects of global warming, especially on sea level. Significantly, the meeting was supported by the Dutch Ministry of Housing, Physical Planning and the Environment. Its purpose was to bring together scientists from a wide range of backgrounds and disciplines concerned with the history, scale, measurement and meteorological controls of glacier fluctuations. Active engagement of this sort is a necessary prerequisite to the attainment of the more satisfactory level of understanding which is required in order to make sensible forecasts.

The very heterogeneous papers in this volume have been arranged so that those dealing with the more distant past, Palaeozoic glaciations in South Africa, Quaternary history in East Africa and Holocene glaciation in Iceland and South Georgia, preface a useful account of the development and extent of the present international database. Attention then turns to matters such as the practical problems of glacier inventory and mass-balance measurement in remote areas of North America and Greenland. An overview of historic fluctuations in Scandinavia and a cautionary discussion of evidence about the decline of the Little Ice Age in the Himalayas, accounts of the variations of the Rio Plomo glaciers in the Andes and of characteristics of plateau glaciers in arctic Norway, together provide evidence of the care needed in order to obtain reliable chronologies and the need to take into account the possibility of surging, the relevance of topographic controls and the effects of debris cover and avalanching. An entertaining history of nineteenth-century ice trading stands apart from the rest of the book.

The greater part of the volume is concerned with the history, measurement and explanation of mass balance, with equilibrium-line shift and its calculation, englacial temperature distribution and energy-balance calculations, and with response times. Sufficient data are available to allow an examination of relations between climate and mass balance, and between climate and runoff in the European Alps. Comparison of mass-balance histories of the Blue and South Cascade Glaciers in Washington State reveals the importance of synoptic-scale circulation patterns. As 'there is not a single meteorological parameter on any continent, which influences the surface climate of the whole continent as much as the katabatic wind does for Antarctica' the results of measurement of blowing sand in Adelie Land are an obvious choice for inclusion. Some of the most interesting papers come from studies of individual glaciers — notably the Hintereisferner, Argentière and Rhône in the Alps — where work has been under way for a relatively long time and strong groups of researchers have been attracted. Here the modellers have found sufficient basis to indicate to the field workers where more observations are needed and to test the validity of their present approaches.

The literature concerned with glacier fluctuations is now voluminous. Without an acquaintance with the subject it would be a time-consuming business to acquire any sort of overview of the present state of research. This book goes far towards meeting that need, as well as that of people who wish to extend their knowledge of a many-faceted subject. Many outstanding workers have contributed, although the quality is inevitably somewhat uneven. It was surprising to see the resurrection of an over-simple diagram of variations in equilibrium-line altitude through the Holocene, despite a reference to Karlén's work which, despite inadequate dating, has demonstrated the complexity of the Holocene climatic succession in Scandinavia. Good abstracts and very full bibliographies are provided; the supply of clear diagrams is generous. Much has already been achieved; much remains to be done. Stroeven, Van De Wal and Oerlemans conclude that 'we are not going to understand the historic glacier variations without renewed deep and careful investigation of how mass balance of glaciers is related to climatic conditions'.

J.M. Grove

Mechanisms and effects of pollutant-transfer into forests, edited by H.-W. Georgii. 161 mm × 245 mm, pp.ix+361, *illus.* Dordrecht, Boston, London, Kluwer Academic Publishers, 1989. Price Dfl.185.00, US$94.00, £61.00.

The book contains papers presented at the third Oberursel symposium in November 1988, devoted to the problem of how airborne pollutants adversely affect forests — the trees and the soil beneath. The majority of the papers have German authors, three have Dutch authors and two Austrian, reflecting the regions of western Europe with the greatest apparent damage.

The book reflects the efforts of scientists from many different disciplines to improve our understanding of the physical and chemical processes that lead to the observed damage. No single cause can be identified — more likely several components acting together are responsible. Various hypotheses exist as to how acid rain affects trees, and each may have some validity in different conditions. Five of these are:

(i) Ulrich's hypothesis in which acid rain acidifies the soil and releases toxic aluminium ions that may damage the fine roots and result in insufficient and unbalanced uptake of nutrients.

(ii) Acidification of the soil resulting in the fine-root system being confined to the upper layers of the soil, making the trees much more susceptible to periods of water stress (Eichhorn).

(iii) Acid rain leaches essential nutrients from the leaves; an effect which is increasingly probable if the stomata have been damaged by ozone and cannot open and close as efficiently as they should.

(iv) Very acid fogs cause damage to the wax coatings of the leaves and thereby lower the water-holding capacity of the trees — a result particularly serious in times of drought (Hogrebe and Mengel).

(v) Nitrates and ammonium compounds in the rain can promote excessive growth which can make the trees more susceptible to damage from other stresses like cold.

The book is subdivided into five sections: deposition into forest areas, deposition of organic compounds, case-studies (involving models, and field and laboratory techniques), investigations on fog and dew, and the effects of atmospheric pollutants on vegetation.

Some additional points of particular interest to the reviewer emerged from reading these papers. Jaenicke explains that the greater dry deposition of particulates observed within forests is due not to enhanced impaction (wind speeds are too low for this to be efficient) but to an increase in typical residence time within the trees, allowing more coagulation of particles and resulting settling. Grosch and Georgii show that at mountain stations the ionic concentrations in snow relative to those in rain ranged by factors of 1.1 to 4.5, due, it is hypothesized, to more efficient below-cloud scavenging by snow, resulting from a slower rate of descent (longer residence time) and an improved collection of ions by the filigree structure of the snowflakes. Kroll and Winkler note that deposition of pollutants on hills, due to the direct interception of wind-blown cloud droplets, is high and can be higher than that deposited by precipitation. This confirms findings in the Great Dun Fell study in England, and it is perhaps a pity that no paper from those involved in the study was given at the Oberursel meeting.

Although normally I find books presenting the proceedings of conferences rather inadequate because of their fragmented and incomplete nature, this one is an exception. By concentrating on a rather limited number of closely related topics in which a great deal of current research is taking place, a rather useful and complete picture is given. The book has been produced with commendable speed, and although type-faces vary from paper to paper, all are easily readable. At £61, it is expected that libraries, and some individuals with an interest in forestry and acid rain, will be keen to buy it, and I would encourage them to do so.

F.B. Smith

Satellite photographs — 21 October 1989 at 1200 GMT

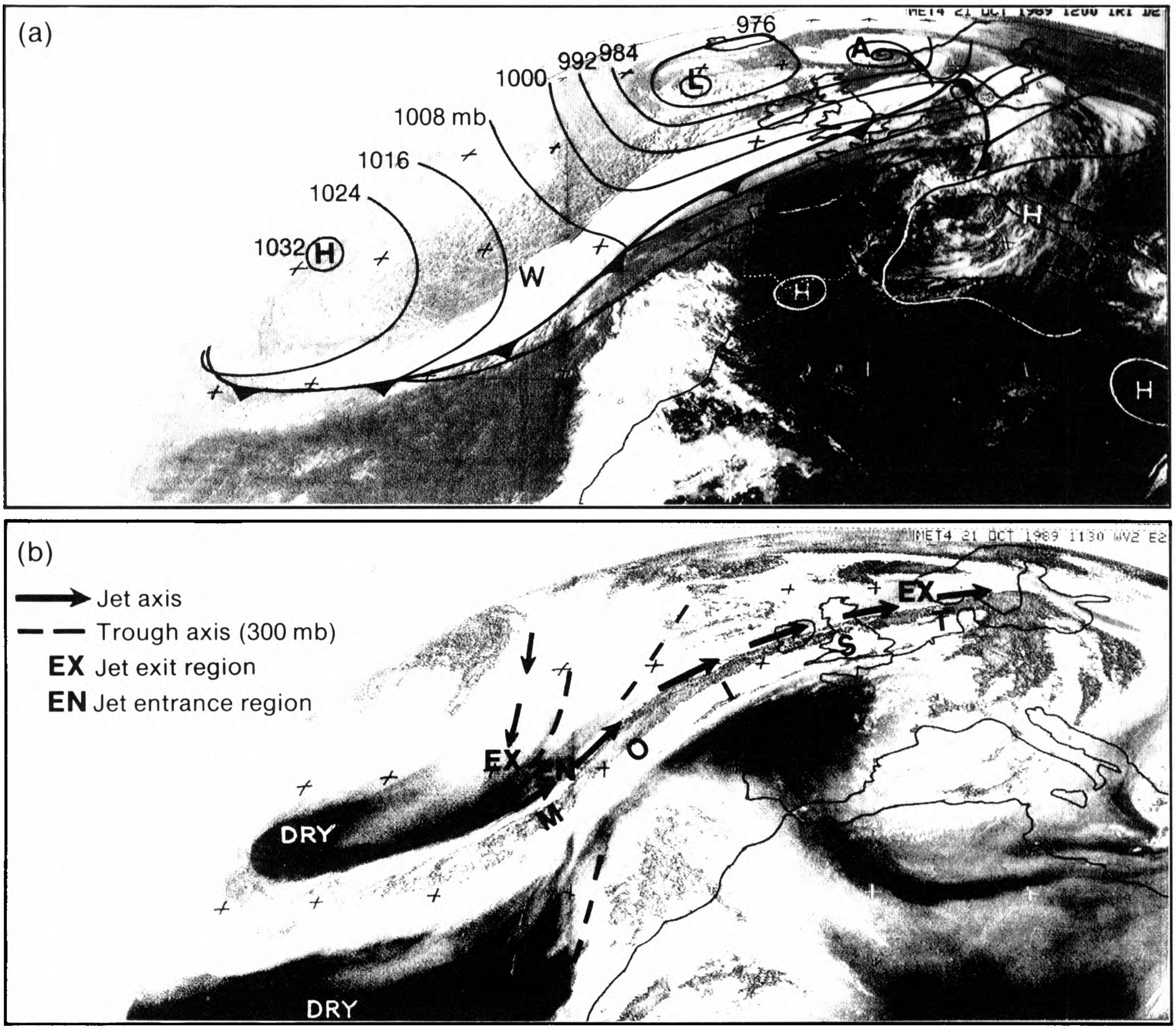

Figure 1. (a) Space-view Meteosat infra-red image with superimposed surface analysis, and (b) space-view Meteosat water vapour image with superimposed significant 300 mb features. An 'enhancement curve' has been applied so as to sharpen up the moisture boundaries. The change from black to white represents the transition from very dry to moist air in the upper troposphere. The second black to white scale within the moist region represents only very moist and saturated cloudy air (at cirrus levels). Within the latter range, the water vapour sensor acts in a similar manner to the infra-red — the whiter the shade the colder the cloud top.

The dominant feature in these infra-red and water vapour space-view Meteosat images (Fig. 1) is a distinct band of cloud and upper-tropospheric moisture associated with a classical cold front extending from western Europe to the mid-Atlantic. This band and other features on the images can be related to synoptic-scale analysis at the surface and 300 mb.

The sharp southern and northern edges of the band mark the surface cold front and jet stream respectively. (In the water vapour image, the enhancement — see figure caption — particularly highlights the rear moisture boundary.) Winds within the jet reached 190 kn at 12 GMT at Long Kesh (N. Ireland). Within its left exit is a comma-shaped cloud (labelled A on the infra-red image) depicting a vigorous depression near Scandinavia while further upstream in the entrance region, the protrusion of cloud (W) indicates possible development of a wave.

Over southern Europe and the Mediterranean, the infra-red image shows a large region of cold cloud-tops suggesting disorganized cirrus patches. However, as is frequently observed when patchy upper cloud is present, the water vapour image indicates a coherent moist envelope within which the cirrus has formed.

G.A. Monk

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'.

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