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The Meteorological Office main marine data bank

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Summary

This paper describes the development of the Meteorological Office archive of marine data. There is some discussion of the limitations of the data and a brief outline is given of the services, based upon analysis of the data in the archive, available to industry.

1. Introduction

Marine data have been collected from the birth of the Meteorological Office in the mid 1850s and indeed the Office owes its existence to concern about the effects of adverse weather on maritime operations and loss of life at sea. In this paper some idea is given of the scope of the Meteorological Office archive of marine data, the difficulties in preparing and using it, and an indication of the services available to industry as a result of its development.

The main source of data has always been observations made by deck officers during the course of their normal duties aboard merchant ships. Data are also received from light-vessels and ocean weather ships, and in more recent times from buoys, oil and gas platforms, and soon from satellites. Fig. 1 summarizes the main sources of data.

Most of the maritime nations collect and archive marine data from ships of their national merchant fleets regardless of the position of the vessel at the time the observation was made. Since the position at any time is known only by the operator, meteorologists studying particular oceanic areas used to find it difficult to discover just how many ships were in the area at any given time and, hence, how representative their own national archive might be.

In the early 1960s the National Meteorological Services of a number of countries, under the auspices of the World Meteorological Organization (WMO), nominated nine countries each of which was to be responsible for the collection and archiving of marine data from a nominated area. Fig. 2 shows the

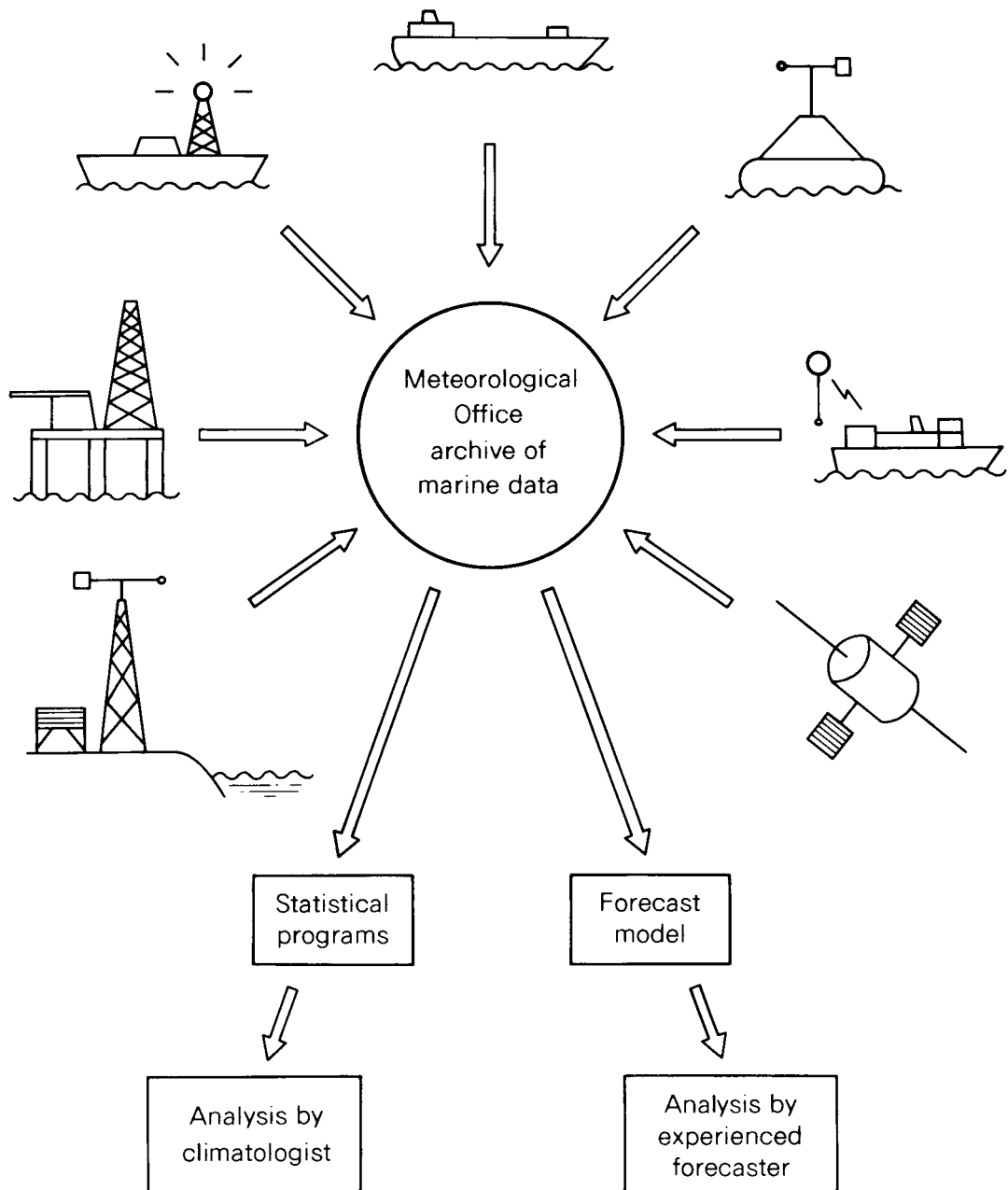


Figure 1. Schematic representation of the Meteorological Office marine data processing system.

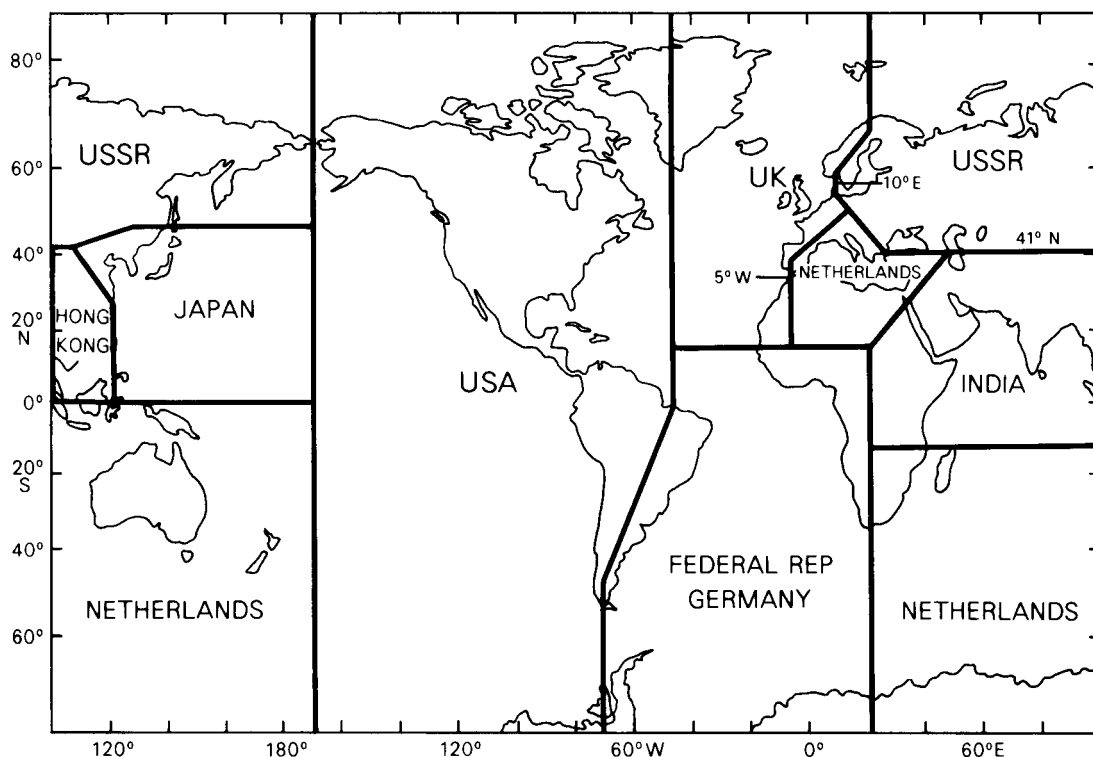


Figure 2. Areas of responsibility of eight nations acting as data centres under the provisions of WMO resolution 35.

area of responsibility of each of the eight countries remaining in the scheme. All countries send data from their ships to the collecting centre for the area in which the ship happens to be at the time the observation was made. This exercise in international co-operation is working well, aided by modern computer techniques for sorting and exchanging data. Thus, under the provisions of WMO Resolution 35, the Meteorological Office has a complete archive of marine data for the North Atlantic from 1960 to date.

2. The development of the Meteorological Office main marine data bank

Meteorological data from British ships had been keyed on punched cards before the Second World War, and the process was continued during and after the War. A major effort was made in the late 1940s to accelerate keying of historic data so that much of the contents of logbooks held in document archives was transferred to cards. Sorting and analysis of data were still relatively laborious, relying on the electro-mechanical Hollerith machine. During the 1960s some marine data were stored on magnetic tape, and computer analysis became possible, but little serious effort had been directed towards the historic data.

In 1972 the Meteorological Office purchased an IBM 360/195 computer and also set up a Systems Development Branch to produce software systems for the new machine. One of the projects allocated to the new branch was to sort and archive the historic marine data, to develop a system to deal with the data collected under the provision of WMO Resolution 35, and to merge these data with those from

other sources. At about the same time an international project to extract and archive Historic Sea Surface Temperatures (HSST) and some other marine meteorological parameters was started. The United States Climatological Data Center (Asheville) was the leading organization, largely because of its ordered data base which was considerably in advance of that held by any other centre. The timing of the project was unfortunate as it diverted effort from the main marine data bank to produce a data base (HSST) that was scientifically valuable but not of great interest to commercial operators.

At first sight it may seem a simple process to create a data bank from data already on punched cards. The reality was very different; the cards had been produced with little quality control and without regard to coding changes and so it was necessary to produce programs to cope with each different code form and hybrids which worked on mixed codes. Hybrids were necessary because mariners often did not change codes on the agreed date and sometimes the change-over was spread over a year or two.

Many other problems were found and solved: for example some ships timed observations by GMT, others by local time, and some even by ship's watches. The whole process was complicated by the amount of data, estimated at about 40 million individual observations. This total included a global collection of data purchased from the United States Climatological Center in the late 1960s and known as TDF 11 after the tape shelf number used for storage in Asheville. Historic German data acquired in 1945 were also added. One difficulty in merging data from a number of different sources is avoidance of duplication, so software had to be developed to identify and remove duplicate observations.

The data bank has been designed for direct access. This means, in principle, that data for a given location and time can be extracted directly, by use of comprehensive indexes, thus avoiding a sequential search. In this respect it is more advanced than some other archives which use sequential storage on magnetic tape with a separate record of what is contained on each tape. At present, however, the Meteorological Office archive is also in advance of technology, because direct access devices of the mass storage type, which have sufficient capacity to accommodate the entire meteorological data archive (Shearman 1980), are not yet available. Thus the data are still stored on magnetic tapes, limiting the speed of access. Transfer of the data bank to an appropriate mass storage system, when available, should be relatively easy without reformatting.

The final stage of development of the data bank has depended upon further international co-operation. Exchange agreements have been made with the United States, Netherlands and the Federal Republic of Germany so that all available data for their respective areas of responsibility can be added to the data bank. Arrangements have also been made to purchase the Hong Kong collection. Fig. 3 shows the current status of the main marine data bank.

3. Quality control of data

Data cannot be used with confidence unless information is available regarding their quality. Clearly it was impossible to rely upon a manual scrutiny of the vast amount of marine data to be processed, and so a computer-based quality-control system was developed. The computer programs were designed to be used on historical data and also to process future British and foreign data. Historic data originating before 1960 were quality controlled entirely automatically, while data after 1960 were also subjected to some manual verification. The historic data received only 'second-stage' quality control whereas contemporary data are subjected to a two-stage computer check. There is an initial brief scrutiny of the manuscript logbook when it is received to identify obvious coding errors followed by the first stage of computer checking which consists mainly of fairly crude range checks and is designed to screen keying and other gross errors. The second stage checks the internal consistency of each observation and also carries out some more detailed range checking using background fields of air and sea temperature. After each stage the suspect data are either rejected or manually amended. During second-stage

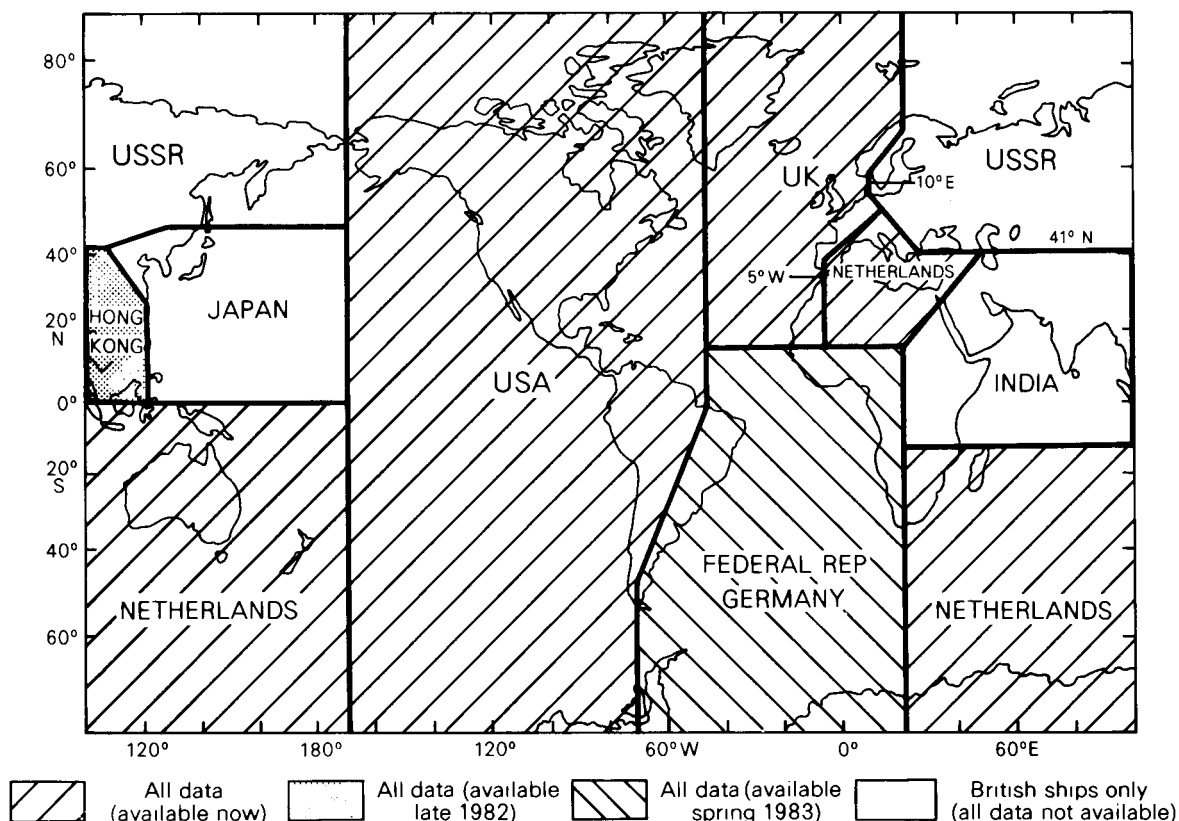


Figure 3. Status of the Meteorological Office global archive of marine data.

quality control the reason for any change that has been made is stored, together with the original data, in a separate, but cross referenced, quality control data set. This technique ensures that original data are never lost and may be restored if necessary.

Data from other countries are processed in the same way, except for the initial logbook scrutiny which cannot be made. Areal quality control, based on comparisons with surrounding observations and widely practised with land data, is not attempted because the observing network is in a state of flux as ships move between ports. Thus the selection of known reliable 'neighbouring' observations is almost impossible, though it would be possible to use analysis techniques from the numerical modelling schemes to perform some areal checking. However, such methods are based upon pressure fields so that the related wind checking is relatively coarse and aimed at achieving a comparatively smooth field. Similar checks are available for temperatures. It is unlikely that such methods would be any more effective than those based on range checking with background fields. If they were made more rigorous, the data could be too heavily smoothed; legitimate climatic extremes could then be lost. The quality-control routines are used on data from merchant ships, light-vessels and ocean weather ships because all these constituent data sets of the main marine data bank are designed to the same format specification. The only exception is the data from oil and gas platforms; these data are stored in the same format, but lack the detailed present-weather code essential for the quality control.

4. Accuracy of data

The data from merchant ships are based largely on visual estimates, although there is a strong preference for instrumental data in some quarters on the grounds that these must be better than mere estimates. There are a number of sources of instrumental data at present, mainly ocean and other weather ships, light-vessels, oil platforms and buoys. The physical parameters most considered are probably those relating to wind and waves. The Meteorological Office marine climatology group has made a comparison of visual and instrumental data, examining closely instrumental data as part of that study (Graham 1981). Such data are only as good as the exposure and observing practice associated with them. On weather ships the anemometer is mounted on a yard-arm 20 metres above the sea and is subject to a series of impulses as the ship rolls and pitches. The reported winds are spot values taken from a dial gauge, supposedly averaged, by eye, over 15 seconds. The effective height of the anemometer is unknown because it depends upon the state of the sea and the ship's motion.

Winds are measured on light-vessels by using hand-held anemometers and the exposure is entirely dependent on the location and stance of the observer. Although winds are nominally one-minute averages, it is much more likely that they are closer to 15 second spot winds. The least satisfactory collection of wind data comes from oil and gas platforms because exposure is always a compromise, and often poor, because of the nature of these large and complex structures. The anemometer height is often 50 metres to 100 metres above sea level and it is rarely clear whether attempts have been made to reduce winds to sea level using a simple formula or, indeed, what period has been used for wind averaging.

Such data are usually adequate for synoptic forecasting purposes, despite their shortcomings, because the mainstay of the synoptic analysis is the pressure field; wind observations give additional information to the forecaster and are considered in the context of the general synoptic situation. This is analogous to the position over land where winds are greatly affected by frictional and other effects to produce turbulence. Wind measurements to be used for climatological purposes need to be consistent and should 'stand alone'. Visual observations of wind speed are made primarily from state of sea and, hence, are effectively at sea level. They are equivalent to winds averaged over a period of about one hour, because the response time of the sea is equal to or greater than an hour. Therefore, they form an internally self-consistent body of data. The Meteorological Office study does not reveal any evidence that measured data currently available are any better than visual data. Data from the DB 1 buoy are an exception to this finding. However, the record is so short that it is not acceptable for most climatological purposes.

Visual estimates of wave heights and wave periods are not as reliable as reports of wind speeds; the subjective apportionment into wind wave and swell wave is often dubious and, for climatological purposes, it is preferable to combine the components to give a resultant wave height unless there is a very good reason to isolate one particular component. There is a large body of visual wave data and a reasonable wave climatology can be obtained despite the wide scatter of values and the existence of erroneous estimates. However, estimation of extreme waves is probably best done from the wind field because, on average, three times as many ships report winds as waves, and the effect of erroneous or outlying wave heights upon an extreme value analysis can be disproportionate. In passing it should be noted that the separation of waves into wind and swell components, and sometimes even the reporting of more than one wave train, is of value synoptically. This is another example of the forecaster being able to use data of a lower quality than is acceptable for climatological purposes.

The visual estimate of wave heights remains the only way of obtaining a satisfactory wave climatology because there are very few instrumental records of a suitable length within the continental shelf area. There are records from wave recorders on light-vessels, notably that at Seven Stones, but

such recorders are not considered reliable for the entire period between vessel refits. Thus the Seven Stones record reduces from 20 years on site to about 10 years of reliable record.

5. The importance of wind averaging times

Several references have been made to the time period used for wind averaging and the concern of the climatologist about the length of period used. Fig. 4 shows six hours of wind speed record from an anemomograph on an oil platform. Winds may be extracted from this record as averages over various periods from ten minutes to several hours. The Meteorological Office traditionally uses a wind averaged over the ten-minute period preceding each hour as the synoptic wind for that hour, and an average wind over the entire hour for climatological purposes. An examination of the trace shown in Fig. 4 reveals a considerable variability in ten-minute mean winds, some being larger, some smaller, than the corresponding hourly mean wind. If a sufficiently large number of observations is used the mean ten-minute wind and mean hourly wind will be almost identical, but the standard deviation of ten-minute winds will be much higher. This means that a frequency distribution of ten-minute winds will be different in shape from that of hourly winds, and that extreme winds estimated from the two distributions will differ. In fact the extreme derived from the distribution of ten-minute winds is 7 to 8% higher than that from the hourly winds. The variability in the one-minute wind is even higher than for the ten-minute wind, and it is also likely that a mean over a long period of one-minute winds read from a dial will be higher than the corresponding mean hourly wind. The dial will indicate large fluctuations in wind, and the human observer will probably tend to bias his estimated mean value for one minute towards the higher gust. Even without this effect the extreme wind derived from the one-minute distribution is approximately 19% higher than that derived from hourly mean winds.

Thus it can be seen that the wind averaging time must be known, and should be the same throughout the body of data used for any analysis. This is clearly not so for some instrumental data especially when different instrumental data sources are combined. On the other hand, visually observed winds by officers on board ship have been shown to be climatologically self-consistent within the acceptable tolerances, despite their apparent subjectivity in the eyes of the non-mariner.

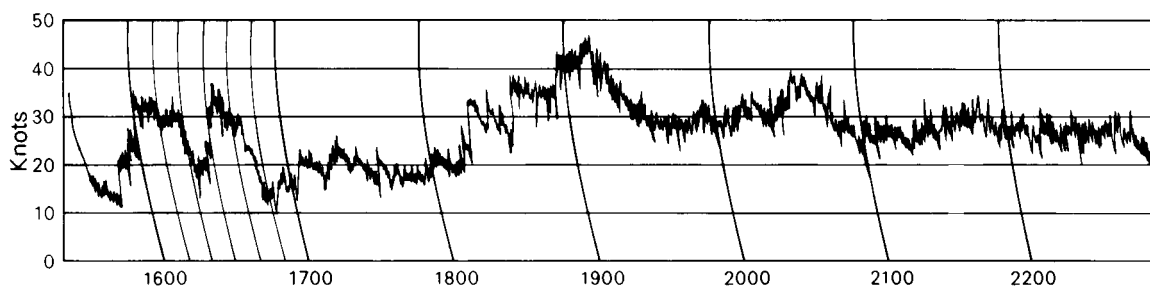


Figure 4. A copy of a six hour period of an anemograph trace from an anemometer mounted on an oil platform.

6. Length of record

With the exception of those from the ocean weather ships and light-vessels, most instrumental records of wind and wave are short, consisting of less than five years of data. Some wave records are less than one year in length. Even if the difficulty of applying an extreme-value analysis technique to a small number of values could be overcome there must always be doubt regarding how representative the short period of data will be when compared with the long term climate.

Figs. 5 and 6 show the year-to-year variations in the percentage frequency of occurrence of several categories of wind speed and wave height. The data used were visual observations from merchant ships for an area off the east coast of Scotland. The year-to-year variations are quite marked and it is easy to see that both frequency distribution and extremes derived from a year or two of data will probably not be representative of long term conditions.

7. Analyses available from the Meteorological Office Marine Climatological Bureau

Analyses can be produced for most of the traditional meteorological parameters for locations anywhere in the world. A short list is given in Table I. The Marine Climatology Bureau of the

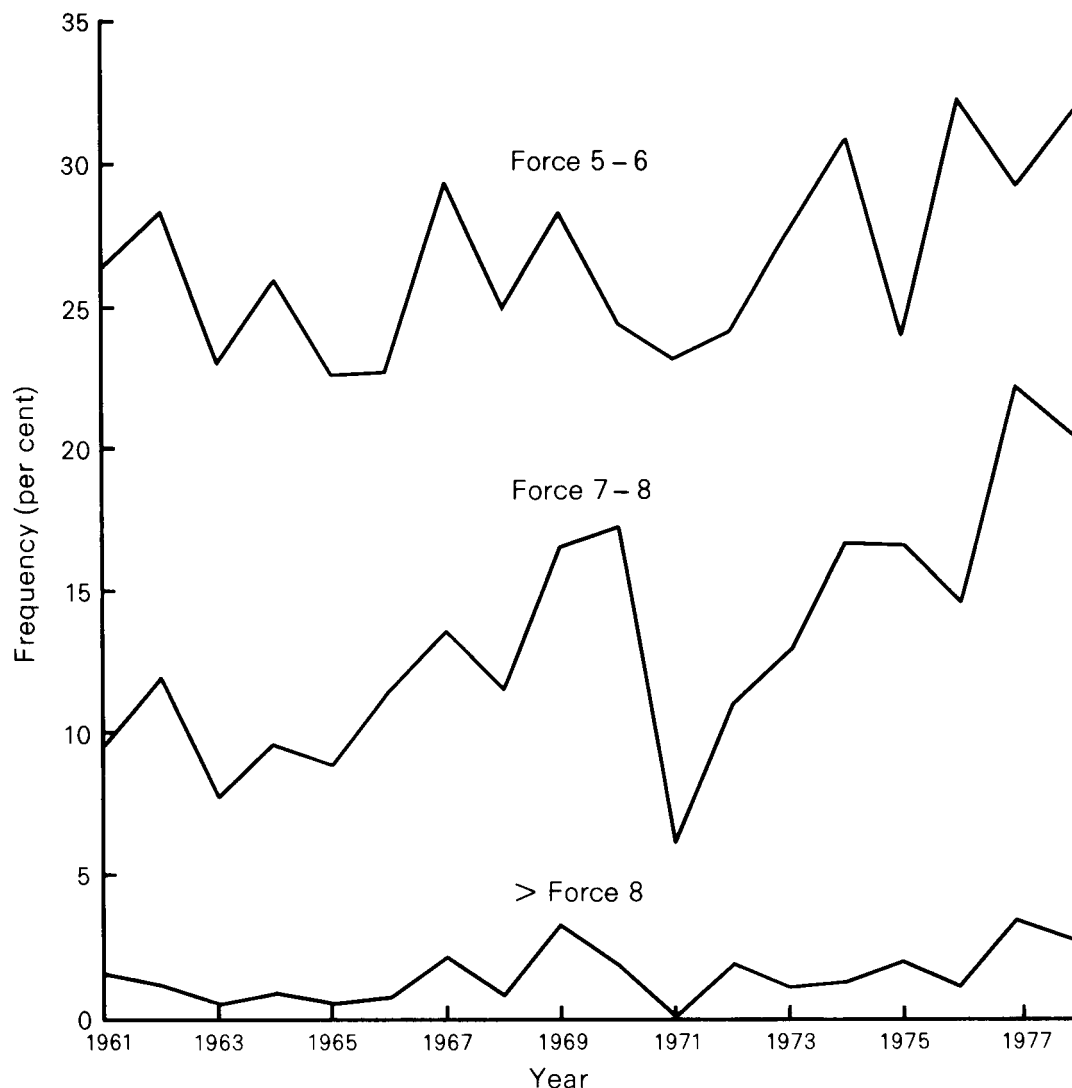


Figure 5. Percentage frequency of occurrence of winds in each year calculated from visual observations from an area 57°N to 59°N, 2°E to 2°W.

Table I. *A selection of parameters available from the climatological archive*

Wind: speed and direction
 Weather: past and present
 Cloud: type and amount
 Temperature: air, dew-point, wet-bulb and sea
 Wind waves: height and period
 Swell waves: height, direction and period
 Visibility
 Air pressure
 Sunshine/radiation

Meteorological Office has concentrated upon development of a number of standard sub-programs that produce commonly required analyses from the data stored in the main marine data bank. These computer programs can be assembled to provide information in the form of computer printout for the customer, or as the starting point of an investigation which will end with a comprehensive report.

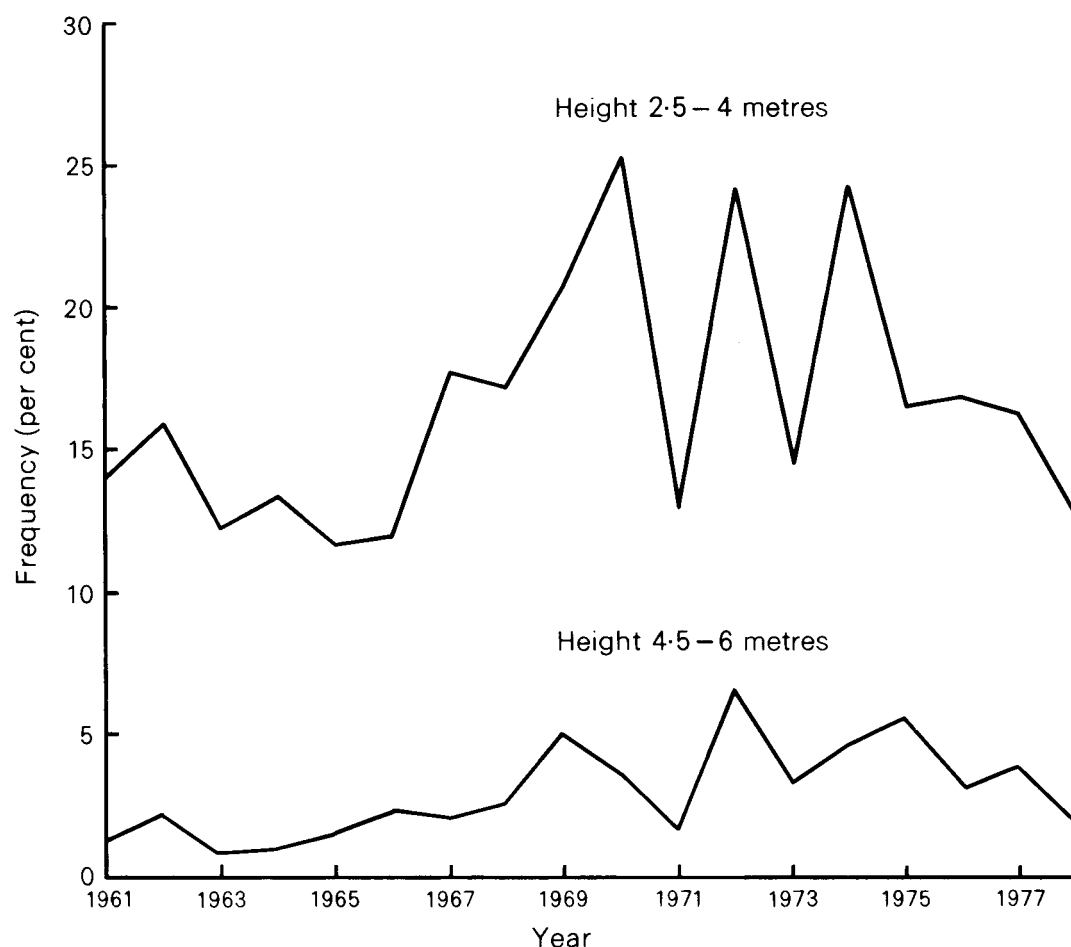


Figure 6. Percentage frequency of occurrence of wave heights in each year calculated from visual observations from an area 57°N to 59°N, 2°E to 2°W.

Some examples of typical sub-program analyses are shown in Table II. Use is made of computer graphics so that graphs of percentage exceedences, Weibull extreme-value plots, wind roses and histograms can be produced quickly on microfilm or on paper. In addition to standard analysis programs already available, specialized software can be developed to deal with customers' individual requirements.

Table II. *Analyses produced from the climatological archive*

Wind frequency according to month, direction, and speed
 Waves according to month or season, direction of movement, period and height
 Air temperature according to month
 Dew-point temperature according to month
 Sea surface temperature according to month
 Visibility according to month

Although most investigations involve some computer analysis of data, few enquiries can be answered automatically. Considerable effort is made to discuss the customers' problems and requirements in order to find the best way of presenting environmental data to meet those needs. In general, every effort is made to give an answer to even the most difficult of problems, whilst stating firmly any reservations which have to be made because of the inadequacies of the data or uncertainties referred to above.

As well as knowledge of marine climatology, the members of the Bureau have individual experience and expertise in such fields as weather forecasting, meteorological statistics, computer programming and systems analysis and research. They also have access to staff engaged upon research in many relevant branches of meteorology and will seek advice from other experts as necessary.

8. Conclusion

The Meteorological Office has expended a significant amount of its resources upon the development of a global archive of marine data. Much of the data consists of visual estimates which, despite their limitations, form a consistent body of information that can be used by an experienced analyst with more confidence than could reasonably be shown for the short instrumental records available. This situation is unlikely to change significantly until a number of well-exposed robust instruments are deployed and left on site for ten years or more. Although the data bank, or parts of it, can be purchased by meteorological consultants, and small amounts have been in the past, it is the current position that the computer archive maintained by the Meteorological Office is unique within the United Kingdom. The only comparable data banks are held by a few of the corresponding national authorities in certain other countries. The marine enquiry bureau is therefore confident in its ability to answer marine climatological enquiries from the most trivial to the most complex. Problems can be tackled that are considered intractable by many other organizations.

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Concentrations of Aitken nuclei in the boundary layer round the British Isles

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Summary

Aitken nucleus (AN) measurements made round the coastline of the British Isles within the boundary layer are presented and discussed. The aerosol concentration in maritime air masses, which are modified as they pass over land, is shown to depend mainly upon the land track upwind of a particular location, with local effects due to anthropogenic nuclei sources.

1. Introduction

Many experiments have been conducted with the aim of exploring variations in the horizontal and the vertical in the Aitken nucleus (AN) concentration. In particular, many data gathered from aircraft flights round the British Isles have already been published by Day (1955, 1957) and by Durbin and Murgatroyd (1964) and some success was achieved in relating high particle concentration to likely industrial sources upwind. Also, it was recognized that the land areas represented the major source of aerosol in the AN size range (Day 1957) but no quantitative explanation of the measured horizontal variability in boundary layer concentrations was attempted.

It has been suggested that the majority of AN particles formed over land consist mainly of ammonium sulphate and are formed *in situ* by a gas to particle conversion process which probably involves a photochemical reaction (see e.g. Haaf and Jaenicke 1980), the necessary compounds for the conversion from gas to particulates probably arising from natural vegetation. Observations of a diurnal cycle of the AN concentrations, which support this hypothesis, have been made in the USA by, e.g., Mamane and Pueschel (1980) and in the east of England by Kitchen *et al.* (1982). In complete contrast to these conclusions, Ayers and Bigg (1982) have made extensive aircraft measurements of aerosol concentrations downwind of Australian cities and concluded that the continental AN originated mainly from anthropogenic, rather than natural sources.

Interest in aerosol measurements has been revived recently partly because of the possible effects of aerosol concentration and composition upon the radiation budget of the atmosphere and hence e.g. the heat budget of the boundary layer (see e.g. Moores 1982). The modification of air masses by passage over the British Isles may be of importance in causing spatial variations in these effects. The work described here provides a simple explanation of the major horizontal variations in AN concentration observed in three case studies.

2. Experimental details

AN concentration measurements were obtained using a standard 1957-type Pollak counter on board the C-130 aircraft of the Meteorological Research Flight (Kitchen 1982). In the Pollak counter the Aitken nuclei are converted into fog droplets by means of an adiabatic expansion in a cloud chamber. The extinction of a parallel light beam passing through the fog is measured and is related to the nucleus concentration. The measurements were made within the boundary layer between 150 and

1000 m above sea level around the British Isles. The effects of sampling at different temperatures and pressures will have introduced errors in AN concentration as described by Pollak and Metnieks (1960, 1961). Likely uncertainties in concentrations measured using a Pollak counter have been quoted as 5% by Metnieks and Pollak (1959) but a thorough investigation by Podzimek *et al.* (1981) has suggested that errors at the extreme ends of the instrument range may be larger than this. Order of magnitude variations were observed during the present experiments, however, and instrumental errors have been ignored as they are not significant in relation to the following discussion.

The data consist of measurements made at intervals of 1.5 to 2 minutes which at aircraft speeds is equivalent to a horizontal distance of 9 to 12 km between samples. The sample volume of the Pollak counter is about 260 cm³ which is obtained in a time of about 8 s (equivalent to 800 m). Each measurement was therefore considered as being a point sample. The three flights described took place on 10 July 1979, 22 and 26 January 1982 and are referred to as Days 1, 2, 3 respectively hereafter.

The measurements during Day 1 (Fig. 1(a)) were made entirely over the sea at a height of approximately 1000 m above sea level north from the North Wales coast out over the Irish Sea and to the north of Ireland to 57°N 8°W, followed by the reciprocal course back towards the North Wales coast. On Days 2 and 3, almost identical flight tracks were flown round the coastline of England, Wales and Ireland (Figs. 1(b) and 1(c)). Most of the observations on these latter two days were made at 150 m above sea level, but transits across land areas were at heights of 600–800 m.

The synoptic conditions, in particular the wind field, on the three days are obviously of importance in the interpretation of the aerosol data. The observed surface winds are shown in Figs. 1(a), 1(b) and 1(c) along with an analysis of the surface pressure field obtained using an objective scheme of Purser and McQuigg (1982). Conditions on Day 1 were anticyclonic in the region of interest with an inversion capping the boundary layer which, from the midday Aldergrove radiosonde ascent, was near 1500 m. In contrast, on Days 2 and 3, the situation was cyclonic with a broad westerly flow across most of the British Isles. On these days, there was no marked inversion as the air mass was unstable with widespread deep convection, particularly over the more northern parts of the flight tracks. Care was taken to avoid sampling within precipitation.

3. Results and discussion

The measured AN concentrations are presented in Figs 2(a), 2(b) and 2(c) as a function of time. The data from periods when the aircraft was considered to be above the boundary layer (i.e. during the transit to the Welsh coast on Day 1 and the transits over central Scotland on Days 2 and 3) have been omitted. The most obvious feature of the AN concentration measurements is that during some parts of the flights, the concentrations were very low ($< 1000 \text{ cm}^{-3}$) with small variability, whereas during the remainder of the time when concentrations were generally at a higher level there occurred a number of sharp peaks which were poorly resolved by the measurements, i.e. their extent in the across-wind direction was probably less than about 10 km. The lowest concentrations were observed in air which appeared not to have passed over land in the British Isles and therefore represented background concentrations in the North Atlantic air with a long ocean track. Minimum concentrations were about 100 cm^{-3} on Days 2 and 3 and about 800 cm^{-3} on Day 1 and are typical of the North Atlantic background (see e.g. Moore 1952). On Days 1 and 2 the air arriving on the western coasts of Britain had passed around the northern flank of an Azores anticyclone, whereas on Day 3 the air mass was Arctic in type. The air mass origin does not therefore explain the difference in the minima.

In order to investigate possible reasons for the increased AN concentrations in air which passed over land, three correlation coefficients have been calculated, which are based on three alternative

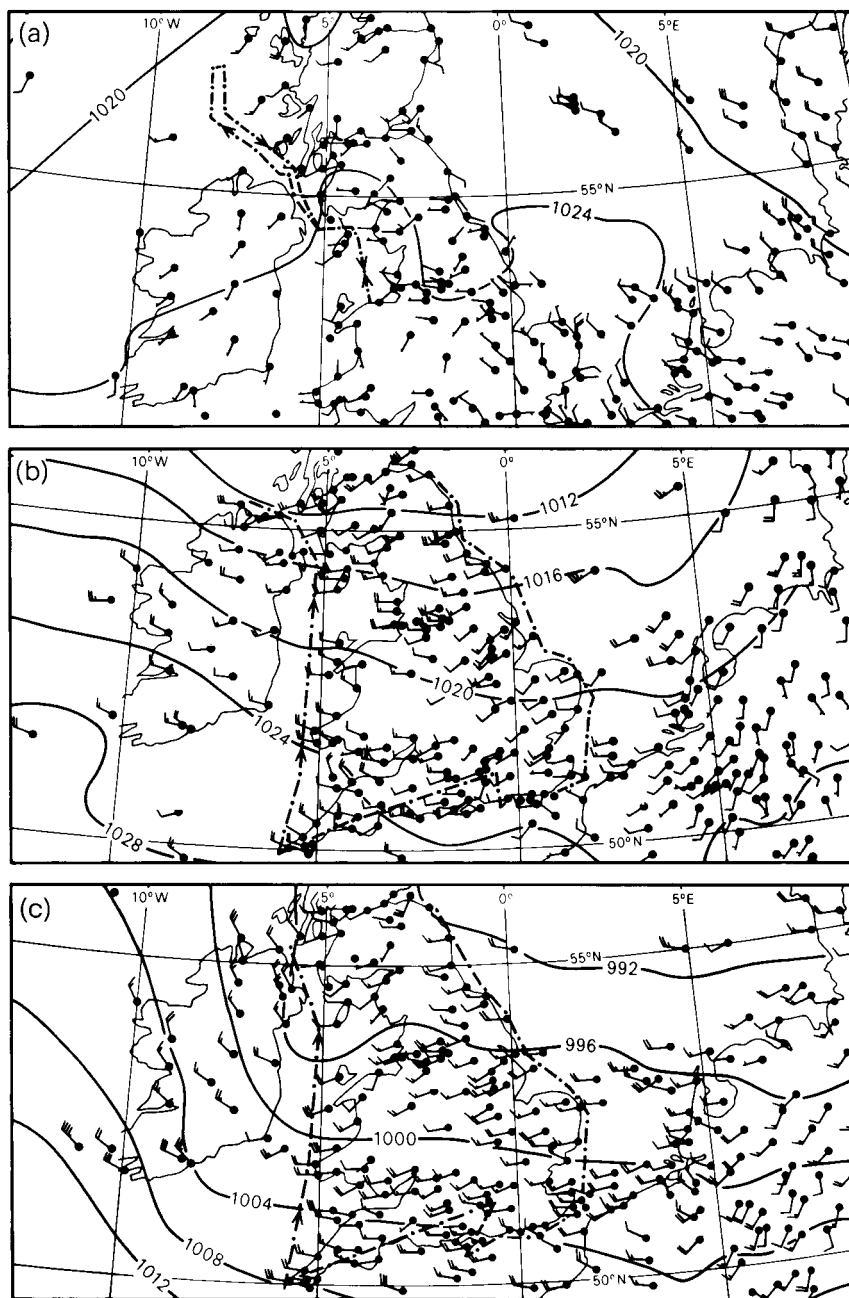


Figure 1. (a) Map of the British Isles showing surface winds and pressure analysis for 12 GMT on Day 1 (10 July 1979). The part of the aircraft track for which data are plotted in Fig. 2(a) is marked by a dash-dot line.

(b) Similar to 1(a) but for 12 GMT on Day 2 (22 January 1982).

(c) Similar to 1(a) but for 12 GMT on Day 3 (26 January 1982).

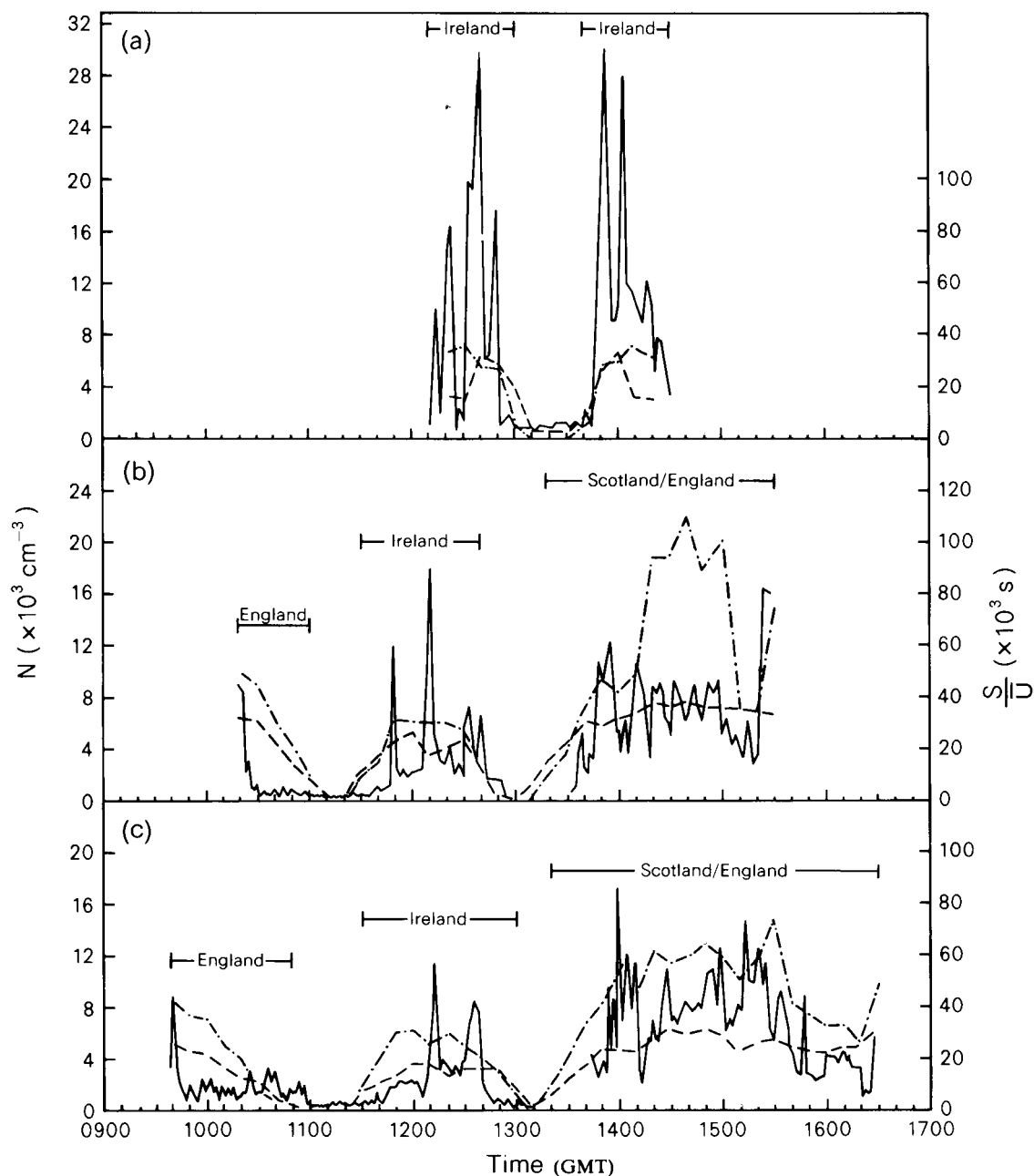


Figure 2. (a) Measurements of AN concentrations (solid line), estimated values of S/U (dash-dot line) and calculated values of N at 10-minute intervals from integration of equation (1), all plotted against time (GMT). Those periods when the aircraft track was downwind of land are marked by horizontal bars.

(b) Similar to 2(a) but for Day 2.

(c) Similar to 2(a) but for Day 3.

hypotheses. The starting point for two of the three hypotheses is the simple budget equation of Lopez *et al.* (1976)

$$dN/dt = \phi/h - KN^2 \quad \dots \dots \dots (1)$$

where N is the AN concentration at time t
 ϕ is the nucleus flux (production rate)
 h is the mixing layer depth
 K is a coagulation constant.

Application of this equation assumes that the aerosol composition and size distribution remains uniform to the extent that a single value of K can be used and also that precipitation scavenging was not significant. Both assumptions are necessary because of the lack of experimental data. This equation was previously successfully used to explain diurnal cycles of AN concentration in an experiment conducted at Cardington, Beds (Kitchen *et al.* 1982). In that experiment, a value of K of about $2.4 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$ was obtained which was in agreement with that inferred from observations by Mamane and Pueschel (1980) (ϕ/h was estimated to be about $0.13 \text{ cm}^{-3} \text{ s}^{-1}$).

The three alternatives which are considered are as follows:

(a) Production over the land areas on the three days was uniform in space and time, but zero over the sea and this production was not offset by coagulation. Ignoring the coagulation term in equation (1), and integrating following an air parcel, we have $N \propto \phi S/h\bar{U}$, where S is the length of the land track upwind of a point and $1/\bar{U}$ is the mean reciprocal wind speed along that track.

(b) The lifetime of AN in the boundary layer is short compared to S/\bar{U} , i.e. coagulation dominates equation (1). As in (a) the production over land was uniform in space and time, but zero over the sea. Concentrations would quickly reach a plateau over the land and rapidly decay once the air passed over the sea again. In this case, over the sea, the AN concentration is given by

$$1/N - 1/N_0 \propto KS'/\bar{U} \quad \dots \dots \dots (2)$$

where N_0 is the AN concentration over land and S' is the distance downwind of the land.

(c) The last possibility considered is that the AN concentration depended solely upon whether a point lay in the lee of land in the British Isles. The concentration N therefore is not described by equation (1), but by a step function which takes a value of 1 downwind of land and 0 elsewhere.

These three hypotheses have been tested using the observations in the following way. Back trajectories from points on the aircraft track at approximately 50 km intervals were estimated. The task of calculating such a large number of trajectories objectively from analysed wind fields was considered unjustified for this application and they were estimated by drawing streamlines by eye. The surface wind directions were used over the land and the geostrophic wind over the sea. Whilst the surface wind was probably most appropriate for the observations made at 150 m above sea level on Days 2 and 3 it might have been better to use the geostrophic wind over both land and sea on Day 1. For the sake of treating all the data uniformly, however, the same method was adopted for Day 1 as for Days 2 and 3. These trajectories were used to calculate three correlation coefficients between N and S/\bar{U} , $1/N$ and S'/\bar{U} , and N and the step function defined in (c) above. These coefficients are therefore a measure of the success of each of the hypotheses (a), (b) and (c) above in describing the concentration observations. Table I contains the different correlations for each day. In all cases the best correlation was between N and S/\bar{U} with a maximum value of the coefficient of 0.79 on Day 3. There was some evidence of a relationship between N and S'/\bar{U} on Day 1, but little support for either of hypotheses (b) and (c) on Days 2 and 3. The values of S/\bar{U} used in this analysis have also been plotted in Figs 2(a), 2(b) and 2(c).

Table 1. Correlations between measured Aitken nucleus concentrations and calculated parameters based upon estimated trajectories.

k_{NS} is the correlation coefficient between N and S/\bar{U} .

k_{NH} is the correlation coefficient between N and a step function which takes the value 1 downwind of land areas and 0 elsewhere.

$k_{NS'}$ is the correlation coefficient between $1/N$ and S'/\bar{U} .

Day	k_{NS}	k_{NH}	$k_{NS'}$
1	0.76	0.59	0.68
2	0.66	0.35	0.35
3	0.79	0.34	0.48

The strength of the relationship between upwind land track and AN concentration justifies the extension of the analysis to see whether the inclusion of both production and coagulation terms is capable of describing the measurements quantitatively. As mentioned above, some values of ϕ/h and K have previously been derived by Kitchen *et al.* (1982). These were inserted into equation (1) and the equation integrated to give values of N at points on the aircraft track. These calculated values are plotted on Figs 2(a), 2(b) and 2(c) for comparison with the observations. An additional assumption implied here is that a single value of ϕ/h applied to all the cases. This assumption is necessitated because of the uncertainty in specifying h on Days 2 and 3, in the absence of any inversion. Also that ϕ/h and K are approximately the same in the present cases as those inferred from the Cardington measurements. In view of the crude theory and gross assumptions, the agreement between N observed and calculated is surprisingly good, with a large part of the horizontal variability accounted for. This result may be fortuitous as the estimated error in ϕ/h alone was of the order of 50% (Kitchen *et al.* 1982).

The above theory, however, does not account for the local sharp increases in AN concentration because it assumes that the source of AN is uniform over the land area. Most of the peaks in AN concentration were measured downwind of major industrial areas or conurbations, e.g. on all three days a marked increase in concentration was observed downwind of Belfast. The implication therefore is that a sizeable fraction of the AN were anthropogenic in origin. In order to estimate a lower bound to this fraction, the area of the peaks was calculated (by taking a 20-minute mean as a baseline) and compared to the total area of the measured AN time series (Figs 2(a), 2(b) and 2(c)). The fraction calculated in this way was highest on Day 1, at about 30%, whilst on Days 2 and 3 it was about 10%. This difference may have been due to the more stable conditions on Day 1 resulting in higher peak concentrations.

Fixing an upper bound to the anthropogenic fraction is more difficult, but has been attempted by reference to the work of Ayers and Bigg (1982). From measurements downwind of Australian cities, Ayers and Bigg found a direct proportionality between population and anthropogenic AN production. The present observations were not sufficiently detailed to enable fluxes from cities in the UK to be calculated following the method of Ayers and Bigg (1982). It is possible, however, to estimate the average surface flux of AN if it is assumed that the anthropogenic production per person is the same in the British Isles as in Australia. From Fig. 1 in Ayers and Bigg (1982), the AN production is estimated to be 8×10^{13} per second per person. Therefore over the Irish Republic with a population density of 45 km^{-2} , ϕ calculated in this way is about $3.6 \times 10^5 \text{ cm}^{-2}\text{s}^{-1}$. Over the UK with an average population density of 230 km^{-2} , ϕ is about $1.8 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$. Taking a somewhat arbitrary value of $h = 1500 \text{ m}$ (as on Day 1), then ϕ/h exceeds the value inferred from the observations of Kitchen *et al.* (1982) by over an order of magnitude. This difference is sufficiently large to suggest that any

relationship between AN production and population is probably not the same in the British Isles as in Australia, but does not rule out the possibility that all the AN observed in the present cases were anthropogenic in origin. This is not considered likely in view of the evidence of a dominant natural source, at least in rural areas (see Introduction).

4. Conclusions

Whether the majority of AN observed in the boundary layer over land are of anthropogenic or natural origin remains in some doubt. However, production of AN clearly occurs over the land areas of the British Isles and it seems likely that with a westerly airflow, there is a strong longitudinal gradient of AN concentration. On western coasts receiving air direct from the Atlantic, concentrations are likely to be $< 1000 \text{ cm}^{-3}$ and on most of the east coast at least an order of magnitude higher. If spatial variations also occur in boundary layer concentrations of larger particles in the aerosol spectrum (in the range 0.1 to 10 μm radius) then there may be corresponding variations in cloud microphysical structure, attenuation of incoming solar radiation and visibility. Systematic horizontal variations in aerosol may therefore be of importance in a number of areas of meteorological interest and the interaction between aerosol and solar radiation in particular is being actively studied at present.

Acknowledgements

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Further composite rainfall records for the United Kingdom

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Summary

Details concerning further composite rainfall series are presented for England and Wales. Together with previously produced series the new series will provide a basis for many studies including water resources.

Introduction

By far the best source of composite rainfall records for the United Kingdom is that put together by Tabony (1980). This gives composite series of monthly observations back to before 1860 for 39 sites in the United Kingdom and Eire. The 39 sites are listed, together with seven others constructed by the author, in Wright and Jones (1982). Tabony's (1980) data set also includes a number of records for continental Europe particularly for France, Italy, Sweden, the Netherlands and the Federal Republic of Germany. Further details of this data set and some analyses of it may be found in Tabony (1981). The method of construction of a composite record is described by Craddock and Wales-Smith (1977), Craddock (1977) and Jones (1981).

The composite series have been produced for a diversity of regions and, in the author's opinion, for most sites within the UK it should be possible to produce a composite rainfall record extending back to at least 1870 within 40 km of the chosen site. The apparent lack of long-period records on site compilations such as RAINMASTER produced by the Meteorological Office should not prove a hindrance. Consultation of the annual volumes of the excellent publication *British Rainfall* from 1865 will enable records for earlier years to be found.

The new rainfall series

As a result of recent work the author has produced homogeneous composite records for a further 15 sites. This note contains details about each site, duration of individual site records, corrective factors, etc. It is impracticable to publish all the monthly rainfall totals, but, copies can be obtained from the author in an appropriate computer media form e.g. computer listing or magnetic tape. Copies of the series will also be lodged with the Meteorological Office.

The author's work has concentrated on specific river catchments, so the new series are centred on three main regions—Devon (River Exe), south-eastern parts of Wales and neighbouring parts of England (River Wye) and northern England (Rivers Eden and Tees). Site locations and length of records for the 15 new sites are given in Table I. The Carlisle site is also given by Tabony (1980), but the record has now been extended back to 1757 making Carlisle the third longest homogeneous rainfall series in the UK.

In Appendix A the individual site records used, years of observations, heights etc. are listed for all 15 composite sites. In Appendix B the stations used to produce the composite records are given, together with the corrective factors used to adjust the older rain-gauge sites to the key site. These appendices contain the basic information for each site. For each composite record the time and effort required can be judged from the record for Cirencester (Jones, 1980). The author has also produced homogeneous

Table I. *New homogeneous rainfall records for sites commencing before 1860*

Gauge No.	Gauge name (Key site)	First year of monthly records	National Grid reference	Height metres
1	Carlisle	1757	NY390544	35
2	Darlington	1843	NZ285134	30
3	Barnard Castle	1856	NZ056164	171
4	Banbury	1850	SP458418	91
5	Bedford	1846	TL081463	29
6	Taunton	1859	ST229238	22
7	Tiverton	1854	ST035103	79
8	Cullompton-Bradinch	1837	SS994034	69
9	Ross-on-Wye	1859	SO606235	50
10	Leominster	1831	SO501587	72
11	Kington	1841	SO339576	155
12	Penrith	1851	NY497259	191
13	Appleby	1857	NY684198	146
14	Patterdale	1860	NY391163	146
15	Newton Rigg	1846	NY493310	171

Table II. *Homogeneous rainfall records for sites commencing after 1860*

Gauge No.	Gauge name (Key site)	First year of monthly records	National Grid reference	Height metres
1	Winsford	1897	SS906348	189
2	Bulland Lodge	1864	ST054273	229
3	Honeymead	1871	SS797392	378
4	Clayhanger	1865	ST022230	165
5	Exford (Lower Thorne)	1875	SS843383	290
6	Huntsham*	1874	SS990180	241
7	Dulverton	1911	SS912280	134
8	Crediton	1865	SS832006	91
9	Monmouth	1867	SO507126	16
10	Hereford*	1861	SO482433	82
11	Sarnesfield	1870	SO368509	122
12	Hay-on-Wye	1884	SO181393	84
13	Talgarth	1899	SO136354	183
14	Brecon	1867	SO037276	168
15	Evancoyd*	1885	SO261630	227
16	Llanddewi-Ystradenay	1885	SO107685	234
17	Builth Wells	1896	SO038530	229
18	Llysdinam	1882	SO009584	197
19	Llanbadarn	1895	SO097777	297
20	Llwyn Madoc	1881	SN903524	223
21	Tremothic Farm	1873	SO359317	198
22	Broadfield House	1875	NY440443	155
23	Haresceugh	1887	NY610428	244
24	Blencarn	1876	NY637312	170
25	Kirkby Stephen	1865	NY771077	191
26	Askham Hall	1865	NY515239	186
27	Wasdale Pike	1869	NY537084	564
28	Mosedale Cottage	1867	NY496095	440
29	Kidmoor	1869	NY479193	335
30	Nunwick Hall (Penrith SW)	1872	NY568352	99

* Sites where earlier rainfall records are available but which do not form a continuous link with the present series.

rainfall records for a further 30 sites with starting dates between 1861 and 1911. The names, length of record and location of these sites are given in Table II.

Some details concerning the rainfall series

Where possible, in forming a composite rainfall series, it is best to use as few as possible different gauge records, preferring those nearest the key site. For all the sites this criterion was adhered to. It can be seen from the Appendices that for most sites more gauge records were collected than necessary. The extra gauge records were used to verify the 'catch at the site records' used in the composite record.

Some of the key sites are relatively close together and it proved necessary on three occasions to use part of the same source record for two composite series. Cullompton and Tiverton both use the Halberton record for the year 1957 while the series for Barnard Castle and Darlington both use years from Catterick (Tunstall), although in this case the years used in each series are not the same. Kington and Leominster both use the years 1856 and 1857 of the Orleton record.

At Kington the source record from Lynhales (Robinson) has two corrective factors caused by a change of site. In this case the site change was documented in the 10-year rainfall books at the Agriculture and Hydrometeorology Branch of the Meteorological Office. Where a site change or gauge change was suspected, but not documented, the particular record was rejected and replaced by an alternative. This proved possible in most cases because of the abundance of gauge records. The major exception to this was the Castle Road record for Bedford. It appears from comparisons with other gauges that this site was at Castle Road only since 1904. The record shows a distinct inhomogeneity before 1902.

By far the longest series produced is the extension of Tabony's (1980) record for Carlisle back to 1757. Apart from the records used from Dumfries and Applegarth Manse (Dumfriesshire) all the records for producing the Carlisle series are from within 10 miles of Carlisle. Unfortunately, only annual values are available for some years in the 1780s for the Dumfries record. The main bases of the extended record are the two records from Carlisle, those kept by Dr J. Carlyle between 1757–1783 in Abbey Street and by Mr Pitt at Shaddongate between 1801–24. The latter observer also took daily air temperature readings for the same period and these are also available.

Conclusions

The new composite series presented here together with previous published series, particularly those given by Tabony (1980), facilitate studies of the long term spatial variability of rainfall and its spectral behaviour (e.g. Tabony 1977, 1981), as well as riverflow reconstruction (e.g. Wright and Jones, 1982).

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Appendix A. Individual site records collected at each key site.

Gauge No.	Gauge name	Years of observations (Missing years in parentheses)	Observer(s)*	Height metres
1	<i>Carlisle</i>			
	Carlisle (Tabony)	1845 →	Carlisle Council	35
	Athenaeum	1841–1848	N. Fisher	?
	Harraby	1840–1846	J. Atkinson	?
	Carlisle (Elliot)	1835–1842	Dr Elliot	?
	Wigton	1822–1826	J. Pemberton	?
	Wigton, Aikbank	1792–1809	Revd J. Golding	?
	Carlisle, Shaddongate	1801–1824	Mr Pitt	12
	Carlisle, Abbey Street	1757–1783	Dr J. Carlyle	25
	Dumfries	1775–1789	Dr Copeland	?
	Whinfell Hall	1829–1833	W. Robinson	?
	Applegarth Manse	1827–1850	Revd W. Dunbar	55
	Scaleby House	1863–1940	R. A. Allison	34
2	<i>Darlington</i>			
	South Park	1923 →	Mr J. Morrison	30
	Public Park	1898–1922 (1907/9/12)	Mr J. Morrison	46
	Hummersknott	1898–1930 (1919)	Mr J. Short	61
	Elcott Hurworth	1890–1903	Revd W. E. Short	37
	Hurworth Grange	1890–1915	Mrs Backhouse	49
	Cleveland Parade	1874–1917	S. Hare (W. W. Willmott)	49
	South-east Gardens	1859–1897 (1873/4)	J. Richardson	43
	Catterick (Tunstall)	1866–1888	H. G. Marshall	107
	Richmond	1843–1872	J. Miller	168
3	<i>Barnard Castle</i>			
	Bowes Museum	1922 →	Curator	171
	County School	1888–1950	E. Wells (Bursar)	168
	East Layton	1875–1913	Miss Maynard (Miss Proud)	175
	Whorlton	1879–1894 (1880)	Miss Dodgson	129
	Greta Bridge	1869–1974	T. Dodgson	131
	Catterick (Tunstall)	1866–1888	H. G. Marshall	107
	Winston	1856–1867	T. Dodgson	140

Appendix A. *continued*

Gauge No.	Gauge name	Years of observations (Missing years in parentheses)	Observer(s)*	Height metres
4	<i>Banbury</i>			
	Grimsbury	1886 →	Superintendent	91
	West Adderbury	1892–1967	Lt.-Gen. Sir E. Graset	103
	High Street	1852–1887	T. Beesley	105
	Wroxton	1876–1885	A. R. Tawney	149
	Cotefield Bodicote	1876–1891	T. E. Cobb	117
	Parson's Street	1850–1872	J. E. Jarvis	104
	Bodicote	1894–1924	J. F. Starkey	118
	Bloxham Grove	1890–1914	Revd G. Warriner	118
5	<i>Bedford</i>			
	Observatory	1831–1843 (incomplete)	Admiral Smyth/ Mr Glanville	?
	Bedford	1851–1865	Dr H. Barker	32
	Western Street	1869–1893	D. Roble	34
	Castle Road	1878–1960 (1903)	Newbury family	30
	Tempsford Hall	1873–1892	Col. W. Stuart	24
	Clapham Park	1875–1888	J. Howard	67
	The Park (Mowsbery)	1906–1973	Borough Engineer	36
	Bedford (Meteorological Office)	1957 →	Meteorological Office staff	85
	Cardington (Meteorological Office)	1953 →	Meteorological Office staff	29
	St. Peter's Street	1888–1908	W. Godfrey	35
	Amphill Road	1902–1908	T. Pearce	27
	Cardington Village	1846–1890	J. McLaren	27
	Cardington Village (Post)	1848–1869	J. McLaren	27
	The Grove	1888–1899	W. B. Graham	33
6	<i>Taunton</i>			
	Vivary Park	1910 →	Taunton Borough Council	22
	Milverton Old Halls	1877–1944	Bere family	76
	Cothelstone House	1875–1921	C. E. J. Esdaile	131
	Blagdon Hill Reservoir	1894–1921	H. J. Coles	179
	Claremont	1891–1901	E. Ball	24
	Norton Fitzwarren	1888–1894	H. Ruddle	43
	Bishop's Lydeard House	1872–1889	C. Smith	56
	Fulland's School	1865–1884	N. Reed	?
	Castle	1855–1874 (incomplete 1858–9)	G. Gillett	15
7	<i>Tiverton</i>			
	Willand, Losinga	1972 →	Mrs M. Godfrey	79
	Willand	1958–1971	I. M. Godfrey	75
	Halberton	1940–1962	Miss M. G. Izat	91
	Halberton	1906–1929 (1917–20)	Capt. G. Izat	73
	Blundell's School	1929–1941	E. G. Pierce	82
	Hartnolls	1913–1930	Maj.-Gen. Bowles	69
	St. Aubryn's Park	1921–1940	Mr Fox-Strangeways	120
	Ivy Place, St. Peter's Street	1880–1909	H. S. Gill	82
	Cove	1862–1894	W. N. Row	140
	Hayne	1854–1864	W. H. Gamber	122

Appendix A. *continued*

Gauge No.	Gauge name	Years of observations (Missing years in parentheses)	Observer(s)*	Height metres
8	<i>Cullompton-Bradninch</i>			
	Bradninch, Westfield	1959 →	C. W. Beer	69
	Halberton	1940-1962	Miss M. G. Izat	91
	Bradninch	1905-1956	Miss H. R. Hepburn	91
	Cullompton	1881-1952	T. Turner (Foster, Trezise)	62
	Bradninch Vicarage	1877-1887	Revd W. A. Strong	96
	Strathculme	1864-1882	C. R. Collins	48
	Clyst Hydon	1847-1880	Revd J. Huyshe	61
	Bradninch	1842-1873	C. Matthews	71
	Broadhambury	1837-1873	Revd W. Heberden	122
9	<i>Ross-on-Wye</i>			
	Alton Court	1966 →	Welsh Water Authority	50
	Ross, Perrystone Court	1890-1973	Mr T. Greenaway	158
	Ross, Graig	1859-1943	H. Southall	65
10	<i>Leominster</i>			
	Leominster	1966 →	Welsh Water Authority	72
	Kimbolton, Grantsfield	1913-1968	Miss D. W. Hutchinson	129
	Farm	1883-1912	E. H. Southall	79
	West Lodge	1858-1882	E. H. Southall	76
	Orleton	1831-1896	T. H. Davis	59
	Pembridge, Weobley	1888-1929	T. L. Hall	88
11	<i>Kington</i>			
	Lyonshall	1942 →	R. H. Green	155
	Lynhales	1927-1944	Mrs R. F. Hibbert	189
	Sunset	1919-1936	H. Langston	151
	Pembridge, Weobley	1888-1929	T. L. Hall	88
	Lynhales	1867-1917	S. Robinson	173
	Orleton	1831-1896	T. H. Davis	59
	Titley	1841-1855	R. B. Boddington	180
12	<i>Penrith</i>			
	Tirrill	1969 →	R. F. Porter	191
	Castle Park	1938-1974	Borough Engineer	149
	Benson House	1913-1956	A. B. Sinclair	152
	Fell Lane, Fir Bank	1866-1930	H. Lester	175
	Nordana	1887-1908	G. V. Smith	198
	Brougham Hall	1851-1885	Mr A. Lodge	149
	Penrith	1835-1854 (1840-50)	Mr Bird	?
13	<i>Appleby</i>			
	Castle Bank	1890 →	Lady Holmes	146
	Bongate	1941 →	J. F. Whitehead	151
	Appleby	1857-94	Dr Armstrong	135
14	<i>Patterdale</i>			
	Patterdale Hall	1835 → (1957-60)	Mr A. Milne/Miss C. Marshall	146
	Greenside Mine	1872-1961	Basinghall Mining Syndicate Ltd	335
	Grisdale Ruthwaite Lodge	1889-1935	Mr A. Milne/Miss C. Marshall	534

Appendix A *continued*

Gauge No.	Gauge name	Years of observations (Missing years in parentheses)	Observer(s)*	Height metres
15	<i>Newton Rigg</i> Newton Rigg	1883 → (1950, 1894–99)	Cumbria College of Agriculture and Forestry	171
	Hutton John	1916–1968	F. Huddleston	210
	Blencowe	1871–1896	T. Fawcett	183
	Greystoke Castle	1887–1925	A. Tremayne-Butler	198
	Greystoke Castle	1846–1874	T. G. Benn	213

* Where there has been more than one observer, only the observer who took the readings over the longest period is given.

Appendix B. *Individual site records used to form composite series together with corrective factors*

Gauge No.	Gauge name	Years used	Factor
1	<i>Carlisle</i>		
	Carlisle (Tabony)	1845 →	1.0
	Harraby	1840–1844	0.864
	Carlisle (Elliot)	1835–1839	0.946
	Applegarth Manse	1834	0.842
	Whinfell Hall	1829–1833	0.582
	Applegarth Manse	1827–1828	0.842
	Wigton	1825–1826	0.969
	Carlisle, Shaddongate	1801–1824	1.019
	Wigton, Aikbank	1792–1800	0.869
	Dumfries	1784–1791	0.703
	Carlisle, Abbey Street	1757–1783	1.112
2	<i>Darlington</i>		
	South Park	1923 →	1.0
	Hummersknott	1920–1922	1.0094
	Public Park	1919	1.0
	Hummersknott	1918	1.0094
	Cleveland Parade	1877–1917	0.9993
	Catterick (Tunstall)	1873–1876	1.0083
	Richmond	1843–1872	0.8789
3	<i>Barnard Castle</i>		
	Bowes Museum	1922 →	1.0
	County School	1895–1921	1.0204
	Whorlton	1881–1894	1.0918
	East Layton	1875–1880	1.0833
	Greta Bridge	1869–1874	1.0906
	Catterick (Tunstall)	1868	1.2295
	Winston	1856–1867	1.2585

Appendix B. *continued*

Gauge No.	Gauge name	Years used	Factor
4	<i>Banbury</i>		
	Grimsbury	1968 →	1.105
	West Adderbury	1925–1967	1.0
	Bodicote	1894–1924	0.964
	Bloxham Grove	1890–1893	1.009
	Cotefield Bodicote	1886–1889	0.993
	High Street	1873–1885	0.997
	Parson's Street	1850–1872	1.0
5	<i>Bedford</i>		
	Cardington (Meteorological Office)	1969 →	1.0
	Cardington (Meteorological Office)	1968	1.17
	Cardington (Meteorological Office)	1954–1967	1.0
	Castle Road	1904–1953	0.948
	St. Peter's Street	1900–1903	0.973
	The Grove	1891–1899	0.962
	Cardington Village	1846–1890	0.936
6	<i>Taunton</i>		
	Vivary Park	1910 →	1.0
	Blagdon Hill Reservoir	1894–1909	0.8485
	Norton Fitzwarren	1888–1893	0.9346
	Bishop's Lydeard	1884–1887	0.9792
	Fulland's School	1865–1883	1.1533
	Castle	1859–1864	1.1116
7	<i>Tiverton</i>		
	Willand, Losinga	1972 →	1.0
	Willand	1958–1971	0.965
	Halberton	1942–1957	1.0161
	Blundell's School	1929–1941	0.9383
	Halberton	1921–1928	0.8665
	Hartnolls	1917–1920	0.8906
	Halberton	1906–1916	0.9744
	Ivy Place	1892–1905	0.9189
	Cove	1862–1891	0.8768
	Hayne	1854–1861	0.8768
8	<i>Cullompton-Bradninch</i>		
	Bradninch, Westfield	1859 →	1.0
	Halberton	1957–1958	1.035
	Bradninch	1953–1956	1.026
	Cullompton	1881–1952	0.9771
	Clyst Hydon	1847–1880	1.1051
	Broadhambury	1837–1846	1.0455
9	<i>Ross-on-Wye</i>		
	Alton Court	1974 →	1.0
	Ross, Perrystone Court	1936–1973	0.9625
	Ross, Graig	1859–1935	0.982
10	<i>Leominster</i>		
	Leominster	1969 →	1.0
	Kimbolton, Grantsfield	1913–1968	1.0338
	Farm	1896–1912	1.0513
	Farm	1883–1895	0.9459
	West Lodge	1858–1882	1.1226
	Orleton	1831–1857	0.9964

Appendix B. continued

Gauge No.	Gauge name	Years used	Factor
11	<i>Kington</i>		
	Lyonshall	1945 →	1.0
	Lynhales	1927–1944	1.069
	Sunset	1919–1926	1.0765
	Pembridge, Weobley	1918	1.211
	Lynhales	1874–1917	1.0237
	Lynhales	1867–1873	1.1566
	Orleton	1856–1866	1.1616
	Titley	1848–1855	1.199
	Titley	1841–1847	1.0241
12	<i>Penrith</i>		
	Tirrill	1975 →	1.0
	Castle Park	1954–1974	1.233
	Benson House	1931–1953	1.2208
	Fell Lane, Fir Bank	1874–1930	1.3212
	Brougham Hall	1851–1873	1.2562
13	<i>Appleby</i>		
	Castle Bank	1890 →	1.0
	Appleby	1857–1889	1.0
14	<i>Patterdale</i>		
	Patterdale Hall	1961 →	1.0
	Greenside Mine	1957–1960	0.9453
	Patterdale Hall	1860–1956	1.0
15	<i>Newton Rigg</i>		
	Newton Rigg	1951 →	1.0
	Hutton John	1950	0.7285
	Newton Rigg	1926–1949	1.0226
	Greystoke Castle	1887–1925	0.8517
	Blencowe	1874–1886	0.9218
	Greystoke Castle	1846–1873	0.9265

Notes and news

Retirement of Dr Gwyn James

Dr D. G. James. Chief Meteorological Officer, Meteorological Research Flight, Farnborough, retired from the Meteorological Office on 17 September 1982 after a career of 32 years.

Gwyn James was educated at Barry County School and University College, Cardiff. After two years working at the Telecommunications Research Establishment (Malvern) and in industry, he returned to Cardiff to complete the honours course in mathematics and in 1950 obtained a Ph.D. for research into flow over two-dimensional aerofoils. He joined the Meteorological Office later that year as a Scientific Officer and after a period of forecasting training was posted to the Meteorological Research Flight at Farnborough. There he did pioneer work on the measurement of the fine scale structure of convection.

In 1954 Dr James moved to the Forecasting Research Division at Dunstable where he developed statistical techniques for forecasting dissipation of stratocumulus and formation of cirrus, and in November of that year was promoted to Senior Scientific Officer. In December 1956 a posting to the Central Forecasting Office began a period of upper-air forecasting duties which were to take him, during 1958, to Christmas Island and in 1959 to London (Heathrow) Airport.

In 1960 Dr James returned to research, joining the High Atmosphere Branch at Kew Observatory. There he became responsible for developing data interpretation techniques for the Meteorological Office's first satellite experiment. He was promoted to Principal Scientific Officer in 1961 and, shortly after, spent a year with the Satellite Group of the US Weather Bureau. During that period in Washington he studied the application of satellite cloud pictures to forecasting and took part in ground-based experiments which were to lead to development of the first instrument for measuring atmospheric temperature profiles from space. Dr James was to return to the USA in 1964 and 1969 to participate in critical tests of this satellite instrument and the experience led to his involvement, as a consultant to the European Space Research Organization, in a study of a possible European polar-orbiting meteorological satellite.

But that is jumping ahead. In 1963 Dr James rejoined the High Atmosphere Branch, by then at Bracknell, and developed balloon-borne sensors to measure atmospheric radiation and stratospheric humidity. After a brief spell in the Forecasting Research Branch, he was transferred in 1966 to the newly formed Cloud Physics Branch. He headed the cloud dynamics group and took a major part in the planning, execution and data analysis for Project Scillonian, an important series of field-studies of warm fronts involving deployment of radars on the Isles of Scilly and our meteorological research aircraft.

Dr James was promoted to Senior Principal Scientific Officer in July 1971 and took up the post of Chief Meteorological Officer, Meteorological Research Flight. His first major task was planning and preparation for conversion of a Hercules C-130 into the Flight's main research aircraft. It had been agreed that the aircraft would take part, in the summer of 1974, in an international experiment, known as GATE, to study organized convection over the tropical Atlantic. Delays to delivery of the aircraft resulted in only six months being available for installation and testing of the meteorological instrumentation. Through his enthusiasm and organizing ability the task was completed in time for the C-130 to play a major role in GATE. In following years, he collaborated with research branches and outside organizations to extend the scope of on-board instrumentation, particularly for cloud physics and atmospheric chemistry. A measure of his achievement is that the C-130 is now one of the best meteorological research aircraft in the world, much in demand for international collaborative experiments (such as JASIN and KONTUR) and providing observational data for many research projects in the Meteorological Office. Until quite recently Dr James flew regularly in the C-130.

Dr James's enthusiasm linked with a balanced judgement have gained him the respect and co-operation of all who have come into contact with him. These qualities and his wide experience have been particularly valuable in management of the Meteorological Research Flight. He is a keen golfer and, as befits a Welshman, a talented singer with wide interests in music. He has thoughts of moving from Virginia Water to be nearer the hills of Wales. We wish Gwyn and his wife Vida a long and happy retirement. *Hir oes a llawenydd iddynt!*

D. E. Miller

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NOTICES

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An aircraft encounter with a tornado

By W. T. Roach and J. Findlater

(Meteorological Office, Bracknell)

Summary

The loss of an aircraft near Rotterdam on 6 October 1981 was attributed to an encounter with a tornado. Evidence supporting this claim is presented, followed by a discussion of the associated meteorological situation. A rough estimate of the probability of encounter with a tornado is given and some aspects of the use of radar in detecting and forecasting severe storms and tornadoes are briefly described.

1. Introduction

At 1604 GMT on 6 October 1981, a Fokker F-28 aircraft (PH-CHI) took off from Rotterdam *en route* to Eindhoven. There were thunderstorms in the area and the aircraft, flying at 3000 ft (900 m), entered one of them a few minutes after take-off. After a short period of moderate turbulence in cloud, the aircraft suddenly encountered extreme turbulence in which the starboard wing was detached and, at 1612 GMT, the aircraft crashed near Moerdijk, about 25 km south-south-east of Rotterdam, with the loss of all occupants.

It soon transpired that a tornado was reported just west of Moerdijk a few minutes before the crash, and in fact a police launch travelling east along the Hollandsch Diep had not only taken a series of photographs of the tornado, but also — less than a minute later — of the cloud of smoke rising from the aircraft impact explosion. This, together with other evidence provided by the Director of the Aeronautical Inspection Directorate of the Dutch Civil Aviation Authority showed that it was very likely that the aircraft encountered the tornado circulation in cloud shortly after the tornado funnel had lifted from the ground.

The flight safety implications raised by this incident led the Dutch and British Civil Aviation Authorities to ask the United Kingdom Meteorological Office to assess the probability of a tornado encounter in flight, and whether it was necessary or possible to make special arrangements to forecast tornado conditions.

Since, as far as we are aware, this is the only case of an aircraft encounter with a tornado whilst in flight for which it so happened that adequate evidence was available, the Dutch Civil Aviation Authority agreed that an account of the incident should be published after the findings of the official enquiry were released.

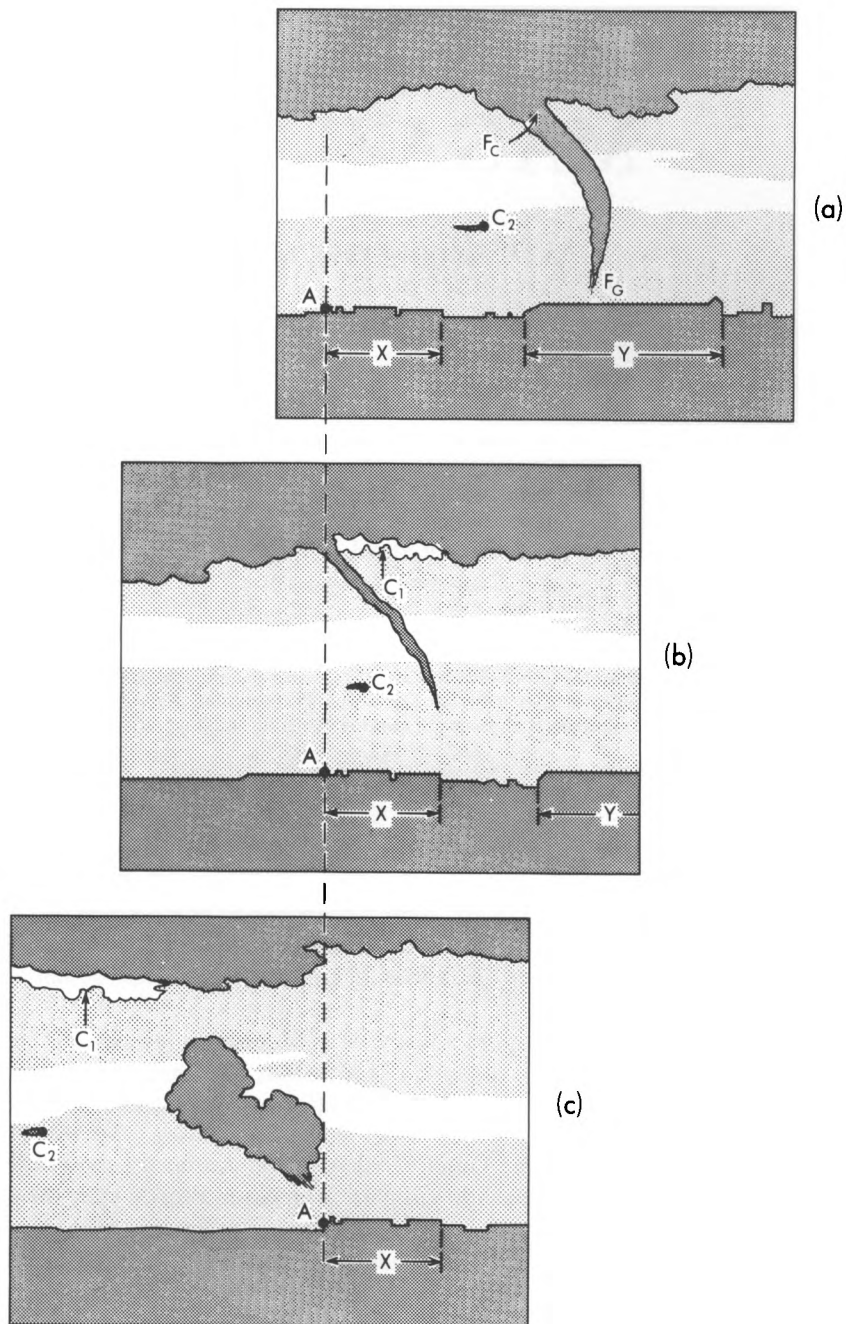


Figure 1. Drawings based on photographs 1, 8 and 16 of the series taken from the police launch. The labelling is explained in the text. Fig. 1(c) shows the cloud of smoke ejected from the aircraft crash. The corresponding photographs are shown on the facing page.



There are three parts to the account: the first presents and discusses the evidence that the aircraft did encounter a tornado circulation; the second discusses the meteorological situation; and the third presents an estimate of the probability of aircraft–tornado encounter in the United States and in north-west Europe.

2. The evidence for tornado encounter

The evidence for encounter of the F-28 aircraft with a tornado is based on the following material kindly provided by the Dutch Civil Aviation Authority:

- (a) Fifteen prints of the Moerdijk tornado and two prints of the aircraft explosion cloud taken by a police launch on the Hollandsch Diep. (See Fig. 1.)
- (b) Two colour prints of the same tornado from another site a few minutes earlier.
- (c) A 1:10 000 scale map of the Moerdijk area indicating the aircraft track, the location of the police launch and the position from which the colour photographs were taken, with direction lines. Also indicated is the tornado track based on surface damage. (See Fig. 2.)
- (d) A copy of the flight record recovered from the aircraft wreckage. (See Fig. 3.)
- (e) Hourly maps of radar echo distribution for the period 1300–1700 GMT on 6 October 1981.

Unfortunately, but not surprisingly, the times of the photographs were not recorded. However, the lateral movement of cloud features C_1 and C_2 relative to a fixed ground point A (Figs 1(a) and (b)) enabled a relative time scale to be assigned to the police launch prints. Confidence in this procedure is given by a plot of the coordinates of C_1 and C_2 against each other which shows an almost perfectly straight line (correlation coefficient 0.997) (Fig. 4). Also plotted against C_2 are the coordinates of the bottom (F_G) and the visible top (F_C) of the tornado funnel. These show rather more scatter about a straight line, but indicate that the tornado circulation as a whole was moving at a roughly constant speed.

C_1 and C_2 are also identifiable on the prints of the aircraft explosion cloud. Backward extrapolation of the two explosion cloud images enables a time of aircraft–ground impact to be located on the relative time scale (Fig. 4) within fairly narrow limits.

The colour photograph direction lines drawn on the Moerdijk map yield an angular calibration on these photographs of 0.037 radians per centimetre from which it appeared that the width of the tornado funnel near cloud base was about 100 m and decreasing, and the height of cloud base was about 400 m. The tornado damage path indicated in the map was over 300 m wide and showed that the funnel cloud marks the centre of a much bigger circulation.

There were no direction lines drawn for the police launch photographs, and it proved difficult to identify surface features appearing on the prints with those on the map. However, the images of the tornado and associated cloud are of similar size on both colour and police launch photographs, and were taken from a similar distance (about 2 km). Using this fact, it appears that building complexes X and Y on the photographs (Fig. 1) were probably those marked X and Y on the map (Fig. 2), and this has been assumed in the subsequent analysis. The point A marking the left of the building complex X on Fig. 1 was directly in line with the aircraft impact point, and is thought to correspond with the point A on Fig. 2.

The location of the centre of the tornado circulation at the time of aircraft–ground impact is estimated to lie near α on Fig. 2, and is obtained by extrapolating the line F_C to the impact point on the relative time scale in Fig. 4.

Evidence from the flight recorder, (Fig. 3) has been used to estimate the location of the aircraft along its track at 5-second intervals relative to time of impact as marked in Fig. 2.* The accelerometer record

*For the purpose of this estimate, ground speed was assumed equal to indicated air speed corrected for descent angle. Corrections for wind (outside the tornado circulation) and for air density are of the order of 5% and are neglected.

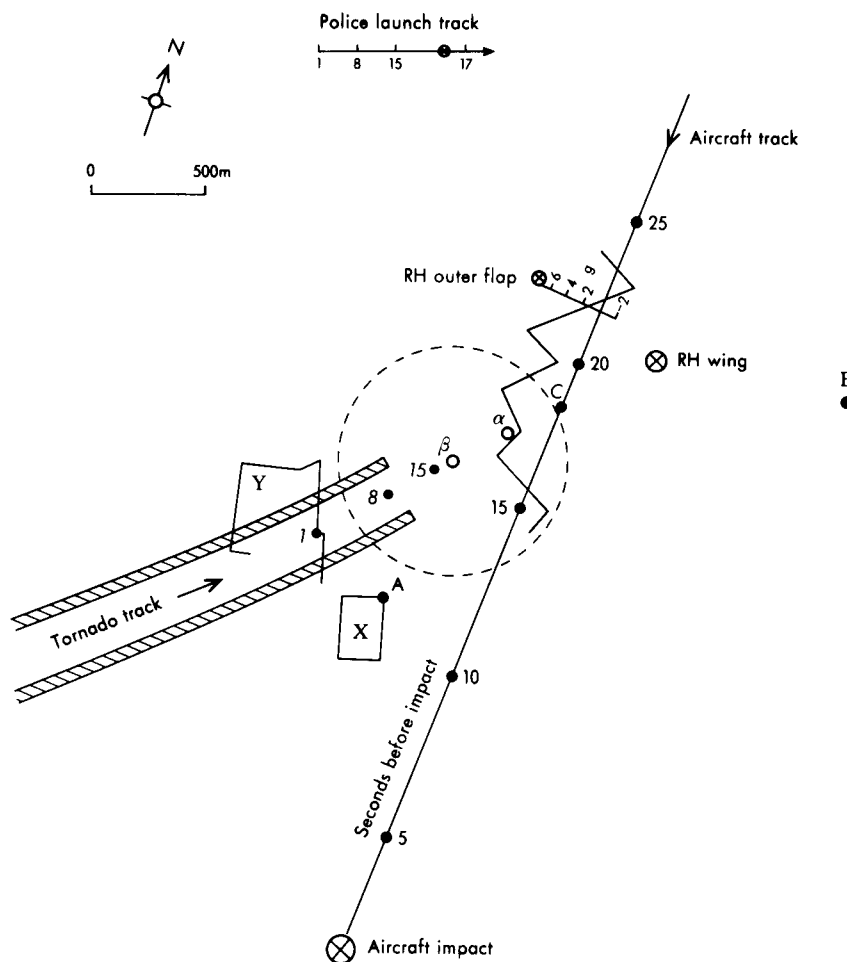


Figure 2. Sketch map of tornado and aircraft tracks. Labelling is explained in the text.

has been superimposed on the aircraft track in Fig. 2. The main 'g-spikes' are close to the intersection of the aircraft track with the projected tornado track (C in Fig. 2) about 18 seconds before impact, and to the position of impact of the starboard wing and flap, while the disturbance in which the g-spikes are embedded appears to have affected about 1 km of the aircraft track. However, C appears to be ahead of the estimated centre of the tornado circulation (α) when the aircraft crashed 18 seconds later. The location of this circulation at the time the aircraft was at C cannot be directly estimated as the speed of the tornado is not known and the relative time scale (Fig. 4) has not been calibrated. However, there are indirect indications:

(a) The sequence of radar pictures (one of which is shown in Fig. 14) show that the storm complex which passed over the site of the accident was moving north-east at about 20 m s^{-1} . It is likely that the tornado circulation was being carried by the storm complex at about the same speed.

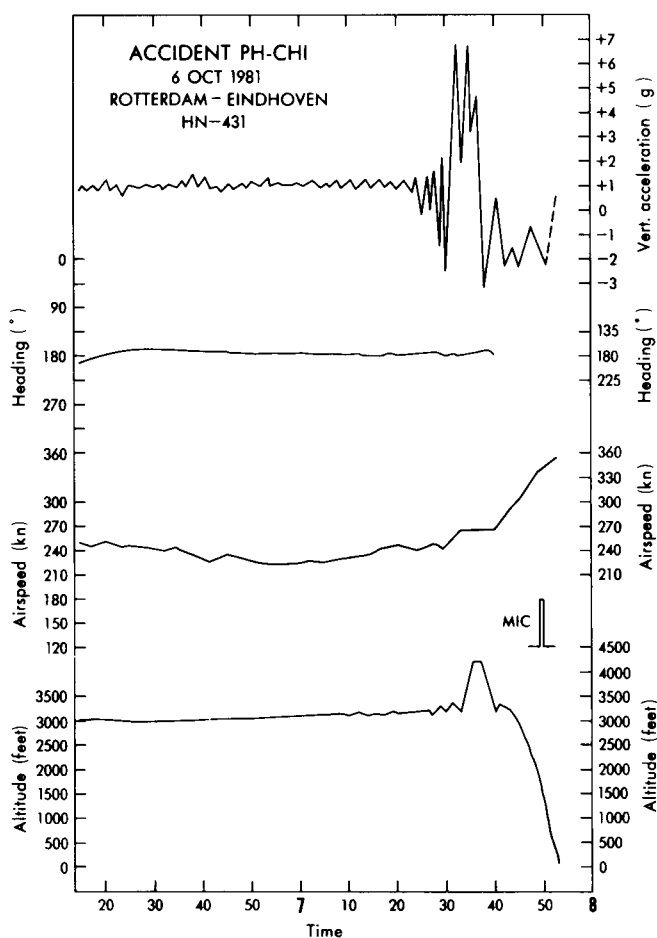


Figure 3. Copy of part of the flight record recovered from the crashed aircraft. Time is in minutes and seconds from take-off.

(b) Reference to Fig. 2 shows that the funnel cloud was moving about 50% faster than the police launch. The inferred speed of 13 m s^{-1} for the police launch seems fast if photographs were being taken from it, but it may have been trying to 'keep up' with the funnel. We consider that the speed of translation of the tornado circulation was about 15 m s^{-1} .

The estimated position of the centre of the tornado circulation when the aircraft was at C (Fig. 2) is probably within 200 m of β . A circle of 500 m centred on β intersects the aircraft track during the latter part of the most disturbed part of the g -trace. Hence it appears that the aircraft probably encountered the tornado circulation and crashed as a result.

Finally, the temporary indicated height increase of about 300 metres, due to a recorded decrease of pressure of 29 mb, immediately after the main g -spike is of interest. This may be partly real owing to the large vertical velocities usually associated with tornado circulations, and partly spurious owing to the drop of pressure within the tornado and/or rapid attitude changes of the aircraft after or during the detachment of its wing creating anomalous aerodynamic effects at the altimeter orifice.

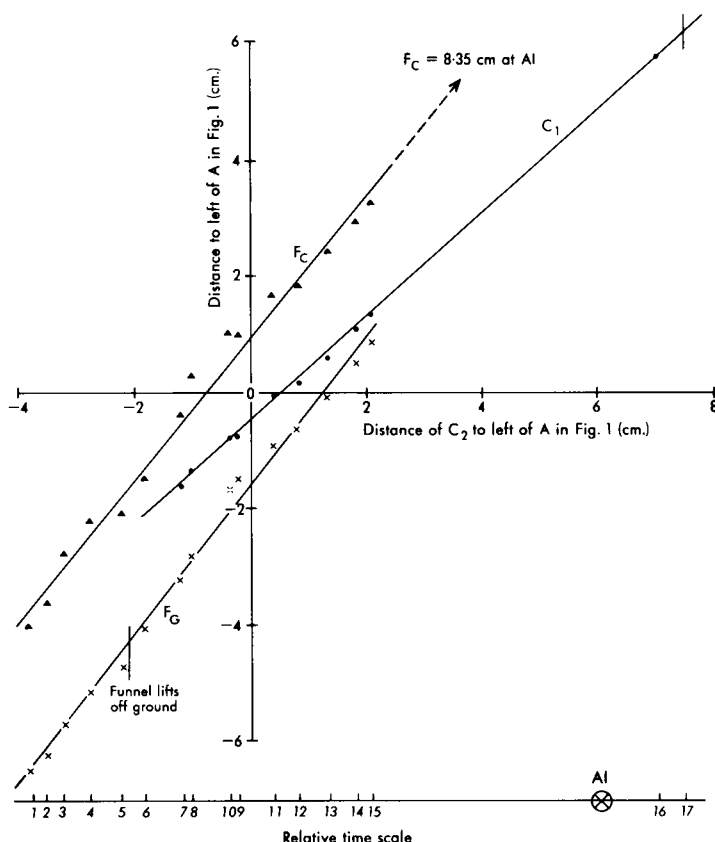


Figure 4. Establishment of a relative time scale using the police launch photographs. Explanation is given in the text.

3. The meteorological conditions

3.1 General situation

At 1200 GMT on 5 October 1981 a small depression was approaching the north of Ireland from the west whilst a diffuse warm or quasi-stationary front lay close to the line Lisbon–Paris–Cologne. This front, originally of double or complex structure, was analysed in differing forms and positions by different meteorological centres. In this report, however, it is considered to be the genesis of a warm front since it developed more pronounced characteristics as warm advection set in over the continent of Europe. A depression west of Portugal induced a wave on the front which developed and moved north-eastwards to become centred in the English Channel by 1200 GMT on 6 October. Meanwhile the associated warm front advanced northwards across Europe, passing over most of the Netherlands between 0600 and 1800 GMT. The cold front of the same depression moved quickly across the Bay of Biscay and France, and passed over the Netherlands between 1500 and 2000 GMT.

Subsequently, the wave depression moved over the North Sea and amalgamated with the Atlantic depression which had become slow moving near the north of Scotland. Fig. 5 shows the general synoptic situation at 1200 GMT on 6 October 1981 and the depression tracks as given in the relevant *Daily Weather Summary* of London Weather Centre.

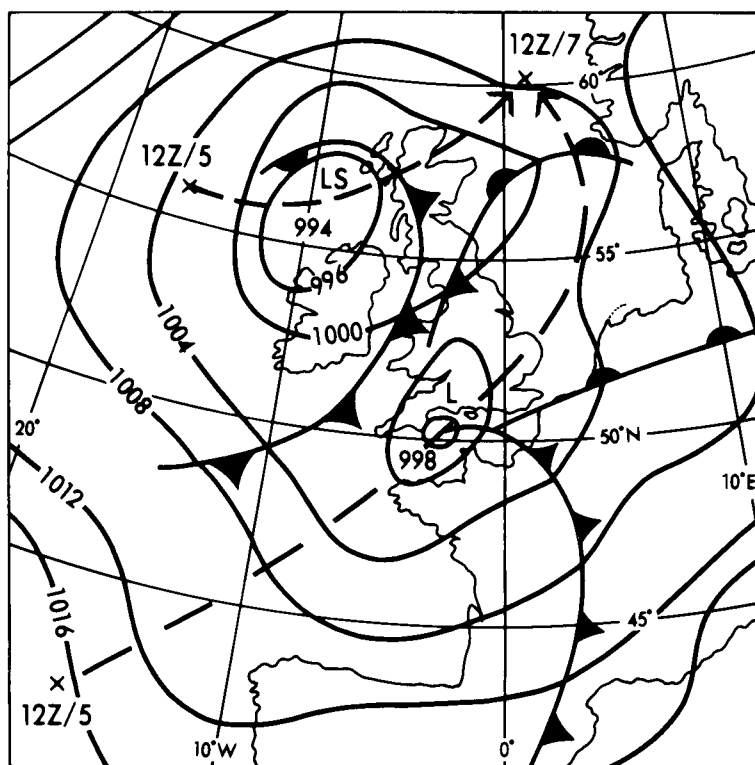


Figure 5. Synoptic situation at 1200 GMT on 6 October 1981.

3.2 Surface charts

Hourly surface charts from 1200–1800 GMT have been analysed in detail but only those for 1200, 1500 and 1800 GMT are reproduced in Figs 6–8. By 1500 GMT (Fig. 7) rain associated with the warm front had cleared from the Rotterdam area which was then covered by a light southerly flow of warm moist air with dew-point temperatures of 15–16 °C. The cold front was advancing rapidly from the west at about 26 m s^{-1} preceded by outbreaks of thundery rain and thunderstorms. Observational evidence indicates that the area of thundery activity ahead of the cold front was typified by generally stronger surface winds, a reduction in the fall of pressure and a distortion in the surface pressure field. The characteristics suggest that cold air was overrunning the surface cold front in the lower levels. There is insufficient evidence to place the upper cold front precisely, and indeed it may have been a diffuse feature, but what evidence there is, and considerations of continuity between the hourly analyses, indicate that the overrunning cold air extended to 90 km or more ahead of the surface feature. The surface and upper cold front positions are shown in Figs 6–8 and the hourly positions and speeds of these fronts are shown in Fig. 9; this shows that the upper cold front, heralding the arrival of thunderstorms, crossed the accident site at approximately 1545 GMT and the surface cold front passed the same site at about 1640 GMT bringing clearing weather.

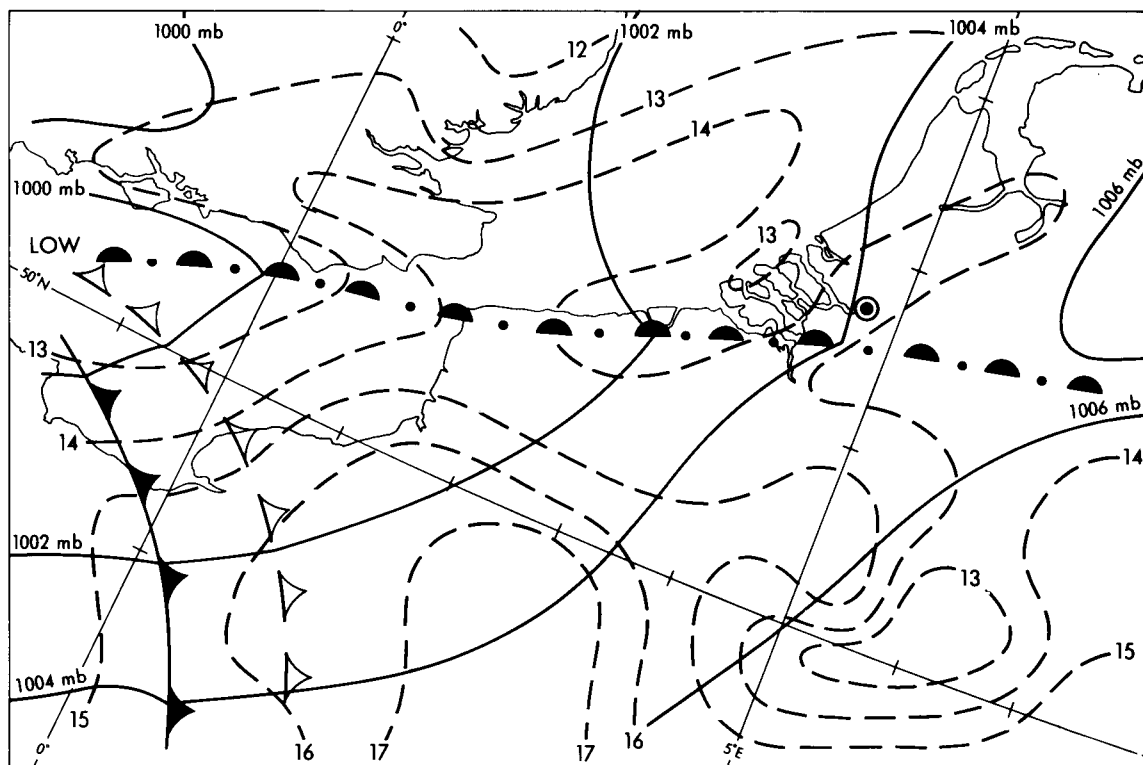


Figure 6. Surface analysis for 1200 GMT on 6 October 1981, showing distribution of wet-bulb potential temperature (θ_w) at the surface.

3.3 Upper-air charts

At 1200 GMT on 6 October 1981 a major upper trough lay to the west of the British Isles with a strong jet stream on its eastern flank. At 300 mb the jet axis was from the south-west over central France with a speed of 50 m s^{-1} . At 500 mb and 700 mb the speeds on the jet axis were 37 m s^{-1} and 30 m s^{-1} respectively. At 700 mb and 850 mb the jet displayed several axes. Fig. 10 illustrates the jet axes at 850 mb with speeds of $22\text{--}27 \text{ m s}^{-1}$ and Fig. 11 shows the sounding made at Trappes at 1200 GMT. A feature of particular interest at 850 mb is the very strong cyclonic shear zone lying along the coasts of France and Belgium and extending to the western part of the Netherlands at 1200 GMT.

An analysis of 850 mb wet-bulb potential temperature, (θ_w), also shown in Fig. 10, indicates the position of the northward-moving warm front and, less markedly, the cooler and drier air over France behind the cold front. The geometry of the analysis between Paris and Brussels indicates some intrusion of the cooler and drier air ahead of the position of the surface cold front at this time preceded by a tongue of somewhat warmer and moister air. Values of θ_w at the surface level near Paris and the area to the north-east were typically $16\text{--}17^\circ\text{C}$ in south-south-westerly winds of 10 m s^{-1} or less whilst at 850 mb air from the south-west with the value of θ_w at Paris of 13°C was penetrating overhead at more than 20 m s^{-1} . It is unfortunate that no upper-air sounding at 1200 GMT was made in the zone between the two fronts to confirm the marked potential instability, and latent instability, which must have been building up in the area north and north-east of Paris at this time, though the Trappes ascent was made just ahead of the upper, probably diffuse, cold front and indicates some of the characteristics of the zone.

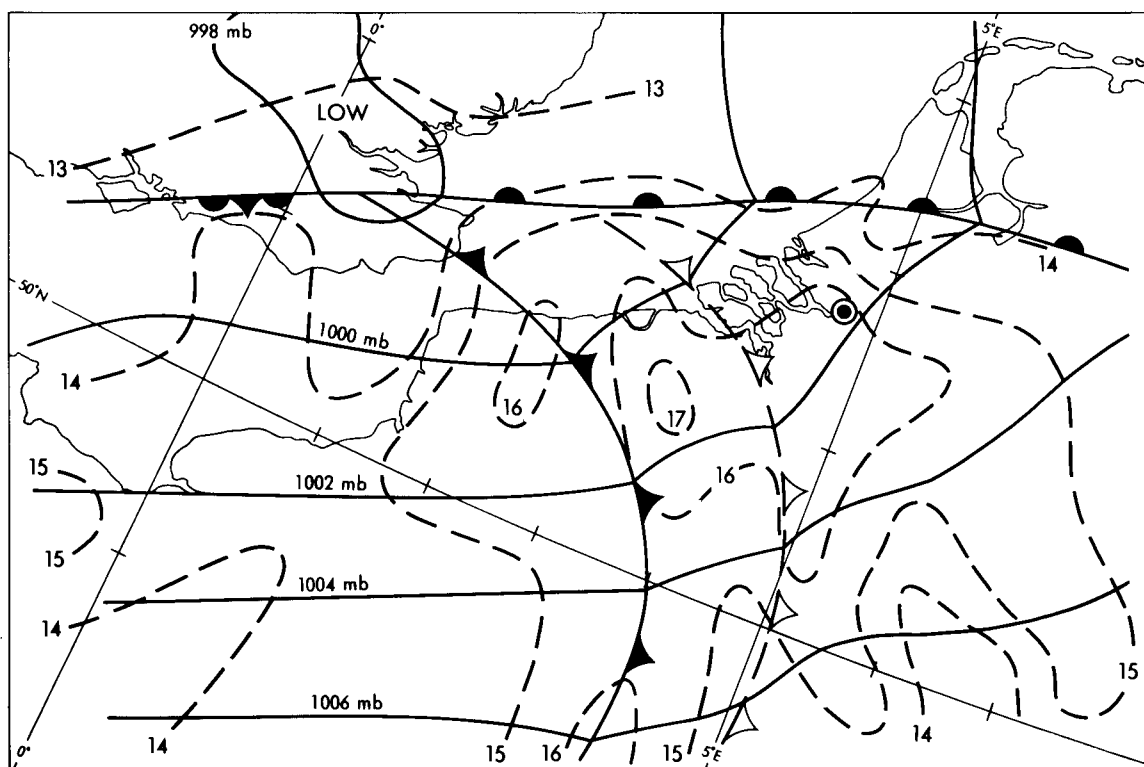


Figure 7. As Fig. 6 but for 1500 GMT.

3.4 Autographic records

The only relevant autographic records near the observed tornado track or the scene of the accident were from an anemograph situated at an air pollution monitoring station at point B in Fig. 2. A reproduction of the records of surface wind direction and speed is shown in Figs 12(a) and (b). The wind speed in the original record is shown as a series of dots at short time-intervals but this record has been simplified in Fig. 12(b) by showing lines denoting maximum, mean and minimum wind speeds only.

The record shows increasing wind speeds between 1535 and 1545 GMT with a gradual veer of surface wind from east of south to a little west of south, probably due to the downward transfer of momentum from the increasing south-westerly winds above the surface as the upper cold front passed. A second increase in wind speed occurred between 1640 and 1650 GMT and the wind veered to a westerly at 1650 GMT as the surface cold front passed. Between these two events lighter surface winds of about $4\text{--}7\text{ m s}^{-1}$ obtained and marked directional changes took place. These directional changes are analysed in Fig. 12(c) and sketched streamlines suggest that a tornado cyclone (see Fujita 1959) passed the station between 1612 and 1622 GMT disturbing the generally south-westerly wind field, and that a cyclonically rotating vortex passed a few hundred metres to the north of the anemometer site at 1619 GMT. It has been shown earlier that the aircraft intercepted the tornado circulation in cloud within a minute of 1612 GMT when the tornado funnel had lifted from the surface. The assumed speed of that tornado, though dissipating at the surface, would have placed it a few hundred metres to the north of the anemometer site at about 1613–1614 GMT some 5–6 minutes earlier than a vortex was deduced to have passed there.

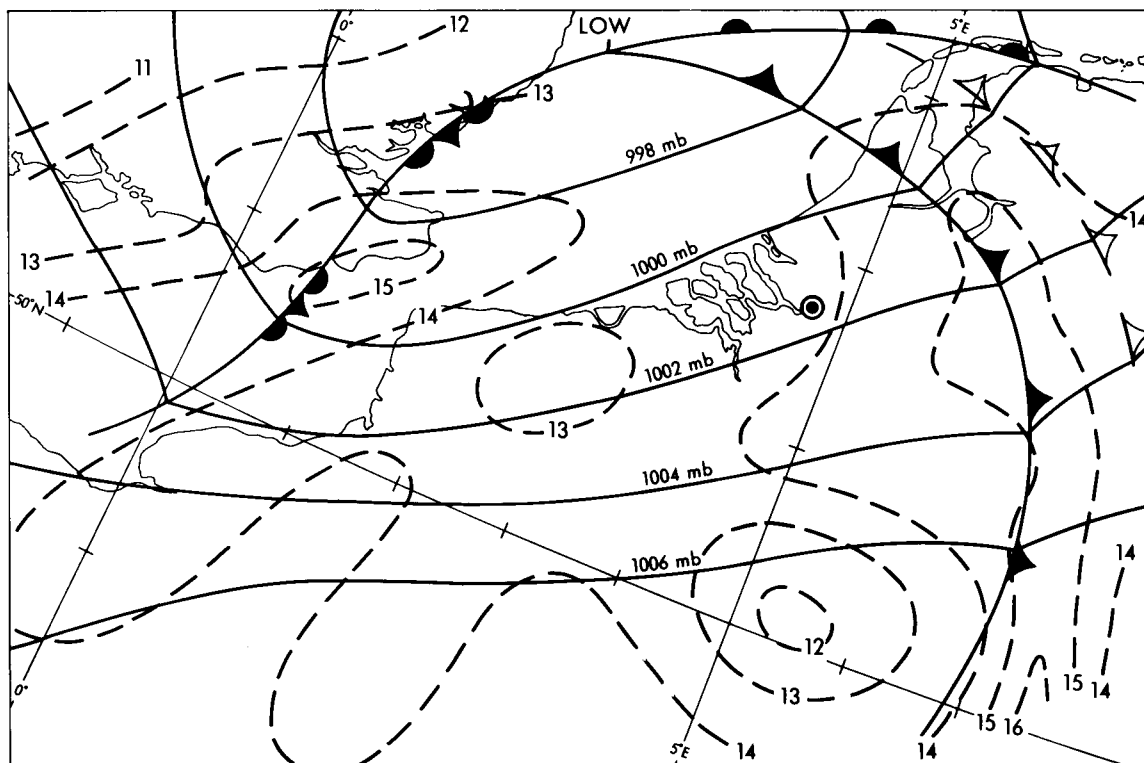


Figure 8. As Fig. 6 but for 1800 GMT.

However, there may be an error in the timing of the anemograph record or there may have been more than one tornado or vortex in the wider area of the tornado cyclone. Indeed, eyewitnesses, and one photograph, give evidence of two tornado funnels in the area just before the accident.

3.5 Discussion

Potential instability produced in the zone between the surface and upper cold fronts by differential advection was released mainly by lifting due to convergence in the area. Surface wind convergence was pronounced in a discrete area shown in Figs 13(a), (b) and (c) and the area of maximum convergence passed close to the accident site shortly after 1500 GMT (Fig. 13(b)). The positions of surface wind reporting stations used to compute divergence and vorticity are shown by dots in Fig. 13.

The development of convergence was associated with a zone of cyclonic vorticity lying along the coast of continental Europe into the southern North Sea (Figs 13(d), (e) and (f)). A line of maximum vorticity can also be discerned in association with the cold fronts, and this line passed across the accident site with the cold fronts. It can be deduced that the area and line of maximum cyclonic vorticity resulted in surface convergence which in turn contributed to the release of potential and latent instability. The instability extended through a deep layer as shown by the reporting of thunderstorm activity by the United Kingdom Sferic (atmospheric) network. This activity was remotely located at 1200 GMT in an area of approximate radius 65 km over northern France and located hourly until 1800 GMT. Hourly positions of the centre of this area are shown in Fig. 9 and it is evident that this area was centred somewhat behind the upper cold front and ahead of the surface cold front. The centre of the area passed between

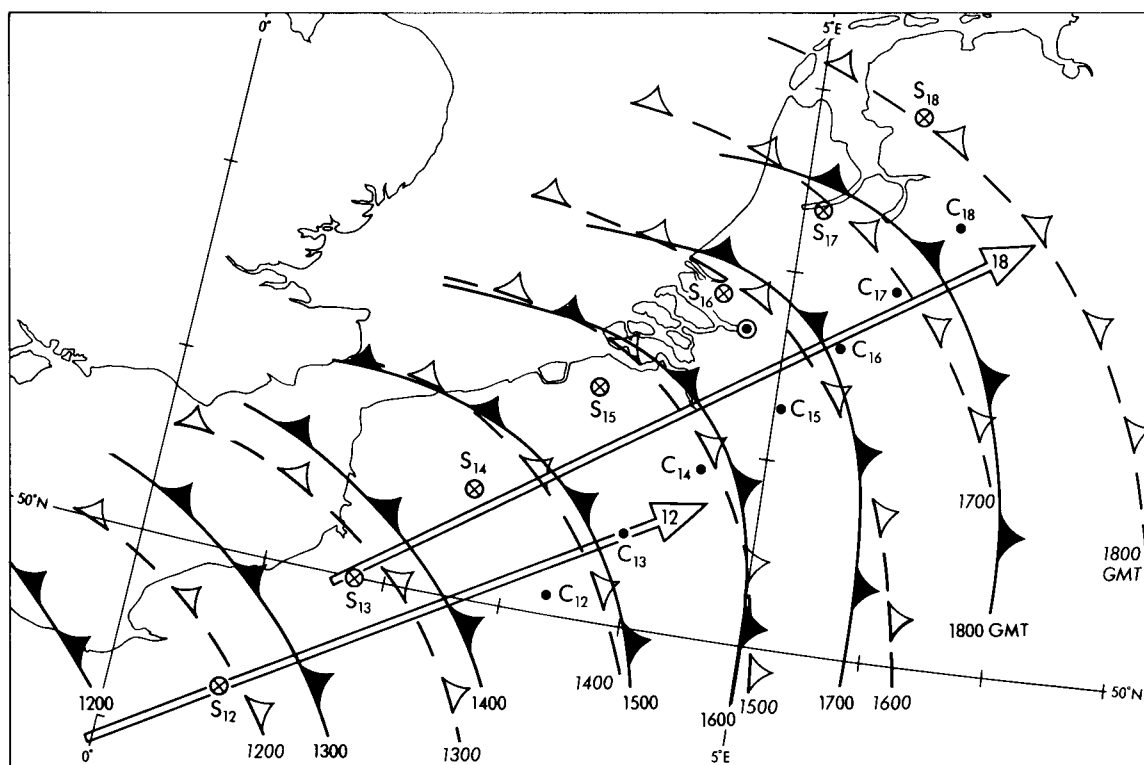


Figure 9. Continuity chart, 6 October 1981.

- △ — △ — △ Upper cold front
- ▲ — ▲ — ▲ Surface cold front
- ⊗ S_{hh} Centre of Sferic (thunderstorm) activity at hour hh (GMT) (Radius of active area 65 km approximately)
- C_{hh} Position of maximum surface wind convergence at hour hh (GMT)
- ⇨ hh Jet axis at 850 mb at hour hh (GMT)
- ⊙ Accident site

Rotterdam and the accident site at about 1600 GMT and one of the radar images from De Bilt at this time is shown in Fig. 14, on which the frontal positions have been superimposed. The position of the jet axis at 850 mb at the same time, interpolated from the 1200 and 1800 GMT positions shown in Fig. 9, is also included in Fig. 14. The centre of the area of maximum convergence passed to the south-east of the accident site between 1500 and 1600 GMT. Three-hourly positions and interpolated hourly positions are included in Fig. 9.

The radar images taken from De Bilt at hourly intervals indicated that the organized thunderstorm cells associated with the area between the surface and upper cold fronts were moving at about 25 m s^{-1} past the south and east of the accident site, whilst those passing to the west and north of the site were travelling at about 17 m s^{-1} . Since the accident site lay on the northern flank of the jet axis at low level in the zone of pronounced cyclonic shear, and hence in a region of cyclonic vorticity, upward motion and

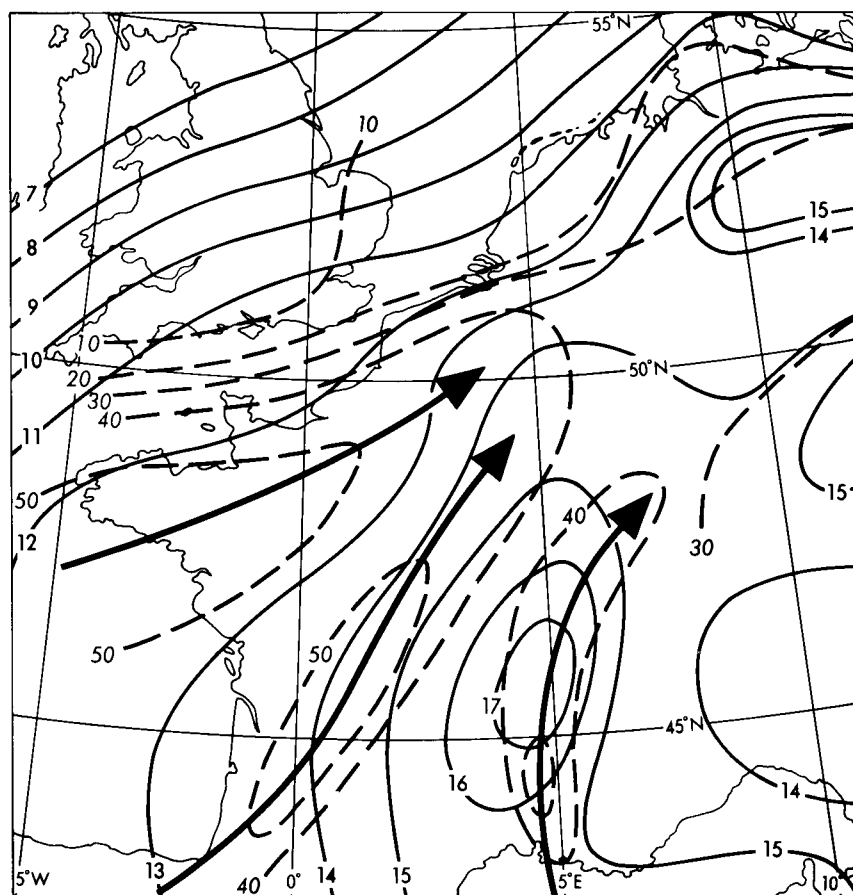


Figure 10. Selected streamlines and isotachs (dashed lines) of 850 mb flow at 1200 GMT on 6 October 1981. θ_w at 850 mb is indicated by continuous lines. (Isotachs are in knots; 1 kn = 0.5148 m/s⁻¹)

the subsequent release of latent heat and potential instability would further locally intensify the low-level convergence and lead to the concentration of cyclonic vorticity with which tornadic storms are associated. In these circumstances tornado cyclones form, with diameters typically of 5–40 km, and may contain one or more actual tornadoes.

It was reported that a hook-shaped radar echo was visible on a photograph of the De Bilt radar image at 1600 GMT in the southern part of the large echo which adjoins the accident site in Fig. 14. No precise position or size has been given for this significant echo and it cannot be discerned on the radar tracing in Fig. 14. However, hook-shaped radar echoes have often been reported in the United States just prior to the appearance of surface tornadoes, and the dimension (along the wind) of 13 km of the tornado cyclone deduced from Fig. 12 and the dimension (across the wind) of 14 km of the swath of damage of tornado funnel sightings at Moerdijk, Hellegatsplien, Ridderkerk and Puttershoek to Hendrik Ido Ambacht, provide very strong evidence of the presence of a tornado cyclone on this occasion.

It has been suggested by several authors (e.g. Browning and Ludlam (1962), Browning (1965a, b), Browning and Atlas (1965), and Carlson and Ludlam (1968)) and by experience, that the formation of organized severe local storms requires that several conditions should be satisfied. These are:

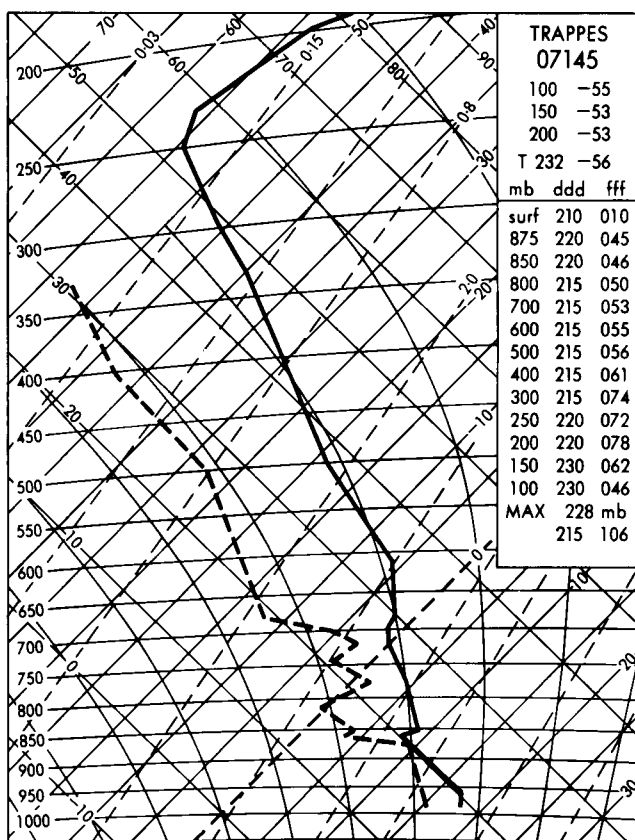


Figure 11. Upper-air sounding from Trappes (France) at 1200 GMT on 6 October 1981. Wind speeds (fff) are given in knots (1 kn = 0.5148 m s⁻¹).

(a) A supply of warm moist air at low levels. The possibility of severe storms should be considered if θ_w exceeds about 15 °C, but cannot be ruled out at lower values of θ_w .

(b) Great depth of instability.

(c) Great buoyancy indicated by a large excess of surface or low-level θ_w over the saturation wet-bulb potential temperature (θ_s) in the middle or upper troposphere.

(d) Vertical wind shear extending from a jet stream of about 50 m s⁻¹ at 300 mb down through the convective layer with strong directional shear of the order of 15 m s⁻¹ between the surface and 850 mb levels (intense warm advection) is particularly favourable for storm formation.

(e) Trigger action by daytime surface heating, low-level convergence, or orographic uplift.

(f) Northward advection of air warmed over Europe, especially Spain, may form a lid to small-scale convection such that low-level moisture is confined beneath it and high buoyancy can develop before it is finally released.

The meteorological conditions upwind of the accident site prior to that event correspond well with these criteria. Surface values of θ_w in excess of 16 °C had spread into the Netherlands by 1500 GMT (Fig. 7) and a great depth of real latent instability was evident from the upwind Trappes sounding at 1200 GMT near the upper cold front, where θ_w at the surface was 17 °C and θ_s at 500 mb was 14 °C (Fig. 11).

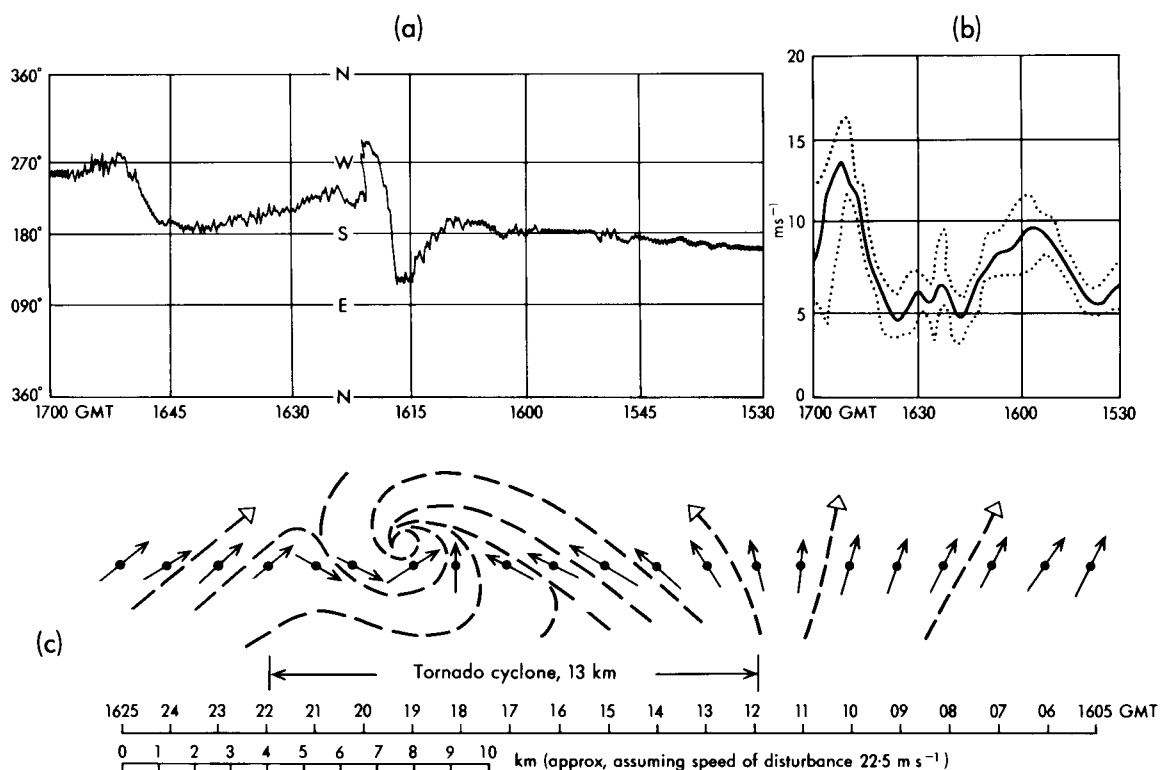


Figure 12. Anemogram traces (a), (b) from air pollution monitoring station at Moerdijk on 6 October 1981 and the deduced airflow (c) in the vicinity. The site of the anemometer is at point B in Fig. 2.

Also, pronounced low-level warm advection was taking place and the shear between the winds at the surface (240° , 5 m s^{-1}) and 850 mb (220° , 23 m s^{-1}) at Trappes was 18 m s^{-1} . With surface winds over the Netherlands at 1500 GMT of 180° , 7 m s^{-1} and 850 mb winds of 240° , $22\text{--}24 \text{ m s}^{-1}$ penetrating into the area (240° , 27 m s^{-1} at De Bilt at 1800 GMT) the shear in the lowest 150 mb was at least 20 m s^{-1} in the vicinity of the accident site. Daytime heating and pronounced low-level convergence were present to release the instability. The instability may have been suppressed earlier in the day by the shallow stable layer evident at Trappes at 1200 GMT between the levels of 860 and 853 mb.

It may be concluded that the air mass between the surface and upper cold fronts was favourable for the development of severe convective storms, and it was especially so in the area bounded in the south by the axis of the jet stream at 850 mb and in the north by the coastline on the edge of the strong upper winds at 850 mb.

4. Estimated probability of aircraft–tornado encounter

4.1 Background

Climatological tornado statistics in the United States are used to estimate the frequency of encounter in the 'worst' tornado areas, and are then related to the (rather small) amount that is known about UK tornadoes. It is assumed that tornado occurrence over south-east England is roughly representative of that over low-lying parts of north-west Europe. The basic method is as follows:

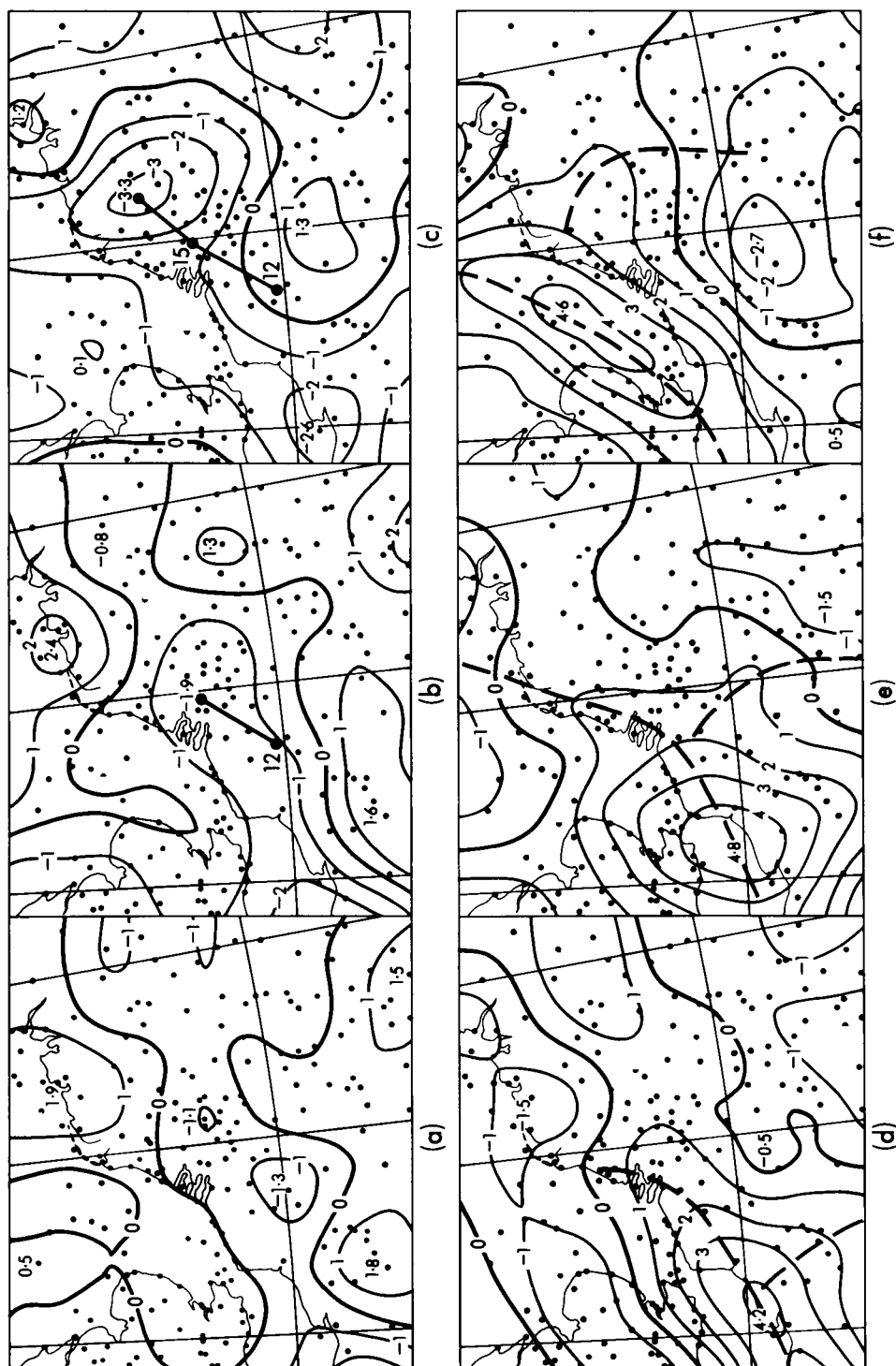


Figure 13. Surface wind divergence and vorticity on 6 October 1981.
 Divergence at (a) 1200 GMT, (b) 1500 GMT, (c) 1800 GMT
 Vorticity at (d) 1200 GMT, (e) 1500 GMT, (f) 1800 GMT
 Units: 10^{-5} s^{-1}

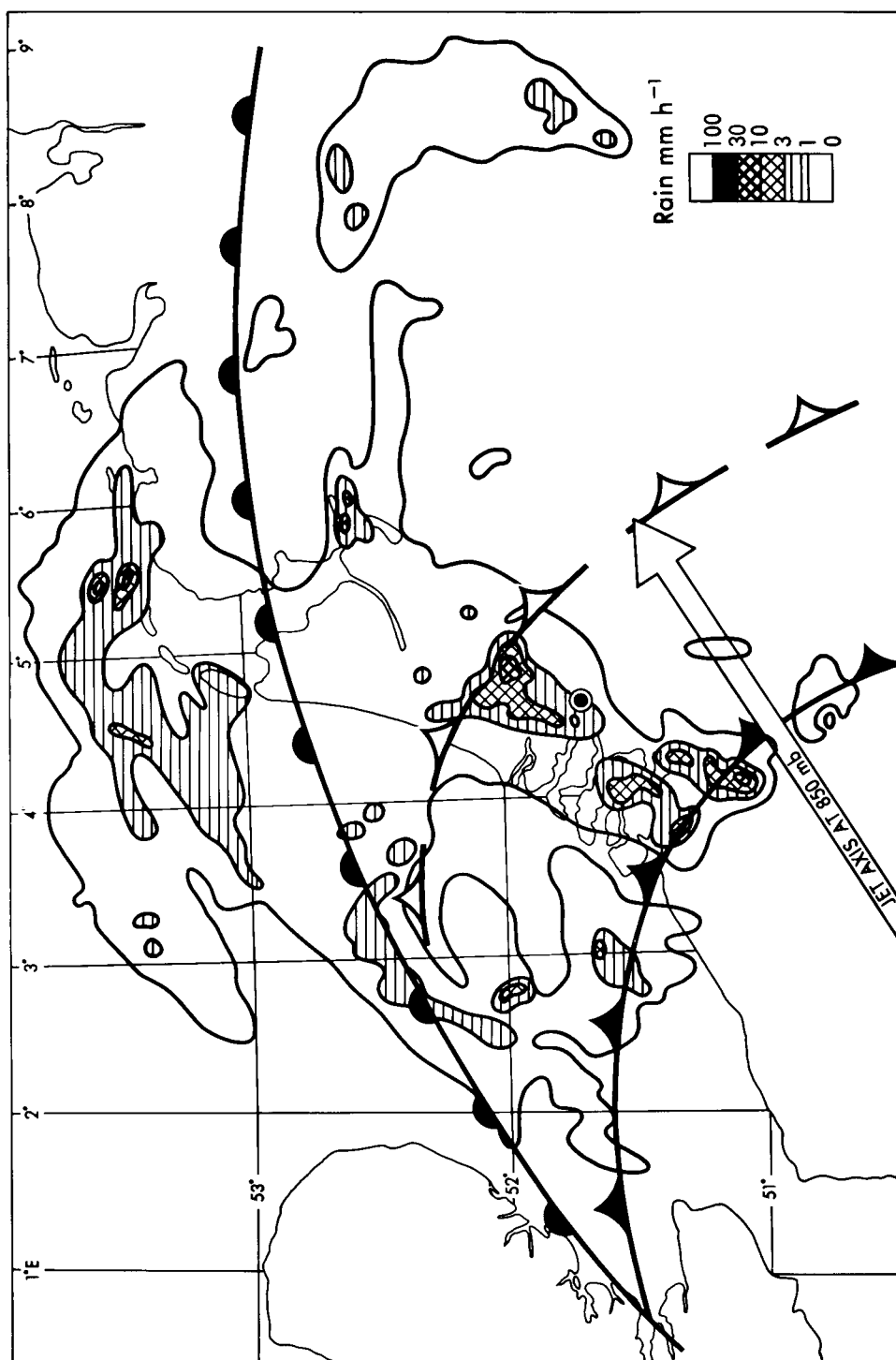


Figure 14. Radar images of rain areas recorded at De Bilt at 1600 GMT on 6 October 1981. Frontal positions and the jet axis at 850 mb are superimposed.

(a) *Return period.* From the statistics of tornado frequency and size distribution now available in some quantity from the United States, it is possible to estimate the return period (T) of a tornado at a given point. If the statistics for a given point apply over a fairly large area, then an aircraft flying over the area will encounter a tornado about once in period T .

(b) *Tornado frequency and damage area.* There is a range of some 4 to 5 orders of magnitude in the damage area produced by one tornado. About 90% of tornado damage in the United States is caused by the relatively few large tornadoes — typically at least 300 m in diameter and with path length greater than about 15 km. In the United Kingdom tornado frequency per unit area per year is comparable to that in the United States (Fujita 1973), but the associated damage area is far less.

(c) *Vertical extent of tornado circulation.* Tornadoes are spawned by meso- or tornado-cyclones which are intense circulations up to a few kilometres in width generated by the thunderstorm circulation. These circulations can be detected in cloud by Doppler radar up to half an hour before the associated tornado touches down. There is some evidence that the most intense circulation in a developed tornado occurs 100–200 m above the ground, and above this the vortex widens and the wind speeds decrease somewhat. Nevertheless, there is now evidence (Lemon *et al.* 1982) that the tornado circulation may extend through most of the depth of the storm and constitute a hazard to aircraft at all heights in the storm, including possibly those storms that spawn funnel clouds which do not reach the ground. Thus frequency of aircraft encounter based on surface damage area may result in some underestimate.

4.2 Computation

(a) *United States.* Tornado frequency in the United States is highest in the mid-west states (Tecson and Fujita 1979) with totals over the period 1916–78 approaching 200 per 10^4 km².

Fujita and Pearson (1973) have characterized tornado intensity by a three-dimensional scale of wind speed, path length and path width. These three properties are usually well correlated and it is sufficient in practice to use one scale of intensity — the F -scale. The distribution of tornadoes over the F -scale is given in Table I.

Table I. *Distribution of United States tornadoes.*

F -scale	0	1	2	3	4	5
Frequency (%)	22	34.5	29	11	3	0.5
Damage area (km ²)	0.0025	0.025	0.25	2.5	25	250

This yields an average of 2–2.5 km² of damage area per tornado which, multiplied by a frequency of 3 per 10^4 km² per year gives a damage area of about 7 km² per 10^4 km² per year, or a return period (T) of $10^4/7$ — about 1400 years — implying one aircraft encounter per 1.3×10^7 flying hours. This result is comparable with that given by Hill and Johnson (1982). This Table is uncorrected for the increasing efficiency of reporting of the smaller tornadoes over the last two decades. Correction for this increases tornado frequency, but reduces mean damage area per tornado and so has little effect on aircraft encounter probabilities.

(b) *United Kingdom.* There is much less evidence available from the United Kingdom, but enough to make some estimate. It appears (Lacy 1968, Meaden 1976) that the annual frequency of reported tornadoes ranges from 5 to 60 with an average of 20 to 30. Practically all of these occur east and south of the mountains of Wales and northern England. This corresponds to a frequency of 1 per 10^4 km² per year, increasing to a maximum of about 5 in the home counties area. This is comparable to the worst area of the United States, but UK tornadoes rarely exceed an intensity of $F2$. Meaden (1976) reports that the frequency of tornadoes of intensity ≥ 4 on the Meaden scale (corresponding to about $F2$) is a maximum

in the Midlands of about 20% of the total frequency. In order to assign an F -scale to UK tornadoes, we note that the United States frequencies given in Table I fit a Poisson distribution quite well:

$$P(F) = \exp(-\bar{F}) \cdot \frac{\bar{F}^F}{F!},$$

where $P(F)$ = probability of tornado of intensity F and
 \bar{F} = mean intensity.

$\bar{F} \simeq 1.3$ gives a 'best fit' to the frequencies in Table I. Accordingly, a Poisson distribution with $\bar{F} = 0.8$ corresponds to 20% of tornadoes of intensity $F \geq 2$ and gives us Table II.

Table II. *Estimated intensity distribution of United Kingdom tornadoes.*

F -scale	0	1	2	3
Frequency (%)	45	36	15	4
Damage area (km ²)	0.0025	0.025	0.25	2.5

This gives an average area of 0.1–0.2 km² per tornado, implying a return period of the order of 15 000 years in the home counties area, or an aircraft encounter frequency of the order of once per 10⁸ flying hours.

These figures are based on surface damage area, and are likely to be underestimated owing to broadening of the tornado circulation with height. We have little information on which to correct for this, but suggest that encounter frequencies should be increased by a factor of 3 to take crude account of it. This yields:

$$\text{Frequency of aircraft-tornado encounter} \left\{ \begin{array}{l} \text{United States} \\ \text{United Kingdom} \end{array} \right\} \text{ once per } \left\{ \begin{array}{l} 10^6-10^7 \\ 10^7-10^8 \end{array} \right\} \text{ flying hours in 'worst' areas}$$

The low-lying areas of France and Germany are climatologically not very different from south-east England, so that the above figures for the United Kingdom are probably fairly representative of much of the low-lying areas of north-western Europe.

The estimate for the United States suggests that tornado encounters 'ought' to be fairly frequent. An analysis of aircraft accidents by the National Transportation Safety Board (1978) shows that during the 3.6×10^7 hours flown by general aviation in 1976, 7 non-fatal accidents were partly or wholly attributed to 'local whirlwinds'. Moreover, 167 accidents (i.e. 5 per 10⁶ flying hours) were also attributed to 'wind shear, turbulence in cloud/thunderstorm, downdraughts and updraughts, and thunderstorm activity'. It is possible that some of these accidents, particularly those in cloud, may have been associated with tornado cyclone circulations. Thus our estimate of tornado encounter frequency does not appear to be obviously misleading.

5. Conclusions

Evidence is presented which supports the claim that the loss of an aircraft near Rotterdam was due to an encounter with a tornado. The meteorological situation exhibited most of the features associated with tornado- and hail-generating storms of the United States. In addition, intense radar-echo complexes moving rapidly north-east are characteristic of severe organized storms often observed in the United States.

Severe storms in north-west Europe are too rare to warrant a special severe-storm forecasting service on the United States pattern, but there may be some merit in forecasters acquiring some familiarity with synoptic and radar features associated with severe storms, particularly those forecasters who will be using the UK Radar Network Display.

Lee (1967) reported a significant association between radar echo intensities of storm cores and the turbulence experiences on research aircraft flying through these cores. More recently (NOAA 1978) it has become possible to detect developing tornado cyclones within storms up to half an hour before the first tornadoes touch down. However, the prospects of detecting tornadoes by the plan display of the UK Radar Network are not good. Browning (private communication) writes:

Tornadoes are associated with thunderstorms having intense echoes as seen on a plan display, but they often occur in the (right) flank of the echo away from the precipitation core. It is not very helpful to look for rapidly rising radar tops because some of the severest storms are already in a steady state, and in any case it is difficult to do a rapid volume scan to identify the rate of rise of individual tops. (Note that we do not obtain any vertical storm-top information in the UK weather radar network, but we do use Meteosat half-hourly infra-red imagery to spot high tops with rapidly expanding anvils.)

Hook echoes are known to be unreliable indicators of tornadoes, even in the USA, since they are sometimes obscured by other echoes, especially at long range. At other times, fortuitous echo distortions may look like hook echoes to the untrained eye. In the UK, hook echoes are very rare and will not be seen by the current display resolution of 5 km.

It is the view of the authors that some service which alerts aviation to the possibility of severe storms and which might operate on a similar basis to that of the wind shear alerting service at Heathrow (but with access to a suitable radar display) would be better than no service at all.

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061.3:519.2:681.3

COMPSTAT 82

By R. C. Tabony

(Meteorological Office, Bracknell)

The COMPSTAT symposia on computational statistics are held under the auspices of the European section of the International Association for Statistical Computing, a branch of the International Statistical Institute. The first COMPSTAT meeting was held in Vienna in 1974, and since then they have been held every two years and gained a wide popularity. The 5th symposium was held at the Paul Sabatier University, Toulouse from 30 August to 3 September 1982, and brought together over 500 people whose main interest lay in the development and promotion of statistical software.

The conference was organized so that a day would begin with two invited speakers addressing an auditorium which contained seating accommodation for all. Thereafter a series of contributed papers, limited to half an hour each, were read in parallel in four lecture theatres. A display of posters was held in a large room, while a permanent exhibition was mounted in the main hall. All the major software enterprises were represented here, and gave continuous demonstrations of their packages and facilities. The majority of participants at the symposium were European, but there were also speakers from the USA, Australia and Japan.

The main concern of the conference was the development and improvement of packaged statistical software. All aspects were covered, from data-base management through exploratory data analysis to the latest statistical theory and numerical algorithms to use in packaged programs. Now that many packages contain a wide variety of statistical techniques, emphasis was placed on the need to design user-friendly systems, with easy data manipulation, good documentation, and clear presentation of results. The use and influence of micro- and array-processors in statistics, and the use of computers in teaching statistics, were also discussed. The only applications area considered lay in the fields of archaeology and history.

Many papers took the form of an advance in theory, or the introduction of a new algorithm, followed by its implementation in the form of saleable software. Other papers compared the strengths and weaknesses of the many packages now on the market and, to the writer, these were some of the most interesting presentations.

The writer's presence was due to a contribution on the estimation of missing data. This is a ubiquitous problem, and one which has not received the attention it deserves from the compilers of statistical packages. The BMDP suite* is one of the few packages to contain a program for estimating missing

*BMDP Biomedical Computer Programs, P-series. Health Sciences Computing Facility, Department of Biomathematics, School of Medicine, University of California, Los Angeles.

values, and I was given the opportunity of reporting its poor performance when applied to climatological data. There was little of this user feedback at the symposium, and more of it would have been very relevant to the aims of the gathering.

Much of the work of organizing the symposium fell on A. de Falguerolles, who acted as secretary to both the Organizing Committee, chaired by P. Ettinger, and the Scientific Program Committee, chaired by H. Caussinus. The Proceedings were edited by H. Caussinus, P. Ettinger and R. Tomassone. The policy of limiting each contributed paper to six pages ensured that each author concentrated on the main points of his argument, and this makes for easier reading than would otherwise be the case.

Notes and news

Retirement of Captain G. A. White

Captain G. A. White, Extra Master, retired from the Meteorological Office on 31 December 1982 after spending the past 13 years as Marine Superintendent and adviser to the Director-General on all matters concerned with the meteorological requirements of the mercantile marine.

When Gerald Arthur White joined the Office in 1969, he already had a long and varied career in the merchant navy behind him. This started in August 1941 when he became a cadet in the Canadian Pacific Steamship Company. Whilst he was transiting the Panama Canal on 7 December of that year it was rumoured that Japanese aircraft carriers were in the vicinity and likely to make an attack on the Canal. On arriving on the Atlantic side of the Canal word was received regarding Pearl Harbor. In the following August when homeward bound in the North Atlantic his ship was sunk by enemy action. In his next voyage he was again in a heavy convoy attack and, shortly after, when he was again outward bound, his second ship was torpedoed and sunk. Later he was in the first convoy to pass from Gibraltar to Port Said after the Mediterranean had been closed to allied shipping for many months. After surviving further convoy attacks he was promoted to 5th Officer in June 1944 and later that year obtained a 2nd Mate's Certificate. Less than a year later he was in Java when fighting broke out with the Indonesians and he again came under fire.

During 1949 and 1950 Captain White attended the University College of Southampton, School of Navigation, and obtained both a Master Mariner's Certificate and an Extra Master's Certificate. He was promoted to Chief Officer in the Royal Fleet Auxiliary in 1950 and then spent 18 months with the British forces involved in the Korean campaign.

From 1954 to 1955 he lectured at King Edward VII Nautical College, London but, preferring a more active life, returned to sea to command a geophysical survey vessel. By 1958 he had family commitments and decided, in his own phrase, 'to swallow the anchor'. He joined the Marine Survey Service of the Department of Trade as a nautical surveyor and examiner of Masters and Mates, taking up an appointment on the Central Board of Examiners in London. At this stage one of his tasks was to set and mark the examination papers for mariners on meteorology and oceanography. After three and a half years he was moved to surveying duties in Liverpool and in January 1965 was promoted and posted to Newcastle. In 1968 he was elected a younger brother of Trinity House.

On 1 November 1969 Captain White joined the Meteorological Office as Marine Superintendent. The following years have been difficult for all the merchant navies of the world as mercantile fleets have declined, and Captain White has worked tirelessly to maintain the quality of the liaison between the Office and the shipping industry. The main functions of the Marine Division for which he was responsible are to operate the United Kingdom Ocean Weather Ship (OWS), to recruit and maintain the Voluntary Observing Fleet, to obtain and archive high quality observations from the Voluntary Observing Fleet and to provide meteorological services to the shipping community including running a ship routing service and answering marine enquiries.

From 1970 to 1977 Captain White was closely concerned with planning the future of the UK North Atlantic Ocean Station (NAOS) Ocean Weather Ships. After initial plans to replace the then-existing four Castle Class ships with purpose-built vessels were cancelled, it was decided to refurbish two of the 30-year-old existing ships. This major task was finally completed in 1977 when the ex-*Weather Monitor* sailed from Manchester as the 'new' OWS *Admiral Beaufort*. Captain White also took part in the protracted negotiations which led to the termination of the original International Civil Aviation Organization NAOS Agreement and its replacement by the existing NAOS Agreement under the auspices of the World Meteorological Organization. Later, during 1980 and 1981, he arranged for the sale of the OWS *Admiral Beaufort* and *Admiral FitzRoy* and the closing of the OWS Base at Greenock, when these were replaced in early 1982 by the single time-chartered OWS m.v. *Starella* which now sails from Fleetwood.

Throughout his time as Marine Superintendent, Captain White has maintained close and cordial relationships with the shipping industry both personally and through the efforts of his Port Meteorological Officers. This effort has been successful in maintaining the UK Voluntary Observing Fleet at over 500 ships in spite of the reduction in the total number of British merchant ships from over 3000 in 1970 to approximately 900 by the end of 1982.

Captain White has been Editor of the *Marine Observer*, a quarterly journal of maritime meteorology, which has as its main purpose the encouragement of a high standard of observing not only of meteorological conditions but also of a wide range of phenomena at sea. He has also been an active and well-liked member of the international marine meteorological community, where his sound and authoritative advice has led to invitations for him to act as the WMO representative at the Intergovernmental Maritime Organization Assemblies, on the Marine Safety Committee and on the Subcommittee on Safety of Navigation. He has also been principal delegate for the UK on the WMO Commission for Marine Meteorology and a member of the UK delegation to the NAOS Board.

Captain White is married and has three children. We wish him a long and happy retirement.

D. N. Axford

100 years ago

The following extract is taken from *Symons's Monthly Meteorological Magazine*, February 1883, 18, 3.

A PALACE OF ICE.

WHILE the climate of England is oscillating between the close moisture of May, the bitter north-east winds of March, and the sleet and fog of November and December, Canada is rejoicing in the steady cold but bright and dry weather, upon the recurrence of which everyone in the Colony reckons, and reckons not in vain. Winter there is a source of great profit and of keen enjoyment. Without the regular frosts and dry snows with which the country is visited, half the work of the farm and of conveying the produce of the forests and the farm to market, would have to be left undone; and while the agriculturalist and the lumberer look forward to the advent of a steady "cold spell" — to say nothing of the opportunity that is afforded of laying up a store of ice for summer use — the people generally are not slow to avail themselves of the pleasure of sleighing, skating and tobogganing. This year the citizens of Montreal have inaugurated a new institution in the shape of a magnificent "Crystal Palace," which has been erected in Dominion Square in that city. Instead of glass and iron, ice is the material of which this building is constructed. Slabs of ice from the St. Lawrence, 40 inches high and from 14 to 20 inches in breadth and height, are the "bricks"; and these crystal blocks, piled on one another, are cemented together by a spray of water poured over them, which froze as it fell, and bound the whole together in a homogeneous mass. Of such material has a huge transparent palace been built, measuring nearly 100 feet square in the

interior, with walls 25 feet high, and with towers 15 feet square and 30 feet in height; while from the centre rises a massive tower 32 feet square and 100 feet high. The roof is constructed of rafters of wood, upon which were spread cedar branches; these, again, being cemented together, like the walls of the structure, by a spray of water, which froze them into a solid mass, with long icicles depending from the roof in most picturesque confusion. When the bright sun falls upon this glittering palace with its frosted roof, the effect is indescribably beautiful; while at night, illuminated with thousands of electric lights within and without, the spectacle is, if possible, of even greater brilliancy.

Printouts of weather data

Following the cessation of the *Daily Weather Report* at the end of 1980, and at the request of a number of organizations, the Meteorological Office has produced retrospective printouts of the coded synoptic messages for the 50 stations which used to feature in it. Since January 1982, when the new international synoptic codes were introduced, the output has been modified to present the information in a semi-plain language format. This was partly to save users the trouble of learning the new codes and partly because the increased variability of the synoptic messages created difficulties in formatting. The printouts are now available on paper or microfiche. The current charges (exclusive of VAT) for microfiche are £4.75 per week, £12.00 per month and £32.00 per quarter whilst paper output is available on a weekly basis at £6.10. Universities and other educational establishments may apply for reduced rates.

Tabulated upper-air data, similar to those which appeared in the *Daily Aerological Record*, could also be made available. Requests for data or for further information on these services should be addressed to:

The Director-General
Meteorological Office, Met O 3
London Road
Bracknell
Berkshire RG12 2SZ

Requests for daily synoptic information in chart form, should be addressed to:

Principal Meteorological Officer
London Weather Centre
284-286 High Holborn
London WC1V 7HX

Honour

In the Birthday Honours list for 1982 it was announced that Mr F. A. Gordon (Professional and Technology Officer III) of the Meteorological Research Flight had been awarded the British Empire Medal.

Obituary

We regret to record the death on 19 September 1982 of Mr A. E. Radford, Assistant Scientific Officer, as a result of a traffic accident in France. Alan Radford joined the Office in August 1978, and had spent all his brief career at Gatwick Airport.

He was a motor sport enthusiast, and also devoted much of his spare time to helping to run the youth club in the south Sussex village where he lived and had been brought up.

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NOTICES

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A re-evaluation of the cloudiness factor in the Ångström and Penman equations for assessing short-wave and long-wave radiation exchanges at a surface

By B. Henderson-Sellers

(Department of Civil Engineering, University of Salford)

P. Tucker

(Department of Geography, University of Liverpool)

and B.G. Wales-Smith*

(Meteorological Office, Royal Air Force Akrotiri)

Summary

On a monthly time-scale the equation derived by Penman for estimating net radiation at the earth's surface, using Campbell-Stokes sunshine duration data, appears to underestimate the net outgoing long-wave radiation. The operation of the Campbell-Stokes recorder as a radiation integrator under variously cloudy conditions is studied and, working on a daily basis, it is proposed that the term in the equation involving observed and theoretical maximum duration of bright sunshine be replaced by one which allows, in a physically realistic manner, for the unreliability of the sunshine recorder in cloudy weather. The arguments used are supported by data.

Introduction

In thermodynamic studies of a water body, the energy exchanges at the air-water interface must be specified — either from direct observation or, more commonly, calculated from readily available meteorological data. (To obviate this, some models, e.g. McCormick and Scavia (1981) use a known value of the water surface temperature T_s whilst others (e.g. Sundaram and Rehm, 1971; Noble, 1981) use the quasi-empirical concept of equilibrium temperature.) The surface energy balance (or budget) includes incoming short-wave (solar) radiation, outgoing and incoming long-wave radiation (from the atmosphere and clouds), energy fluxes associated with sensible and latent heat transfer, and specified values for reflectivities. (Except in extreme cases it can be safely assumed that the energy flux associated with precipitation can be considered to be negligible for the purposes of the present discussion.) The net

*Now at London (Heathrow) Airport.

Symbols

a	constant in Cowley equation = 0.29 (average value)
a'	constant in Ångström equation
A_L	long-wave reflectivity
b	constant in equations (3), (8) and (9)
D	maximum number of sunshine hours per day
e_d	vapour pressure (mb)
e_{sa}	saturated vapour pressure at temperature T_a
n	number of sunshine hours per day
T_a	air temperature
T_w	water surface temperature
ϵ_a	emissivity of atmosphere
ϕ_0	net short-wave irradiance after reflection
ϕ_∞	solar radiation at the top of the atmosphere
ϕ_c	sensible heat flux
ϕ_d	direct component of short-wave radiation
ϕ_{dc}	direct component of short-wave radiation under cloudless skies
ϕ_e	evaporative energy flux
ϕ_L	sum of non-radiative energy losses ($= \phi_e + \phi_c + \phi_{r2}$)
ϕ_n	net radiation
ϕ_N	net energy available
ϕ_q	net long-wave radiation lost ($= \phi_{r2} - \phi_{r1}$)
ϕ_r	atmospheric long-wave radiation received at surface (before reflection)
ϕ_{r1}	atmospheric long-wave radiative flux (after reflective losses)
ϕ_{r2}	long-wave radiative loss
ϕ_s	short-wave radiation incident at surface
ψ	latitude
U	relative humidity
σ	Stefan-Boltzmann constant ($= 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$)

radiation is then available to the water body either to heat up the surface layer or to be transported vertically downwards by turbulent diffusion or both. The application which motivated this work was a study of the thermal stratification cycles of lakes and reservoirs (wherein large-scale advection into or out of the water column can be neglected). Hence it is assumed that the total energy fluxes available to the water body will be the energy flux (per unit area) multiplied by the lake surface area. It is thus vital to quantify as accurately as possible all the energy terms which make up the surface energy balance. In this paper we show that recent data on the effects of clouds on evaluating short-wave radiative fluxes suggest that a modification should be made to the formulae previously used.

The surface energy budget

The total surface energy budget for a lake can be represented by the following equation:

$$\phi_0 + \phi_{r1} - \phi_L = \phi_N \quad \dots \quad (1)$$

where ϕ_N is the net energy available, ϕ_0 is the net short-wave energy (i.e. after reflection), ϕ_{r1} the net incoming long-wave radiation and ϕ_L the sum of the energy losses given by

$$\phi_L = \phi_e + \phi_c + \phi_{r2} \quad \dots \quad (2)$$

where ϕ_e is the evaporative energy flux, ϕ_c the sensible (convective) heat flux and ϕ_{r2} the long-wave (black body) radiative loss.

Some of the formulae for each of these terms are reviewed in Henderson-Sellers (1976, 1980). In particular we consider here the two formulae incorporating a cloudiness factor, viz. the Ångström (1920) formula for short-wave irradiation,

$$\phi_s / \phi_{sc} = a' + b n/D, \quad \dots \quad (3)$$

and the expression for atmospheric (long-wave) irradiance given either by (a):

$$\phi_r = \frac{\phi_{r1}}{(1 - A_L)} = \epsilon_a \sigma T_a^4, \quad \dots \quad (4)$$

where ϵ_a is given graphically by Raphael (1962), data to which the curve

$$\epsilon_a = 0.688 + 0.125(1 - n/D) + 0.443 \times 10^{-4} U e_{sa} \quad \dots \quad (5)$$

has been fitted by Henderson-Sellers (1976), or (b) Penman's (1948) relation for net long-wave radiation lost $\phi_q (= \phi_{r2} - \phi_{r1})$ (see e.g. Wales-Smith 1980) where,

$$\phi_q = \sigma T_a^4 (0.56 - 0.08\sqrt{e_d}) (0.10 + 0.90 n/D). \quad \dots \quad (6)$$

Wales-Smith (1980) showed that 7-year average calendar-month estimates of net radiation calculated from meteorological data obtained at Kew and Eskdalemuir, using the equation which Penman (1948) derived from Ångström (1925) and Brunt (1932), are greater than comparable values of net radiation measured at the two locations. He showed, further, that the short-wave term in the equation gave very good estimates of average calendar-month global radiation measured at the two locations. In both comparisons the regression constants in the equation were derived from larger bodies of radiation and sunshine duration data than those used in the 7-year comparison.

He assumed, therefore, that the difference must be due to underestimation of net outgoing long-wave radiation (ϕ_q). This quantity is not measured directly at Meteorological Office establishments but indirect data may be obtained from measurements of net irradiation (ϕ_n) and global irradiation (ϕ_s) if an accepted value of the short-wave albedo of grass (0.25) is used in the equation

$$\phi_q = (1 - 0.25) \phi_s - \phi_n. \quad \dots \quad (7)$$

He compared individual monthly values of the above quantity (for Kew, Eskdalemuir and Aldergrove) with corresponding values obtained from the long-wave term in the equation derived by

Penman (1948) and showed that the relationships at all three stations are similar. He then derived empirical, interim, monthly factors to adjust estimates of ϕ_q for operational use in a Meteorological Office (hydrometeorological) model.

Here we present observational and theoretical evidence that suggests that equation (6) underestimates ϕ_q as a consequence of the fact that values of n/D measured by a Campbell–Stokes sunshine recorder are on some occasions very poorly correlated with the incident irradiation (as measured by a solarimeter for example). It will be shown that in these cases an augmented value of n/D results in better agreement between calculated and observed values.

The Ångström equation

The Ångström equation (equation (3)) has been much discussed in the literature, especially by Glover and McCullough (1958) who identified a latitudinal variation in the coefficient a' . They recommend the equation

$$\phi_s/\phi_\infty = a \cos \psi + b n/D \quad \dots \quad (8)$$

where ψ is the latitude and the coefficients are given as $a = 0.29$ and $b = 0.52$ valid over the latitude range 0° to 60° . Indeed it seems likely that this relationship is reasonably well satisfied for mean monthly values. Cowley (1978) solved a set of linear regression equations between daily global solar irradiation and duration of bright sunshine for ten stations in the United Kingdom which record both parameters. He found that the Ångström equation applied well to partially sunny days but that sunless days formed a separate population, often being associated with situations where multi-layered or thick clouds predominate, resulting in lower irradiation. Accordingly he adopted a modified equation

$$\phi_s/\phi_\infty = \delta \{a + b (n/D)\} + (1 - \delta) a' \quad \dots \quad (9)$$

where δ is defined by ($\delta = 0$ if $n = 0$, $\delta = 1$ if $n > 0$), and

where a , b and a' all show a spatial variability. He presented annual average values of a and a' over the British Isles and values for b for June and December over Great Britain. However, results of a more recent experiment (discussed here) in Cornwall suggest that these relationships cannot be unique on a 'daily' basis since the effect of cloud type (not only amount) and cloud thickness can have a considerable effect on determining the degree of 'burn' of the card of a Campbell–Stokes recorder.

An underestimate of n/D by the Campbell–Stokes recorder causes the value of ϕ_q (from equation (6)) and to a lesser extent ϕ_s from equation (3) to be underestimates and it will be shown under what meteorological conditions this may occur. A suggested correction factor leads to an improved agreement between ϕ_q (calculated) and ϕ_q (observed) depicted graphically by Wales-Smith (1980) — see later discussion.

Experimental details and observational results

The study was undertaken over a two-month period (July to August 1980) at a site in St Austell in Cornwall ($\psi = 50.3^\circ\text{N}$). Two instruments were used: the standard Kipp and Zonen solarimeter, which measures the energy flux by integrating the radiation distribution over a hemisphere, operating within the wavelength range of $0.3 - 2.5\mu\text{m}$, and the Campbell–Stokes recorder which consists of a solid glass sphere seated within a bowl so that radiation from the sun is concentrated on a card. If the radiative flux is strong enough a burn mark will result and this is taken to represent the number of hours of sunshine, n .

Insolation

For all days during the study period a continuous trace was obtained from the solarimeter and compared with the 'burn' of a Campbell–Stokes recorder and the observed clouds (height, type and

thickness). Since it is evident that an equation of the form of equation (8) cannot be expected to give instantaneous values, comparisons are undertaken quantitatively by integrating the continuous trace by quadrature methods to derive total daily values of energy in J m^{-2} . Over the period of study this value was observed to be in the range 5.4×10^6 to $17.3 \times 10^6 \text{ J m}^{-2}$ per day. The data for the daily totals of observed irradiation, cloud cover and calculated values for ϕ_s from equation (8) (at a latitude of 50.3°) are given in Table I.

On shorter time-scales (e.g. of minutes) the correlation is poorer. Indeed it may be these short time-scale non-correlations which are responsible for the poorly correlated points of the above two data sets. For example, it should be noted that on 8 and 22 August 1980 the daily insolation totals at St Austell were similar whereas the recorded sunshine amounts differed by a factor of 2. The present investigation aims to elucidate some possible causal mechanisms for such discrepancies.

Often the type of cloud, or its thickness, or its height — or some combination of all three — is readily demonstrated to be the controlling factor. For example, a total cover of high cirrus may well fail to prevent the radiation from being measured by the Campbell–Stokes recorder.

The records for 9 and 16 July display the effects of individual clouds. With thin white cirrus clouds obscuring the sun temporarily any drop in irradiance is very small (less than 200 W m^{-2}) and occurs with a less distinct rate of change than when the cloud is cumuliform. Lightly shadowed, white cumulus of medium thickness caused a decrease of 400 W m^{-2} to 500 W m^{-2} depending on its vertical extent, whilst a dark, heavily shadowed, thick cumulus cloud could cut out 700 W m^{-2} to 800 W m^{-2} (midday figures).

Table I. Daily insolation values, observed and calculated

Date August	Observed insolation (irradiation) ($\text{J m}^{-2} \times 10^6$)	n/D	Calculated insolation (equation (8)) ($\text{J m}^{-2} \times 10^6$)
7	5.982	0.020	6.922
8	13.106	0.290	11.891
10	5.249	0.041	7.301
15	12.893	0.470	15.207
22	13.010	0.612	17.807
25	14.043	0.396	13.843
26	17.360	0.825	21.731
27	9.415	0.182	9.895

Sunshine hours

On ‘ideal’ days with zero cloud (and hence maximum sunshine), the burn created by a Campbell–Stokes recorder would have smooth edges and a greatest thickness at noon, tapering off towards late evening and early morning. Fluctuations in the power received will cause a variation in the thickness of the burn and indeed at a certain energy level the absence of a burn altogether. It is generally assumed that the length of the burn gives a measure of the extent of sunshine, such that the absence of a burn is taken to be indicative of the presence of clouds obscuring the sun’s disc.

However, a different situation arises with thick intermittent cumulus cloud. In these circumstances the length of period between two passing clouds controls whether a burn is achieved, since there appears to be a limit to the minimum duration of energy required to create a burn. On such days the drop in energy (of the order of 500 to 700 W m^{-2}), caused by the cloud passing between the sun and solarimeter, is sudden and this is shown by the way the burn stops at its previous thickness with no tapering or other effects. (There are good examples of these sharp breaks on 15 August, particularly at 0905 and 1245 GMT — see Fig. 1(a).) During hazy or extensive broken thin cloud the break in burn is more gradual with a slight tapering of thickness, as found at 1430 GMT on 25 August (Fig. 2).

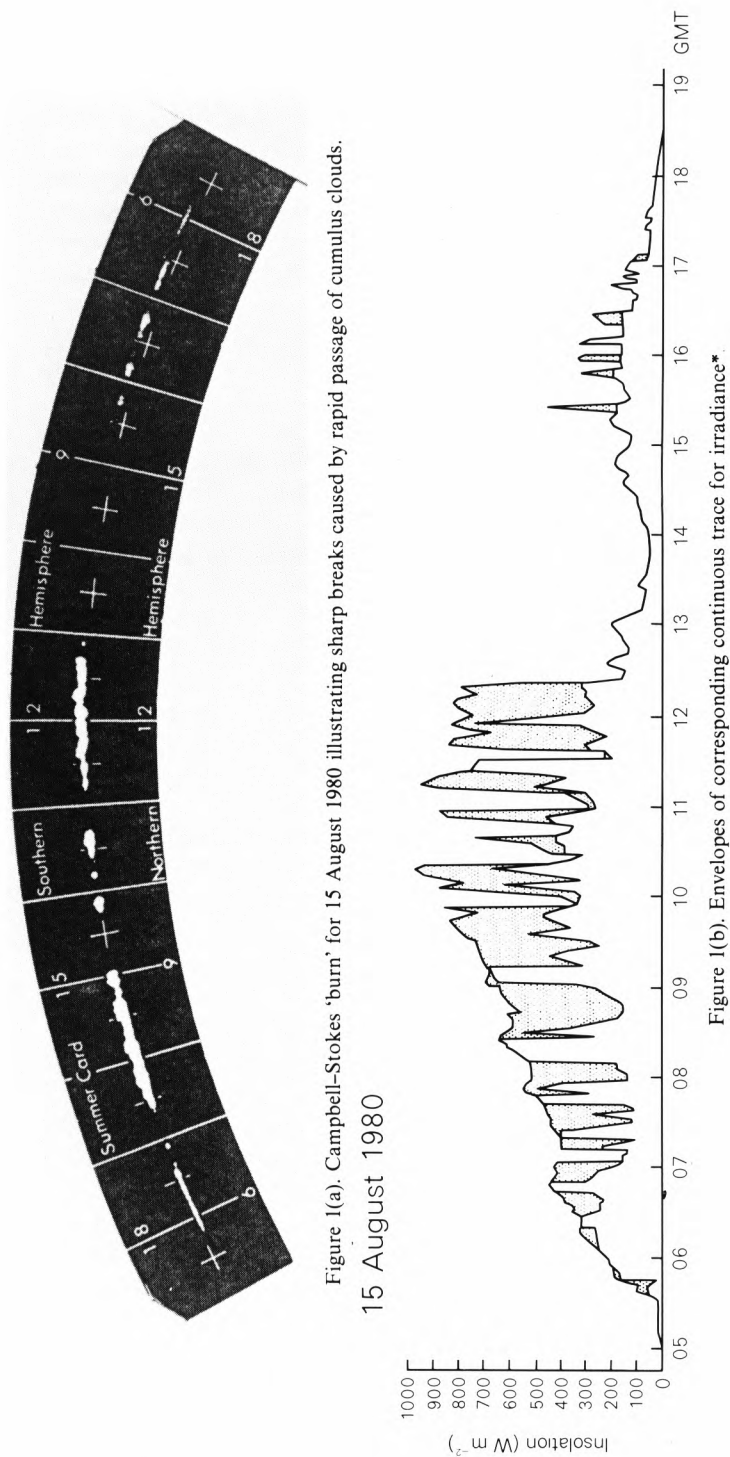


Figure 1(a). Campbell-Stokes 'burn' for 15 August 1980 illustrating sharp breaks caused by rapid passage of cumulus clouds.

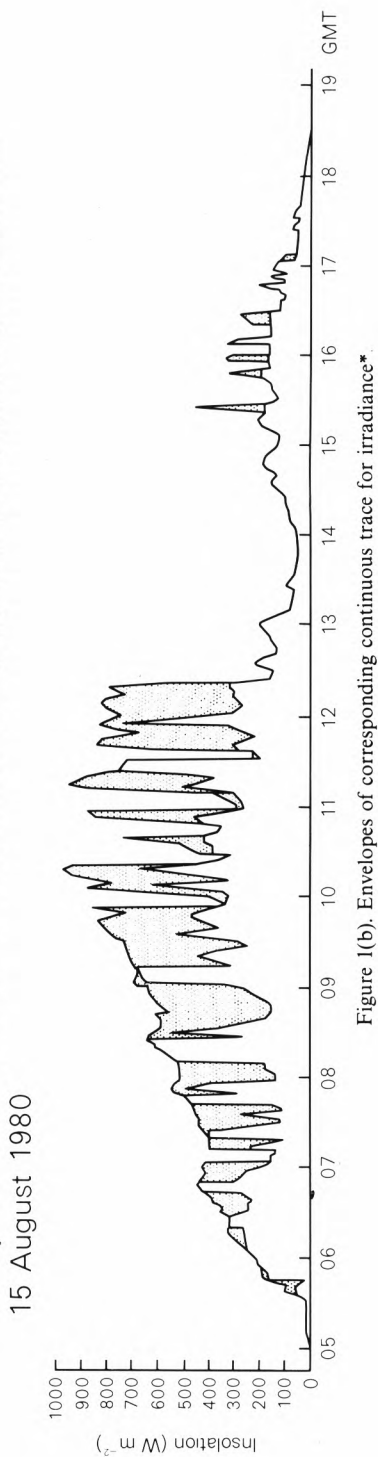


Figure 1(b). Envelopes of corresponding continuous trace for irradiance*.

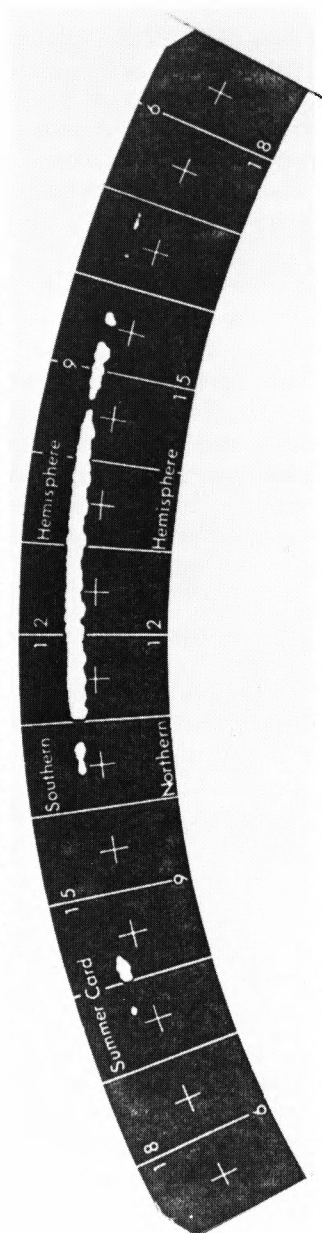


Figure 2(a). Campbell-Stokes 'burn' for 25 August 1980 illustrating tapering of burn resulting from breaks in extensive cloudy/hazy conditions.

*The original traces often contained extremely rapid fluctuations impossible to reproduce; the printed figures show 'envelopes' between which such fluctuations occurred, with the area between these envelopes being stippled. Features in the original trace of duration five seconds or less have been smoothed out.

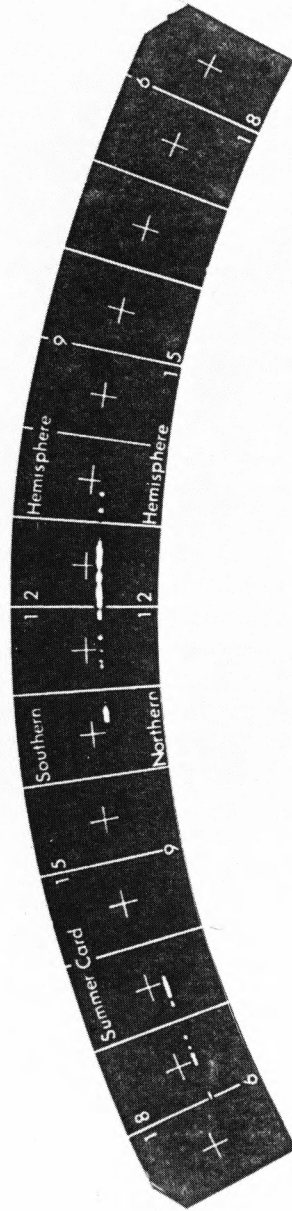
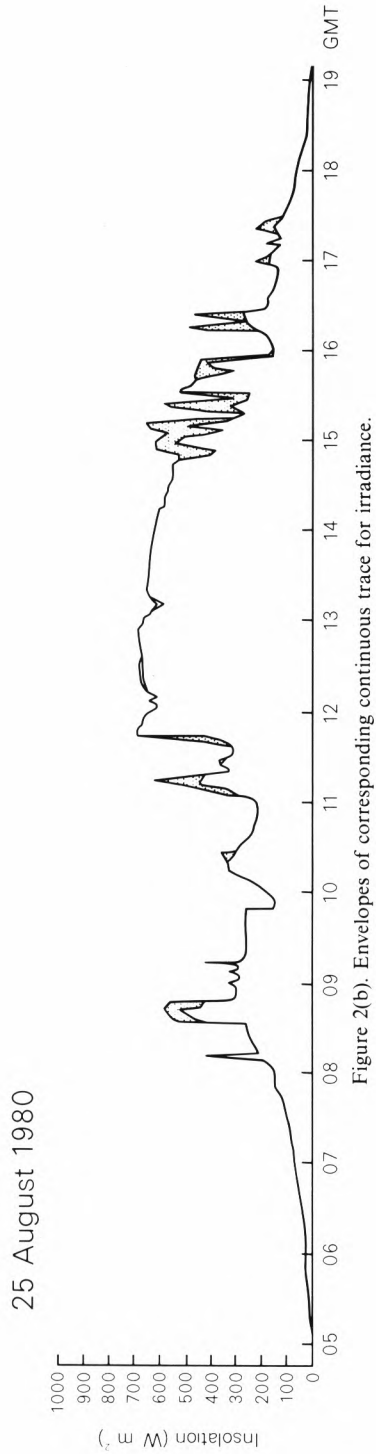
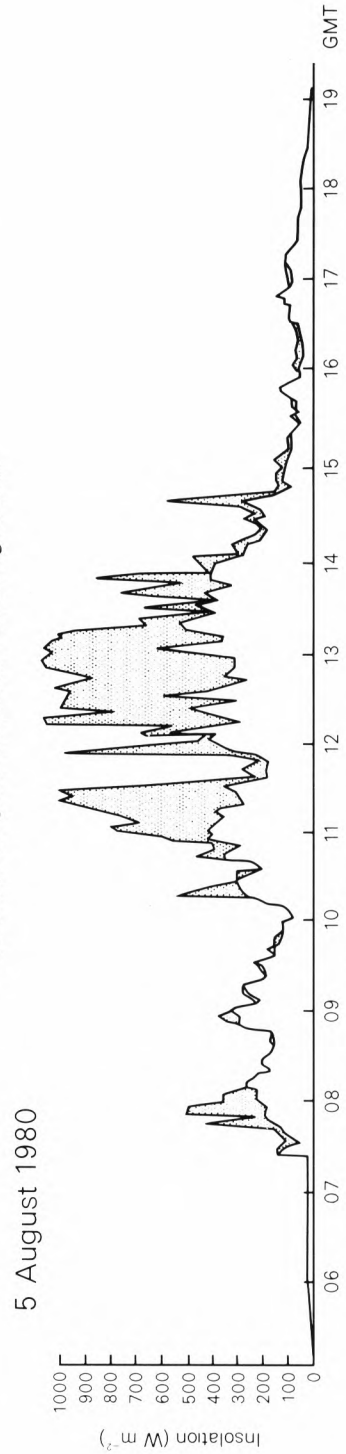


Figure 3(a). Campbell-Stokes 'burn' for 5 August 1980.



A study of 5, 8 and 22 August, all days of intermittent cumulus cloud and fine sunny spells, demonstrates the relative importance of period and amplitude for maxima of irradiance. As mentioned above, both 8 and 22 August recorded the same daily total of energy received but different sunshine hours on very similar days. The peaks on the 22nd are sharper than those on the 8th, rising and falling in 10 to 20 seconds. This means that the irradiance reaches a peak value more often than on the 8th, thus allowing it to maintain its burning influence on the sunshine card. On 5 August, a day when many peaks lasted for only 5 to 10 seconds, it was found that the duration of the peaks was more important than amplitude. For example, some peaks as high as 1000 W m^{-2} were of too limited duration to create an impression on the card and the trace was ephemeral (Fig. 3), despite hot, intermittently sunny conditions. In such conditions it is suggested that the 'overburn', noted by Suckling and Hay (1977) and by Painter (1981), may be instead an under-recording of the irradiation either because of slow instrumental response times or by the sampling procedure (e.g. Painter (1981) assumed the instantaneous value every minute to be representative of these continuous data — clearly not the case in the example outlined above).

The minimum value of the power required to create a burn appears to vary with the time of day (a factor not incorporated into the design of the Campbell–Stokes sunshine recorder). Brooks and Brooks (1947) note that the sun must be 5° above the horizon before a burn is recorded. This present study suggests that noon values of energy required for a burn tend to be higher than those in the evening and morning. For example, during the period between 0900 and 0930 GMT on 27 August, a sunshine burn was recorded with minimum energy values of 250 W m^{-2} . However, during the period between 1100 and 1200 GMT a minimum level of 350 W m^{-2} was obtained but relatively little sunshine (less than half an hour) recorded. On 15 August at and just before 1800 GMT sunshine is recorded when the isolation trace is always below 200 W m^{-2} . However, at 1100 GMT minimum values were as much as 300 W m^{-2} and at 1300 GMT 200 W m^{-2} , both with no corresponding sunshine. This is in good general agreement with Painter (1981) who found the threshold irradiance required to produce a burn varied in the range $106\text{--}285 \text{ W m}^{-2}$.

Another method of relating net insolation to sunshine burns is to correlate the burn width with a value of solar energy. The best day to study was 26 August as it had the most nearly continuous burn. Table II

Table II. *Relation between sunshine burn width and irradiance.*

Sunshine burn width	Irradiance (W m^{-2})	Conditions
26 August		
2 mm	150	Evening
3 mm	600	Midday haze
22 August		
5 mm	1000	Midday peaks

shows the values obtained on both 26 and 22 August. Certainly a linear relationship is suggested. Table III gives insolation values and burn widths for Akrotiri, Cyprus, during June 1981. Again a linear relationship between burn width and irradiance is strongly suggested. Further data collection to substantiate and verify any such relationship is recommended.

Discussion

Our observations show that in cases of intermittent thick cumulus cloud which obscures the sun's disc such that the periods between observations may be small, a sunshine burn may not be recorded even

Table III. Numbers of cases corresponding to 60-minute sunshine burn.

Intensity of global irradiance is continuously indicated (as voltage) in the meteorological office at Akrotiri, Cyprus (34°35'N). The table shows the variation of irradiance intensity (mV), measured at the beginning of each clock hour corresponding to a 60-minute Campbell-Stokes recorder burn during the succeeding hour in June 1981.

	Global irradiance intensity (mV)											Typical burn width (mm)
	2.0 to 2.9	3.0 to 3.9	4.0 to 4.9	5.0 to 5.9	6.0 to 6.9	7.0 to 7.9	8.0 to 8.9	9.0 to 9.9	10.0 to 10.9	11.0 to 11.9	12.0 to 12.9	
Local time (GMT + 2h)												
0600	24											1.0
0700			25	2								1.1
0800					17	10						1.2
0900						1	22	7				1.4
1000								3	26			1.6
1100									7	22	1	1.8
1200									4	25	1	2.0
1300								1	22	6		1.8
1400						1	1	23	4			1.6
1500				1		13	16					1.4
1600		1		13	14							1.2
1700	1	23	5									1.1

(1.125 mV is equivalent to 100 W m⁻²)

when incident radiation values are high. In an extreme case (5 August, cf. 22 August) it has been observed that the Campbell-Stokes evaluation of n/D may result in an underestimate of the incident radiation by a factor of 0.65 (corresponding to an underestimate of n/D by a factor of 0.44, i.e. less than half the hours of sunshine were recorded).

In less extreme cases it is possible that an underestimate by about 10–15% may occur frequently. Here we take a numerical example to compare the data of Wales-Smith (1980), the Penman (1948) equations, and the direct solar radiation model of Suckling and Hay (1977).

Example

True values: $n/D = 0.35$ $1 - n/D = n_c = 0.65$
 Observed say $n/D = 0.30$ $n_c = 0.70$

In this case the estimate of ϕ_s from Ångström's equation (equation (8)) is replaced by a new estimate ϕ'_s given as (UK latitudes);

$$\phi'_s = \phi_s \frac{0.18 + 0.55 \times 0.35}{0.18 + 0.55 \times 0.30} = 1.08 \phi_s$$

However, a much greater effect is seen in the calculation of ϕ_q (equation (6)). Here ϕ_q is replaced by ϕ'_q :

$$\phi'_q = \phi_q \frac{0.10 + 0.9 \times 0.35}{0.10 + 0.9 \times 0.30} = 1.12 \phi_q$$

As this phenomenon can be considered to be restricted to the summer months (UK) when convective cloud formation occurs as a result of enhanced irradiation, this suggests that Wales-Smith's ratio of $\phi_q(\text{measured})/\phi_q(\text{predicted by equation (6)})$ in Fig. 4 should be multiplied by a conversion factor of

about 1/1.12 in the summer months (see solid curve in Fig. 4); suggesting that the Ångström and Penman approach is acceptable when the factor n/D is correctly estimated in this way.

One modelling solution to this has been presented by Suckling and Hay (1977) (although their total cloud model does not appear to be simple enough for daily use unless a wide data base is available). They acknowledge the problems of unreliability of the sunshine recorder and use a parameter n_e to measure an effective cloud amount. This is given by

$$n_e = \frac{n_c A + B(1-n/D)}{A + B}, \quad \dots \dots (10)$$

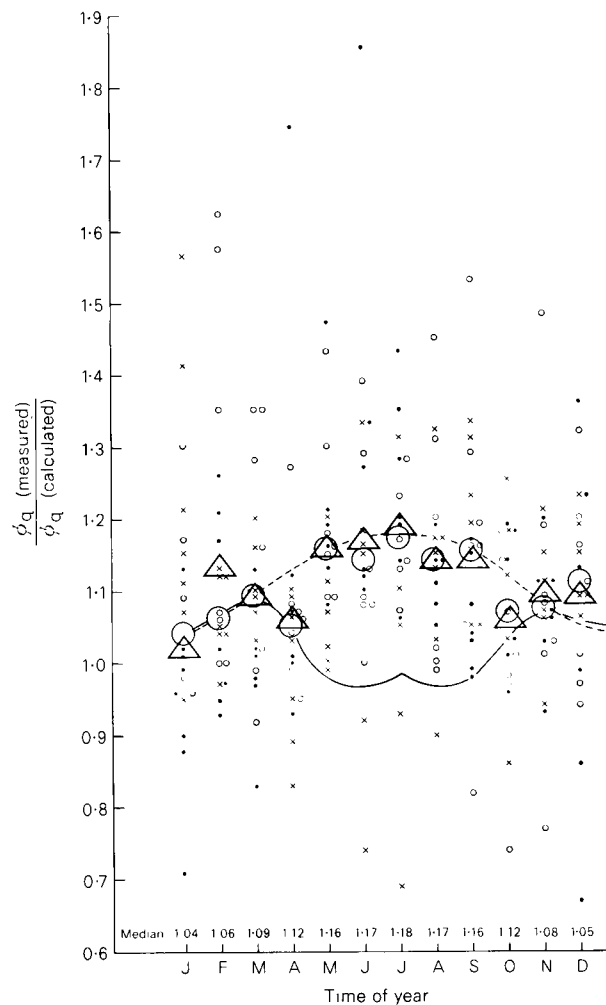


Figure 4. Values of ϕ_q (measured)/ ϕ_q (calculated) for three stations: Kew (.), Eskdalemuir (o) and Aldergrove (x) (means (\triangle), medians (\circ)), after Wales-Smith (1980) together with suggested corrected curve (solid line).

where A and B are chosen empirically. This is designed to modify the incoming solar radiation ϕ_{∞} to give the direct component ϕ_d from

$$\phi_d' = \phi_{dc}(1-n_e) \quad \dots \quad (11)$$

(where ϕ_{dc} is the cloudless sky value of ϕ_d).

For the numerical values given here in comparison with the simpler calculation of

$$\phi_d = \phi_{dc} n/D \quad \dots \quad (12)$$

it is found that

$$\phi_d' = \phi_d \times \frac{(1 - \frac{1}{2}(0.65 + 0.70))}{0.30} = 1.08 \phi_d.$$

Alternatively, using this value of n_e to replace the factor $1-n/D$ in the Ångström equation gives a correction factor (with $A=B=1$) of

$$\phi_s' = \phi_s \frac{0.18 + 0.55 \times (1-0.675)}{0.18 + 0.55 \times 0.30} = 1.04 \phi_s.$$

It can thus be concluded that the effective cloudiness factor of Suckling and Hay (1977) does seem to compensate adequately for the unreliability of the sunshine record under conditions of intermittent cumulus clouds as described here.

We therefore suggest that the Penman formulations used in Wales-Smith (1980) are better estimates of ϕ_s and ϕ_q when n/D is replaced by $1-n_e$ where n_e is given by equation (10) which uses observed sunshine amounts and observed cloud amounts — both factors which have been measured over long (historical) periods.

For lake studies, these equations are useful for calculating the net heat stored in the water. During periods of extreme convective activity, we advocate the use of n_e in place of n . Hence observations are required not only of sunshine hours but also of cloud amount (neither of which is difficult to obtain in general).

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A cloud-like land feature in satellite imagery of Saudi Arabia

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Summary

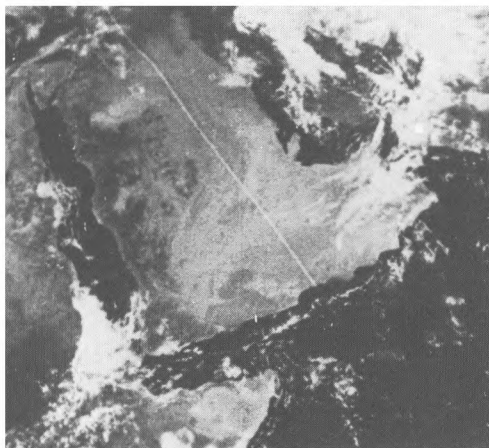
A cloud-like feature regularly appearing in satellite photographs of the Arabian Peninsula is demonstrated to be the Great Nafud Desert which is covered with highly reflecting sand.

Viewers of meteorological satellite imagery of the Arabian Peninsula are sometimes deceived by an apparent cloud in north-western Saudi Arabia, which is actually a terrain feature.

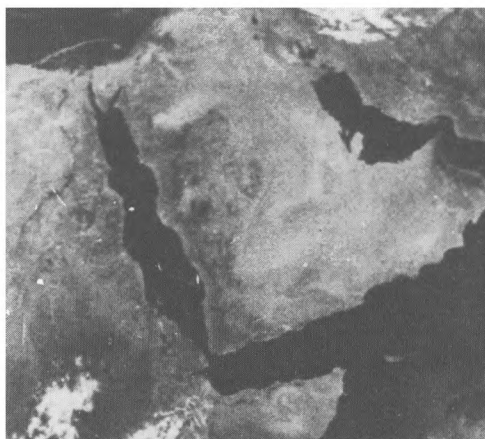
The feature is shown in Fig. 1, in a visible-band image for each of the four seasons of the year 1979 (images from the GOES satellite deployed at 58°E during FGGE). The 'cloud' feature appears just south and substantially east of the south tip of the Sinai Peninsula. The location and shape of the feature are constant through the year, while the reflectivity is essentially so.

Fig. 2 is a typical Meteosat image of the same area. The persistent feature is less bright than the cumuliform complexes to its south, but about as bright as the cirrus shield above the convective clouds.

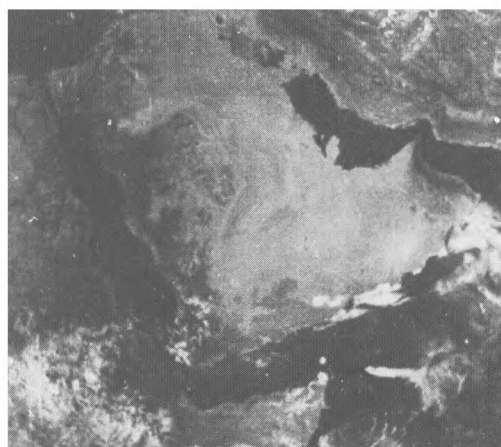
Fig. 3 shows the feature as imaged by NOAA-7. At the higher resolution of the AVHRR (Advanced Very High Resolution Radiometer) system, greater detail, including tonal gradients within the cloud-like feature, are evident.



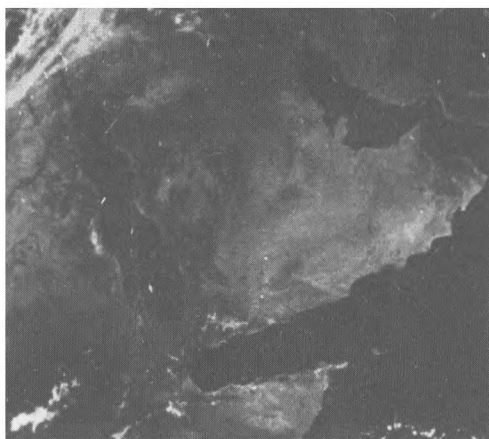
(a) 11 January 1979, 0730 GMT



(b) 28 April 1979, 0730 GMT



(c) 8 July 1979, 0430 GMT



(d) 6 November 1979, 0730 GMT

Figure 1. GOES (I0) views of the Arabian Peninsula in the visible band. The persistence of the cloud-like feature in north-west Saudi Arabia throughout the year indicates the feature to be permanent and not a result of vegetative or other temporal tonal variations.

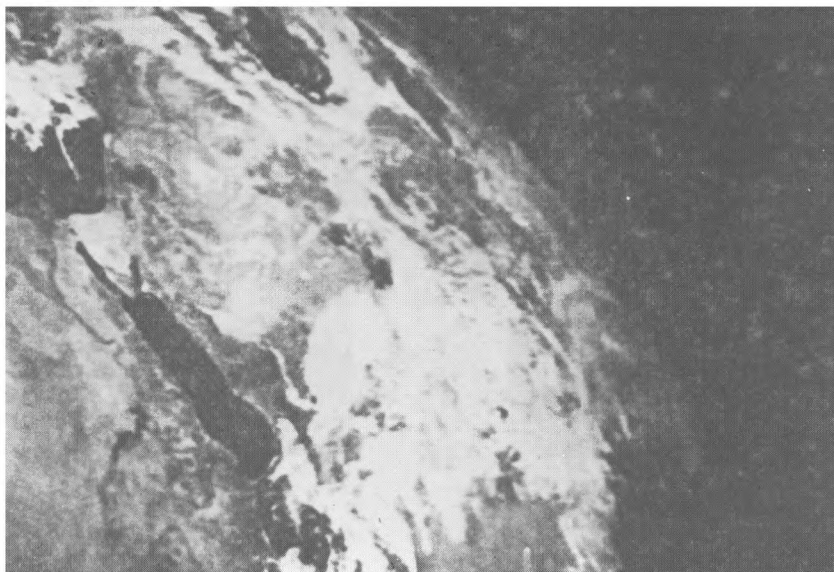


Figure 2. Typical Meteosat visible image showing the stationary 'cloud'.

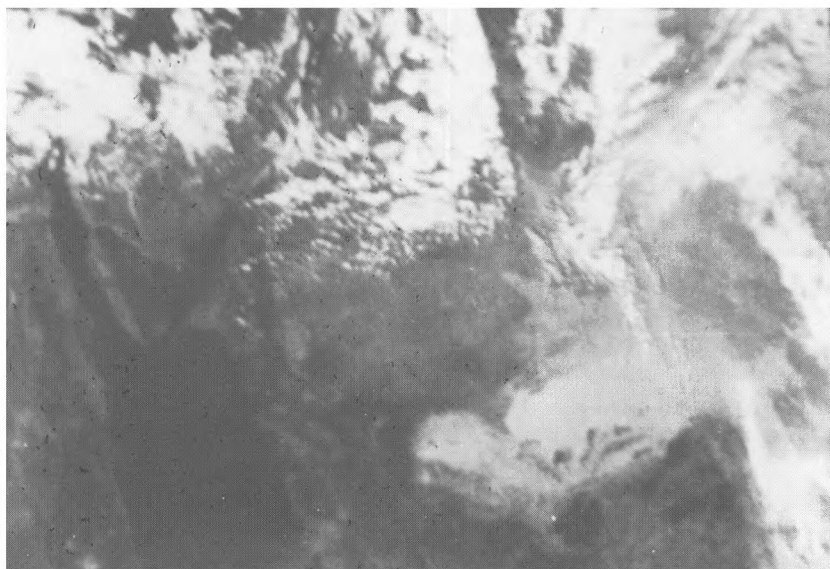


Figure 3. NOAA-7 Channel 2 (0.725–1.10 μ m) AVHRR view, 13 March 1982, 1146 GMT. At this higher resolution the 'cloud' resembles the head of a snarling dog or wolf.

The feature under discussion is occasionally apparent (as a very small tonal contrast) in infra-red images at night. This implies variations in land surface that influence nocturnal radiational properties.

Fig. 4 shows the landforms of Saudi Arabia and adequately identifies the persistent 'cloud' as the Great Nafud Desert. Note the similarity in shape of the Desert shown here with the shape shown in Fig. 3. Resemblance to a canine head is suggested in both.

This aspect is also evident in Fig. 5, from a LANDSAT image that has been enhanced to accentuate topographic detail. Fig. 6, a close-up photograph of a portion of Fig. 5 (junction of the canine's left ear and head), dramatically shows the differences in sand surface texture, which presumably result in the bogus cloud.

It is to be noted that the Great Nafud 'cloud', for reasons as yet unknown to us, appears to be more highly reflective than the much larger, and equally barren, Empty Quarter Desert (Ar Rub Al Khali in Fig. 4) in south-east Saudi Arabia. The higher contrast of the former may be due to the terrain of igneous origin that borders the western Great Nafud (Ferguson, personal communication).

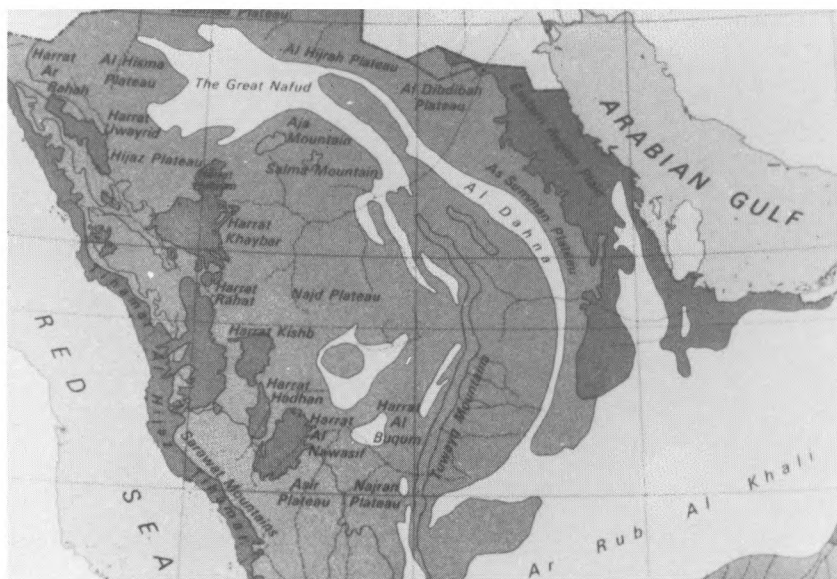


Figure 4. Landforms of Saudi Arabia (Bindagji 1980). The cloud-like feature in Figs 1–3 is co-located with the desert identified as the Great Nafud.

Acknowledgements

We express our appreciation to NOAA-NESS for GOES imagery, to Mr H. H. Bindagji for authorizing reproduction of Fig. 4 from his *Atlas of Saudi Arabia* (Oxford University Press, 1980), and to Mr K. P. Ferguson Jr, Remote Sensing Specialist, US Geological Survey, Saudi Arabian Mission, for access to the LANDSAT image copied in Fig. 5.



Figure 5. The Great Nafud as depicted on a 1:2 000 000 scale mosaic of the Arabian Peninsula. The mosaic is derived from LANDSAT high-pass filter, Band 7 imagery enhanced to emphasize topographic details. (US Geological Survey, Saudi Arabian Mission, 1979)



Figure 6. Close-up photograph of a portion of Fig. 5, showing the change in sand texture resulting in the cloud-like appearance of the Great Nafud Desert.

Awards

L. G. Groves Memorial Prizes and Awards

The first award of prizes for two years took place on Monday 15 November 1982 at the Main Building, Ministry of Defence, Whitehall. The Vice Chief of the Air Staff (Air Marshal P. R. Harding, C. B.) presided, and the Inspector of Flight Safety, RAF (Air Commodore T. H. Stonor) read the citations.

Air Marshal Harding introduced the proceedings and explained that the 1981 prizes and awards were the last to be given under the old arrangements. In 1983, as a result of further generous bequests made by the late Mrs Dorothy Groves, it was hoped to enlarge the scope of the awards to include, for example, teams as well as individuals. He offered his congratulations to the present winners and called on Mr Nicholas Abbott, as representative of the Groves family, to present the prizes.

Mr Abbott, in his opening remarks, thanked everyone who had been concerned with making the arrangements for the ceremony; he then presented the winners with their prizes and certificates, adding his own personal congratulations.



L. G. Groves Memorial Prize and Award winners with Mr Nicholas Abbott, Air Marshal P. R. Harding and Air Commodore T. H. Stonor. Seated, left to right: Mr Nicholas Abbott, Air Marshal P. R. Harding, C. B., and Air Commodore T. H. Stonor. Standing, left to right: Flight Lieutenant P. J. Bennett, Corporal S. G. Yates, Mrs E. C. Squires and Dr P. Ryder.

The 1981 Aircraft Safety Prize was awarded to Flight Lieutenant P. J. Bennett of the Royal Aircraft Establishment, Bedford for his paper introducing a modified head-up display of power margin in Harrier and AV-8 aircraft. The citation was as follows:

'The paper describes a head-up display symbol which presents the power margin available in a simple and easily assimilated form. Pilots of Harrier aircraft are vitally concerned with power margin, particularly in the hover, yet here the workload is high and to ensure safe and correct flight the pilot must devote much of his attention to outside visual cues. Flight Lieutenant Bennett's idea decreases the pilot workload during this critical stage of flying by enabling important engine parameters to be assimilated without having to refocus the eyes and look at head-down display. The new head-up display uses inputs of jet pipe temperature and engine speed to display the excess power available in a simple analogue form. It has been extensively evaluated in flight and has been found to reduce workload significantly. The modification is inexpensive and is being actively pursued by staffs in both the UK and USA.'



Flight Lieutenant P. J. Bennett, winner of the Aircraft Safety Prize, receives his citation from Mr Nicholas Abbott. In the background is his prize — a painting of the RAE Bedford Harrier aircraft by aviation artist Mr Chris Golds.



Dr P. Ryder, winner of the Meteorology Prize, with Mr Nicholas Abbott and Air Marshal P. R. Harding.

The 1981 Meteorology Prize was awarded to Dr P. Ryder, now Head of the Systems Development Branch of the Meteorological Office, for his work on cloud physics with the following citation:

'Dr P. Ryder has made major contributions to research in cloud physics. In recent years he developed a system for studying the large-scale structure and dynamics of cloud systems by means of dropsondes released from the Meteorological Research Flight C-130 aircraft. These sondes can be tracked automatically from the aircraft, providing high precision wind profiles. Sensors on the sondes telemeter data on temperature, humidity and pressure back to the aircraft. As Head of the Cloud Physics Branch from 1976 to 1982, Dr Ryder gave strong leadership to his research team. He guided design and development of cloud microphysics instrumentation on the C-130. He also fostered theoretical work so that experiments using these facilities could be designed to test and extend our understanding of the role of physical processes in clouds. His analysis of the meteorological factors in helicopter icing problems was typical of an ability to apply deep understanding of physical processes to operational problems.'

The Meteorological Observer's Award for 1981 was made to Mrs E. C. Squires of the Meteorological Research Flight, Royal Aircraft Establishment, Farnborough with the following citation:

'Mrs Squires joined the Meteorological Research Flight in January 1978 and has been employed in a variety of research support roles. A major part of her work has been as a flight test observer in the Hercules C-130 and the Canberra (before it was withdrawn in 1981) and more recently in the role of Flight Leader. In all of these tasks she has earned the respect of the RAF aircrew as well as of her scientific colleagues, not only for her undoubted expertise and competence in the flying roles but also for her unbounded enthusiasm for her work in the air and on the ground. She has made, and continues to make, a most valuable contribution to the MRF research program.'

It is worth noting that Mrs Squires is the first woman to gain one of the Groves Memorial Prizes or Awards, and we offer her our especial congratulations.



Mrs E. C. Squires, winner of the Meteorological Observer's Award. Mr Nicholas Abbott and Air Marshal P. R. Harding admire her prize — a reproduction of the Admiral's Barometer designed by Robert FitzRoy who commanded HMS *Beagle* on Darwin's famous voyage.



Mr Nicholas Abbott congratulates Corporal S. G. Yates, winner of the Second Memorial Award.

The 1981 Second Memorial Award was made to Corporal S. G. Yates, Air Traffic Control Section, RAF Binbrook, Lincolnshire, in recognition of his originating a booklet entitled 'Last Look Checks' for use by runway controllers. The booklet has now been issued by Strike Command and it is now in daily use as a timely reminder to the operating staff. The citation is as follows:

'An important task undertaken by runway controllers is to scrutinize each aircraft carefully as it lines up for take-off to ensure, as far as can be determined, that it does not get airborne with some defect which has gone unnoticed. At stations which do not have runway controllers, Air Traffic Control (ATC) staff may be able to perform the same function from the tower. In order to perform this particular task properly, ATC staff, and where they are established, runway controllers, must be familiar with the home-based aircraft but it will be less easy to become sufficiently familiar with aircraft from other units, particularly aircraft that visit infrequently.

'Corporal S. G. Yates originated a series of diagrams to enable all ATC staff to familiarize themselves with the relevant features of RAF aircraft they are likely to encounter. The diagrams show the location of blanks, pins, plugs and locks which should be removed before take-off, specific panels which should be checked for security and those areas where fuel venting may be expected.'

Notes and news

50 years ago

The following extract is taken from the *Meteorological Magazine*, March 1933, 68, 31–35.

The Great Snowstorms of February, 1933

CONTRIBUTED BY THE FORECAST DIVISION, METEOROLOGICAL OFFICE

A series of intense and prolonged snowstorms, one of the worst within living memory, occurred in most districts of the British Isles during the period Thursday, February 23rd to Sunday, February 26th, 1933, and it is proposed to give a preliminary account of the storms and of their meteorological aspects.

According to the daily Press the storms were the worst experienced since the well-known snowstorms of January 17th–21st, 1881.

[Here followed a detailed discussion of the synoptic situation and the forecasts that were issued.]

The main storm commenced in Ireland and Wales on the evening of the 23rd, and was continuous for more than 24 hours over the greater part of both countries (with the exception of the north) and drifted in an easterly wind which increased to gale force. During the night of the 23rd a rainfall equivalent of 1.69in. fell at Pembroke. Over a considerable area in south Wales the level fall probably reached or exceeded two feet. Many villages were isolated, and railway traffic was badly delayed, the Irish Mail from Fishguard arriving at Paddington 13 hours late. Many telegraph wires were broken down by the weight of snow, and photographs in the Press showed the wet nature of the snow near the south coast of Wales. In Wales and Ireland the statements in the Press that the storm was the worst for 50 years were quite probably justified. A letter from Hacketstown Rectory, Co. Carlow, reports a "record" snowfall with numerous 6- to 10-foot drifts. Over most of southern England the storm was less severe than that of December, 1927. It was, however, severe over a large area in the south-west, though on the south coast only sleet and rain were reported. During the 24th the storm spread eastward, and then extended

northward slightly beyond the Scottish border, and included northern Ireland. A fair degree of severity was maintained in the Midlands and north, and trains were delayed by heavy drifting, which was helped by the fact that the temperature was still below the freezing point. Towards the east the severity of the storm fell off rapidly, and the east coast had little snow. In London there was a moderate fall which lay on open spaces, but had almost disappeared by next morning.

On the 25th and 26th there was sleet and rain in the south, but further considerable snowfall in many other districts. The change from rain and sleet to snow took place surprisingly far south, considering the strength of the south-easterly wind. It was not only a question of height above sea level, since snow fell on low ground also, for example at Ross-on-Wye at 7h. on the 26th, and also at Cranwell, where 8 inches were lying. At 13h. on that day it was still snowing at Birmingham. No doubt the air at low levels was quickly cooled as it penetrated inland, both by the snow on the ground and by snow falling into the surface layer from above.

In Yorkshire the fall was heavy and continued until the evening of the 26th, when no less than 28 inches were lying at Harrogate. Conditions were already severe in this region before the main storm, and the total snowfall was probably as heavy as in south Wales. A number of villages were isolated in Yorkshire and Derbyshire. At Buxton the average depth was estimated to be fully two feet.

The Snowstorm in Breconshire

The snowfall here on February 24th was a record for more than 20 years. All roads were completely impassable to traffic. Towns in the hills had huge drifts 10 and 14ft deep in places. I registered 1.61 inch in the rain-gauge — the snow was 18 inches on the level in the valley. I was up on the mountains all that morning with local farmers looking for sheep and, although I am about in all weathers, never remember anything like the conditions. The wind was terrific and the drift absolutely choking — it was so bad that one could only see about 20 yards and we were forced to shelter in the rocks on the way down as one couldn't face the drift without choking. I estimated the wind on the summit of the mountain as about Force 9, in the valley only Force 7. All the sheep were smothered and we had to leave them and shelter ourselves. We were almost snowed up when we ventured back, the drifts being 16 feet in the hollows, and it took us nearly 4½ hours to go three miles. I think we were lucky to get back.

R. G. SANDEMAN.

Dan-y-Parc, Crickhowell, Breconshire. March 2nd, 1933.

Obituary

We regret to record the death on 10 September 1982 of Mr A. R. Parry, Assistant Scientific Officer, of the Synoptic Climatology Branch. Arthur Parry joined the Office in 1947 after service in the Army and the RAF Meteorological Branch. For the next 20 years he worked at various forecasting outstations including Prestwick, Rheindalen and Shawbury. In 1967 he was posted to Headquarters and worked in the Central Forecasting, Observational Requirements and Practices, and Boundary Layer Branches before joining the Synoptic Climatology Branch in October 1981.

Arthur Parry had an amiable and helpful personality, and got on well with his colleagues. During part of the time that he was at Headquarters he played the drums for the Bracknell Brass Band and also helped with a local Cub Pack.

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NOTICES

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Extreme value analysis in meteorology

By R. C. Tabony

(Meteorological Office, Bracknell)

Summary

The theory of extreme values assumes that maxima (or minima) are drawn from infinitely large samples of independent observations belonging to a single population. Failure to satisfy the theory, therefore, can be due to using too small a sample or to the inclusion of observations from more than one population. It is demonstrated that in meteorology these reasons are often alternative expressions of the same problem, namely lack of data.

A series of extremes may be regarded as belonging to the same population if a single forcing factor is responsible for the whole range of extremes encountered. This is seldom true of meteorological variables. It is shown that analyses of annual extremes are commonly to be preferred to those based on monthly data.

When observed extremes fall well short of a physically imposed upper limit it is suggested that they can appear to be unbounded above. For short duration rainfall this can be interpreted as being due to changes in the organizational structure of convective storms as we pass from the lesser to the greater extremes.

1. Introduction

A knowledge of the highest and lowest values which meteorological variables are likely to attain in a given number of years is important to many aspects of engineering design. The analysis of extreme values is therefore a topic of great importance in meteorology. A good introduction to the subject is given by Kendall and Stuart (1977) while comprehensive accounts are given by Gumbel (1958) and Galambos (1978).

Many extreme value analyses of meteorological variables have been undertaken in the past. In the United Kingdom, for instance, temperature has been analysed by Hopkins and Whyte (1975), wind by Hardman *et al.* (1973), and rainfall by Jenkinson in the *Flood Studies Report* (Natural Environment Research Council, 1975). The application of extreme value analysis to meteorological data is seldom without its problems. Hopkins and Whyte, for example, found that the predicted upper bound of temperature was too low, while Jenkinson found that rainfall extremes appeared unbounded above. Hardman *et al.* encountered problems with outliers, i.e. observations which, when plotted on extreme value probability paper, did not lie on the same general curve as the remainder of the data. An example of an outlier is shown in Fig. 1 which displays maximum temperature in June at Ivigtut on the south-west coast of Greenland. Most of the observations lie between 13 °C and 23 °C, but the highest recorded temperature is 30 °C.

In this paper the assumptions behind the theory of extreme values are examined and the difficulty of meteorological observations in meeting them is discussed. Suggestions are made as to how the various

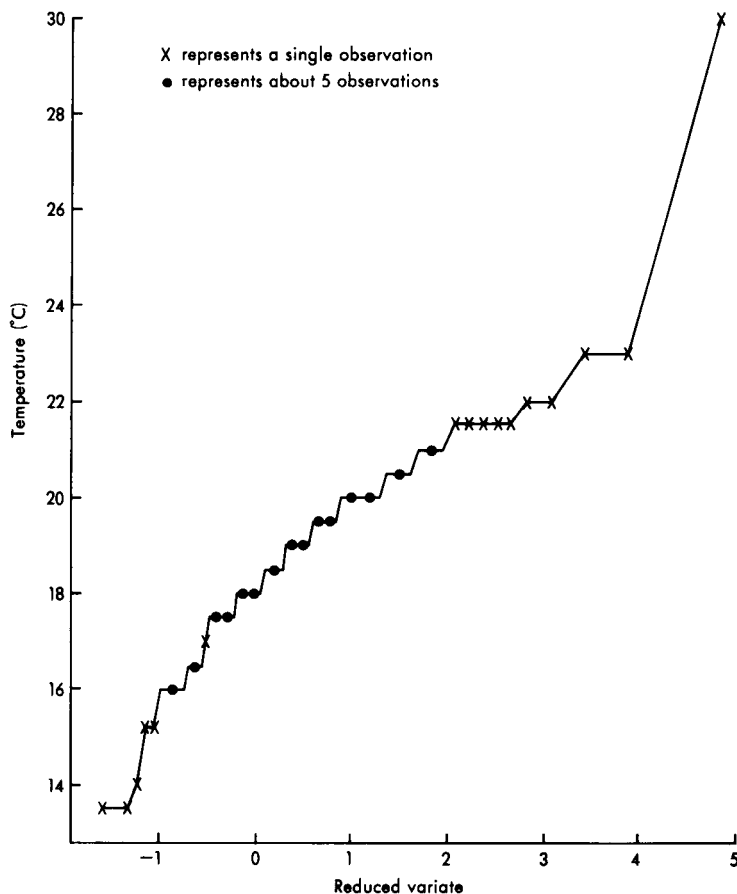


Figure 1. Maximum temperatures for June at Ivigtut, 1875-1960.

problems posed by analyses of meteorological extremes may best be interpreted. All the data used are tabulated in Appendix 2. They were either held in manuscript form within the Meteorological Office or extracted from the year books of the appropriate country.

2. Theory

Consider a series of independent observations belonging to the same population and divided into samples each containing N observations. The series of extreme values is constructed by selecting the highest (or lowest) observation from each sample. In the trivial case of $N = 1$, the sampling procedure would obviously result in the parent distribution itself. If $N = 2$, then each choice of maximum value in the sample will result in a bias towards higher values, and as N increases it is clear that the new distribution will progressively depart from the parent distribution. The differences are illustrated in Fig. 2 which displays schematically the probability density functions $f(x)$ of the parent and extreme value distributions. The theoretical extreme value distribution is approached asymptotically as N approaches infinity.

An extreme value distribution is usually expressed in terms of the cumulative distribution function $F(x)$, and when this is plotted against x an S-shaped curve is obtained. It is usual to transform $F(x)$ to a new variable y , known as the reduced variate, in which the cumulative probability distribution is represented by a straight line when plotted against x (see Fig. 3). The reduced variate can be related to the return period T . The value x which has the probability $1/T$ of being exceeded in any one sample is said to have a return period of T .

A general solution to the extreme value problem was obtained by Jenkinson (1955) in the form

$$x = x_0 + a \frac{(1 - e^{-ky})}{k}$$

where y is defined from the equation $F(x) = \exp(-e^{-y})$.

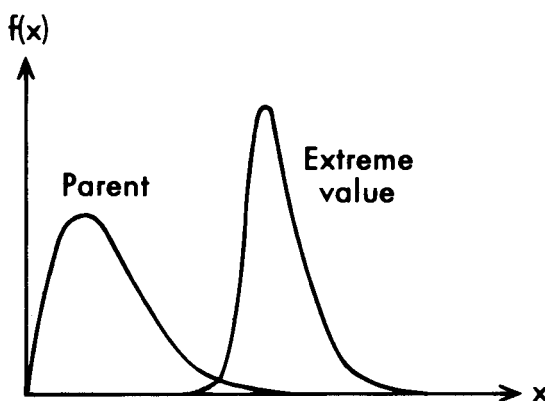
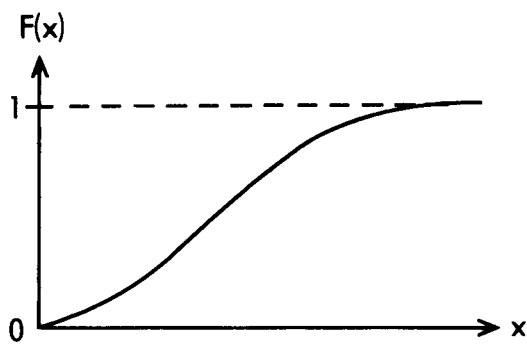
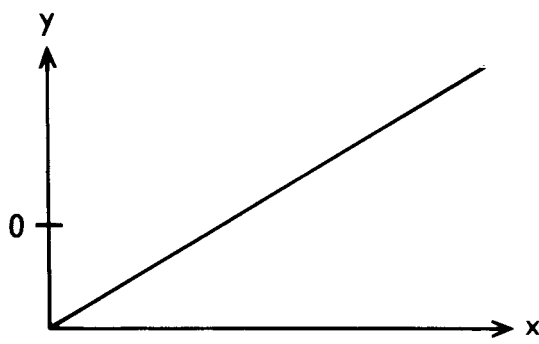


Figure 2. Probability density functions of parent and extreme value distributions.



(a) $F(x)$ plotted against x



(b) Reduced variate y plotted against x

Figure 3. Cumulative probability function of extreme value distribution.

On a graph of x against y , x_0 is the value at $y = 0$ (which is exceeded by about two-thirds of the observations), α is the slope at $y = 0$, and k is a curvature parameter. The solution may be categorized into three types corresponding to separate solutions previously obtained by Fisher and Tippett (1928). They have come to be known as Fisher-Tippett types I, II, and III and are characterized by their different shapes when plotted on a graph of x against y (see Fig. 4).

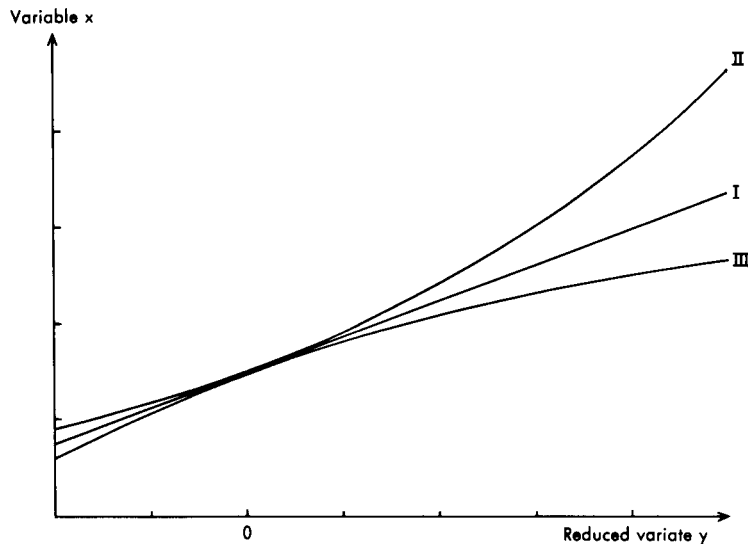


Figure 4. Fisher-Tippett distributions types I, II and III.

Type I corresponds to $k = 0$ and forms a straight line. It is the solution popularized by Gumbel (1958) and is unbounded above and below.

Type II corresponds to $k < 0$ and is bounded below but not above.

Type III corresponds to $k > 0$ and is bounded above but not below.

Fisher and Tippett (1928) obtained their stability postulate by assuming that the original data were independent and identically distributed (i.e. belonged to a single population). Galambos (1978) shows that asymptotic extreme distributions can exist if these conditions do not hold, but they will not necessarily be those of Fisher and Tippett. The application of her results, however, requires that the distribution of the original observations is known, and this is seldom the case in practice.

In meteorology, the problems caused by the lack of independence of the data appear to be limited to the associated reduction in the number of independent values. The problems caused by observations not being identically distributed, and by extremes not being drawn from infinite samples, are, however, considerable, and are discussed in the following sections.

3. Small samples

A series of independent and identically distributed observations will only yield a set of maxima that conform to an asymptotic extreme value distribution if the maxima have been drawn from infinitely

large samples. In practice this is never achieved. The extent to which the asymptotic theory can be applied depends on how quickly the extreme value distributions approach their limiting form. Fisher and Tippett (1928) show that when the parent distribution is normal convergence is slow, while Cook (1982) demonstrates that an analysis of the square of wind speed converges more rapidly than that of wind speed itself.

Exactly how large N must be to satisfy extreme value theory within acceptable limits is an important but difficult question to answer and will vary from one application to another. Some useful guide-lines may, however, be given. The selection of maxima from a very large sample ensures that they are almost certainly drawn from the tail, which may be loosely defined as the top 10-15%, of the parent distribution. If N is so small that some of the maxima are not being drawn from the tail then this is an indication that the assumptions of extreme value theory are not being met.

For monthly maximum temperatures the number of observations from which extremes may be extracted is about 30, but serial correlation reduces the number of independent values N to about 10. This is clearly insufficient to ensure that all the maxima are drawn from the tail of the parent distribution. When N exceeds 100, however, experience indicates that observed extremes usually fit the asymptotic extreme value theory very well. For maximum temperatures this would mean taking, say, ten Januarys at a time.

In any extreme value analysis a failure to draw observations from the tail of the parent distribution will be most readily apparent in the less extreme observations. There the influence of the parent distribution may be expected. Since the type I distribution has a skewness of 1.14 these effects will be most evident when the parent distribution has negative or large positive skewness. This is illustrated in Fig. 5 for maximum temperature in January at Oxford. The general extreme value distribution has been fitted by simulating five year maxima using a computer program designed by Jenkinson (1977). Although the general curve is clearly bounded above, and may be fitted by a type III distribution, the lowest four points clearly reflect the negative skewness of the parent distribution.

The contrast with the effects of a positively skewed parent distribution is evident in Fig. 6 which displays maximum temperatures for August at Santander on the north coast of Spain.

Points drawn from a normal distribution are plotted on extreme value probability paper in Fig. 7. It can be seen that a sample of normally distributed observations could easily be accepted as belonging to an extreme value type III distribution. In practice, the only criterion for obtaining a set of data which displays linearity on extreme value probability paper is that it should have a skewness close to 1.14. Since positively skew distributions are common in meteorology, this explains why many sets of 'extreme values' appear to be well fitted by the type I distribution even though N falls short of that required by theory.

4. Mixed distributions

The discussion in section 3 assumed that the extremes were drawn from a single population. Where the observations are derived from several independent populations each may be treated separately. One area where this approach has been adopted is in the analysis of winds in regions affected by tropical storms (i.e. hurricanes, typhoons). The general methodology is well described by Gomes and Vickery (1977).

If the data contain samples from Q populations, and the distribution of extremes of the q th population are denoted by $F_q(x)$, then the distribution of extremes associated with the mixed distribution is given by

$$F(x) = \prod_{q=1}^Q F_q(x).$$

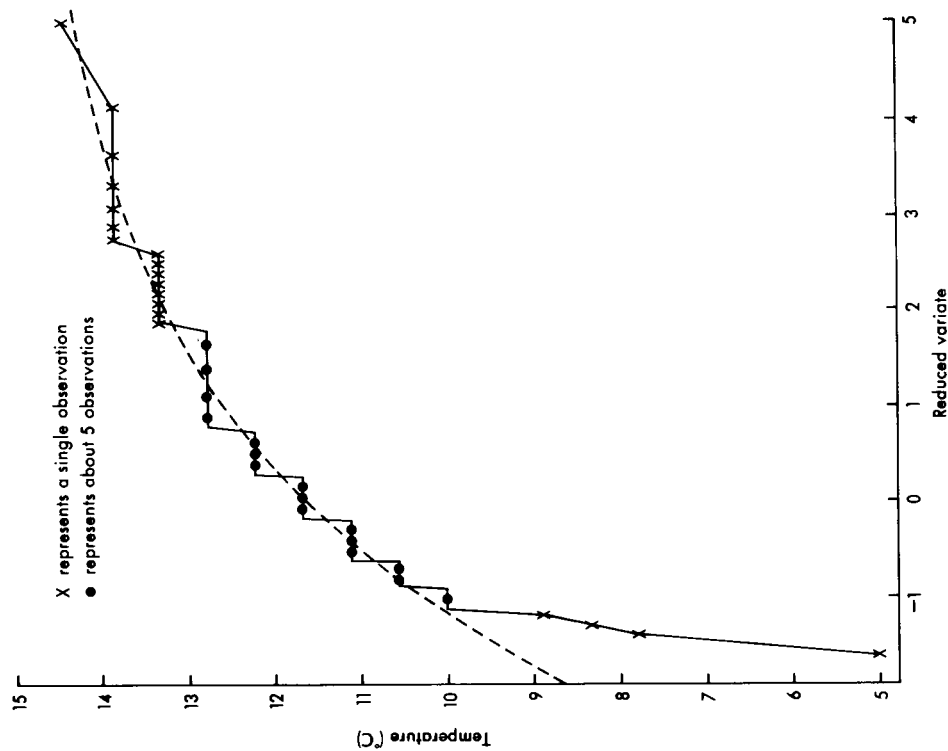


Figure 5. Maximum temperatures for January at Oxford for 1871-1970. The general extreme value distribution is represented by the dashed line.

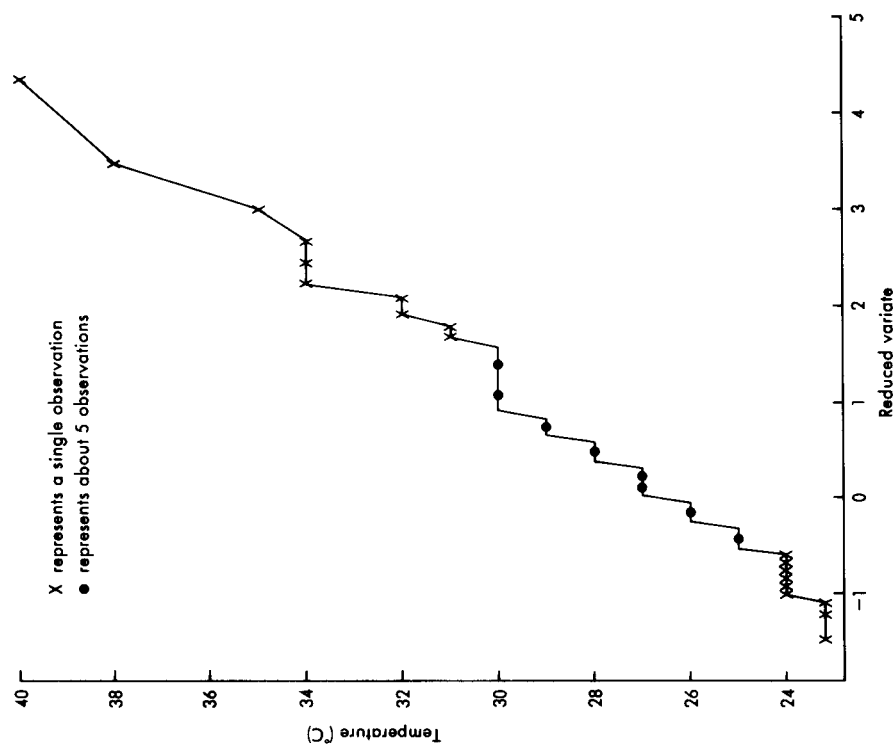


Figure 6. Maximum temperatures for August at Santander, 1927-80.

A simple example is illustrated schematically in Fig. 8. The extreme winds are assumed to belong to two populations, those due to hurricanes and those due to other causes. Each set of extremes is assumed to belong to a type I distribution. The combined probability distribution will then appear to be unbounded above and to be similar to a type II distribution. Fig. 9 presents an extreme value plot of winds for Progreso on the Yucatan peninsula of Mexico. In this example the discontinuity in the data is exceptionally well marked.

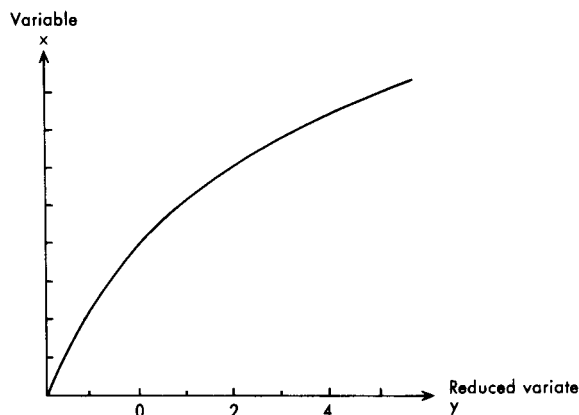


Figure 7. Normal distribution plotted on extreme value probability paper.

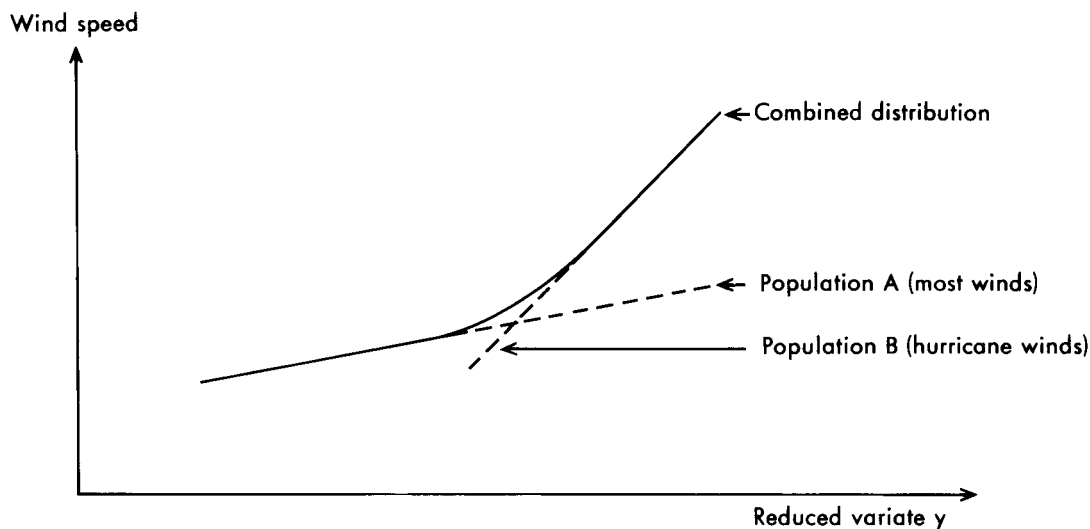


Figure 8. Extreme value analysis of observations drawn from two populations.

5. Seasonal variations

Most meteorological variables undergo a pronounced seasonal variation and consequently the observations cannot be regarded as coming from the same population. By extracting annual maxima, therefore, the theory of extreme values may well not be properly satisfied.

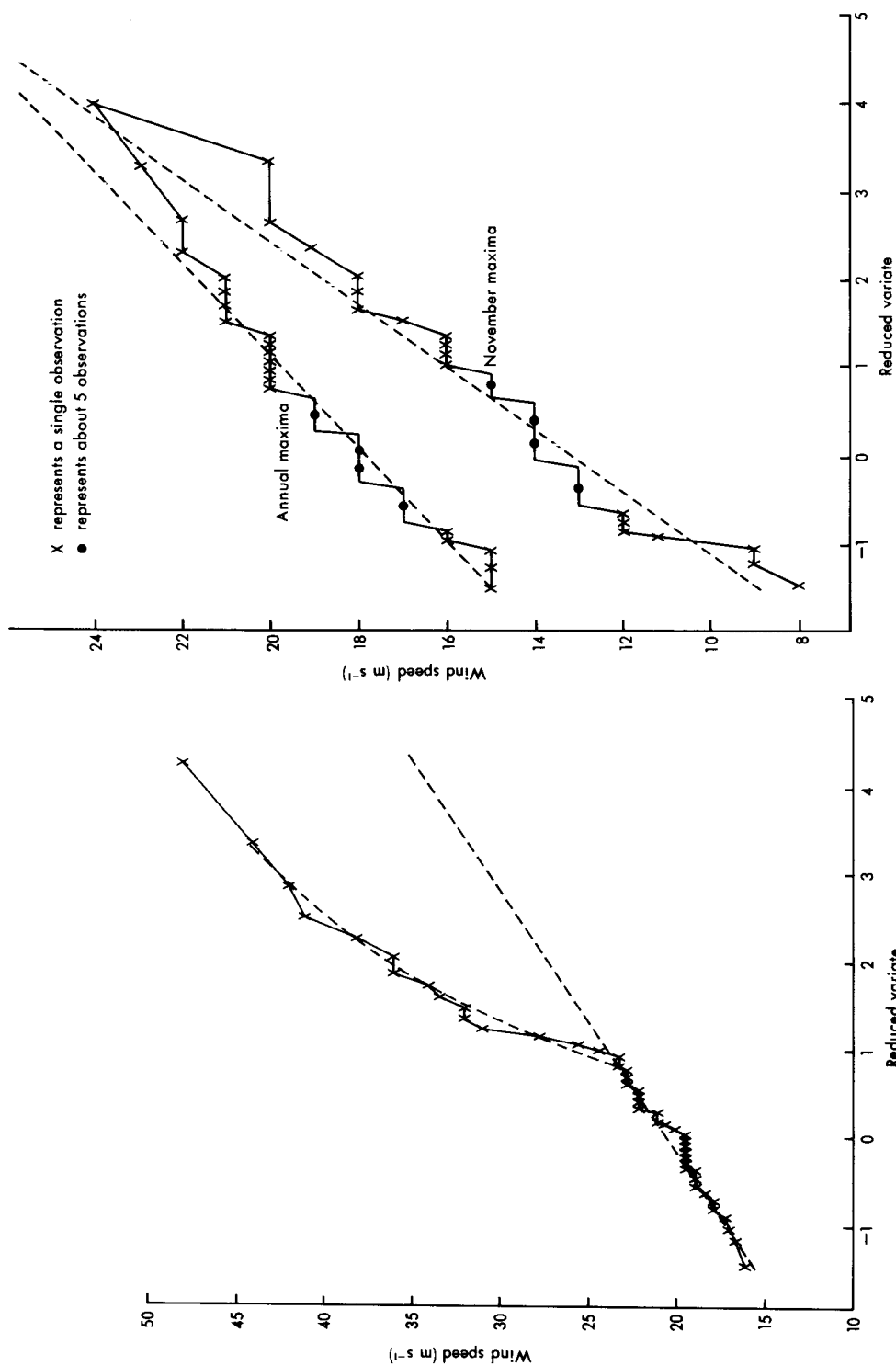


Figure 9. Annual maximum gusts at Progreso, 1921-1965.

Figure 10. Annual and November maxima of mean hourly wind at Durham, 1938-78.

Consider a variable (e.g. wind) whose values rise to a seasonal maximum in (say) November. Suppose that the strongest wind was recorded in November and that a type I distribution is fitted to maximum values for November and the year. The results are illustrated using observations from Durham in Fig. 10. In general, the maxima for November are below that for the year and in some cases the differences are considerable. The highest maximum in November, however, is equal to that for the year and so the slope of the November maxima is greater than that for the year. As a result linear extrapolation of the November extremes will lead to higher estimates than those obtained from the annual analysis. Clearly linear extrapolation of both lines is not possible. Either the slope of the annual fit has to increase towards that of the monthly or the slope of the monthly relation has to decrease towards that of the annual.

Carter and Challenor (1981), analysing winds and wave height, obtain return values from linear extrapolation of the monthly extremes. The annual maxima are taken to represent a mixed distribution in which the data for each month are regarded as belonging to different populations. Carter and Challenor point out that, when choosing the number of intervals into which a year is divided, a balance has to be struck between reducing the variation within intervals and having sufficient data in each interval to maintain reasonable convergence to the asymptotic extreme value distribution. In meteorology, an interval of time as short as one month is seldom sufficient to enable the latter criterion to be satisfied.

To illustrate the point, consider the wind. One can easily imagine a month which is mainly anticyclonic with no deep depressions passing close to a station; a low maximum wind is then recorded for the month. Similarly, for short duration convective rainfall, one can easily imagine a summer month in which very little thunderstorm activity takes place; a low maximum rainfall is then recorded. At Kew, for instance, the highest daily rainfall in July 1977 was only 5 mm while in the Decembers of 1967 and 1976 the highest mean hourly wind speeds were only 17 knots. It is these low maximum values that are responsible for the steep slope of the plots of monthly maxima. These 'extremes' are clearly not being drawn from the tail of the parent distribution. In other words, for monthly maxima, N is too small.

The relative merits of a direct analysis of annual maxima and the recombination of monthly extremes can be illustrated by the example of maximum temperatures at Oxford. Assume that annual maxima always occur in June, July or August (this is nearly always the case). An analysis of annual maxima may then be equated to an analysis of maxima in summer, for which N is about 30. The average maximum temperature at Oxford ranges from 18.4 °C to 20.9 °C in June, 20.9 °C to 21.6 °C in July and 19.8 °C to 21.5 °C in August (1941–70 figures). Average temperatures, therefore, show a range of 3.2 °C in the three month summer compared to 2.5 °C, 0.7 °C and 1.7 °C in the individual months. The difference between the methods, therefore, lies between a temperature range of 3.2 °C and a sample size N of about 30 for the annual analysis, and a temperature range up to 2.5 °C and a sample size of about 10 for the monthly analysis. The sample size of 10 is so small that the verdict clearly lies in favour of the analysis of annual extremes. Suppose, however, that a sufficiently long time series was available for the highest temperatures in a calendar month to be extracted once every M years. The fact that an annual analysis has a sample size about three times larger than a monthly analysis becomes less important as M increases and eventually the recombination of monthly maxima becomes the best technique.

For estimating values of environmental parameters associated with return periods beyond the length of record, i.e. for purposes of extrapolation, the relative merits of the two techniques can only be assessed by the kind of abstract arguments used above. However, for estimating the values corresponding to small return periods within the length of record, i.e. for purposes of interpolation, the relative merits of the two techniques can be tested against data. This was done by using monthly and annual maxima of mean hourly wind at Scilly from 1927–81. The results, displayed in Fig. 11, show that the estimates of annual maxima obtained by combining distributions of monthly maxima were all too high; similar findings were found when wind data from other stations were analysed. As the technique

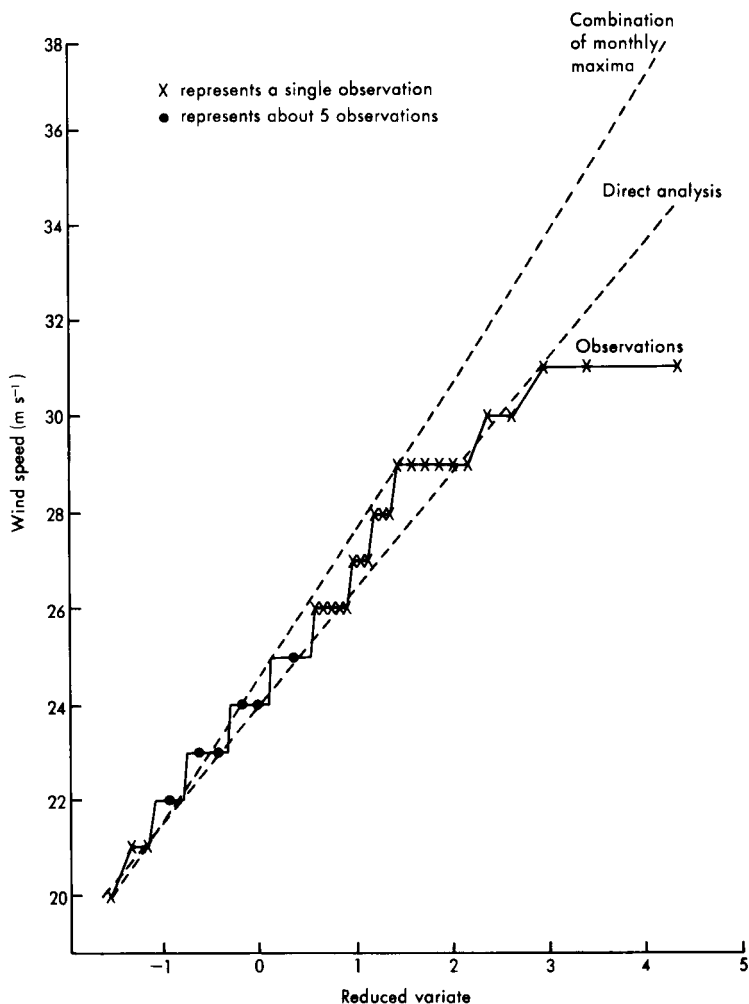


Figure 11. Annual maxima of mean hourly wind at Scilly, 1927-81.

recommended by Carter and Challenor (1981) fails to provide a good representation of observed annual maxima, one can have little confidence in its use for purposes of extrapolation.

6. Populations and forcing factors

The theory outlined in section 2 required that the extremes be drawn from a series of observations which belonged to a single population. This condition may be relaxed to enable the original observations to belong to several populations. As long as the extremes are drawn from just one of these populations, and the sample of original data belonging to that population is large enough, the theory will be satisfied.

Consider a station in a monsoon climate where the winds can be regarded as belonging to two populations associated with the NE and SW monsoons. If the strongest wind in a year is always associated

with the SW monsoon, then the series of annual maximum winds can be regarded as belonging to one population, but the appropriate sample size will not be 365, but 180 (say).

Thus application of extreme value theory need not be restricted to cases where observations are drawn exclusively from a single population. Provided all the extremes belong to one population, and the associated sample size is large enough, the original data series may be comprised of observations from a large number of sources.

Meteorological observations may be assigned to different populations according to the external mechanism or forcing factor chiefly responsible for producing the observation. A series of extremes may then be regarded as belonging to the same population if a single forcing factor is responsible for the whole range of extremes examined. In meteorology there are so many degrees of freedom that this condition is rarely completely satisfied. In practice it is reasonable to regard the observations as belonging to the same population if one forcing factor is dominant.

Consider maximum temperatures in summer at a place like Oxford. The mean temperature (thickness) of the lower half of the troposphere may be regarded as the dominant forcing factor. Dynamical subsidence, sunshine, and state of ground are other relevant factors since they determine the mean lapse rate of temperature in the lower half of the atmosphere. If these additional factors vary widely on the hottest days of the year, conventional extreme value analysis may not fit annual maximum temperatures.

Suppose a location could be found that was almost permanently overcast, then the extremes of maximum temperature might follow a type III distribution with thickness as the dominant external factor. However, the observations would be drawn from cloudy days instead of sunny ones; if there was then one sunny day the maximum temperature would be higher than before and the type III curve would no longer provide a good fit to the observations. This would be because sunshine had become a second and important forcing factor.

In their analysis of annual maximum temperatures over the United Kingdom, Hopkins and Whyte (1975) found that a type III curve, fitted to all the data, produced an upper limit (37.5°C) close to the highest recorded temperature. They considered this to be too low because, on the days which produced the lower maxima, a combination of high thickness and prolonged sunshine may not have been achieved and so these observations may be regarded as belonging to a different population from the majority of the maxima. This form of heterogeneity in annual extremes has previously been suggested by Jenkinson (1969). By combining a 1000–500 mb thickness of 5760 m (30 m above the highest observed in a 30-year record at Crawley) with a lapse rate observed at Cheltenham in July 1976, a maximum temperature of 43°C seems possible in some places in southern England.

In some locations, especially near coasts, wind direction is another possible forcing factor. Imagine a coastal resort where the maximum temperature is almost always limited by a sea breeze. If on rare occasions a sea breeze fails to develop, much higher temperatures than usual would be observed. A type III curve would not provide a good fit to observations from these occasions.

In Britain, the best examples of the effect of a second forcing factor on temperature are found in places affected by the föhn. Fig. 12 displays a plot of maximum temperatures for January at Aber in North Wales. The majority of observations may be fitted by a type III curve, probably representing occasions when thickness is the dominant factor, but the more extreme points may be regarded as lying on another curve in which the föhn is a forcing factor. The föhn is quite capable of producing the highest temperatures observed (18°C) since on those occasions temperatures at 900 mb were around 11°C . As föhns are rare, the events plotted in Fig. 12 will not represent extremes selected from a large sample and there is no question of them satisfying the asymptotic theory of extreme values. The dotted lines sketched through the föhn events in Fig. 12 are therefore purely empirical; a very large amount of data would be needed before all the maxima could be drawn from a large sample of föhn events.

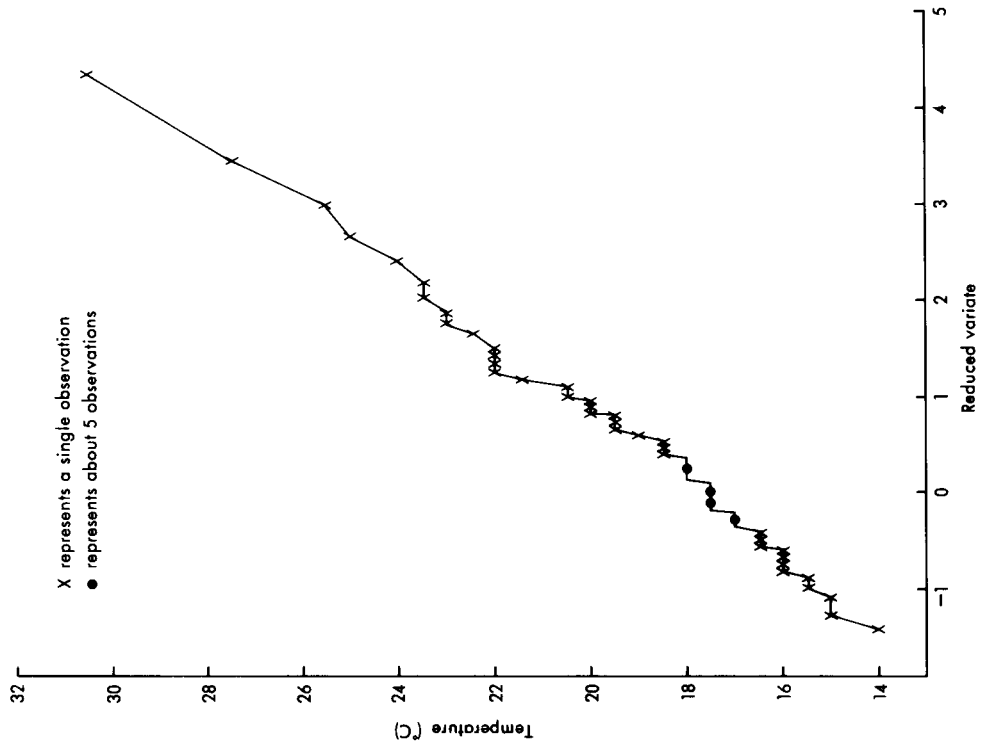


Figure 13. Maximum temperatures for June at Teigarhorn, 1922-75.

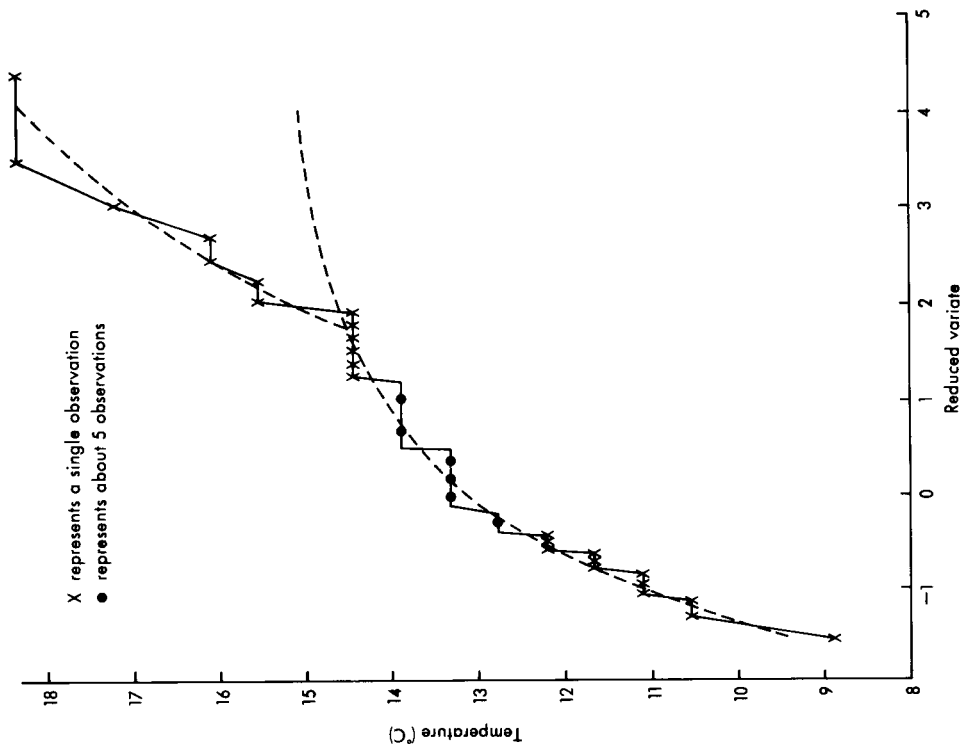


Figure 12. Maximum temperatures for January at Aber, 1925-78.

Another example of topography introducing additional forcing factors concerns the case of the Sheffield gales of 16 February 1962. These are described by Aanensen (1965) and were caused by standing waves set up by the Pennines. Much stronger winds were observed than if topographic effects had been absent and so this event belongs to a different population from the majority of gales at Sheffield.

The outlier in the data for Ivigtut, presented in Fig. 1, was probably caused by a föhn. Temperatures of 30 °C around southern Greenland are quite possible as is evident by a plot of maximum temperatures for June at Teigarhorn in south-east Iceland (Fig. 13). There the appearance of a type I curve is caused by the absence of a dominant forcing factor for many contiguous points, with thickness, wind direction, sunshine and föhn all playing a part.

7. Populations and sample sizes

In general, any set of data can be divided into a number (Q) of populations. As Q increases, the number N of independent cases from which the extremes are selected decreases. Thus while the aim of dividing data into separate populations is to provide a firmer foundation for extreme value analysis, this aim is negated by a decrease in N . The failure to satisfy extreme value theory is really due to one cause — lack of data. The two reasons advocated so far (mixed populations and insufficiently large N), are often different ways of expressing the same problem.

Consider the example of maximum temperatures for January at Oxford (Fig. 5). In section 3, the lack of homogeneity in the data was expressed by saying that N was too small. The lower values of the maxima were clearly not being drawn from the tail of the complete distribution. There is another way of looking at the problem. The majority of observations in Fig. 5 will be associated with incursions of tropical maritime air across the country. These can be regarded as constituting one population. The lower January maxima in Fig. 5 are clearly not associated with tropical maritime air and can, therefore, be regarded as belonging to a different population.

In section 6, Hopkins and Whyte's (1975) analysis of annual maximum temperature was discussed. The failure of the type III distribution to provide sensible extrapolations was attributed to the lower maxima belonging to a different population from the majority. An alternative way of expressing the problem is as follows. Hopkins and Whyte show that the lowest annual maximum at Oxford is 23 °C. Since the average maximum in July is around 22 °C, an observation of 23 °C is clearly not being drawn from the tail of the parent distribution. Hence the failure to obtain a good extreme value analysis can be ascribed to an insufficiently large N . By extracting maxima every five years, and so increasing N , the lowest maxima is raised to 29 °C and the maxima examined are much more representative of the tail of the parent distribution.

Similarly, consider a plot of extreme winds at a place like Progreso (Fig. 9) where hurricanes are a feature of the climate. The immediate reaction is to ascribe the lack of a good fit to a general extreme value distribution to the presence of two populations, i.e. those winds due to hurricanes, and those due to other causes. Suppose, however, that sufficient data were available for a long series of centennial (as opposed to annual) maxima to be extracted; then all the extreme events would be caused by hurricanes, and a good extreme value analysis for a single population could be obtained. It follows that the plot in Fig. 9 may be regarded as an inadequate sampling of hurricanes, i.e. the lack of fit to a general extreme value distribution is caused by a too small value of N .

The formation of a combined probability distribution from a number of populations (as indicated in section 4) is only valid if the populations are independent. Determining the independence of populations may not be easy and many of the different populations described above probably could not be considered independent. In any analysis, therefore, it is sensible to keep the number of populations to

a minimum and, where possible, to regard the data as belonging to a single population. In general, this aim will be furthered by the choice of as large a value of N as possible (e.g. five-year maxima instead of annual maxima).

8. Rainfall and the type II distribution

Annual extremes of daily and hourly rainfall are frequently best fitted by a type II distribution; this has always caused problems of interpretation. In the *Flood Studies Report* (Natural Environment Research Council, 1975), Jenkinson groups observations according to the magnitude of the fall which has a return period of five years. He shows that the greatest departures from a type I distribution occur for five-year falls of 20 mm in England and Wales and 15 mm in Scotland and Northern Ireland. These falls correspond to a duration of about an hour, a typical duration for thunderstorms. The departure from a type I distribution is also greater in England and Wales than in Scotland or Northern Ireland. These facts suggest that the type II appearance of the observations may be related to the behaviour of individual convective storms.

Warrilow (1981) has shown that by taking the distribution of storm movement into account modest rainfall extremes which belong to a type III distribution following the storm (Lagrangian) are converted to a type II distribution when observed at a point (Eulerian). This is likely to account for most of the type II behaviour of observed rainfall extremes. Other possible contributory factors are as follows:

(i) The complete distribution of short-duration rainfall displays large positive skewness, so any failure to satisfy extreme value theory due to insufficiently large N will result in a concave upward distribution of the lesser extremes.

(ii) Most of the larger extremes will be due to thunderstorms, but in many places some of the lesser extremes may be due to frontal rainfall. The mixture of populations would then give rise to a type II appearance to the observations. As convection will be dominant in the heaviest frontal rainfalls as well as in thunderstorms, however, the distinction between the two may not be as great as at first appears. Some of the heaviest rainfalls have been frontal in origin, but have contained embedded thunderstorms. If consideration is restricted to convective storms, however, it is true that as we pass from the lesser to the greater extremes, the organizational structure of storms also changes, from single cell through multicell to supercell. Hence the increasing organizational structure of storms as we pass from small to large return periods is likely to contribute to the type II distribution of rainfall extremes.

(iii) In certain areas, topography may encourage the development of stationary storms and give rise to a distribution of storm movements different from that considered by Warrilow. In districts thus affected, the conversion from the Lagrangian to the Eulerian frame of reference will result in some spectacular type II curves, and very large point rainfalls may have relatively modest return periods. In the United Kingdom, some of the large storms that have occurred in south-west England, together with the Hampstead storm of 1975, may enter this category.

9. The upper bound

Many sets of meteorological extremes are well fitted by the type I distribution, but this is unbounded above. Where physical considerations impose bounds, the highest extremes may not belong to the same population as the more modest extremes and will be represented by a type III distribution.

For events related to the duration of a single physical entity, e.g. a thunderstorm, a gale, or an afternoon maximum temperature, it is clear that an upper limit to extremes must exist. For longer duration events, e.g. monthly rainfall, which involve a succession of physical entities, a realistic

physically imposed upper limit is more difficult to visualize and evaluate. Most practical applications are concerned with short duration events for which the concept of an upper limit is valid, and consideration is now restricted to these cases.

The return period at which extremes approach the upper limit varies widely with element. Over the United Kingdom, for instance, maximum temperatures appear to approach their upper bound for return periods around 100 years, while for rainfall Jackson (1979) shows this does not happen until return periods of the order of a million years are reached. For a given element, the return period at which the upper bound is approached will also vary from place to place.

Consider maximum temperatures and compare typical inland and coastal sites. For any given return period, the maximum temperature on the coast will be lower than that inland. The upper limit on the coast, however, may be the same, or nearly the same, as inland. Although optimum conditions will be more rare, it is still possible to visualize a set of conditions in which the highest coastal temperatures would be nearly the same as those inland. The situation is illustrated schematically in Fig. 14. The inland station is represented by curve A, and the coastal resort by curve B. The upper limits at both locations are similar, but the return period at which this is approached is larger on the coast.

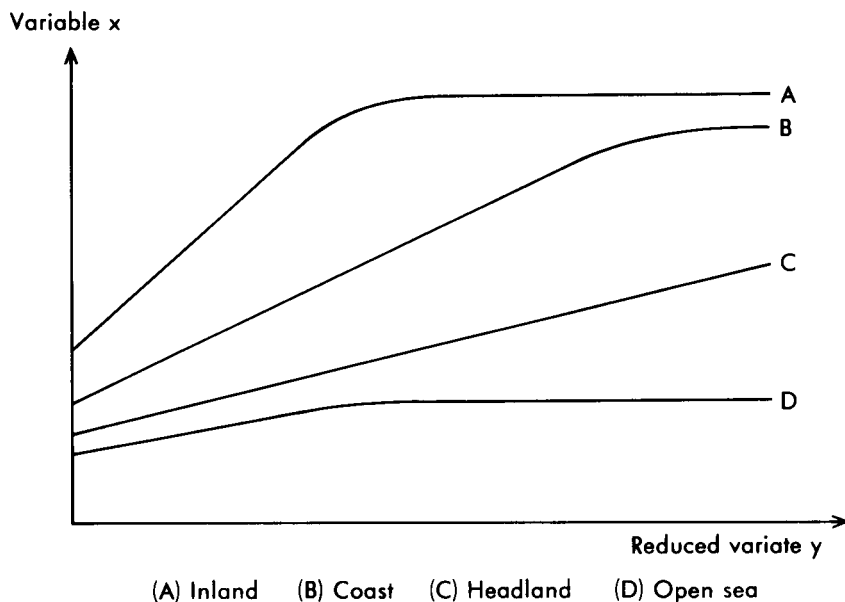


Figure 14. Schematic extreme value analysis of temperature.

Now consider the change from a linear stretch of coastline to a headland. For any given return period, the headland will experience lower temperatures than the remainder of the coast and the highest temperatures experienced inland may never be reached. The slope of the extreme value analysis, although smaller than that for other inland or coastal locations, may well remain linear for longer return periods than in the previous two cases. This is illustrated by curve C in Fig. 14. Over the open sea (curve D), however, the probable maximum temperature will be much lower than over the land and will probably be approached at a similar (modest) return period. These ideas are illustrated using real data (as far as is possible) in Fig. 15.

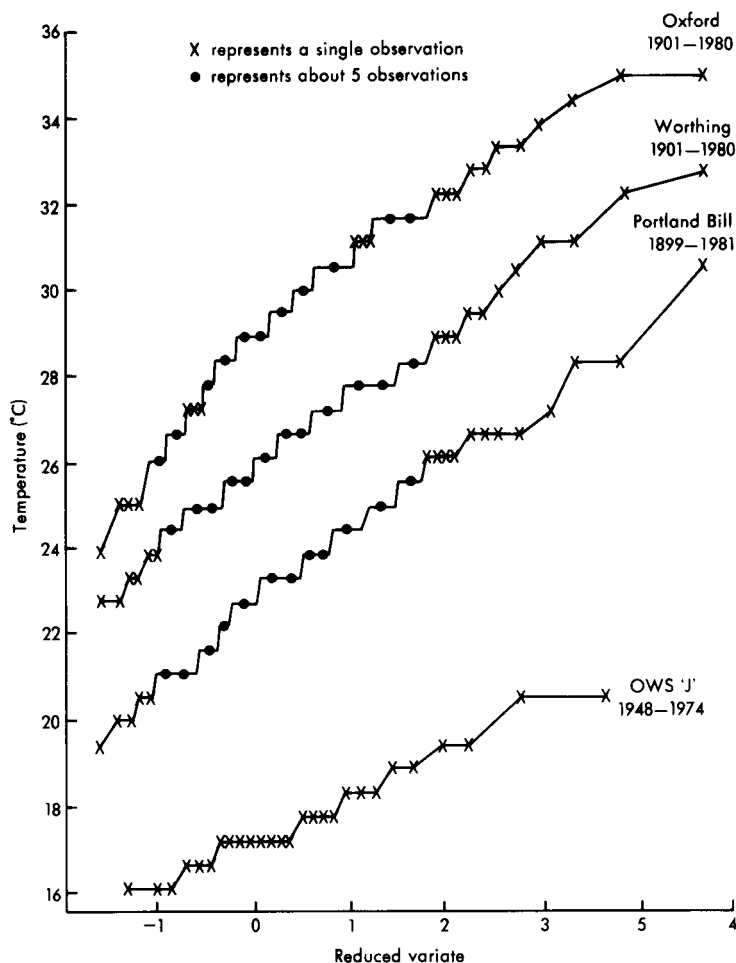


Figure 15. Annual maximum temperatures at Oxford, Worthing, Portland Bill and OWS 'J'

The same arrangements may be extended to other elements. In the case of wind, for instance, curve A may represent places like the Faeroes, where intense depressions are frequent; curve B may then represent places further South, e.g. Valentia, where deep depressions are less frequent but still possible. In the case of rainfall, districts with frequent thunderstorms will be represented by curve A while curve B represents places where they are less frequent, but still possible.

When a set of extremes fall well short of their upper limit a highly skewed parent distribution and an inadequate sampling of limiting physical conditions are indicated. The lack of data for extreme value analysis is then acute. If the observed extremes are believed to belong to the same population as those near the upper limit, it can be argued that the observed extremes are not being drawn from the tail of the single population. Alternatively, if it is argued that the observed extremes are being drawn from the tail of one population, then there are grounds for thinking that the highest possible extremes belong to another population. Using either argument, the observed extremes are likely to display the appearance of being unbounded above.

10. Practical considerations

There are two main approaches to the estimation of extreme events:

- (i) Analysis of the tail of the parent distribution.
- (ii) Direct analysis of the extremes.

When all the observations belong to a single population, a mathematical distribution may provide an exact fit to the original observations and both techniques will then give the same results. An example is the representation of Brownian motion by the normal distribution. In these circumstances, the only reason for using extreme value theory is the convenience of data analysis. The fitting of a parent distribution involves handling many observations, not all of which may be available. If a series of extremes are available, it is much easier to analyse them.

When a set of observations are not identically distributed, direct analysis of the extremes will give different results from an analysis of the tail of the parent distribution. In these circumstances, a mathematical distribution is most unlikely to provide an exact fit to the original observations. The main body of observations may be fitted reasonably well, but the tails will be poorly represented. Under these conditions, a direct analysis of extremes is clearly indicated, but it is in just these circumstances that the theory of extreme values is not satisfied. The dependence of a series of observations on more than one forcing factor is therefore responsible both for providing a good reason for performing a direct analysis of the extremes, and for ensuring that the theoretical assumptions on which such an analysis is based are not satisfied.

It has been shown that in meteorology there are usually a large number of forcing factors operating on a given set of observations. Sometimes it is possible to divide the observations into two or more categories each belonging to separate populations, but it is more usual for there to be a gradual change in the forcing factors and their relative importance across the spectrum of observations. The advantage of extreme value analysis is that it restricts the range of observations under consideration and thereby limits the changes in the forcing factors involved. The greater the value of N that can be used, the more restricted the range of extremes considered and the more likely it is that those selected can be regarded as belonging to one population.

When an extreme value analysis is performed on data from mixed distributions, any extrapolation lacks theoretical justification. Any results based on interpolation, however, are likely to be the best obtainable and will certainly be superior to those derived from the tail of a fitted parent distribution. The larger the value of N that can be used, the more reliable will be any limited extrapolation that is attempted.

In any practical application, however, a balance has to be struck between the number of observations from which the extremes are selected and the number of those extremes contained in the available record. Although an increase in N may reduce the systematic error, the smaller number of points available for analysis will increase the random error and, with the record lengths commonly found in meteorology, this is likely to be important. Volume I of the *Flood Studies Report* (Natural Environment Research Council, 1975) gives the standard errors (SE) associated with fitting a type I distribution as,

$$\begin{aligned} \text{SE}(x_0) &= 1.05\alpha / \sqrt{M}, \\ \text{SE}(\alpha) &= 0.78\alpha / \sqrt{M}, \\ \text{and SE}(X) &= \sqrt{(1.11 + 0.52Y + 0.61Y^2)}\alpha / \sqrt{M}, \end{aligned}$$

where x_0 is the intercept, α the slope, M the number of extremes and Y the value of the reduced variate corresponding to an estimate X of the variable under analysis. The second of these equations shows that if M is as small as ten then the standard error of the slope is as much as 25% of the value of the slope. It is an inescapable fact that extreme value analysis is a technique which demands a large amount of data for its successful implementation.

11. Conclusions

The theory of extreme values assumes that the maxima (or minima) are drawn from infinitely large samples of independent observations that belong to a single population. Failure to satisfy the theory may therefore be due to selecting extremes from too small a sample or the inclusion of observations which belong to more than one population. These reasons, in meteorology, are alternative ways of expressing the same problem, namely lack of data.

Most meteorological variables undergo a pronounced seasonal variation and consequently the observations cannot be regarded as coming from the same population. The problem may be tackled by regarding monthly maxima as belonging to separate populations and then combining them to obtain a distribution of annual extremes. This approach, however, is likely to be compromised by the inclusion of insufficiently extreme monthly observations and it may be better to perform a straightforward analysis of annual maxima.

In meteorology there are so many physical processes involved in the creation of a series of observations that defining a single population is difficult. In practice, a set of data may be regarded as belonging to the same population if a single forcing factor is primarily responsible for the range of extremes encountered. Topography can often act as a second forcing factor. It can cause high temperatures or strong winds through föhns and standing waves and produce high point-rainfalls by encouraging the development of stationary storms.

The return period at which extremes approach a physically imposed upper limit varies widely with element and location. When a set of maxima lie close to the physically imposed upper bound, a type III distribution of the extremes may be expected, but when the observed extremes fall well short of their upper limit, they may appear to be unbounded above. For short duration rainfall this may be interpreted as being caused by changes in the structure of convective storms as we pass from the lesser to the greater extremes.

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Appendix 1 — Plotting positions on extreme value probability paper

Intuitively, one expects a return period of about M to be associated with the largest of a series of M observations. This thinking is expressed by ascribing a cumulative probability p to the m th ranking observation of

$$p = \frac{m}{M+1} \quad \dots \quad (A1)$$

This formula was first suggested by Weibull (1939) and was popularized by Gumbel (1958). The data used in this paper were plotted according to the relation

$$p = \frac{m - 0.31}{M + 0.38} \quad \dots \quad (A2)$$

This equation was first proposed by Beard (1943) and has been widely used in the Meteorological Office following its adoption by Jenkinson (1969).

If 100 years of data are available then to the first ranking observation is attributed a return period of 101 years by equation (A1) but 145 years by equation (A2). The difference between the two is essentially the difference between the mean and the median.

If 1000 years of data are available then the event with a return period of 100 years may be approximated by the value of the 10th ranking observation. The distribution in time of these 10 largest events is not uniform. Their separation is bounded below by one and so a positively skew distribution emerges in which the median separation is less than the mean. Thus, while the mean separation of the 10 largest events will be 100 years the median separation will be less than this. Now the largest event in 100 years of data lies close to that whose median recurrence interval is 100 years. It can be shown that the mean return period of such an event is 145 years; this is the result given by equation (A2).

It can now be seen that it is the skewed distribution of the separation of the most extreme events that causes the largest observation in M to have a return period greater than M . The Weibull formula will only be correct if the largest events are uniformly distributed in time. An excellent review of plotting positions in general is given by Cunnane (1978) who recommends the use of the relation

$$p = \frac{m - 0.4}{M + 0.2}$$

The differences in the plotting positions given by the above equations are generally small except for the largest extreme. In the case of a set of extremes which fitted the type I distribution, use of the Weibull plotting positions result in a slight 'type II' appearance of the observations with the position of the largest event having the greatest error.

Appendix 2 — Data

- A = Maximum temperatures in June at Ivigtut (°C) — Fig. 1.
- B = Maximum temperatures in January at Oxford (°F) — Fig. 5.
- C = Maximum temperatures in August at Santander (°C) — Fig. 6.
- D = Annual maximum gusts at Progreso (m s⁻¹) — Fig. 9.
- E = Maximum temperatures in January at Aber (°F) — Fig. 12.
- F = Maximum temperatures in June at Teigarhorn (°C) — Fig. 13.
- G = Annual maxima of mean hourly wind at Durham (m s⁻¹) — Fig. 10.
- H = November maxima of mean hourly wind at Durham (m s⁻¹) — Fig. 10.
- I = Annual maxima of mean hourly wind at Scilly (m s⁻¹) — Fig. 11.
- J = Annual maxima of temperature at Oxford (°F) — Fig. 15.
- K = Annual maxima of temperature at Worthing (°F) — Fig. 15.
- L = Annual maxima of temperature at Portland Bill (°F) — Fig. 15.
- M = Annual maxima of temperature at OWS 'J' (°C) — Fig. 15.

(Bracketed figures are estimates.)

		Year																			
		1871	1872	1873	1874	1875	1876	1877	1878	1879	1880	1881	1882	1883	1884	1885	1886	1887	1888	1889	1890
A						17.4	19.6	21.5	20.0	19.0	18.8	18.0	19.2	18.5	13.5	18.0	16.6	18.3	20.5	15.2	21.3
B		46	53	54	54	55	53	56	55	47	53	51	55	55	55	52	52	52	54	51	56
		1891	1892	1893	1894	1895	1896	1897	1898	1899	1900	1901	1902	1903	1904	1905	1906	1907	1908	1909	1910
A		21.2	20.7	17.4	16.1	21.9	18.0	23.0	20.0	16.9	19.9	21.0	20.6	20.6	19.1	18.4	19.4	17.4	17.8	22.2	17.7
B		52	51	53	54	51	53	50	55	54	53	52	53	54	54	55	56	52	55	50	53
J												89	84	84	85	81	92	79	84	85	79
K												81	78	78	77	77	79	76	80	81	74
L										74	75	79	73	78	75	73	71	74	74	76	72
		1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930
A		17.3	19.9	18.9	14.1	30.1	—	—	16.6	—	19.4	15.2	13.7	18.6	20.2	17.4	21.4	—	20.0	21.7	16.1
B		55	51	52	55	52	57	52	55	52	55	55	57	54	52	55	53	55	56	53	58
C																		30	31	27	38
D												17.2	25.6	17.8	24.4	19.4	19.4	16.1	19.4	18.9	23.3
E																60	60	54	56	63	61
F													16.8	20.3	17.8	23.3	25.2	19.9	17.5	21.5	20.2
I																		30	26	30	29
J		95	87	83	87	82	83	89	84	86	79	89	86	93	86	85	85	80	87	87	89
K		88	84	79	78	77	77	79	78	79	76	87	78	86	75	80	83	78	82	77	83
L		83	79	74	76	74	74	70	73	70	68	81	73	83	68	75	78	70	76	73	74
		1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950
A		19.4	20.2	18.2	16.5	19.4	21.1	16.0	17.4	18.4	16.1	18.6	17.3	17.6	18.0	19.3	16.2	23.1	19.6	19.2	21.0
B		52	55	53	54	54	57	53	54	55	51	48	50	55	56	50	57	56	57	53	54
C		26	32	28	26	26	27	35	23	24	25	24	23	40	30	26	30	31	29	24	27
D		19.4	22.2	27.8	23.3	22.2	22.2	22.2	33.3	20.6	22.8	22.8	19.4	21.1	20.1	18.9	22.2	21.1	34.0	32.0	48.0
E		51	57	56	55	53	57	58	57	57	56	51	52	57	57	52	55	56	56	56	61
F		20.3	23.6	22.1	23.9	20.6	27.8	20.9	22.7	30.5	22.2	25.7	18.7	19.7	23.0	18.0	17.3	17.0	18.1	22.0	16.0
G									18	15	20	18	17	20	18	19	17	21	22	20	20
H									14	14	20	13	12	16	16	9	13	14	15	13	14
I		24	23	22	26	29	27	23	25	29	24	23	21	27	25	29	31	26	22	25	26
J		75	95	89	86	86	83	87	84	84	85	89	88	92	87	84	84	90	90	89	86
K		77	80	81	82	84	81	77	83	82	80	83	83	80	81	80	76	90	88	81	81
L		74	75	78	80	80	71	74	72	75	73	70	74	67	76	69	(72)	(80)	(77)	—	—
M																			17.2	18.3	16.7

	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
A	21.7	18.6	20.0	16.5	20.5	19.8	19.6	17.8	18.0	18.8										
B	53	52	55	56	53	54	57	55	52	54	53	55	41	54	53	54	55	55	56	51
C	30	29	35	29	29	25	30	26	28	34	30	25	23	34	27	27	25	30	24	25
D	42.0	38.0	17.0	41.0	32.0	44.0	36.0	36.0	31.0	19.4	16.7	18.9	19.4	18.3	22.8					
E	53	53	54	57	57	56	58	65	55	58	55	55	48	57	55	57	57	55	58	58
F	17.5	16.6	18.6	18.7	18.1	19.2	17.7	16.2	17.5	24.1	17.0	17.9	22.2	18.0	17.0	14.3	16.5	18.0	15.2	16.2
G	17	16	18	19	18	21	20	20	17	—	—	22	15	19	21	19	21	23	15	24
H	14	16	15	18	8	18	12	9	14	—	11	12	14	14	18	16	13	15	14	24
I	28	23	25	31	28	25	22	26	25	23	23	29	29	21	27	28	23	22	24	24
J	82	89	90	83	87	82	86	80	91	82	87	77	81	87	81	80	83	89	88	88
K	76	82	80	75	84	77	82	77	82	80	79	73	80	78	73	81	79	82	80	78
L	—	(76)	76	71	76	70	74	70	77	78	71	70	73	77	70	77	71	75	73	75
M	17.2	18.3	16.8	17.2	20.5	17.3	18.2	17.8	19.5	17.7	17.2	17.8	16.0	18.7	19.2	18.7	16.9	20.5	16.4	17.5

	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
C	28	28	32	27	28	30	24	24	27	30	
E	65	56	56	58	58	55	54	52			
F	15.5	19.5	15.0	16.2	15.5						
G	18	20	19	18	17	19	17	18	16		
H	15	20	19	14	13	13	13	17			
I	20	24	24	26	25	24	24	25	31	24	23
J	84	77	85	77	91	94	80	80	85	83	
K	82	79	85	78	85	91	82	74	77	76	
L	79	76	79	75	80	87	77	70	74	72	74
M	17.0	18.4	17.3	16.0							

Forecasting urban minimum temperatures from rural observations

By J. Roodenburg

(Royal Netherlands Meteorological Institute, de Bilt)

Summary

A regression formula has been derived from which the nocturnal minimum temperatures in an urban area may be computed from meteorological variables observed at a nearby airport.

1. Introduction

Many branches of economic activity take an interest in reliable minimum temperature forecasts, especially in an era of increasing energy costs.

For the heavily industrialized and densely populated conglomeration of Rotterdam a minimum temperature forecast is issued every late afternoon valid for the next night.

Until recently, the approach followed by the Regional Weather Office at nearby Zestienhoven ('Sixteen Farms') Airport was to adapt subjectively the official forecast from the Central Weather Office at de Bilt. Often this led to disappointing results, mainly for two reasons:

(a) in the Netherlands, as probably almost everywhere, minimum temperature forecasts traditionally have been verified against observations from well-exposed rural stations, and

(b) no objective or semi-objective method existed as to how the forecast issued centrally should be adapted in order to yield reliable results for an urban site.

The present paper presents a statistical method that includes several simple meteorological variables; as such it is an extension of earlier work done in England (Gordon *et al.*, 1969), in which noon temperatures only were taken into account.

2. Geographical description and data

Fig. 1 shows a sketch of the Rotterdam residential and business area (shaded), the industrial and harbour area (hatched) as well as the location of the urban site (encircled cross). Zestienhoven Airport is shown in the upper left corner.

The urban minimum temperatures were taken from a thermograph placed in a Stevenson screen in a 70 m² garden. The garden is enclosed by buildings on three sides, the fourth side faces the river Maas about 300 metres away.

There is some doubt as to the representativeness of these temperatures, but as no other data were available, representativeness had to be assumed.

All other meteorological information was taken from the records of Zestienhoven Airport; the period covered comprises January 1971 up to December 1973 inclusive. The period July 1980 – June 1981 was used as independent material.

All minimum temperatures in this paper refer to the period 1800 – 0600 GMT.

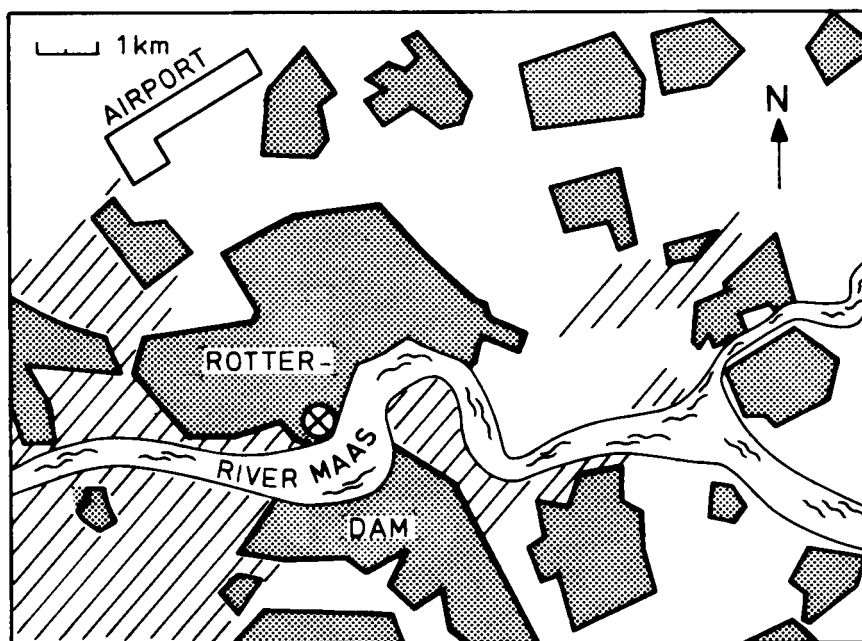


Figure 1. Plan of conglomeration of Rotterdam with urban site (encircled cross) and airport indicated. Shaded: residential and business area. Hatched: industrial and harbour area.

3. A 'first guess' urban minimum temperature

Without clouds, without advection and with neglect of the effect of heat absorbed during daytime, the minimum temperature would solely depend on the maximum temperature of the previous day, the period of time available for cooling and the atmosphere's transparency to long-wave radiation. The latter factor strongly depends on the atmosphere's water vapour content. It seemed a sensible first step, therefore, to link the minimum temperature to some combination of an afternoon temperature and a moisture parameter. This combination would at the same time reflect the length of the cooling period, since high afternoon temperatures and short nights go together. Gordon *et al.* (1969) essentially followed the same train of thought.

The sum of temperature and dew-point, observed at Zestienhoven Airport at 1500 GMT (henceforth referred to as *SUM*) was chosen on the following grounds:

- (a) both temperatures are readily available in operational surroundings,
- (b) 1500 GMT is normally close to the time at which the maximum temperature occurs,
- (c) the dew-point gives an indication of the availability of moisture in the lower layers of the atmosphere, and
- (d) if *SUM* is kept constant, various combinations of temperature and dew-point lead to approximately the same potential wet-bulb temperature (θ_w) as is easily demonstrated on a thermodynamic diagram.

As θ_w is conservative for adiabatic processes, it acts as an air mass identifier which thus, in a broad sense, also applies to SUM . Consequently, SUM should, under the assumptions mentioned above, be well correlated with the subsequent minimum temperature and thus provide a 'first guess'. The next step would be to apply corrections to this first guess in accordance with the actual (or forecast) deviations from these assumptions.

4. Systematic errors in the first guess minimum

A regression equation was derived to obtain the first guess urban minimum temperature:

$$\hat{T} = -0.33 + 0.439SUM \quad \dots \quad (1)$$

where \hat{T} is calculated temperature. The correlation coefficient (r) was 0.947, the root-mean-square (r.m.s.) error was 1.74 °C. This result is somewhat better than that achieved by Gordon *et al.*, who in rural surroundings obtained $r = 0.89$ and r.m.s. error = 2.3 °C. As the variability of minimum temperature is known to be much higher in rural than in urban areas (Böhm and Gabl, 1978) this is not surprising.

Application of equation (1) to independent material (July 1980 – June 1981, every tenth day) yielded Fig. 2. Scatter is considerable. This was to be expected because the ideal no advection and no cloud conditions, assumed in the preceding section, are seldom met in nature. Moreover, the thermal inertia of a large built-up area was not accounted for (Oke and Maxwell, 1975).

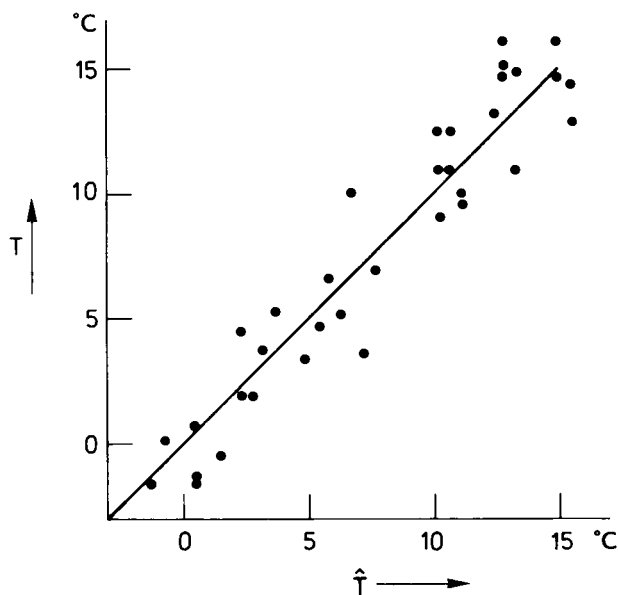


Figure 2. \hat{T} , minimum temperature calculated from equation (1), versus T , the observed minimum temperature.

In order to gain appreciation of the influence of cloud amount and wind speed Figs 3 and 4 were drawn up. They depict the average departures $\langle \hat{T} - T \rangle$, in which T is the observed urban minimum temperature, as a function of cloud amount (oktas) and wind speed in five groups: ≤ 3 kn, 4–6, 7–10, 11–16 and 17–21 kn respectively. Fig. 3 clearly shows that the calculated minimum temperature is on the average too warm on clear nights and too cold on cloudy nights. Cloud amounts were taken from the 0300 GMT observations made at Zestienhoven. Likewise Fig. 4 indicates that the calculated temperature is too high on nights with little wind and vice versa. Again the 0300 GMT Zestienhoven observations were used.

The influence of wind direction is demonstrated in Fig. 5. Here relative cumulative frequencies have been plotted of deviations from the calculated minimum temperature in excess of 1.5°C . It can be seen that the number of too warm forecasts grows rapidly with wind directions between 010 and 100 degrees. The number of too cold forecasts shows a similar behaviour with winds between 200 and 290 degrees. Furthermore it was found that for any direction there was a seasonal variation as well. Fig. 6 gives average deviations for nine direction groups for February and August. Notwithstanding the fairly large scatter around the straight lines (obtained by linear regression), the seasonal influence is unmistakable.

5. Results of a multiple regression analysis

From the observations in the preceding section it was clear that more variables than SUM had to be considered as potential predictors. Apart from cloud cover and wind the seasonal effect, as illustrated by Fig. 6, would also have to be accounted for.

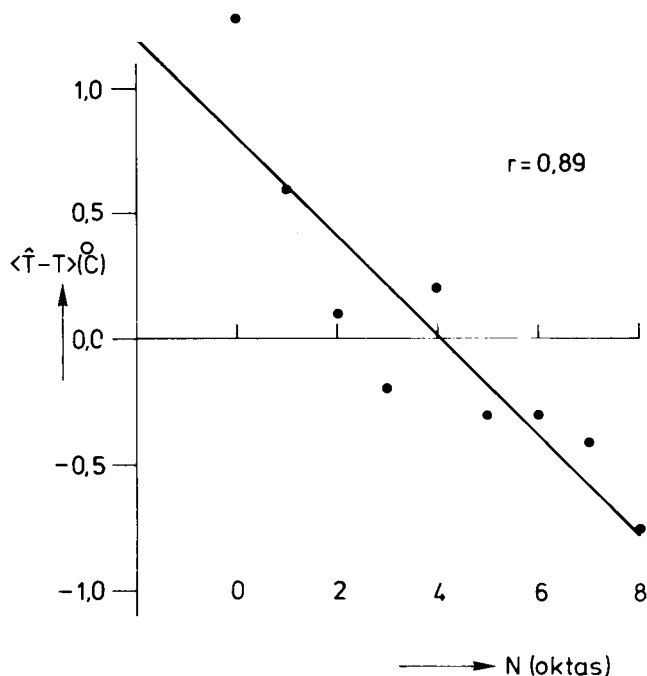


Figure 3. Average deviations from \hat{T} as a function of cloud cover.

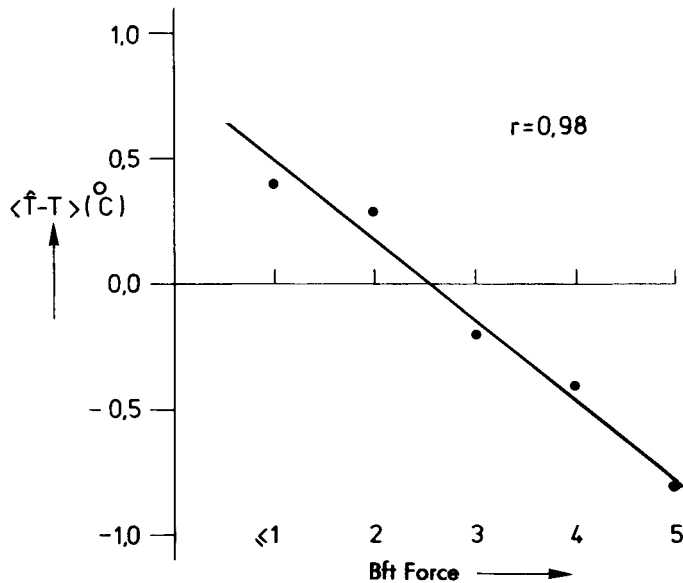


Figure 4. Average deviations from \hat{T} as a function of wind speed.

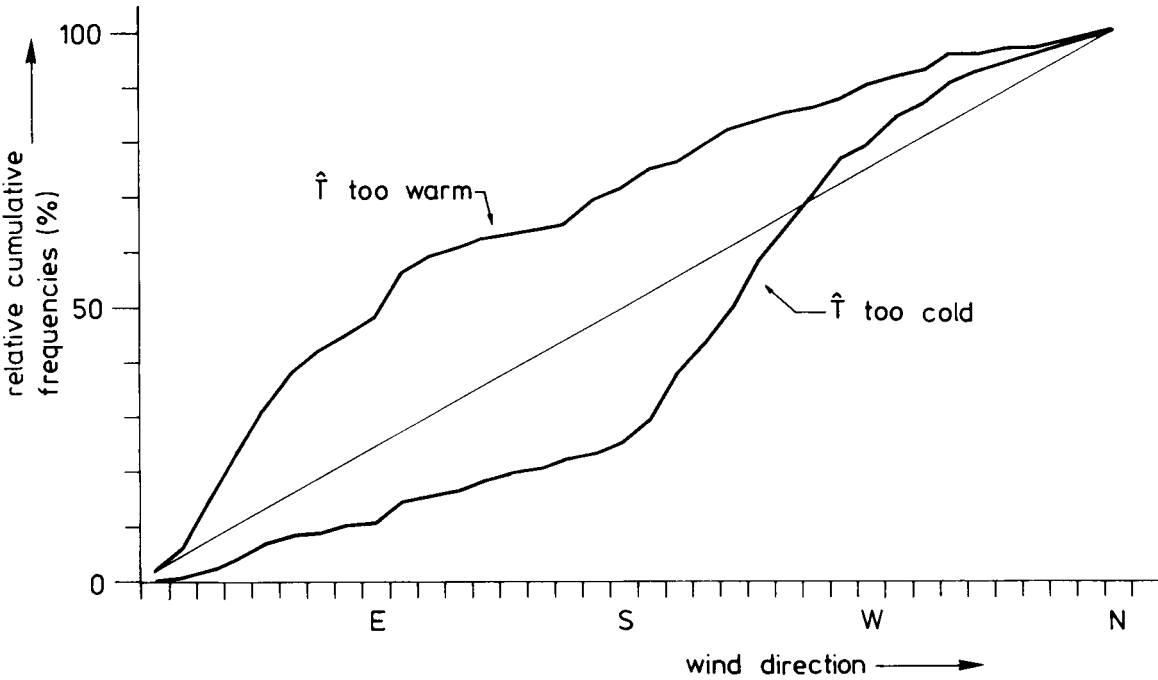


Figure 5. Relative cumulative frequencies of deviations in excess of 1.5°C in relation to wind direction (top curve: \hat{T} too warm, bottom curve: \hat{T} too cold).

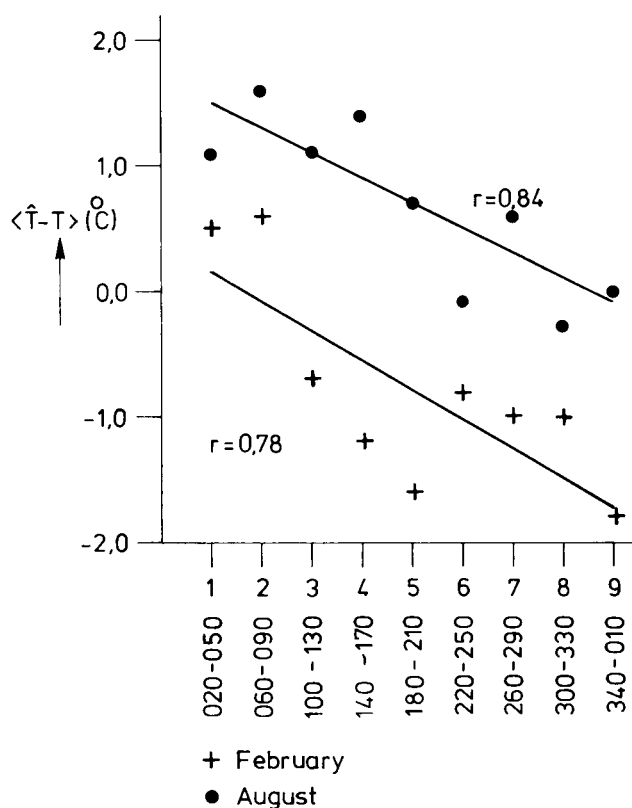


Figure 6. Average deviations from \hat{T} for nine direction sectors for February and August.

The wind data were partitioned into three direction groups: 010–100, 200–290 degrees and remaining directions and into five speed groups: ≤ 6 kn, 7–10, 11–16, 17–21 and 22 or more kn. If the wind speed was six knots or less, the direction was neglected. The groups into which the 0300 GMT wind fitted were assigned a value of 1, the remaining groups a value of 0.

To correct for the seasonal influence, after some experimenting, the best fit (in a least-squares sense) was obtained by a variable S , where

$$S = \sin \{ (m - 4.5) 2\pi / 12 \}$$

where m is the number of the month (January = 1, etc.)

Submission of the complete data-set (January 1971–December 1973) to a forward stepwise regression scheme gave the results listed in Table I. It is clear from Table I that the first four variables noticeably contribute to the reduction of variance. Therefore only these variables were retained in the regression analysis. The following equation resulted:

$$\hat{T} = 0.62 + 0.36SUM + 1.73S + 0.17N - 1.06Y. \quad \dots \quad (2)$$

($r = 0.964$, r.m.s error = 1.43°C ; see Table I for the meaning of the various symbols.)

It is interesting that wind speed does not appear as an independent variable in equation (2) despite the effect demonstrated in Fig. 4; this is because wind speed and cloud cover are correlated to such an extent that only the latter is picked out by the regression analysis.

Table I. *Description and performance of variables*

Symbol	Description	Value assigned	Correlation coefficient	Total explained variance (%)
<i>SUM</i>	Temperature + dew-point (1500 GMT)	As observed	94.7	89.6
<i>S</i>	$\sin \{ (m-4.5)2\pi/12 \}$	Depending on month	85.2	90.9
<i>N</i>	Cloud amount (oktas)	As observed at 0300 GMT	-1.2	92.2
<i>Y₂</i>	Wind direction between 010° and 100°	*	-6.0	92.9
<i>Y₃</i>	Wind direction between 200° and 290°	*	8.4	93.0
<i>B₆</i>	Wind speed 22-26 kn	*	-3.9	93.1
<i>B₂</i>	Wind speed ≤ 6 kn	*	11.7	93.1
<i>B₅</i>	Wind speed 17-21 kn	*	-8.0	93.1
<i>B₃</i>	Wind speed 7-10 kn	*	2.2	93.1
<i>B₄</i>	Wind speed 11-16 kn	*	-11.0	93.1

* As observed at 0300 GMT; if yes: 1, if no: 0.

6. Performance of the equation

Equation (2) was applied to independent material (July 1980 – June 1981), i.e. observed values were used. The results have been listed in Table II. In operational practice, however, cloud amount as well as the sector from which the wind will blow at 0300 GMT has to be estimated some 12 hours earlier. After inserting forecast values into the equation, this effect proved to be quite small (bracketed figures in Table II).

Table II. *Monthly averaged errors* (°C) using observed and forecast values (bracketed) for *N* and *Y₂*.*

	Mean error	Mean absolute error	Root-mean-square error
January	0.05 (0.00)	1.18 (1.15)	1.38 (1.46)
February	-0.01 (-0.23)	1.19 (1.21)	1.40 (1.47)
March	-0.74 (-0.85)	1.41 (1.46)	1.77 (1.77)
April	0.35 (0.24)	0.98 (1.14)	1.23 (1.46)
May	0.25 (0.17)	1.28 (1.14)	1.56 (1.41)
June	0.32 (0.34)	0.97 (1.02)	1.29 (1.24)
July	0.00 (-0.05)	0.79 (0.82)	1.09 (1.14)
August	-0.67 (-0.57)	1.23 (1.27)	1.51 (1.55)
September	-0.14 (-0.23)	0.83 (0.84)	1.01 (1.06)
October	0.11 (0.21)	0.92 (1.05)	1.12 (1.23)
November	0.15 (0.02)	1.27 (1.18)	1.54 (1.46)
December	0.17 (0.00)	0.94 (0.95)	1.09 (1.12)

* Calculated from $\hat{T} - T$.

Verification of the forecasts issued during the months January–March in the years 1971–73, when no objective method was available, gave the average monthly errors displayed in Table III. Comparison of Tables II and III makes it clear that equation (2) performs satisfactorily.

Table III. Monthly averaged forecast errors* (°C).

	Mean error	Mean absolute error	Root-mean-square error
January	-1.67	2.08	2.74
February	-1.72	2.05	2.55
March	-2.13	2.43	2.77

Calculated from $T_{\text{fcst}} - T$.

7. Sources of errors

There are several sources of errors that affect the performance of equation (2). The rather heavy reliance on the representativeness of the afternoon temperature and dew-point certainly is a weak spot. A frontal passage after 1500 GMT may bring in an airmass with entirely different properties. Fortunately, this does not happen often in the temperate climate of western Europe. When it does, the forecaster may be able to adjust the equation by using, as input, temperature and dew-point of the new airmass.

Showers occurring shortly before 1500 GMT may temporarily alter temperature and dew-point considerably, thus leading to an erroneous outcome.

The data set that was available for the present investigation contained only three winters, all of which were rather mild. Therefore, the number of days with snow cover were far too few to warrant any conclusions. It is highly likely, however, that on such days the urban minimum temperature will be underestimated (Chandler, 1965).

Finally the water surface temperatures of the river Maas and the North Sea (at 25 km to the west) may exert an influence. It is believed, however, that only in cases of extremely high or low water surface temperatures will this influence be noticeable in too cold and too warm forecasts respectively.

8. Conclusions

It has been shown that there exists a strong relationship between the sum of temperature and dew-point, observed at Zestienhoven Airport at 1500 GMT, and the subsequent minimum temperature at a site in the Rotterdam urban area. Further refinement could be achieved by taking into account some simple meteorological variables, as well as a correction factor to eliminate seasonal influence. The resulting regression equation performs satisfactorily and may be regarded as a useful forecasting tool.

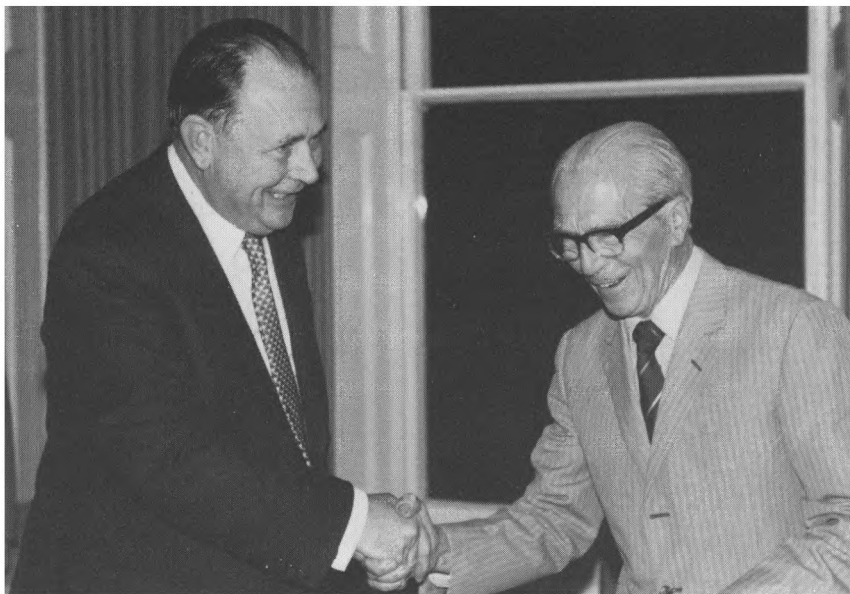
9. Acknowledgements

Thanks are due to Dr A.P.M. Baede for critically reading the manuscript, Mr S. Kruizinga who put a versatile computer program at the author's disposal, for which he is very grateful, and the forecasting staff of Zestienhoven Airport for helpful discussions and enthusiastic co-operation.

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Notes and news



Mr T. Nagle receives his farewell presentation from the Director of Services, Mr F.H. Bushby.



The Principal, Mr S.G. Cornford, makes a presentation to Mr T. Nagle on his retirement.

Retirement of Mr T. Nagle

On 30 September the Office bade farewell to Tom Nagle at a gathering in the College at Shinfield Park. In his ten years as bar steward at the College Tom probably became better known personally to more meteorologists throughout the world than any meteorologist. Indefatigable, cheerful and with knowledge, skill and style born of his West End training and experience, he was absolutely the right man for the job.

The evening was a happy beginning to retirement after 60 years at work. On behalf of the whole Office a presentation was made by the Director of Services, Mr F. H. Bushby, and, on behalf of all past and present members of staff and courses, by the Principal, Mr S.G. Cornford.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For Meteorological Magazine'.

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The work of the Boundary Layer Branch of the Meteorological Office

By C. J. Readings

(Chief Meteorological Officer, Meteorological Research Flight, Farnborough)

P. J. Mason

(Meteorological Office, RAF Cardington)

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(Meteorological Office, Bracknell)

Summary

An account is given of work performed during the last few years comprising (a) observational studies of the boundary layer over flat surfaces including the effects of cloud and stable atmospheric stratification and the special characteristics of flow over the sea, (b) observations of flow over hills and valleys including Ailsa Craig and the Sirhowy Valley, (c) theoretical studies of two-level flow relevant to (a) and (b), and (d) observational and theoretical studies of the dispersion of atmospheric pollutants on all scales.

Introduction

The boundary layer — roughly speaking the lowest kilometre of the atmosphere — is important for many reasons. It provides the immediate environment for many human activities and is of direct consequence to pollution dispersal, structural loading and so on. However, in addition, by bringing about the transfer of heat, momentum and moisture between the earth's surface and the atmosphere above, it plays a large part in determining the properties of weather and atmospheric motion systems on all scales and hence is of more general meteorological importance. The importance of the boundary layer and the gaps in our knowledge of it have long been appreciated by the meteorological community as a whole and over the last decade there have been several large international experiments aimed at furthering our understanding of this part of the atmosphere; notable among these are the Minnesota Experiment, the GARP Atlantic Tropical Experiment (GATE) and the Joint Air-Sea Interaction (JASIN) experiment. The Office has made (and continues to make) major contributions to this work, both over land using the tethered-balloon facility based at Cardington, Bedfordshire, and over the sea using the instrumented aircraft of the Meteorological Research Flight.

The aim of boundary-layer work is to be able to calculate — and hence predict — the properties and effects of the layer both on the large scale, affecting transfers between earth and atmosphere, and on the local scale, where they determine such things as the wind speed at the crest of a particular hill or the pollution in a particular configuration of valleys. The difficulties of this work are exacerbated by the

wide range of scales of motion involved, from the large-scale changes of airflow caused by changing weather systems, or by hills or coasts, to the small-scale eddies caused by blades of grass. The boundary layer is, almost by definition, the region where motions on all these scales interact and no one scale can be treated in isolation from the others. It is, in practical terms, impossible to calculate motions on a wide range of scales simultaneously at the same level of detail. Progress is made by setting up mathematical representations ('models') which reproduce the scale of major interest faithfully and which represent the other scales by means of various simplifications or approximations. The theoretical modelling work, of course, has to go hand in hand with corresponding experimental work to check the adequacy of the models in different situations and suggest ways of improving them where they are inadequate. The required measurements — again involving motions on many different scales — are by no means easy, and improved measuring techniques are still needed in some areas.

Despite many years of work our knowledge of the boundary layer is reasonably satisfactory only for the simplest of situations, namely over flat uniform land with a dry atmosphere that is neutral or slightly unstable. In the presence of clouds, over the sea, over hilly terrain or in stable inversion conditions there is a great lack of good observational data and of models which can represent and predict the phenomena at all adequately. Our current program of work is directed to collecting data and setting up models to cover a wide range of practical situations reasonably well, rather than to refining and perfecting models for the idealized case of flat uniform land and a simple atmosphere. However, in moving towards more realistic conditions, it is important to take one step at a time. Thus, in considering flow over hills and valleys, effort has initially been concentrated on isolated hills of smooth and simple shape rather than the complex geographic features normally met in practice.

Airflow and turbulence within the boundary layer are of course of direct relevance to the dispersion of airborne pollutants. Originally work in dispersion was motivated by an interest in chemical warfare arising out of the First World War. Experiments were carried out over short distances of travel in nearly steady, mostly neutral conditions. The classical diffusion equation provided a theoretical backing but only in the simplest cases. This and subsequent work led to the adoption of the Gaussian plume model which, even today, seems reasonably adequate for many purposes, though attempts to refine it and apply it to complex situations have continued. On the somewhat larger scale, interest in the long-range transport of pollutants received a stimulus from the suggestion that pollutants released by distant sources, notably power-stations, might make important contributions to the increased acidity of rain in certain parts of the world.

This article attempts to review the current interests of the Boundary Layer Branch, seeking to demonstrate the wide range of topics that have to be covered if the needs of customers of the Meteorological Office are to be met. The work is considered under three main headings: firstly the extension of earlier work on boundary layers over flat land to include the effects of cloud, the effects of stable atmospheric stratification and effects occurring over the sea; secondly, work on flow over hills and valleys; and thirdly, work on the dispersion of pollutants in the atmosphere.

The boundary layer over flat surfaces

Introduction

A clear understanding of the structure of quite simple atmospheric boundary layers is basic to progress in more complex areas or actual applications. A distinction must be drawn between observations made over land and those made over the sea. The former are subject to large diurnal variations in the flux of heat energy (which is responsible for the generation of turbulence through buoyancy), normally associated with convective activity in daytime and stable conditions at night.

Conditions over the sea are more constant and heat fluxes generally smaller, with fluxes of water vapour being of more consequence. The surface of the sea is also 'smoother' than the land. These differences are of fundamental importance to theoretical treatments.

A further point worth stressing is the paucity of data above the near-surface layer. Experimental techniques for adequate studies of the atmospheric boundary layer well above the surface have only recently become available, so the bulk of the data available to theoreticians relates to the first ten metres of the atmosphere.

Over land

In the early seventies the Branch was prominent in pioneering detailed studies of the whole (as opposed to just the near-surface) atmospheric boundary layer, using the tethered-balloon facility at Cardington as a platform on which to mount instruments capable of measuring the turbulence structure of the atmosphere. Some of this work was undertaken in collaboration with the Boundary Layer Group at the Air Force Cambridge Research Laboratories, Bedford, Massachusetts, who provided high-quality surface data needed to complement those recorded up to heights of about 2000 metres by the turbulence probes flown from the tethering cable of a kite balloon. This culminated in the Minnesota Experiment, in which the two groups combined their resources to study the structure of the atmospheric boundary layer over an extensive flat plain. Papers based on these data have significantly advanced our knowledge of the atmospheric boundary layer by providing, for the first time, detailed information covering its full depth. Thus, for example, it showed how energy is transferred between the surface and the 'free' atmosphere, how mixing varies with height, how some of our basic theoretical ideas need to be modified if they are to be applied above the surface layer, and so on (Kaimal *et al.*, 1976).

At home, the Branch carried out detailed studies of the way the dissipation of velocity and temperature fluctuations varied with height (Rayment, 1973; Caughey and Rayment, 1974), as well as collaborating with the radar group at Malvern in studying the evolution and erosion of overhead inversions (Palmer *et al.*, 1979; Rayment and Readings, 1974) and with several University groups in studying the development of the convective boundary layer (Moores *et al.*, 1979). More recently the Branch, in collaboration with University College, London, has used an acoustic radar to study the structure of the atmospheric boundary layer (Caughey *et al.*, 1980; Cole *et al.*, 1980). Some of the findings from this work are directly applicable to the forecasting of fog and stratocumulus and a simple acoustic sounder is at present being tested operationally.

Current interest centres on the role of clouds in the atmospheric boundary layer and on stable conditions. Most previous work over land has been concerned with clear boundary layers, despite the prevalence of cloud which can radically alter the characteristics of the atmospheric boundary layer, mainly by providing new sources or sinks of energy. The Branch has started to tackle this topic by considering the measurement of one of the most important parameters, namely the buoyancy, in the presence of cloud. Problems arise because of the difficulty of measuring temperature in the presence of cloud when the temperature sensors become wet. One solution is to measure the total water content together with the wet-bulb temperature. This enables measures of temperature, water vapour and liquid water content to be derived. To this end an instrument based on a commercial Lyman-Alpha hygrometer is being developed, in which liquid water is vaporized before being measured. Preliminary work suggests that an accuracy in temperature of about ± 0.1 °C is attainable, which is quite adequate for the present purposes.

The Branch is also concerned with the structure of stably stratified boundary layers and early last year a limited experimental study of nocturnal boundary layers was mounted in the Fens. During this study, arrays of anemometers and thermometers, together with a sonic anemometer and a new 'mean value' probe, were set up at a site near March, Cambridgeshire. This is a fairly flat site, unlike Cardington (the

site of previous studies — Caughey and Readings, 1975) which is strongly influenced by local ridges. The data should help provide some clear insights into the basic nature of these types of boundary layer, notably their spatial characteristics. This is very important when considering such things as the diurnal evolution of the convective boundary layer, the transitions at sunrise and sunset, fog formation and the spread of pollutants.

In support of this work the Branch is developing an improved instrument to study turbulence structure (and hence mixing and energy transfers), for use in conjunction with the tethered-balloon facility, which will be more flexible, lighter and more accurate than the existing devices. The instrument will take the form of a freely moving vane attached to the tethering cable of the balloon. Velocities relative to the vane will be measured with fast-response propellor anemometers and hot-film sensors, while a magnetometer and some inclinometers will be used to determine the orientation of the vane. Other sensors will monitor temperature, wet-bulb temperature and pressure. The data will be relayed to the ground by radio telemetry where they will be recorded by a computer-based data-acquisition system. This instrument is derived from the 'mean value' instrument which was developed in recent years and has been operated successfully in the field for over a year. An essential difference in the new instrument is the use of fast-response sensors.

It is intended to fly up to ten of the new instruments simultaneously on one cable, so as to make detailed studies of vertical structure, notably in the vicinity of clouds or an inversion. They will complement the facilities provided by the instrumented Hercules aircraft of the Meteorological Research Flight (MRF). The Branch is also considering the use of kites to supplement the tethered-balloon facility.

Over sea

As indicated above, there are substantial differences between atmospheric boundary layers over land and sea, reflecting differences in the basic parameters. Over the years considerable effort has been devoted to the study of the lower atmosphere over the sea using the tools available, notably the instrumented Hercules aircraft of the MRF and tethered balloons. Both facilities were used in GATE (Nicholls and LeMone, 1980; Barnes *et al.*, 1980; Thompson *et al.*, 1980). Current interest centres on JASIN, flights near Britain and KONTUR.

JASIN was a field experiment to study the interaction of the atmospheric and oceanic boundary layers. Proposed some 10 years ago by the Royal Meteorological Society and the Royal Society, it finally reached its climax with two months of intensive operations in the vicinity of Rockall during the summer of 1978, with ships and aircraft of several nations participating. The Office's contribution consisted of the instrumented Hercules aircraft from the MRF and surface instrumentation on three ships, one of which (HMS *Hecla*) served as the base for staff from the Branch who made radiosonde ascents and flew tethered-balloon turbulence probes, as well as supporting an instrumented toroidal buoy. The enormous task of data analysis is not yet complete, but initial results confirm that JASIN should provide valuable insights into the transformations of energy and the mixing processes, as well as providing some information on the role of clouds (especially the coupling between cloudy layers and well-mixed clear regions beneath them). Particularly encouraging has been the wealth of data provided by the Hercules aircraft, which are of sufficient quality to be able to infer wind divergence, geostrophic wind, etc. as well as the more usual meteorological variables, wind, temperature and humidity; this makes it possible to relate detailed structure to large-scale developments.

Separately from JASIN, the Hercules aircraft has been used to study the structure of the atmospheric boundary layer in sea areas around the British Isles in a wide range of stability conditions. Initial work concentrating on the lower levels of the atmosphere has already been published (Nicholls and Readings, 1979, 1981; Nicholls, 1978). Even though these data do not include surface measurements, several

interesting points have already emerged, notably significant differences between 'across wind' and 'along wind' structure and the contrasts between this type of boundary layer and that encountered over land. This work is at present being extended to cover the whole boundary layer, using data gathered during the last few years.

However, work of this nature, involving a single aircraft with no supporting data, will never provide all the information needed and it is desirable to mount more comprehensive experiments specifically designed to concentrate on particular aspects: the latest of these is KONTUR (KONvektion und TURbulenz). This is a study of convective boundary layers which took place in autumn 1981 in the German Bight. Several German research institutes combined to provide extensive surface instrumentation, radiosonde stations, an aircraft and the central organization. The Office's participation was limited to one aircraft, the MRF Hercules. Although data analysis has only just started it is clear that the experiment will complement JASIN by providing data on convective, as opposed to neutral and stable, boundary layers. Several cases where mesoscale organization (e.g. cloud streets) was observed should prove particularly interesting. Both the Cloud Physics Branch and the Meteorological Research Flight are collaborating with the Boundary Layer Branch in this work.

Theoretical work on uniform boundary layers

In order to understand and extend experimental findings and help identify definitive experiments it is necessary to develop relevant theoretical models. Thus, concurrently with the Minnesota experiments and the studies of convective boundary layers (see above), the Branch developed simple analytic models capable of representing broad features of this type of boundary layer (Carson, 1973). In recent years more advanced models capable of representing many more of the features observed in boundary layers have been developed.

Current models depend on separating the spectrum of eddy motions in the atmosphere into two parts, 'large' eddies which are represented explicitly and in detail and 'small' eddies whose effects are represented in a simplified, averaged way. Initial work concentrated on dry neutral boundary layers in which the only types of 'large' eddy represented were long rolls (vortices) with horizontal axes. Such rolls are not uncommon in the atmosphere, particularly over the sea. Results (Mason and Sykes, 1980) depend markedly on the orientation of the rolls with respect to the wind. Another interesting feature is the presence of slow variations on a time-scale of many hours (the Coriolis scale).

The model has been extended to include buoyancy and has already been used to simulate dry convective boundary layers with overhead inversions. The results (which have not yet been published) are very encouraging, reproducing many of the features associated with these types of boundary layer and providing useful insights into the physical processes that occur (see Fig. 1). One notable finding is the dependence of the generation of internal gravity waves, in the stable region above the boundary layer, on the orientation of the rolls.

At present, the model is also being used in a study of stable boundary layers and already it has produced instabilities reminiscent of the 'resonant over-reflection mode' proposed by Davis and Peltier (1980). In this, energy from 'Kelvin-Helmholtz' breakdown is fed into long waves which grow in amplitude, the energy being trapped between the surface and a region of low Richardson number above. Further insights into this and other phenomena affecting the structure of stable boundary layers will no doubt also appear when the model is used to help interpret data from the Fens experiment.

Recently, this two-dimensional model has been further extended to include water (liquid and vapour phases) and it is currently being used to study the structure of cloudy boundary layers. Furthermore, the basic model is being extended to three dimensions, for runs to be conducted on the Meteorological Office's new CYBER 205 computer.

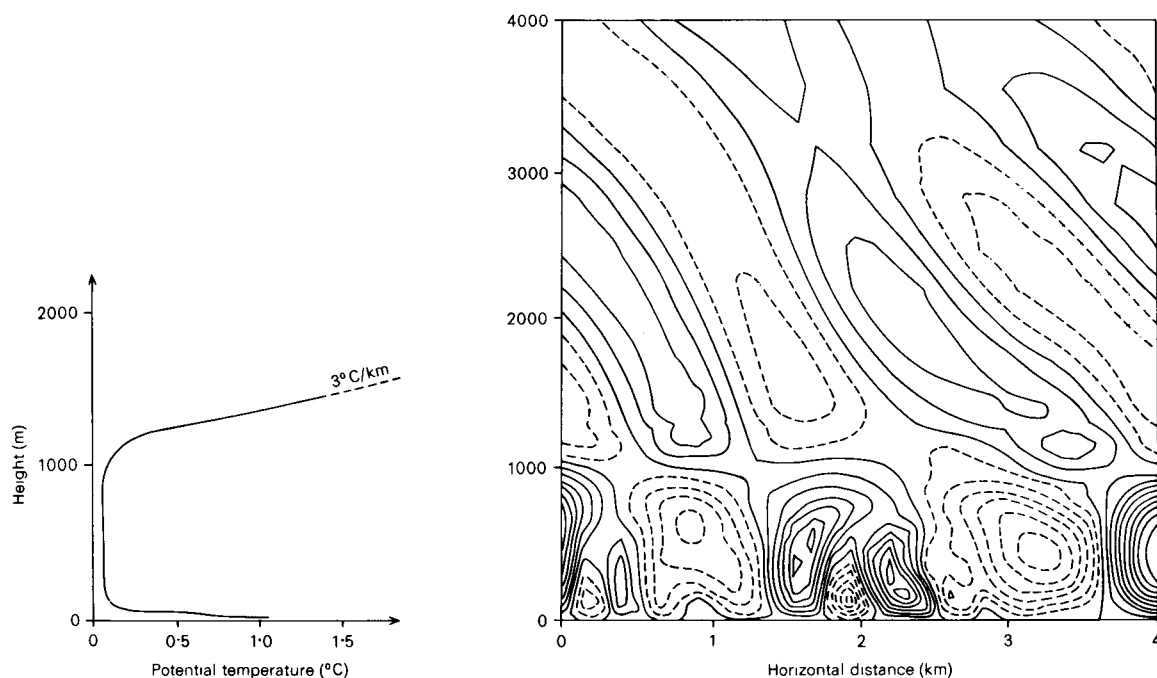


Figure 1. Eddies in and above a dry boundary layer. The main diagram shows results from a two-dimensional model of airflow in a dry boundary layer, with the temperature profile shown in the left-hand diagram. The lines in the diagram are contours of vertical velocity, with a spacing of 10 cm s^{-1} ; solid lines represent upward motion, dashed lines downward motion.

Flow over hills and valleys

Introduction

Many practical problems, including wind stresses on buildings, the selection of sites for the use of wind power, the dispersion of pollutants and the safety of aircraft require a knowledge of how wind velocities and turbulence are affected by hills. There is surprisingly little quantitative information on this; measurements of the wind velocity distribution for specific sites on hills are not uncommon, but until quite recently there have been few attempts to relate them to general characteristics such as height, slope, etc. Almost nothing is known about the turbulence characteristics of such flows. A few years ago the Branch began a series of experiments and theoretical studies, beginning with simple shapes of hills, intended to improve our ability to give practical advice.

Experimental program

The first set of field experiments carried out was on Brent Knoll, a roughly circular hill about 140 metres high, situated in Somerset. This is fairly smooth and quite isolated, with slopes of about 1:5 — rather large for comparisons with simple theory but having the advantage of giving easily measured changes. Wind speeds above the ground were measured at various sites and the data compared with the predictions from a generalized form of the Jackson and Hunt theory (Mason and Sykes, 1979b). The theory was found to give reasonable predictions of the observed velocities; in particular the speed-up at the crest was observed to be about 2.3 compared to a theoretical value of 2.0.

Following this preliminary work, a more ambitious study was undertaken of flow over a nearly circular and isolated hill steep enough to produce flow separation. The site chosen for this work was the island of Ailsa Craig off the coast of Ayrshire, south-west Scotland. This island has a height of 330 metres and, apart from cliffs along the western and southern sides, the terrain has slopes of about 30 to 45°. The object of this experiment was to obtain as full a picture as possible of the three-dimensional flow field under conditions of near-neutral stability. Three types of measurement system were used: anemographs to measure mean wind at 4 metres, turbulence probes supported by a tethered-balloon system giving vertical profile information and the instrumented Hercules aircraft from the MRF giving velocities both upwind and downwind of the island.

The anemographs produced a coherent picture of flow round the island showing reversed flow and separation on the downstream side. Data from the balloon-borne probes indicated that the turbulence structure was highly distorted, with large increases in the cross-wind component of turbulence energy. Aircraft observations revealed a very powerful trailing vortex downstream of the obstacle with its axis orientated along the upstream wind direction, and circulation velocities of the same order of magnitude as the undisturbed horizontal speed (Jenkins *et al.*, 1981).

Subsequent theoretical studies have confirmed that this vortex arises from the elliptical shape of the island. The mechanism is essentially the same as vortex generation by a 'lifting body' such as an aircraft wing. However, it is surprising that with the 'stalled/separated' flow and an ellipticity of 1:1.5, a powerful vortex results.

In 1980 an experiment was mounted in the Sirhowy Valley, South Wales. This is one of a series of valleys with axes lying approximately north-south and together they form a reasonable approximation to a two-dimensional system which is much more amenable to theoretical analysis. As with Ailsa Craig an array of anemographs was used to record flow across the valley while Cardington turbulence probes (Readings and Butler, 1972) monitored turbulence levels from the tops of two masts and from the tethering cable of a kite balloon (see Figs 2, 3, 4 and 5). This pilot experiment revealed several interesting features, notably much higher levels of turbulence than expected. These and other points were studied further last year when a group from the Branch returned to the site with new equipment better suited for use in high turbulence levels. Of particular interest are a sonic anemometer, some hot-film instruments and the new 'mean-value' probe previously mentioned. The weather proved quite favourable with strong westerly flows for much of the time. Thus it should prove possible to identify the main characteristics of the flow from the data set, including the high turbulence levels and the 'separation bubble' which occurs in the lee of the windward ridge. The latter was in fact shown up at times during the experiment by the use of small zero-lift balloons. Tracer experiments were carried out at the same time and will be used to check the analysis of airflow.

Further experiments are planned on a hill in North Uist in the Outer Hebrides which meets all the criteria needed to carry out a definitive experiment, namely it is isolated, easily accessible, of uniform shape and of uniform roughness, being free of hedges, trees and the like. Data obtained from this site, using equipment now becoming available, should be of sufficiently high quality to test the various theories properly, particularly those involving turbulence parameters because, for the first time, changes in turbulence structure should be mainly determined by the general shape of the hill and not reflect local changes in roughness.

Theoretical work

At present there is a sound theoretical basis for the study of laminar flow over obstacles, though numerical investigations of separated flows have only recently been undertaken (Mason and Sykes, 1979a; Sykes, 1978). However, if accurate predictions of wind speed near the surface are to be made, then

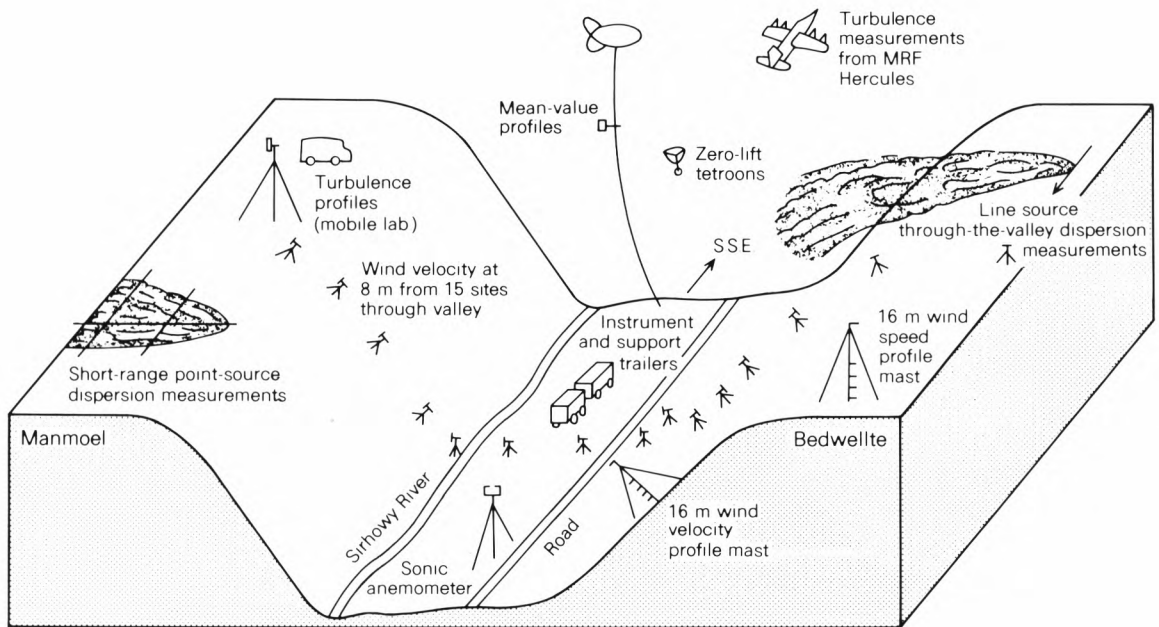


Figure 2. The Sirhowy Valley experiment, 1981

the fact that the atmosphere is turbulent must be taken into account and a convincing model has yet to be formulated.

To compare with the Brent Knoll experiment, Mason and Sykes (1979b) extended Jackson and Hunt's linear analytic theory of flow over gentle topography to three dimensions and it was surprising how well this model predicted many of the features observed experimentally, given the relative steepness of the hill's slopes. Subsequently, however, Sykes (1980) developed a higher order asymptotic theory for flow over a shallow ridge and showed that even a simple representation of the flow (i.e. an inviscid potential flow) is adequate as far as perturbations in mean velocity are concerned, so they are not a sensitive test of theoretical models. Thus, for the case of gentle topography, measurements of more sensitive quantities such as the Reynolds stresses are needed to test the validity of theoretical models adequately; hence the planned experiment in North Uist. Interest in these Reynolds stresses is not academic; they are vital for determining pollution dispersal and wind loading and their details are critical in determining the net momentum transfer between the boundary layer and the free atmosphere above.

In steeper topography, when flow separations may occur, even the mean flows are very poorly understood. The main features revealed by the Ailsa Craig experiment have been qualitatively explained by the application of a three-dimensional laminar-flow model but quantitative work awaits the development of a fully turbulent model. However, the two-dimensional numerical model described earlier has been applied to the site of the field experiment in South Wales. Initial results have confirmed the extent of the surface separation region and it is hoped that the extended data acquired in 1981 will provide further insights into the use of the model.

In turbulent flow over hills, the divergence in the Reynolds stress only dominates the pressure gradient and advective effects in the thin equilibrium region near the surface, so to model such flow successfully a high resolution normal (and close to) the surface is needed. Accordingly a 'terrain-following' (as opposed to the original 'Cartesian mesh') co-ordinate numerical model has now been set up. In this, the

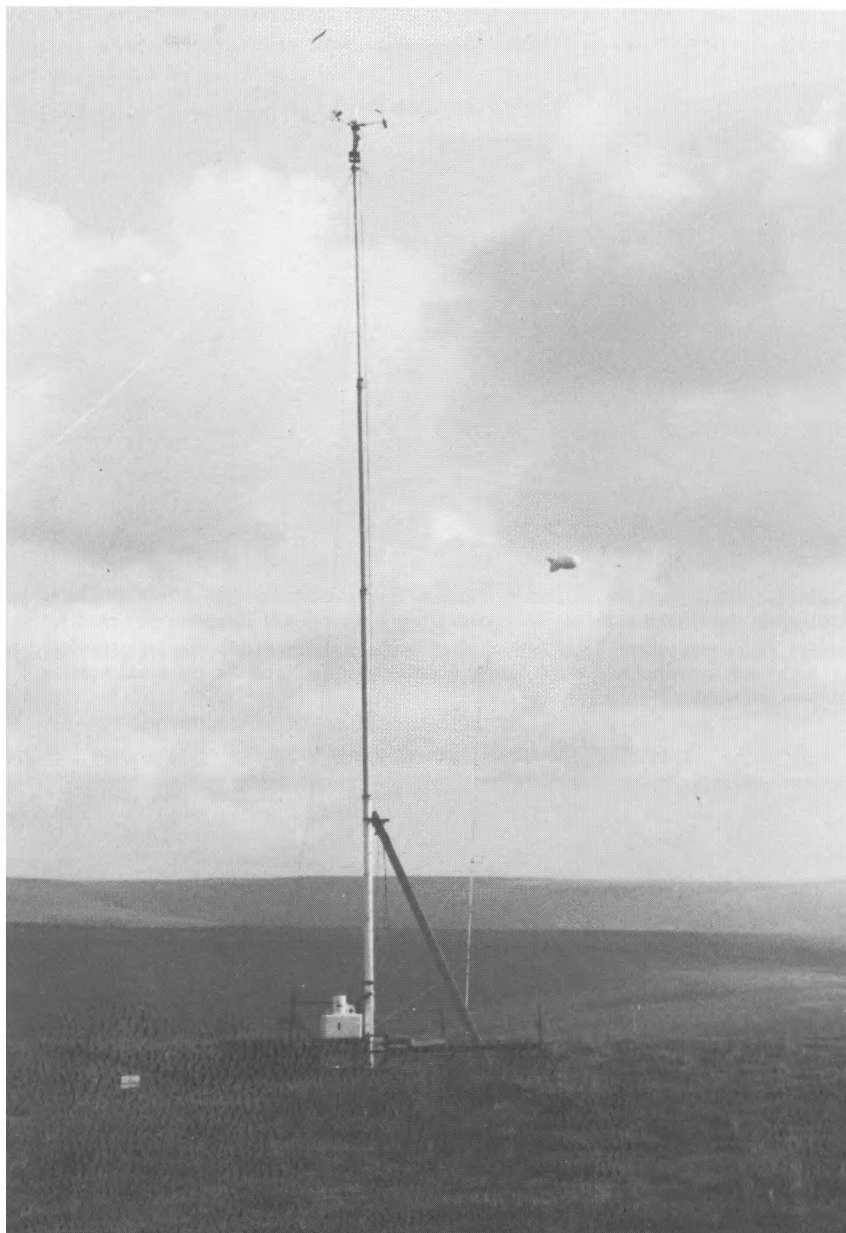


Figure 3. The Sirhowy Valley experiment. Measurements of turbulence levels, requiring fast-response sensors and high-speed data logging, were made on hill tops and in the valley through the use of a mobile laboratory. Seen here is turbulence instrumentation atop a 16-metre mast on one of the hills; a further 16-metre wind profile mast is visible behind, as well as the tethered balloon flown above the valley.



Figure 4. The Sirhowy Valley experiment. The winds which blew in the optimum direction for gathering data on cross-valley flow also brought with them torrential rain which caused flooding of the balloon site and made working conditions difficult around the instrument caravans.

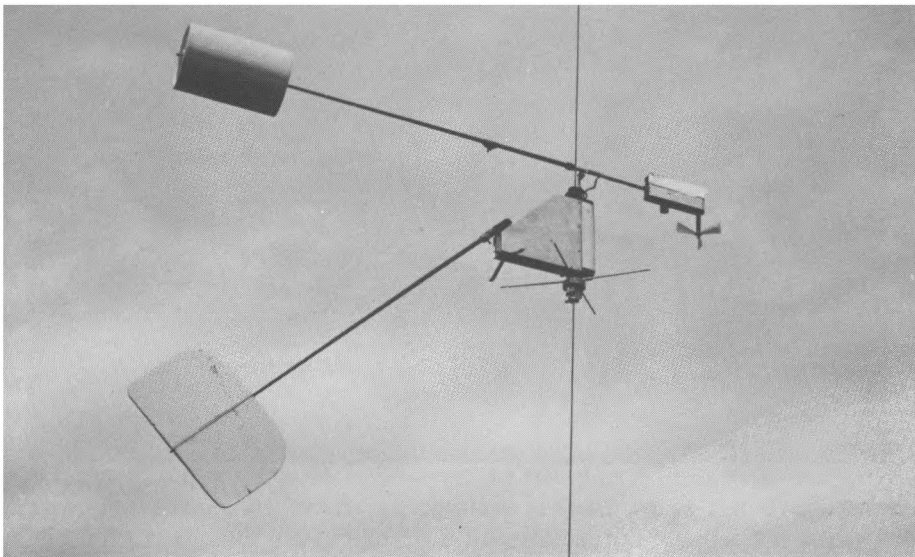


Figure 5. Development of boundary-layer instrumentation. Measurements of wind speed and direction, temperature, humidity and pressure are digitally telemetered every 3 seconds from this prototype mean-value probe supported on a tethered balloon cable. The probe, as well as being used to provide profile data on field experiments, acts as a test bed for some sensors which are to be incorporated into a second-generation Cardington turbulence probe now under design.

surface (as opposed to an absolute height) acts as the reference level, thus helping to ensure that resolution is highest where it is most needed. The model, with this extension, has already been used to study flow over the South Wales valley.

Although the three-dimensional form of the analytic model of Jackson and Hunt and the Branch's own two-dimensional numerical model have provided some insight into flow over surface features, the next big step must be the application of a numerical three-dimensional large-eddy model capable of modelling turbulent flow properly. As already mentioned, the development of such a model is in hand.

Atmospheric dispersion

Introduction

The Office's advice is often sought on how material released into the atmosphere will be dispersed and transported. Typical examples are releases of sulphur compounds, radio-nuclides, toxic materials, inflammable vapours and heavy gases. Some will be accidental and of short duration, others will be continuous over long periods, and each poses different problems. Routine enquiries are generally handled by the Special Investigations Branch, leaving the Boundary Layer Branch free to concentrate on research aimed at furthering our understanding of dispersion and the mechanisms which control it, or to deal with major problems which raise new or non-routine issues.

Dispersion and subsequent deposition processes are important in determining concentrations both in the atmosphere and on the ground. However, a wide range of scales is involved, ranging from a few tens of metres to global distances. Thus it is convenient to divide the ranges of interest into four main categories:

Short range — from the source out to a few kilometres.

Medium range or mesoscale — tens to a few hundreds of kilometres.

Long range — several hundreds of kilometres and more.

Global — this covers interhemispheric and tropospheric-stratospheric exchanges and is not dealt with in this article.

Short-range dispersion

In this range, details of the actual release (i.e. source height, duration, etc.) and the structure of the atmospheric boundary layer all have to be considered. Turbulence plays a dominant role and ultimately its variability limits the accuracy with which concentrations and dosages can be predicted — the problem becoming more acute the shorter the period being considered. This makes the use of sophisticated models difficult to justify in many instances. The Branch has recently carried out a preliminary study of this problem, seeking to relate the sensitivity of a simple Gaussian model to uncertainties in the basic meteorological parameters. Surprisingly, this showed that surface concentrations were not markedly affected by variations in vertical mixing, being much more dependent on variations in the horizontal wind components, though any mean inclination of the flow to the ground was also important. This makes the use of the concept of an eddy diffusivity to represent turbulence processes seem quite reasonable in many instances because, although the consequent errors may be substantial, they are generally acceptable compared with the specifications of other parameters affecting plume dispersal.

The resulting diffusion equation has been solved analytically only for rather idealized conditions, so for more realistic studies numerical techniques have to be used. An alternative approach which the Branch has used for many years (Smith, 1968; Hall, 1975), is the 'random walk' model in which the trajectories of particular elements of fluid (called particles) are calculated through the step-wise

application of equations which simulate the effect of real eddies. In the most recent version developed in the Branch (Ley, 1982), these equations, whilst correlating the motion of the particle with its earlier motion, introduce a new randomly selected impulse at each time-step characteristic of its position which ensures that, in a statistical sense, mass, momentum, energy and shearing stress are conserved. This model has already been used by the Branch to simulate dispersion in neutral conditions; the results show good agreement with experimental data, analytic solutions and established theory. A variant of this model has been developed for use by the Agricultural Meteorology Branch to study crop-spraying under a variety of conditions. At present it is being extended to cover stable conditions and ultimately it is hoped to apply it to unstable conditions and to other cases of practical interest. The technique is also to be used to study the relative diffusion of two or more particles in order to examine the development of short-release clouds and the likely variations of concentrations within a continuous plume. This work has relevance to the detection of odours, chemical defence problems, inflammable vapours and air chemistry.

Two basic processes control the vertical spread of material in the atmosphere, namely mechanical mixing and buoyant mixing. The former is directly related to the wind speed and the latter to temperature differences which lead to the vertical transfer of heat energy either from the surface to the air (a positive heat flux: unstable conditions) or from the air to the surface (a negative heat flux: stable conditions). A positive heat flux encourages vertical mixing while a negative one inhibits it. Normally, however, the heat flux cannot be measured directly on a routine basis so it has to be determined indirectly. A comprehensive set of data on the surface energy balance recorded at Cardington, Bedfordshire, covering a period of one year, is being analysed to see how the heat flux can best be estimated from routine meteorological observations. The first stage of this work, namely developing a method for estimating the reduction of solar radiation by varying amounts of different types of cloud, has already been completed. The results of this work will be used to improve a scheme for assessing the stability of the atmosphere from simple parameters such as wind speed, cloud cover, etc. This scheme, which is widely used, was originally developed by Dr F. Pasquill and has since been extended and put on a firmer theoretical basis (Smith, 1979).

In parallel with this work, precision instrumentation whose output is logged has been established at Porton, Wiltshire, in order to assess various alternative schemes that have been proposed for estimating Pasquill stability. This involves the measurement of variables such as temperature gradient, radiation, and fluctuations in wind direction. Data are also being recorded at a site in Scotland, at Torness, where the Branch has established similar instrumentation at the instigation of the South of Scotland Electricity Board. A nuclear power-station is being constructed at Torness and the meteorological data will be used to determine the dispersion climatology of the area required by the Board for risk assessment analyses.

Another topic attracting great interest at present is the consequences of releasing a large cloud of heavy vapour into the atmosphere. The Health and Safety Inspectorate are sponsoring some field trials involving several controlled releases and the Branch was asked to conduct an experimental study aimed at determining the feasibility of using upwind direction measurements to optimize the moment of release for the gas cloud so that it travels well within the downwind network of sampling monitors. This work, which is now complete, has clearly demonstrated the potential of the technique in slightly unstable conditions when the wind speed is above 3 metres per second.

Medium-range dispersion

Dispersion at short ranges depends mainly on turbulent diffusion but, as the distance of travel increases, the pattern of concentration at a given location becomes increasingly dependent on variations in the general wind flow associated with synoptic developments, on mesoscale circulations (e.g. lee

depressions and sea-breezes) and on the presence of topographic features, as well as on the time-evolution of the boundary layer. Deposition, chemical reactions and the nature of the source must also be considered. It is a complex area to study as few approximations are viable. The results find application in chemical warfare, the spread of viruses and major releases of radio-nuclides.

Here the Branch's work on flow round hills has found application in two areas. The first is in predicting the spread of foot-and-mouth virus by developing a technique which allows for the presence of hills, ridges, etc. This appears to improve significantly the Office's ability to forecast realistically areas at risk (Blackall and Gloster, 1981). It was successfully used by the Agricultural Meteorology Branch to predict the possible spread of the virus during the outbreak in Brittany, Jersey and the Isle of Wight in the spring of 1981. Several countries have expressed an interest in the technique.

The second area of application is to the problem of plume dispersal in laminar flow round an isolated hill. Two findings of particular interest are the large changes in surface concentration which can arise through plume impact and the increase in plume dispersion caused by flow distortion (Mason and Sykes, 1981). In support of this work some tracer studies were carried out during the 1981 Sirhowy Valley experiment. It is hoped that these data will prove suitable for checking the findings of the theoretical models.

Long-range dispersion

At these ranges the distribution of pollutants is basically independent of the characteristics of the source (apart from the duration of release). Trajectories are frequently curved, and elements of the plume may experience several diurnal cycles of the boundary layer. Concentration profiles tend to be rather uniform throughout the depth of the boundary layer and the losses of pollutant by various processes, such as wet and dry deposition, are significant. The lateral width of the 'plume' depends on synoptic developments as well as the period of release (or sampling).

There is considerable interest in this topic, both in Europe and North America, arising mainly from concern over possible damage to the natural environment caused by 'acid rain'. Large areas in Scandinavia and Canada are particularly sensitive owing to the nature of their soils and rocks. The acidity of rain is often quite high ($\text{pH} = 3$ to 4) and a contributory factor to this acidity is the uptake of pollution emitted into the air from fossil-fuelled industrial installations sometimes many hundreds or thousands of kilometres upstream. Unless effectively buffered in the soil there is some evidence that this acid can have lasting consequences for fish populations and other biosystems.

The Branch has played an active role in two major international projects concerned with this problem. The first was under the auspices of the Organization for European Co-operation and Development (OECD) and started in 1971. The second, under the United Nations Environmental Program, was started in 1978. Recently a very simple model has been developed within the Branch to simulate the emission-transport-conversion-deposition cycle of industrial pollutants in Europe. This model produces reasonably realistic estimates of dry and wet deposition in good accord with measured values. It requires very little computer time so it can be used to explore the effects of changing basic parameters such as the rate at which sulphur dioxide is converted to sulphate. Furthermore it can serve as a yardstick by which to judge more complex models, to see whether extra sophistication really produces worthwhile improvements in deposition estimates. The concept of wet and dry synoptic regions is being added to the model in order to judge whether to develop a complex stochastic model capable of simulating the variability of rainfall in space and time. This development is coupled with the use of trajectory analyses, together with radar data from the Meteorological Office Radar Research Laboratories at Malvern, to study the probability of rain occurring at specified points along a trajectory. This relates directly to a theoretical study which introduced a stochastic element, intended to represent the patchy nature of rain,

into a numerical model for predicting the long-range transport of material (Smith, 1981). Current models employ spatially and temporally smoothed rainfall fields and tend to underestimate the long-range transport of pollutants by removing them too quickly.

In support of this work the Branch is also active on the experimental side, notably in a joint experimental study of the long-range transport of pollutants being carried out in collaboration with the Central Electricity Research Laboratories, Leatherhead, as well as the Cloud Physics Branch. This uses chemical samplers installed in the instrumented Hercules aircraft from the Meteorological Research Flight to track the advection of pollutants from a particular source for long distances across the North Sea. The plume from a power-station in South Yorkshire is 'labelled' with two tracer gases so that it can be uniquely identified in both space and time and hence the same portion of plume tracked for long distances. Eleven flights have already taken place including one 'two-day' study when the same plume was tracked across the North Sea for two successive days (see Fig. 6). Plumes have been detected at distances as far as 700 km from the source.

The Central Electricity Research Laboratories are using data from these flights to study chemical transformations in the atmosphere, while the Branch is particularly interested in the travel and structure of plumes and the loss of pollutants from the boundary layer. Analysis has already advanced sufficiently for several interesting points to emerge, notably the generally fragmented nature of the plumes, possibly reflecting the presence of mesoscale features not detected by standard meteorological observations. One such system was found over the North Sea just downwind of the Yorkshire Moors.

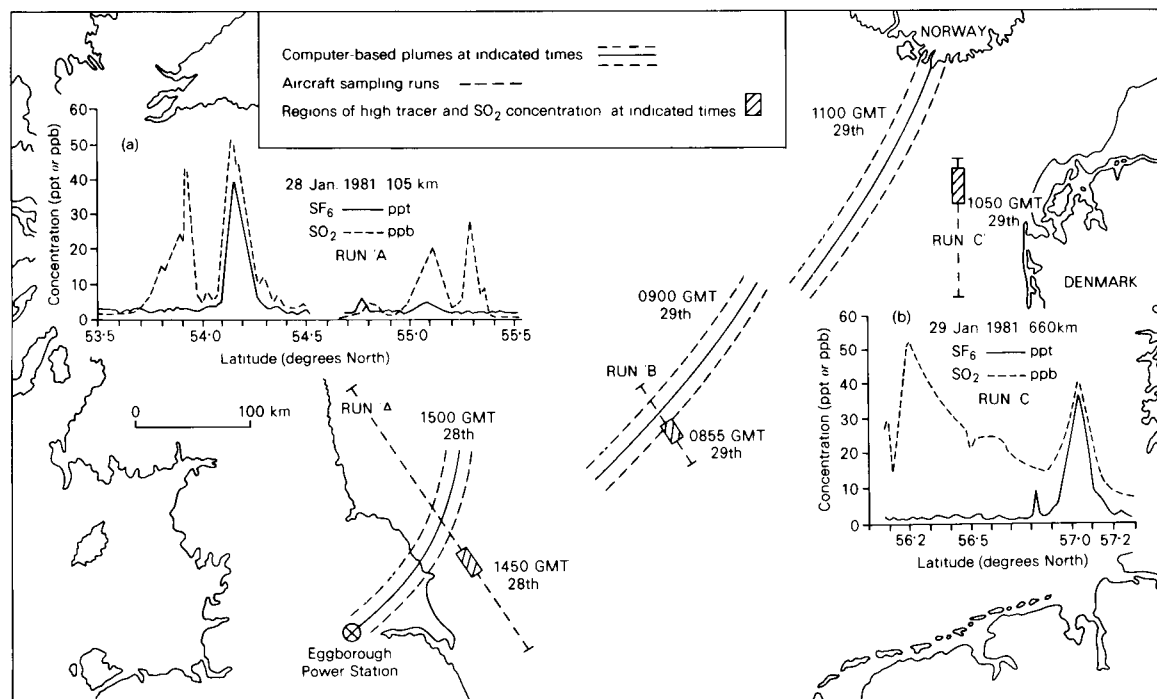


Figure 6. Plume study: two-day experiment, 28–29 January 1981. Inset diagrams (a) and (b): Variation of concentration of sulphur dioxide and tracer with latitude along aircraft sampling runs at 105 and 660 km from Eggborough.

In a similar vein, the Branch participated in a joint study, together with other parts of the Meteorological Office, of the plume from the main explosion of the Mount St Helens volcano, Washington. A trajectory model (basically a modified form of the operational one used by the Central Forecasting Office) was used to study the movement of the plume; it showed that while most of the plume reaching the eastern Atlantic was at low latitudes, fragments moved on a more northerly track towards the United Kingdom and Scandinavia, a prediction confirmed by aircraft observations over The Wash and over southern Scandinavia. Amongst other things, work of this nature has great relevance to the long-range dispersion of radio-nuclides from nuclear installations, whether one is considering small continuous releases (as covered by Article 37 of the Euratom Treaty) or large releases in accidents.

Conclusion

As this article has tried to show, the work of the Boundary Layer Branch covers a wide range of subjects and finds application in many and diverse fields. Many of the enquiries received in recent years cannot be answered in terms of simple idealized pictures of boundary-layer behaviour but require a deep knowledge of the basic turbulence characteristics, physics and meteorology. The Branch cannot study each subject in detail but, by concentrating on a few selected topics chosen because of their immediate relevance, it aims to make substantial progress with these topics, while maintaining a broad level of competence that can be applied to boundary-layer problems of any type, whenever they may arise.

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Exceptional orographic rainfall in the Mountains of Mourne

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Summary

Between 0100 GMT on 27 December and 0900 GMT on 29 December 1978, about 245 mm of rain fell in the central area of the Mountains of Mourne. The synoptic context in which this occurred is examined and it appears that orographic enhancement (by up to 10 mm h^{-1}) of background moderate to heavy rainfall was largely responsible for this exceptional event. The enhancement was associated with a deep, very moist, low-level jet with a core speed of about 25 m s^{-1} , at about the 850 mb level, in a slow-moving synoptic situation. Evidence is also presented which indicates that the enhancement was abnormally high owing to the release of potential instability in the vicinity of the hills.

1. Introduction

The enhancement of rainfall through orographic effects has received recent attention in the literature (Bader and Roach 1977, Browning 1980, and Hill *et al.* 1981). In warm sectors of depressions and in the vicinity of surface fronts, rainfall is frequently found to be much heavier over hills than over adjacent lower ground. Bergeron (1965) first proposed a possible mechanism for this phenomenon. He suggested that raindrops falling from higher-level cloud could wash out sufficient numbers of small droplets in an orographically generated 'cap' cloud to significantly increase local rainfall rates. The largest increases (or enhancements) would be expected when the pre-existing rainfall rates were high and/or when strong, very moist low-level flow was present. In the latter case the liquid water removed from the cap cloud is rapidly replaced by fresh condensation through orographic uplift.

Hill *et al.* (1981) presented eight detailed studies of orographic rain over the 'Glamorgan Hills' (Blaenau Morgannwg) of South Wales, using radar and a network of autographic gauges. These results indicated that most (about 80%) of the enhancement occurred in the lowest 1.5 km above the hills and was more marked at the first range of hills encountered. Thus enhancements over the Brecon Beacons were normally substantially less than those over the Glamorgan Hills. Rain-shadow effects over downstream low ground may also be particularly well marked in enhancement situations (Pedgley 1970).

This paper discusses an example of exceptionally heavy orographic rainfall that occurred between 27 and 29 December 1978 in the Mountains of Mourne, which lie in the south-east of Northern Ireland. Rainfall rates reached 14 mm h^{-1} in the central area of the hills whilst at a nearby coastal site the maximum rainfall rate was about 6 mm h^{-1} . Remarkable rainfall totals accumulated because the rainfall continued for a considerable time in a slow-moving synoptic situation.

In the vicinity of the hills the consequences of the heavy rainfall were dramatic. Thousands of acres of farmland were flooded and many roads became impassable. Sections of the Castlewellan-Banbridge road were washed away and some areas flooded to a depth of about eight feet. The bridge at Tullynisky on the main Banbridge road was damaged by floodwater on 27 December and later was washed away completely.

2. Background to the investigation

The area of particular interest in this study is that bounded by the dashed lines in Fig. 1(a), i.e., the Mountains of Mourne in the south-east corner of Northern Ireland. Also indicated is the position of the Long Kesh radiosonde station which lies about 35 km to the north. During the event to be described the low-level wind direction was east-south-easterly (about 100°) and so the radiosonde station did not provide information on upstream characteristics. Nevertheless, it was not directly downstream from the hills and the observations are taken as giving some guidance to variations of the 600 m wind speed with time close to the hills. Fig. 1(b) illustrates the main features of the topography of the area and shows the

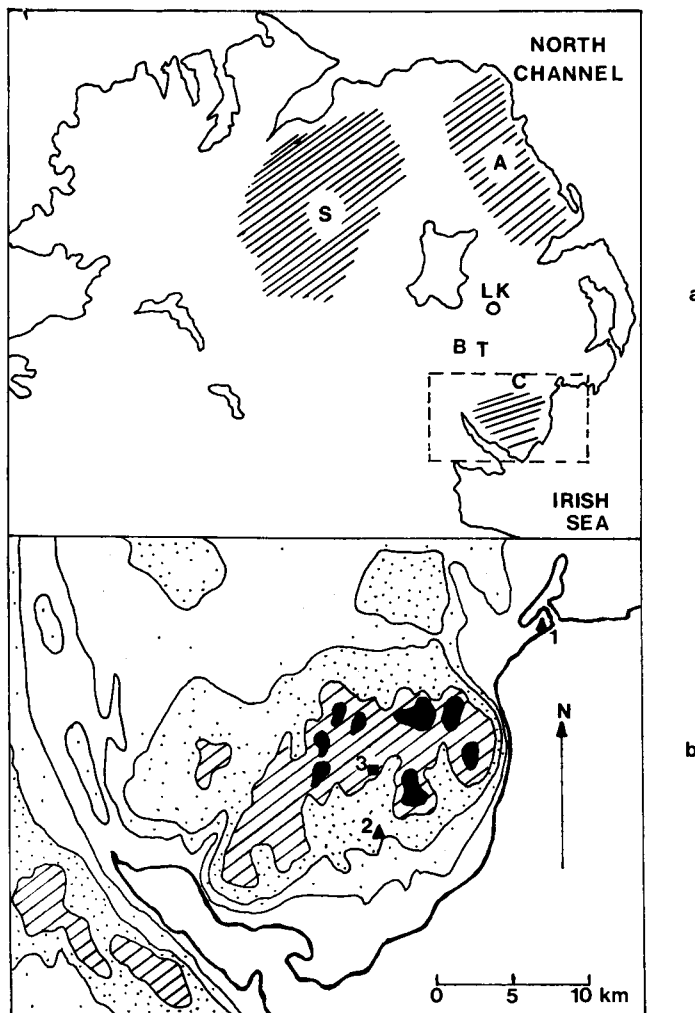


Figure 1. Northern Ireland, showing the area investigated. (a) The experimental area (bounded by dashed lines) and Long Kesh radiosonde station (LK) in relation to Northern Ireland. Also shown are the locations of some places referred to in the text: B — Banbridge, C — Castlewellan, T — Tullynisky, A — Hills of Antrim, S — Sperrin Mountains. Hatched areas indicate high ground. (b) Topographical characteristics of the experimental area (Mountains of Mourne and adjacent regions). Unstippled areas range from 0 to 60m above mean sea level, light stippling from 60 to 120m, heavy stippling from 120 to 300m, hatched from 300 to 600m, and the dark areas represent land above 600m. The principal rain-gauge sites are also shown, i.e. coastal gauge (site 1) and hill gauges (sites 2 and 3).

positions of the principal rain-gauges employed in the study. These are the coastal autographic gauge (site 1, height 9 m), Silent Valley autographic gauge (site 2, height 129 m) and the Miner's Hole magnetic tape event recorder (site 3, height 311 m). It can be seen from Fig. 1(b) that with a wind direction of 100° the coastal gauge is not upstream of the hills, but about 12 km to the north-east. Smaller-scale features of the rainfall field cannot therefore be expected to appear in the rain-gauge traces for the hills and the coast. This aspect is considered further in section 5.

It is useful to examine the variation of annual rainfall with height in the Mountains of Mourne area and how this compares with the results for the Glamorgan Hills of South Wales as presented by Hill *et al.* (1981). The data selected for the Mountains of Mourne are taken from a carefully quality-controlled set of autographic gauges that cover the height range of interest in this study. Higher-level gauges are available but there is doubt as to their accuracy owing to infrequent reading (mainly monthly) and exposure. No attempt has been made to average the height of topography in small areas upstream in the direction of the prevailing wind to obtain an 'effective' gauge height that reduces scatter (see Hill *et al.* 1981) in the height versus amount plot (see Fig. 2). Substantially more rainfall occurs near sea level in South Wales than in the south-east of Northern Ireland. However, the slopes of the two lines are similar

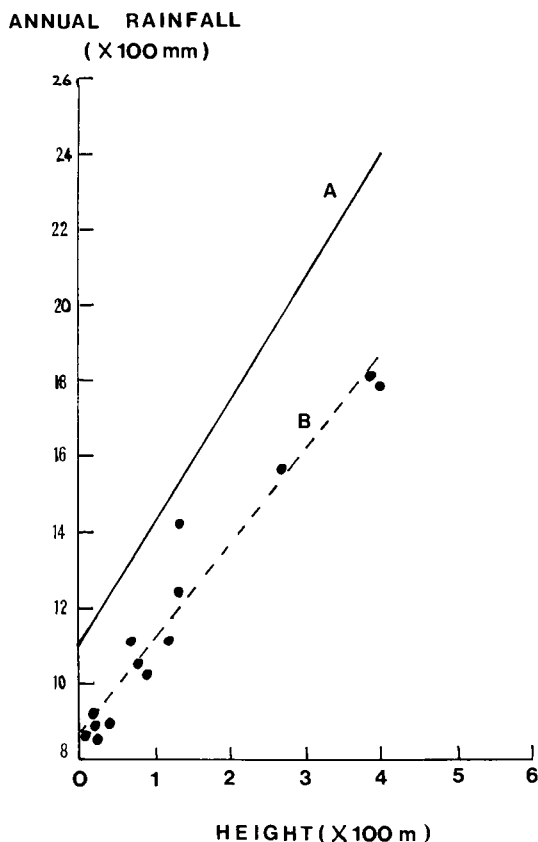


Figure 2. The variation of annual rainfall with height in the Mountains of Mourne (dots) using data from autographic gauges only. Line 'B' is a 'by-eye' fit to the points and line 'A' is a fit to the data for the Glamorgan Hills (see Hill *et al.* 1981).

and, eliminating the dependence of the slopes on the intercepts R_0 (i.e. the rainfall at or near sea level), give the following forms:

$$R_h = R_0 (1 + 0.0029h) \quad \dots \quad (1a)$$

$$R_h = R_0 (1 + 0.0030h) \quad \dots \quad (1b)$$

where equation (1a) applies to the Glamorgan Hills of South Wales and (1b) to the Mountains of Mourne (R_h is the annual rainfall at a height of h metres). In the former case R_0 is 1100 mm whilst in the latter it is about 860 mm. It is interesting that the height dependence is very similar in the two areas, which may imply that similar rainfall enhancement processes are responsible. In the Glamorgan Hills 75% of the total rainfall in the hills was associated with low-level winds (above the friction layer) from the south-west quadrant, whilst 60% of the total fell on the coasts in these situations.

The average annual rainfall on the highest ground is about 2500 mm (Hill *et al.* 1981). If F_h and F_0 represent the fractions of the total rainfall associated with winds from the south-west quadrant, in the hills (at height h) and on the coast respectively, then the average enhancement is given by:

$$\bar{E}_h = \frac{F_h R_h}{F_0 R_0} \quad \dots \quad (2)$$

which for the Glamorgan Hills is about 3.

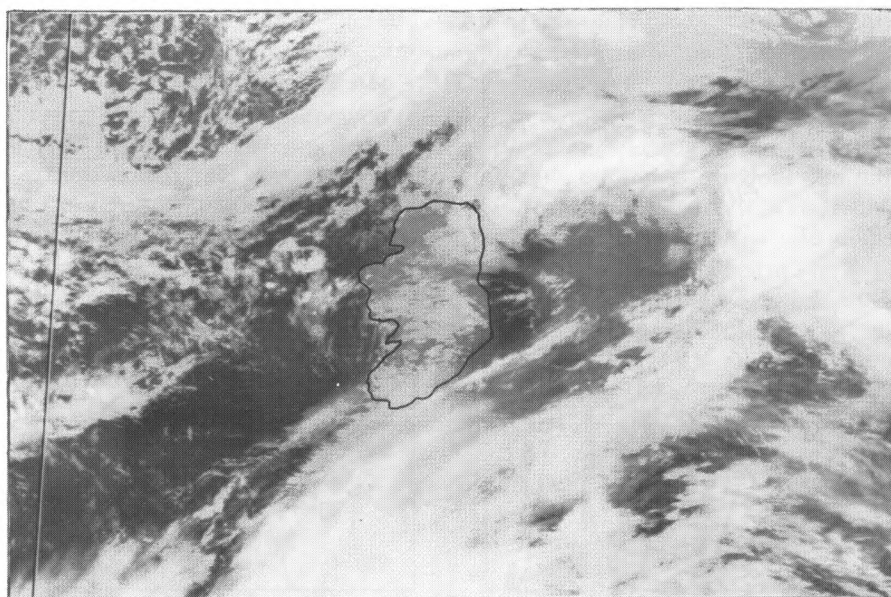
In the Mountains of Mourne onshore winds arise mainly from the south-east quadrant and in this sector about 35% of the annual rainfall falls in the hills whilst the corresponding figure for coastal regions is about 30%. Since the annual rainfall is about 1800 mm in the higher parts of these hills equation (2) indicates that the average enhancement to be expected from the coast to a height of about 300 m is about 2.5.

It should be noted that equation (1b) may have some predictive value in that if R_0 is known for a particular rainfall event then the equation can be used to obtain an estimate of the likely rainfall in the hills (but not on higher ground downwind of the hills). This aspect is considered further in section 5.

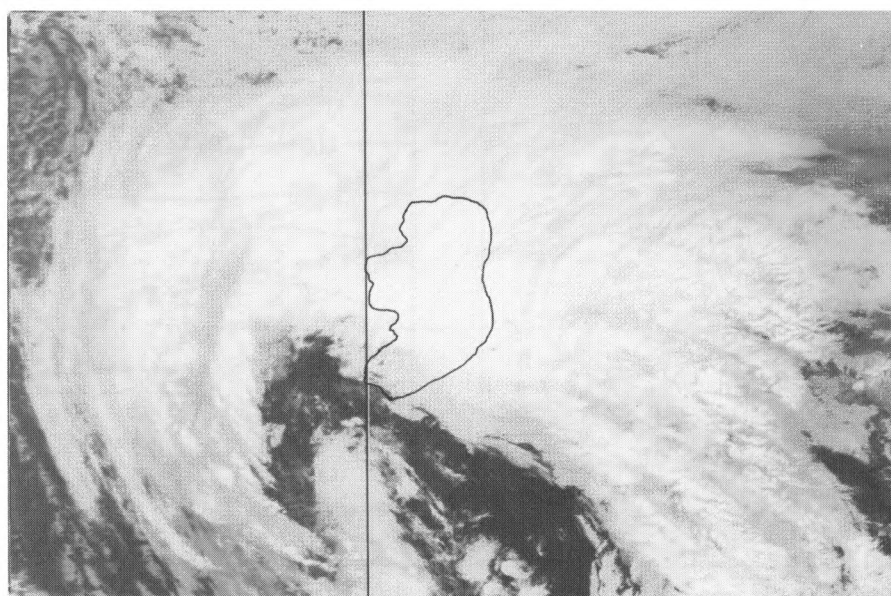
3. Synoptic situation 27/28 December 1978

The primary purpose of this article is to describe, and to offer some explanation for, the exceptionally heavy rainfall that affected the eastern part of Northern Ireland (essentially counties Antrim and Down) during the period 27–29 December 1978. The infra-red satellite images available highlight the synoptic development that occurred as a deepening depression approached the British Isles from the south-west. Figs 3(a) and (b) illustrate the movement of the cloud mass from the south across Ireland on 26 and 27 December.

With high pressure to the north and a developing anticyclone over Scandinavia the system became slow moving over south-west Ireland. Fig. 4 illustrates the movement of the associated rain areas over land (continued by extrapolation over adjacent sea areas). The rain moved quickly northwards across Northern Ireland and was associated with the arrival of very moist low-level air (see Fig. 4). For example, at Long Kesh the relative humidity at 900 m rose from 83% at 0001 GMT on the 27th to reach 96% by midday. By this time the rain had ceased over south-west Ireland following the passage of the warm occlusion indicated in Fig. 4(b). The clearance of cloud behind this front is well revealed by the satellite photograph (Fig. 3(b)). Over Northern Ireland, southern Scotland and northern England, however, the rain area persisted and became slow moving, gradually turning to sleet and snow as colder air moved southwards from northern Scotland. It would seem likely that advection of dry, cold air from the near continent into Scotland also took place as the flow became orientated in an approximate



(a) 0959 GMT 26 DEC 1978



(b) 0916 GMT 27 DEC 1978

Photographs by courtesy of University of Dundee

Figure 3. Infra-red satellite pictures taken at (a) 0959 GMT on 26 December 1978 and (b) 0916 GMT on 27 December 1978.

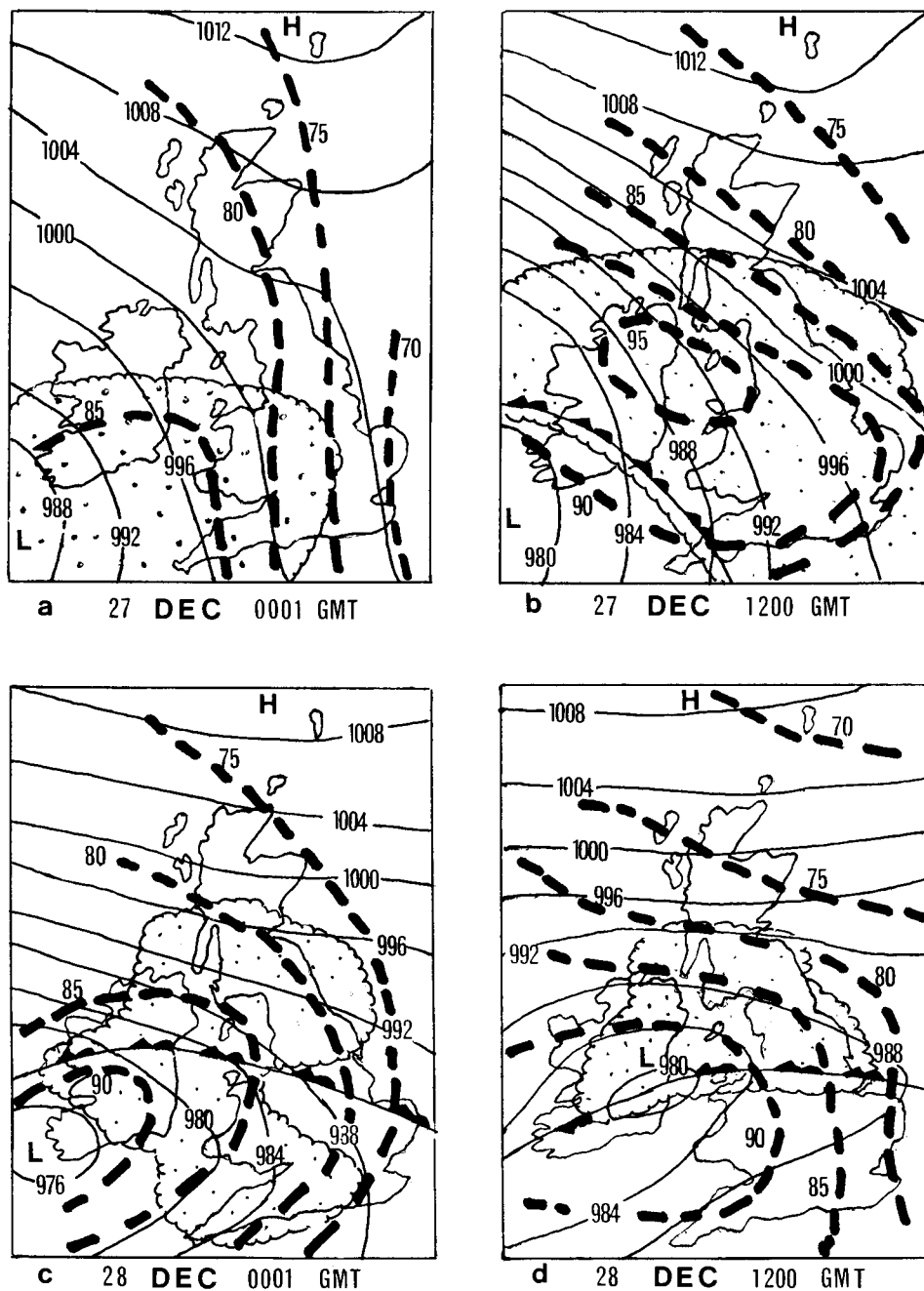


Figure 4. Surface synoptic charts for (a) 27 December 1978 at 0001 GMT, (b) 27 December 1978 at 1200 GMT, (c) 28 December 1978 at 0001 GMT, and (d) 28 December 1978 at 1200 GMT. The stippled area represents the extent of continuous rainfall from land observations and this has been arbitrarily extrapolated to include sea areas. Lines are isobars (mb) and dashed lines indicate relative humidity (%) at 900 m.

east–west direction (see Fig. 4(d)). Since the southwards advection of cold air was nearly at right angles to the flow it seems that ageostrophic motion may have been important, probably as a result of downstream acceleration of the flow (see Fig. 4(b)).

A cross-section of wet-bulb potential temperature (θ_w) extending from Valentia (in south-west Ireland) to Lerwick at 1200 GMT on 27 December is given in Fig. 5 and reveals an extensive baroclinic zone between Long Kesh and Lerwick. A second baroclinic zone occurs from about 600 mb to 480 mb between Long Kesh and Valentia. This is an upper cold front and suggests that the frontal structure corresponds to a warm occlusion, moving slowly northwards, being undercut by cold air at lower levels moving south. The position of the surface occlusion drawn in Fig. 4 is also given in Fig. 5. The locations of areas of potential instability (PI) are shown as stippled areas. These indicate low-level PI in the cold air over Lerwick and at higher levels in the vicinity of Long Kesh and Valentia.

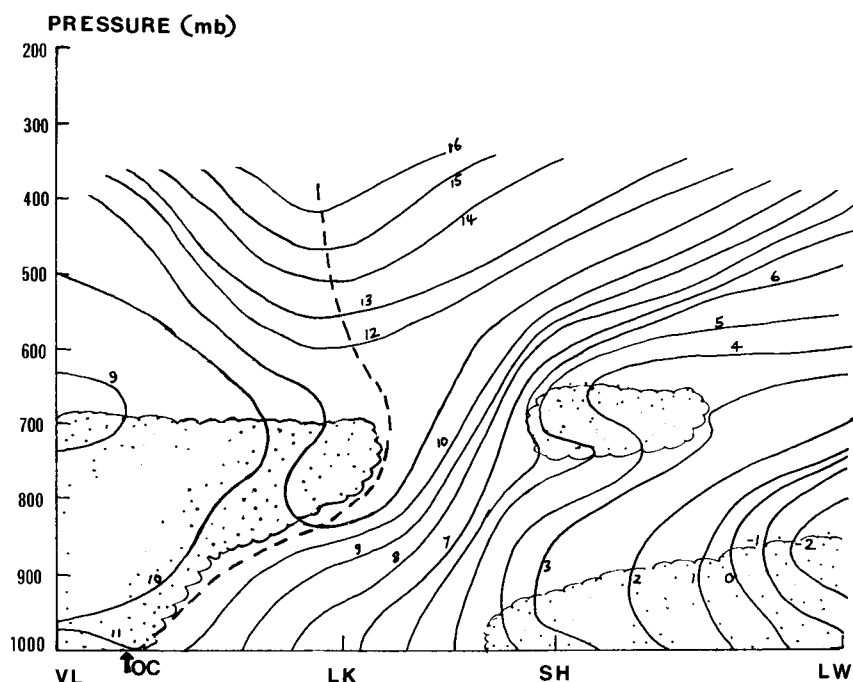


Figure 5. Cross-section of wet-bulb potential temperature ($^{\circ}\text{C}$) from Valentia (VL), in south-west Ireland, to Lerwick (LW), with intermediate stations Long Kesh (LK) and Shanwell (SH) at 1200 GMT on 27 December 1978. Areas of possible potential instability are stippled. The dashed line represents the axis of maximum wet-bulb potential temperature. OC marks the position of the surface occlusion shown in Fig. 4.

Although the middle-level PI in the vicinity of Long Kesh appears marginal it is worth noting that Browning *et al.* (1973) reported cumulus-scale updraughts of up to 5 m s^{-1} in a rainband where radiosondes indicated that $\partial \theta_w / \partial z$ was only about $-0.5 \text{ }^{\circ}\text{C km}^{-1}$.

An important feature revealed by the cross-sectional analysis was the appearance of a strong low-level jet (J2 in Fig. 6). In this diagram the winds have been resolved along 120° (i.e. roughly parallel to the flow at 850 mb at 1200 GMT on the 27th). The low-level jet (core speed about 25 m s^{-1}) lies in a strongly baroclinic zone and has a south-easterly direction. The main tropospheric jet associated with the

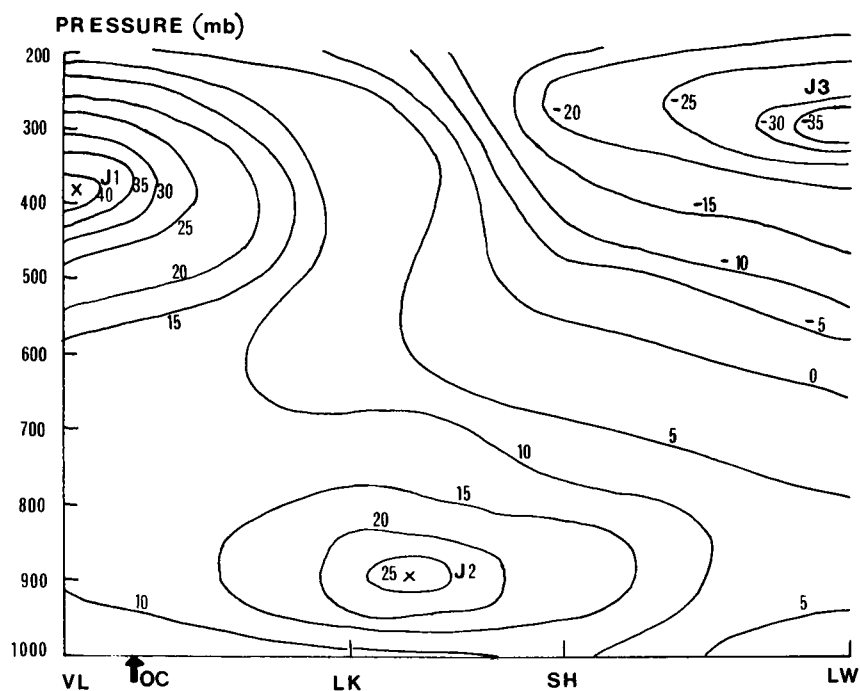


Figure 6. As Fig. 5 for the component of wind speed along 120° . The main tropospheric jets are labelled J1 and J3 and the low-level jet as J2. Wind speeds are in metres per second.

depression is at a height of 400–350 mb and is also from the south-east. A second tropospheric jet (at 300 mb), this time with a westerly direction, is located near Lerwick. The upper-air pattern therefore had the form of a highly distorted ridge lying from south-east to north-west across the British Isles. The spatial relationship between the jets discussed above is illustrated in Fig. 7. This also shows the 1000–500 mb thickness and sea-level pressure fields. The marked thermal ridge and cold trough (to the west of Ireland) decayed as the upper flow became more zonal by midday on the 28th.

Low-level jets associated with mid-latitude fronts have been discussed in the literature by Browning and Pardoe (1973). The airflow pattern shown in Fig. 6 is very similar to the results they presented for cold fronts. Similar features have been observed in association with occluded warm fronts (Kreitzberg 1968). Whilst the width of the jets may be only a few hundred kilometres they usually extend along-wind for thousands of kilometres and are therefore to be regarded as synoptic-scale features.

Fig. 8 shows the detailed airflow at 900 m across the British Isles at 1200 GMT on the 27th. The jet axis lies across Northern Ireland and then passes through North Wales to the west of England. Also shown is the position of the surface occlusion at this time and it is clear that the jet axis is ahead of the surface front and roughly parallel to it.

Browning and Pardoe (1973) suggested that low-level jets form in baroclinic zones and this is supported by the present study. Fig. 9 gives an isentropic analysis for 1200 GMT on 27 December and the dashed area shows the approximate location of the low-level jet (i.e. 900 m wind speed greater than

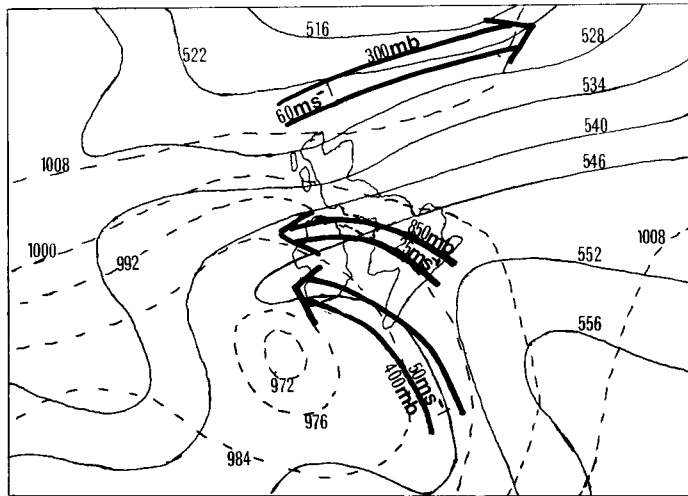


Figure 7. Surface pressure in millibars (dashed lines) and 1000-500 mb thickness fields in decageopotential metres (solid lines) for 1200 GMT on 27 December 1978. The positions and heights of the jet streams are also indicated, with the core speeds in metres per second.

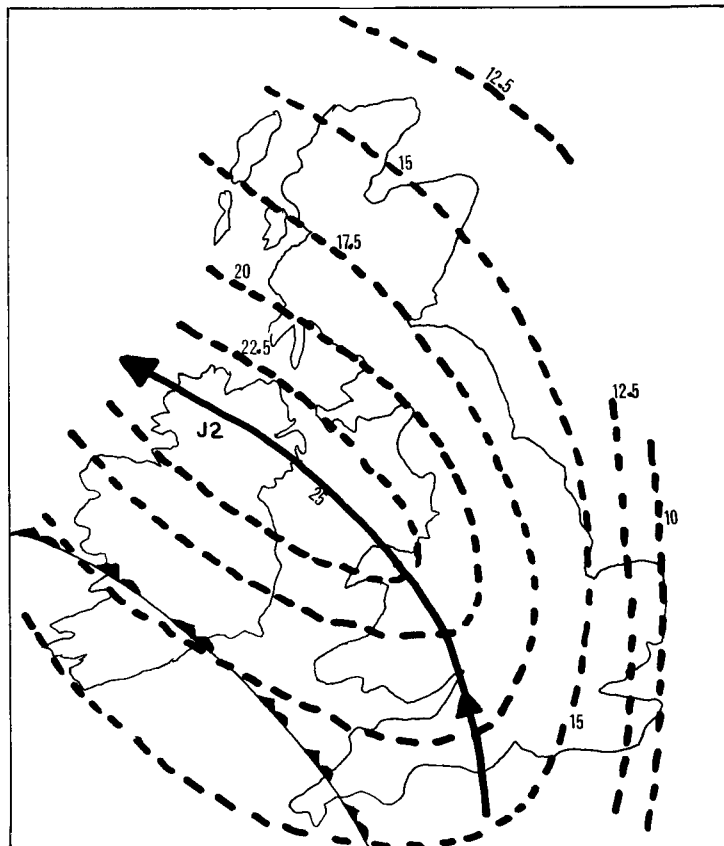


Figure 8. Airflow pattern at 900 m across the British Isles at 1200 GMT on 27 December 1978. The spatial extent and orientation of the low-level jet (J2) is indicated. Wind speeds are in metres per second.

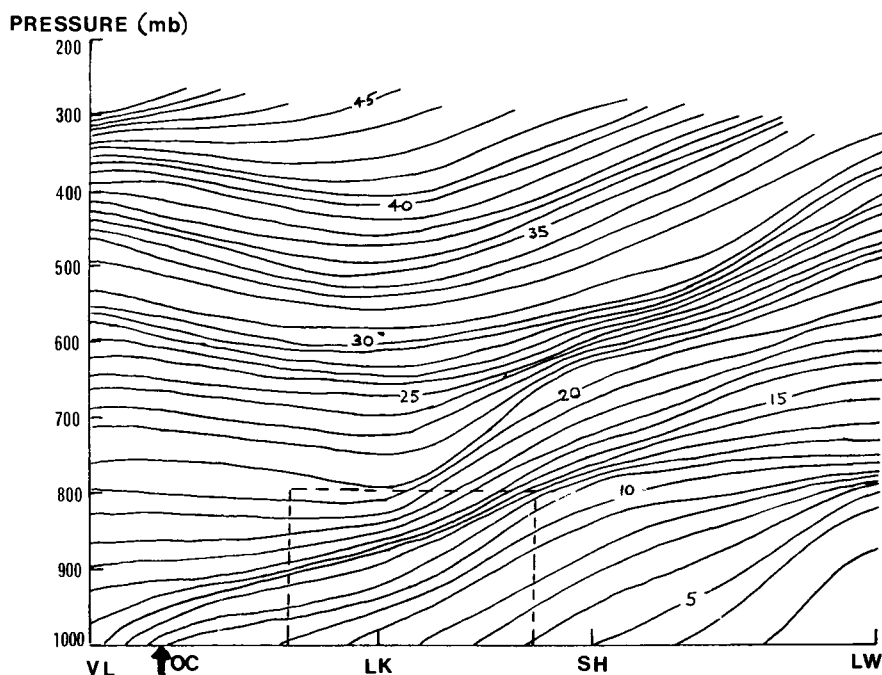


Figure 9. As Fig. 5 for isentropes ($^{\circ}\text{C}$). The extent of the low-level jet (J2) is given approximately by the dashed lines.

about 20 m s^{-1}). In this region the isentropes are tightly packed, with a strong negative gradient northwards. The vector equation which describes the variation of the geostrophic wind with height is:

$$\frac{\partial V_g}{\partial z} = - \frac{g}{fT_v} \nabla_p T_v \times \mathbf{k} \quad \dots \quad (3)$$

where T_v is the virtual temperature, the subscript p indicates differentiation on a surface of constant pressure and \mathbf{k} is a unit vector in the vertical. For a south-easterly geostrophic wind and values of T_v decreasing to the north equation (3) indicates that V_g will decrease with height. Between 850 mb and 750 mb the expected decrease in this instance is about 8 m s^{-1} which is of the same order as that observed. Surface friction acts to reduce the wind speed near the ground and so the net effect is the appearance of an elevated wind maximum (or jet) near 850 mb.

The synoptic development previously outlined obviously resulted in widespread vertical air motion in the vicinity of the British Isles. An attempt to quantify this has been made using the cylindrical cross-section technique described by Pedder (1979). However, in view of the small number of radiosonde stations available and the sensitivity of the results to small errors in wind speed the conclusions can only be regarded as, at best, semi-quantitative. Nevertheless, they do throw some light on the intensity of the vertical motion occurring at the time. The radiosonde stations employed were Long Kesh, Aughton, Shanwell and Lerwick, and the positions of these stations were projected on a circle of about 160 km radius centred over south-west Scotland. Strong upwards motion was indicated at middle levels, i.e. the vertical velocity increased with height to reach about 8 cm s^{-1} at about 450 mb. Analysis of the 1200 GMT Long Kesh radiosonde ascent on 27 December shows that vertical motion of at least this order of magnitude is required to produce moderate rainfall.

4. Rainfall characteristics

The extreme nature of the event under discussion and evidence for a large orographic component in the rainfall totals are well illustrated by the distribution map in Fig. 10. For ease of compilation these totals refer to the period between 0900 GMT on 27 December and 0900 GMT on 29 December 1978 and so are not the maximum falls in the event. In fact, as cold air advected into the region from the north on the 28th and 29th the precipitation turned progressively to sleet and snow. Hence, the total equivalent rainfall in the higher parts (about 300 m) of the central area of the Mountains of Mourne between 0100 GMT on the 27th (when the rain commenced) and 2100 GMT on the 29th (when the snow finally ceased) is not known, but is likely to have exceeded 300 mm.

On the east coasts of counties Antrim and Down about 50–70 mm of rain fell (see Fig. 10) whereas in the hills of Antrim (300–600 m high) over 100 mm fell, and in the Mountains of Mourne, which were directly exposed to the winds off the sea, in excess of 200 mm fell in the central region. Downwind of these hilly areas the rain-shadow effect was remarkably prominent so that only 10 mm of rain were

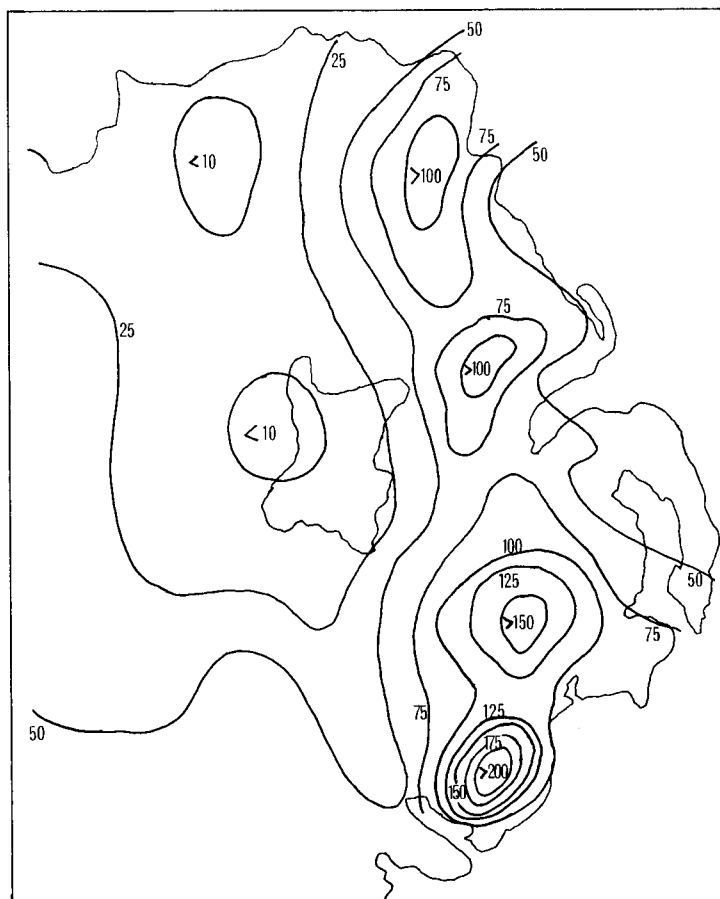


Figure 10. Rainfall distribution over Northern Ireland for the period 0900 GMT on 27 December to 0900 GMT on 29 December 1978.

recorded in the western Lough Neagh basin and the lower Bann Valley. Further west, rainfall totals of about 25 mm were recorded in association with further orographic effects in the Sperrin Mountains. Pedgley (1970) presented rainfall cross-sections through the Snowdonia region of North Wales and obtained rain-shadow effects of a similar order of magnitude in some enhancement situations.

The accumulation of rainfall at the Silent Valley (site 2, Fig. 1(b)) is shown in log-log form in Fig. 11. This represents the maximum fall of rain in a particular period as a function of the duration of the period (see e.g. Jack 1981). The total period analysed was from 0100 GMT on 27 December to 0900 GMT on 29 December, i.e. a 56-hour period in which 245 mm of rain fell. Lines B and A give the once-in-100-years and once-in-1000-years falls as a function of rainfall duration based on 50 years' data from the Silent Valley — hence the once-in-1000-years predictions must be viewed with some caution. This event therefore became rarer than once in 100 years after about 15 hours duration and rarer than once in 1000 years after about 35 hours duration, which emphasizes that on short time-scales (1 to 5 hours) the rainfall totals were not unusually high. However, the cumulative effect of heavy rain maintained for a long time resulted in a two-day rainfall total for this site that is the highest since records began in 1930.

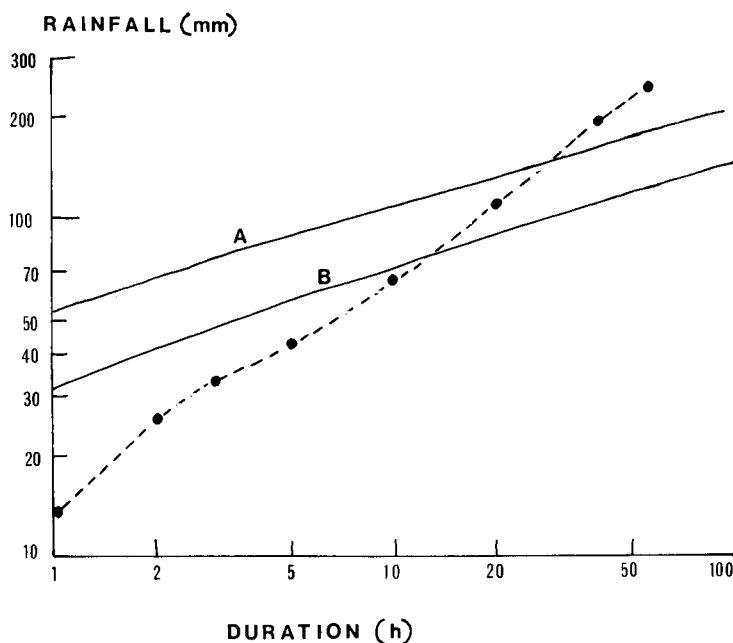


Figure 11. The maximum observed rainfall at the Silent Valley (site 2, Fig. 1(b)) as a function of the duration of the fall, from 0100 GMT on 27 December to 0900 on 29 December 1978.

5. Orographic enhancement

This section considers some aspects of orographic enhancement on 27 December, i.e. before falling temperatures turned the precipitation at the higher levels (and subsequently at low levels) to snow. The enhancement of rainfall (i.e. $P_h - P_0$, where P_h is the rainfall rate in the hills and P_0 the rate at the nearby coast), produced by orographic uplift, has been investigated theoretically by Bader and Roach (1977). In their model, small water droplets in an orographically produced cap cloud are washed out by raindrops

falling from a high-level cloud. Bader and Roach assumed the enhancement was associated with an initially saturated layer extending from the surface to 1.5 km and located entirely below the freezing level. The radar results reported by Hill *et al.* (1981) confirmed the appropriateness of these assumptions and provided convincing evidence for most of the enhancement occurring below 1.5 km above the hills (see e.g. Fig. 12 of their paper). Nevertheless, deficiencies in the model were implied by the observational data; in particular the dependence of the enhancement on wind speed was much greater than predicted whilst the dependence on P_0 was much less than predicted.

More recently Carruthers and Choularton (1983) have extended Bader and Roach's formulation to include the effect of stratification on the airflow over the hills and the influence of wind drift on the precipitation. They have also examined the dependence of the enhancement on hill height and the depth of the cap cloud. These calculations were restricted to hill lengths, L , (roughly speaking one-half the along-wind dimension of the hill or group of hills) ≤ 20 km and heights ≤ 1 km since the 'wash-out' mechanism is felt to be dominant in these cases. For longer hills there is sufficient time for coalescence in the cap cloud to produce raindrops, whilst over higher hills the character of pre-existing middle-level precipitation may be markedly altered. Carruthers and Choularton concluded that for long hills ($L > 7$ km) the simple Bader and Roach model is adequate but that for short hills ($L < 2$ km) it leads to underestimates of the enhancement. However, they could not model the high sensitivity of the enhancement to wind speed as reported by Hill *et al.* (1981) and speculated that this was a consequence of the structure of the low-level jets, normally associated with heavy orographic rainfall, deep moist jets (producing deep cap clouds), being associated with the highest wind speeds. Nevertheless, even for long hills ($L = 20$ km) of 600 m height and a 3 km deep cap cloud with a background rainfall rate $P_0 = 2.5 \text{ mm h}^{-1}$, the maximum enhancement obtainable was only about 2.5 mm h^{-1} .

For the Mountains of Mourne L is about 8 km and so it is expected that the Bader and Roach model should provide reasonable results, except for the influence of hill slope.

In the model a slope of 1:100 was assumed, whereas in the Mountains of Mourne this varies between 1:30 and 1:10. Hill *et al.* (1981) have shown that an increase in slope from 1:100 to 1:40 could result in a 40% increase in orographic enhancement and so it is expected that the model results should be significantly less than those observed. The conditions required for strong orographic enhancement in hilly areas (summarized by Hill *et al.* 1981) were all fulfilled during this event, i.e. a nearly saturated strong low-level airflow (in the form of a low-level jet) was present and appreciable rainfall rates were recorded at nearby coastal sites. Fig. 6 shows that at 1200 GMT on the 27th wind speeds at around 900–850 mb reached 25 m s^{-1} . The average relative humidity in the lowest 1000 m, at this time, was about 93%.

The variation of total rainfall with height on 27 December is given in Fig. 12. On this day about 60 mm of rain fell on the coasts (in the vicinity of the hills) whilst at site 3 (about 311 m) more than twice this amount was recorded. The line labelled 'A' in Fig. 12 is the prediction for this event based on the behaviour of the annual rainfall with height, i.e.

$$R_h = 60(1 + 0.003h) \quad \dots \quad \dots \quad \dots \quad \dots \quad (4)$$

and it is of interest to note that it provides a reasonable fit to the data. This suggests that most of the increase in rainfall with height in the Mountains of Mourne is due to orographic enhancement in similar situations to those described above.

The detailed variations of the low-level wind (heights less than 1.5 km) on the 27th are given in Fig. 13. Profile A (taken at 0001 GMT on 27 December) indicates wind speeds in the range $5\text{--}10 \text{ m s}^{-1}$ and only a weak variation with height. By 0600 GMT on 27 December winds have increased at all levels and there is a suggestion of a low-level maximum at about 600–900 metres.

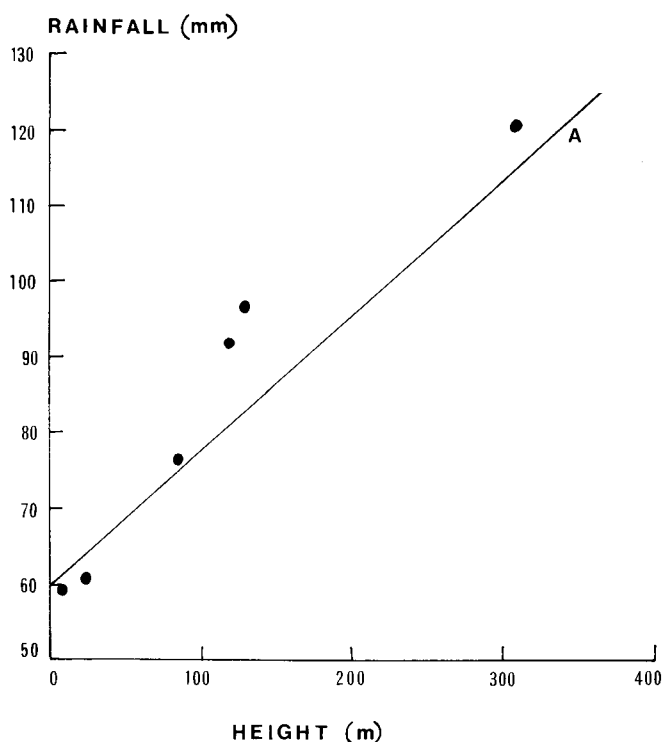


Figure 12. The variation with height of rainfall in the Mountains of Mourne from 0100 GMT on 27 December to 0001 GMT on 28 December 1978. Line 'A' represents the predicted variation based on the behaviour of the annual rainfall with height (Fig. 2).

The increase in wind speed continued in line with the synoptic developments discussed earlier so that by 1200 GMT speeds in the 600–900 m height range approach 25 m s^{-1} . By midnight the gradient had relaxed and wind speeds decreased (profile E).

Shown in Fig. 14 are hourly averages of the rainfall rate in the hills, P_h (site 3 in Fig. 1(b)) and at the coast, P_0 (site 1 in Fig. 1(b)). Initially, with fairly moderate wind speeds, the enhancement, $P_h - P_0$, is small, but increases with time as a consequence of both increasing P_0 and wind speed. Smaller-scale features (i.e. 1 to 2 h duration) in the rainfall records (for example in P_h around 1000 GMT) may be regarded as mesoscale variability. Since the two gauges were not in line along wind this feature cannot necessarily be expected to appear in both records. Hence the area of heavier rain that affected the coastal site around 1500 GMT (and resulted in a negative enhancement for a short time) is not discernible in the record from the hill gauge. The open circles in Fig. 14 give the predictions from the Bader and Roach model, i.e. taking account of the variation of both P_0 and the 600 m wind speed (for intermediate times the wind speeds were obtained by linear interpolation between the sonde ascents). A reasonable fit to the observed variation of P_h is obtained but this deteriorates after 1400 GMT.

Hill *et al.* (1981) identified various factors that could influence the relationship between theoretical and actually observed enhancements. As noted earlier, hill slope is important and the steeper slopes in the Mountains of Mourne should have generated greater enhancement, as was in fact observed. The assumptions made in the model may also underestimate the wind speed near the ground over the hills and greater speeds would increase the vertical component of air motion, produce higher condensation rates and so greater rainfall enhancements.

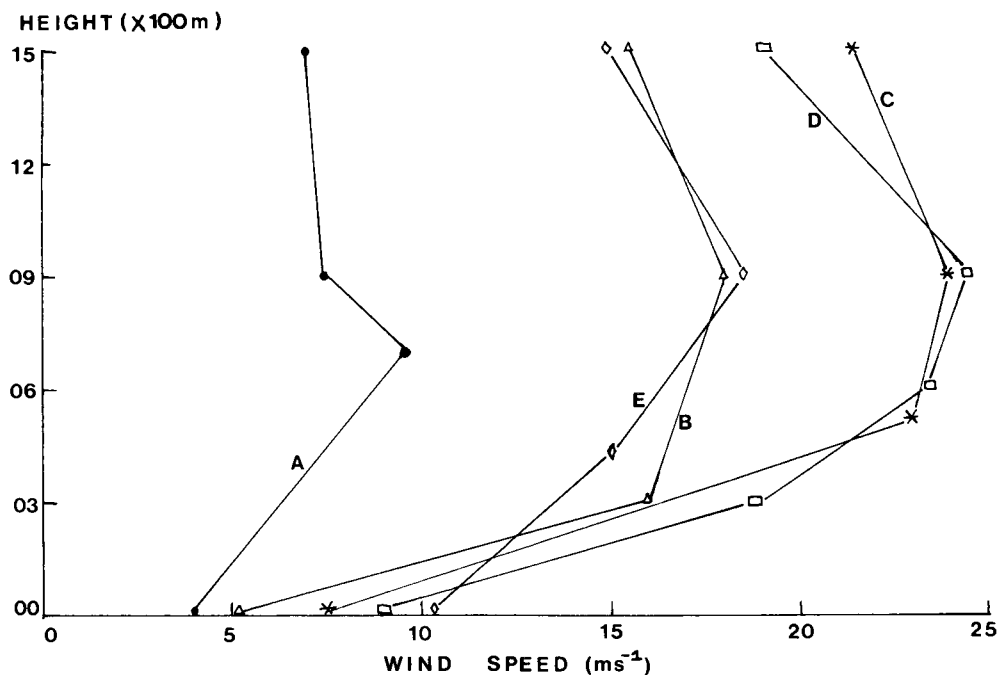


Figure 13. Variation of the wind speed in the lowest 1.5 km on 27 December 1978. Profile times are: A, 0001 GMT; B, 0600 GMT; C, 1200 GMT; D, 1800 GMT; and E, 2359 GMT.

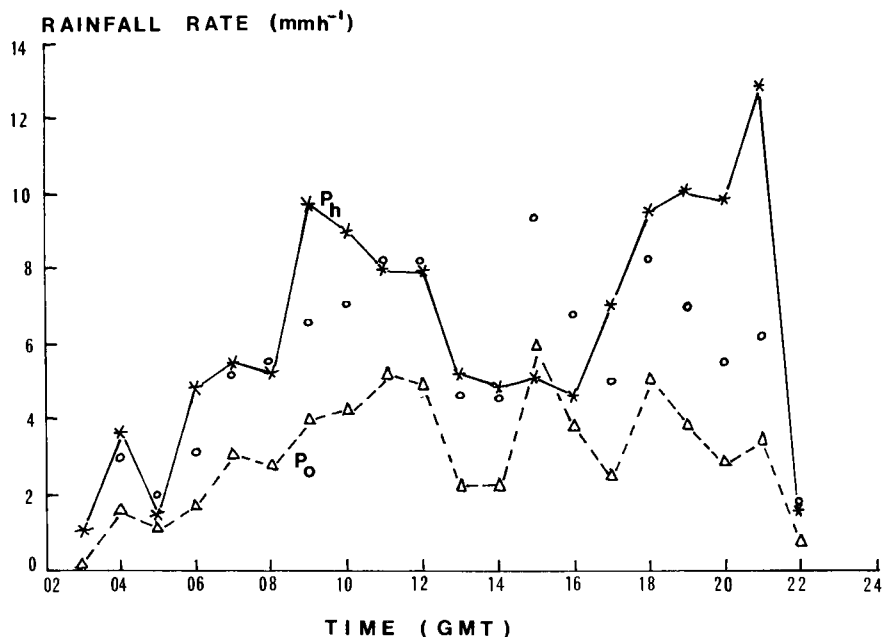


Figure 14. Variations of mean hourly rainfall rates in the hills (P_h , rain-gauge site 3) and at the coast (P_o , rain-gauge site 1). The data points are plotted at the ends of the hours to which they refer. Open circles are the predicted rainfall rates in the hills from the model of Bader and Roach (1977).

Potential instability (which is ignored in the model) is also usually prevalent in strong enhancement situations. This usually occurs in bands at lower and middle levels, although in this instance (see Fig. 5) it would seem that a progressive change from middle-level PI to more extensive PI from the surface to 700 mb was likely as the depression moved slowly northwards. It could be, therefore, that the larger differences between observed and predicted enhancements after 1400 GMT were due to the release of fairly widespread and significant PI in the vicinity of the hills, as proposed by Browning *et al.* (1974). As noted earlier, it is difficult to obtain large enhancements (about 6 mm h^{-1}) without increased rates of condensation in the cap cloud produced by the release of potential instability. Towards the end of 27 December enhancements of close to 10 mm h^{-1} were observed on this occasion (Fig. 14).

A further possibility for poor agreement between predicted and observed enhancements is that P_0 does not approximate to the rainfall rate at the top of the cap cloud (which is the parameter used in the model). This seems likely to be the case in instances, such as that considered here, where PI may have been released by passage over the hills.

The variation of enhancement with wind speed (ignoring the dependence on P_0) is given in Fig. 15. Since the coastal site was not upwind of the hills the enhancements have been averaged over two-hour periods to reduce scatter. The data certainly suggest a wind-speed dependence not unlike that observed in the Glamorgan Hills, although clearly significant scatter is produced by the variations in P_0 apparent

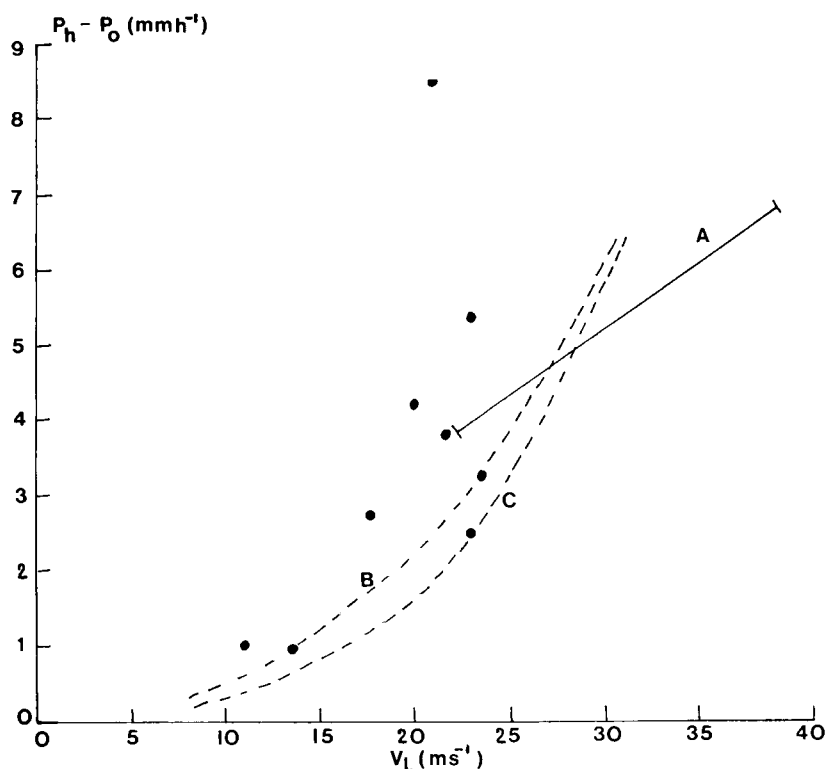


Figure 15. Variation of the rainfall enhancement ($P_h - P_0$) with the 600 m wind speed (V_L). Line A is from Nash and Browning (1977) (20 cases from 1960 to 1974), line B is from Hill (1977) (40 cases, 1974/5) and line C is from Hill *et al.* (1981) (8 cases, 1976/7).

in Fig. 14 (i.e. the larger enhancements are also associated with large P_0 values). However, for wind speeds in the range $10\text{--}15\text{ m s}^{-1}$ it would seem that $P_h - P_0$ is about 1 mm h^{-1} and that to achieve really substantial increases of rainfall rates in the hills, wind speeds of the order of $20\text{--}25\text{ m s}^{-1}$ are required.

There is a noticeable departure in Fig. 15 of the enhancements from the South Wales behaviour at larger wind speeds. These points arise from the data between 1900 and 2100 GMT in Fig. 14 and could well be due to the fact that P_0 at this time is no longer representative of the rainfall rate at the top of the cap cloud, owing to the release of PI in the vicinity of the hills. Nevertheless, even the behaviour at low wind speeds is more marked than the Bader and Roach model predicts.

Hill *et al.* (1981) suggest that some reformulation of the physical processes leading to enhancement may be required and Carruthers and Choularton (1982) draw attention to the low-level jet usually present in major enhancement situations. Deep moist jets will produce thick cap clouds and hence greater enhancement. It could be that the 'apparent' sensitivity of the enhancement to wind speed arises from the fact that the strongest wind speeds are associated with the most active systems which in turn have well-defined jets that form thick cap clouds. However, this possibility does not seem applicable to the cases considered by Hill *et al.* (1981) since the radar observations confirmed that enhancement was limited to a fairly shallow zone above the hill (less than about 1.5 km).

Concluding remarks

The event described in this paper was exceptional in that prolonged moderate to heavy rainfall over low ground in the eastern parts of Northern Ireland was significantly enhanced in hilly areas. This produced a fall at the Silent Valley of 245 mm in 56 hours, which has an expected frequency of occurrence of less than once in 1000 years. At higher levels the precipitation turned to snow early on 28 December and equivalent rainfall totals are not available. However, as noted earlier it seems likely that these exceeded 300 mm at the 300 m level in the central area of the hills.

From the forecasting viewpoint this investigation emphasizes the need to assess the likely importance or orographic effects in particular synoptic contexts. With moist flow and light winds it would seem that enhancements are likely to be small. However, with the combination typical of an intense depression, i.e. strong winds, moist low-level flow and appreciable background rainfall rates, then the effects may indeed be dramatic. Rainfall totals in hilly areas exposed to winds from the sea could easily be two or three times those at nearby coasts. This will inevitably mean greater run-off, higher river levels and increased flooding risk in downstream low-lying areas.

This paper has highlighted one extreme member of a set of similar occurrences currently being analysed in which enhancement occurs in the hilly areas in the east of Northern Ireland when winds are in the south-east quadrant. Similar events doubtless occur in the west and north-west of the Province with moist south-westerly flow, although the protection afforded by upwind hills of the Irish Republic probably reduces the occurrence of extreme events. Hence, the most susceptible area in Northern Ireland to exceptionally heavy rainfall is probably the Mountains of Mourne. If the synoptic situation is slow moving remarkable rainfall totals may accumulate over a period of a few days.

Acknowledgements

Thanks are due to Mr P. Eastwood (Meteorological Office, Belfast) for preparation of Fig. 10 and to Mr F. Wright (Meteorological Office, Belfast) for Fig. 9. Thanks are also due to Met O 9b (outstations investigations section) for the supply of plotted charts and radiosonde data and to Mr R. M. Morris, Mr F. Singleton, Mr F. F. Hill, Dr K. A. Browning, Mr J. Findlater and Dr W. T. Roach, for useful comments and suggestions.

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Notes and news

Building and Construction Climatology Unit

Since 1975 a small unit within the Climatological Services Branch of the Meteorological Office has assisted with the weather-related problems encountered by researchers at the Building Research Establishment (BRE), by staff of other government departments and, to a lesser extent, by the building industry at large. The two posts in this Unit have been funded by BRE. Foremost among the collaborative projects undertaken with BRE have been studies of wind-driven rain, extreme values of snow depth and wind speed, and rainfall during the working day. The Unit has also contributed to the preparation of a pilot booklet *Weather and building operations in the Plymouth region* containing various summaries of weather data pertinent to outdoor construction work.

Financial arrangements for the Unit have been revised recently and, although strong links will be maintained with BRE, it will now be possible for the Unit to expand its activities in the field of Meteorological Office services for the building and construction industries. Efforts will be made to develop climatological services relevant to the needs of those industries, as well as publicizing those services already available. The first promotion by the new Unit, organized jointly with the Public Services Branch, was at the six-day London Building Exhibition at Earls Court last October, during which Meteorological Office services were publicized using a film, simulated forecasting work bench, Prestel and extensive display material.

Requests for information about climatological services for the construction industry may be directed to: Building and Construction Climatology Unit

Meteorological Office Met O 3
London Road
Bracknell
Berkshire
Telephone: 0334-20242 Ext. 2299

International Symposium on Building Climatology

The Central House of Architects in Moscow was the venue for a Building Climatology Symposium which was held from 20–23 September 1982 under the auspices of the International Council for Building Research Studies and Documentation (CIB), the World Meteorological Organization (WMO) and various Soviet organizations. There were over 200 delegates, including 35 from outside the Soviet Union. Twenty-one countries were represented mainly by building science researchers, climatologists, architects and engineers; the six United Kingdom delegates came from the Meteorological Office, the Building Research Establishment, the Welsh School of Architecture (2), Heriot-Watt University and the Northern Ireland Federation of Housing Associations.

The main part of the symposium consisted of three simultaneous technical sessions, during which 40 papers were presented. These dealt with:

- (i) climate and architectural-building design,
- (ii) methods of obtaining and presenting climatic information for building design, and
- (iii) problems of insolation and sun control of buildings and city territory.

Criticisms which could be levelled at several of these papers are that they were too familiar, or too general, or too badly presented to raise significantly the level of awareness of the delegates. The published proceedings of the symposium should overcome the last-named criticism.

The technical sessions were preceded and followed by plenary sessions at which representatives of the organizing bodies spoke, including Professor Drozdov (Head of USSR Research Institute of Building Physics), Professor Sebastyen (CIB Secretary-General) and Dr Jovicic (Chief, Industrial Applications and Climatology Branch, WMO).

There were technical excursions to a large, high-density housing development and to the Research Institute of Building Physics, where the facilities include an impressive artificial sky vault and climatic laboratories where building components intended for use in the USSR are subjected to temperatures as low as -50°C .

After the end of the symposium, a meeting of the CIB Working Commission W71 (Building Climatology) was attended by about 15 delegates. During this meeting there were interesting discussions about the limits of the Commission's competence and about a review of current research carried out recently by W71.

The symposium should be judged as a success, not perhaps when one considers the utility of some of the papers presented, but certainly because of the international (and national) links which were forged or renewed during the week. The organizing committee are to be congratulated on their efforts to ensure the smooth running of the various sessions and excursions. Even the weather had been arranged perfectly, because Moscow was enjoying an 'Indian summer' with prolonged sunshine and daytime temperatures around 20°C .

M. J. Prior

Falklands conflict (operation CORPORATE): honours and awards for Meteorological Office staff

The Director-General held a reception at Headquarters on Monday 18 October 1982 for staff who had been involved in the Falklands conflict from April to July. The South Atlantic Campaign Medal was presented personally to six members of the Mobile Meteorological Unit who were available out of the ten who had qualified for the medal through their service on Ascension Island. The remaining four were currently serving either at Ascension Island or at RAF Port Stanley. The Director-General also congratulated Mr J. Turner, who had received the MBE for his work in bringing the 15-level model into service to cover the South Atlantic and South America some four months ahead of schedule, and Mr W. McQueen, Senior Meteorological Officer at RAF Coningsby, who had received the MBE for his service as Officer Commanding in his reserve rank of Squadron Leader in the Royal Air Force Reserve of Officers, when the Mobile Meteorological Units were first established on Ascension Island and later at Port Stanley airfield. The Director-General also presented letters of commendation from the Permanent Under-Secretary of State to five staff who had been involved with the Falklands conflict either through their service with the Mobile Meteorological Units or in Headquarters support. The reception was attended by members of the Directorate and by Group Captain M. Burton, DD Ops (Nav)(RAF), representing the Air Staff.

The following staff received honours, the South Atlantic Campaign Medal or letters of commendation:

MBE

W. R. McQueen	Senior Scientific Officer	Senior Meteorological Officer, RAF Coningsby.
J. Turner	Senior Scientific Officer	Operational Numerical Analysis and Forecasting Branch, Headquarters Bracknell.



The Director-General of the Meteorological Office's reception for staff who were involved in operation CORPORATE. Back row, from left to right: J. Turner, Squadron Leader W. R. McQueen, Flight Lieutenant P. W. Davies, Sir John Mason, Squadron Leader H. Pettit (ex Officer-in-charge of the Mobile Meteorological Unit, now retired) and Group Captain M. Burton. Front row, from left to right: R. S. Bell, Flying Officer S. W. Galaud, Flight Lieutenant B. Phillips, Flying Officer R. G. Adam, E. E. Williams and Squadron Leader K. J. Maidment.

South Atlantic Campaign Medal

R. G. Adam	Scientific Officer	Kirkwall.
P. W. Davies	Higher Scientific Officer	Observational Requirements and Practices Branch, Headquarters Bracknell.
S. W. Galaud	Scientific Officer	Observational Requirements and Practices Branch, Headquarters Bracknell.
D. R. Kingham	Scientific Officer	RAF Northolt.
K. J. Maidment	Senior Scientific Officer	Headquarters Strike Command.
W. R. McQueen	Senior Scientific Officer	Senior Meteorological Officer, RAF Coningsby.
B. Phillips	Higher Scientific Officer	London Weather Centre.
J. H. Philpott	Higher Scientific Officer	Meteorological Office College.
C. G. Robins	Scientific Officer	RAF Marham.
D. J. Wheeler	Scientific Officer	Headquarters Strike Command.

Letters of Commendation

R. S. Bell	Senior Scientific Officer	Operational Numerical Analysis and Forecasting Branch, Headquarters Bracknell.
P. W. Davies	Higher Scientific Officer	Observational Requirements and Practices Branch, Headquarters Bracknell.
S. W. Galaud	Scientific Officer	Observational Requirements and Practices Branch, Headquarters Bracknell.
B. Phillips	Higher Scientific Officer	London Weather Centre.
E. E. Williams	Higher Scientific Officer	Defence Services Branch, Headquarters Bracknell.

Review

Climate, history and the modern world, by H. H. Lamb. 154 × 233, pp. xix + 387, *illus.* Methuen & Co. Ltd., London, New York, 1982. Price £8.95.

Professor Lamb's latest book, though it follows to some extent the general pattern of his *magnum opus* (*Climate: present, past and future*; Methuen, 1972 & 1977), is by no means a mere abridgment of that massive work but is an essentially new book, designed and written for the educated general reader; the relative amount of space allotted to various topics is, for example, quite different. Two brief introductory chapters are followed by three on 'the development of climate' including discussions of the general circulation and methods of reconstructing past climates, eight on 'climate and history', and five on 'climate in the modern world and questions over the future'.

The author gives, as he usually does, an interesting and readable account of what has now been discovered of the history of the world's climate, concentrating chiefly on the recent post-glacial period — which of course includes the whole development of human civilization out of the palaeolithic. The book is probably weakest on applications of principles of physical science and statistics to the discussion of known or suspected causes of climatic variation. For example, it would have been interesting to have had at least some discussion of how the present arid climate of the Sahara and the much moister climate of only 5000 or so years ago can both be made consistent with the necessary dynamical and energetic constraints of the general circulation of the atmosphere, or how the presence of volcanic dust affects the

partitioning of incident solar radiation between the direct, diffuse, and reflected components. Questions are begged here and there: for example, the decline of Petra (p. 150) is much more likely to have been due to military and economic causes — particularly the rise of Palmyra as a dominant trading centre — than to climatic ones.

The referencing of the book is oddly inconsistent. Some sections are liberally supplied with detailed references for the statements and opinions quoted while others are quite free of such necessary aids to the critical reader. See, for example, figures 90–92.

R. P. W. Lewis

NERC Automatic Weather Station Pool

The Natural Environment Research Council (NERC) have asked us to print the following announcement of a facility which NERC Scientific Services are making available to interested users:

Automatic weather station equipment pool

General

An equipment pool of battery-operated automatic weather stations (AWS) has been set up by the Natural Environment Research Council.

These stations are maintained by the Institute of Hydrology (IH), Wallingford and are offered on free loan to assist approved research projects at NERC institutes and at institutions of higher education. Standard data processing, which consists of a hard copy listing of hourly and daily totals or averages, is provided free of charge.

The AWS Pool is supervised by a small management committee which reports to the Director, NERC Scientific Services (NSS). The committee is chaired by Professor J. B. Thornes of Bedford College.

Equipment

AWS equipment has been developed to meet IH's own research needs, often involving detailed measurement of climate at unmanned remote sites where access is difficult and where electricity is rarely available.

The weather station's three-metre mast supports six sensors: solar radiation, net radiation, wind run, wind direction, air temperature and wet-bulb depression. A ground level rain-gauge completes the station. The sensors are connected via plugs and sockets to a junction box which is provided with extra entry ports for further sensors if required.

Sensor outputs are logged on standard cassettes by the Microdata miniature data logger and interface unit which were designed specifically for weather station data logging. Either the cassette or, if preferred, the complete logger may be changed at the end of the sampling period, normally at two-week intervals. The logger has 11 channels of which 7 are used for the weather station; the remainder are available for monitoring other variables. Use of the spare channels is at the discretion of the user in consultation with the Pool staff. At present, data from these spare channels cannot be processed and would have to be presented as raw data.

Conditions of loan

Borrowers must be able to demonstrate their ability to carry out operational procedures and simple checks on the equipment to be loaned. In the case of equipment set up outside the UK, some additional

training ($\frac{1}{2}$ –1 day) may be necessary. Training is provided by Pool staff and operators should make the necessary arrangements well in advance of the loan period. Site visits by Pool staff can be arranged and the cost may be charged, by prior agreement, to the institution borrowing the equipment.

All borrowers are required to sign a form on which their institution agrees to indemnify Council to the full amount of any loss or damage to equipment arising from any cause whatsoever (deterioration through normal wear and tear excepted). Borrowers are notified of the full replacement value of the equipment listed in their loan application. Borrowers other than publicly funded bodies must provide proof of appropriate insurance.

Borrowers must advise NSS at the earliest opportunity should the return of the equipment, in good working order, on the expiry of the loan period be in any doubt. Except for deployment within the UK borrowers are responsible for collection from and return to the Pool of all equipment borrowed; within the UK IH staff will be responsible for installation and collection. An account of any repairs undertaken on an overseas project must be presented with the returned equipment.

As soon as possible after completion of the project borrowers are required to furnish the management committee with a brief report on equipment performance and also on scientific results. A copy of subsequent reports or publications should be forwarded to NSS.

Council reserves the right to withdraw Pool equipment should exceptional circumstances require this.

Local applications

All applicants are required to submit an application form, which may be forwarded at any time, for consideration by the Management Committee. Application forms are available from:

Natural Environment Research Council
NERC Scientific Services
Polaris House
North Star Avenue
Swindon
Wilts
SN2 1EU
Telephone (0793) 40101 Ext. 335

Applicants for equipment loans who are also seeking research grant support from NERC should, separately, submit the NERC research grant application form (RG1) in the normal way (see Research Grants booklet). Failure to gain a research grant will not in itself preclude an equipment loan.

Further details may be obtained from Dr R. R. Gatten at the above address or from Dr T. J. Dean at the NERC Institute of Hydrology, Wallingford, Oxon, OX10 8BB, Tel: (0491) 38800.

B. F. Rule
Director
NERC Scientific Services

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Radar and rain-gauge observations of a severe thunderstorm near Manchester: 5/6 August 1981

By M. J. Bader

(Meteorological Office, Bracknell)

and C. G. Collier and F. F. Hill

(Meteorological Office Radar Research Laboratory, RSRE, Malvern)

Summary

A severe thunderstorm in the Manchester area during the night of 5/6 August 1981 produced point rainfall totals that occur, on average, less frequently than once in several hundred years at a given location. Observations of this storm from a nearby radar are used as a basis for discussion of the storm cells, the forecasts issued and how fresh insight into extreme rainfall statistics over catchment areas can be gained.

1. Introduction

Heavy, thundery rain fell over parts of England on the two rainfall days between 0900 GMT 5 August 1981 and 0900 GMT 7 August 1981. The characteristics of the rain were particularly interesting because:

- (a) the heaviest rain was concentrated in small areas only,
- (b) the amounts recorded do not occur, on average, more than once every few hundred years at a particular place,
- (c) the development of the storms was explosive and unexpected, and
- (d) the rainfall amounts and storm structure were monitored by radar, providing new insight into the validity of current guidance on rainfall for hydrological applications.

Fig. 1 shows the rainfall distribution for the two days combined. The highest totals were in three areas:

- (a) north-west England in a curved strip from Shrewsbury across the south of Manchester towards Huddersfield, with a maximum of 148 mm located 16 km east-south-east of Chester;
- (b) the south and east Midlands, with a maximum of 141 mm located west-north-west of Northampton, and
- (c) south-east England from Sussex to north-west London.

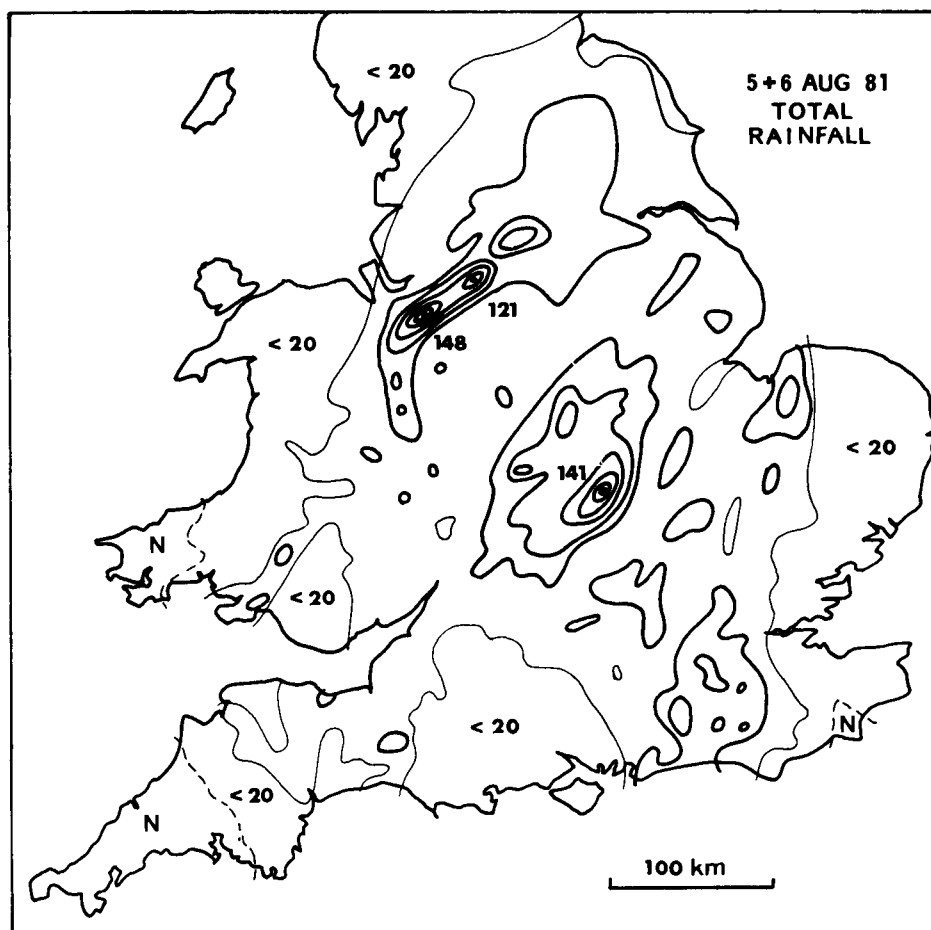


Figure 1. Total rainfall (mm) over 48 hours commencing 0900 GMT, 5 August 1981. Contours at 20 mm intervals. The thin lines are the 20 mm isohyets. (Note that there are no minima contained within any of the areas bounded by 40 mm isohyets.) N indicates areas with less than 0.5 mm.

Over north-west England most of the rain fell during the night of the 5th/6th, particularly between 2100 and 0300 GMT. The main band of storms moved across the southern part of Greater Manchester, producing serious local flooding and causing landslips (see Fig. 2). Over the Midlands, also, the heaviest localized falls occurred in the night, but here there was an additional fall of 30 to 50 mm on the 6th, most of it occurring during the daytime. Over south-east England the rain fell mostly during the morning of the 6th.

In this paper we describe the synoptic background to the thunderstorms in general before looking in more detail at the storms which produced the large totals shown in Fig. 1 over Greater Manchester. We have concentrated on this area of storms because of the proximity of the weather radar at Hameldon Hill, only 30 km to the north of the city of Manchester. This radar, which works on a wavelength of 5.6 cm and a beam width of 1° , recorded information from four different elevations every five minutes throughout the storm. Finally we discuss briefly the problem of forecasting the event.

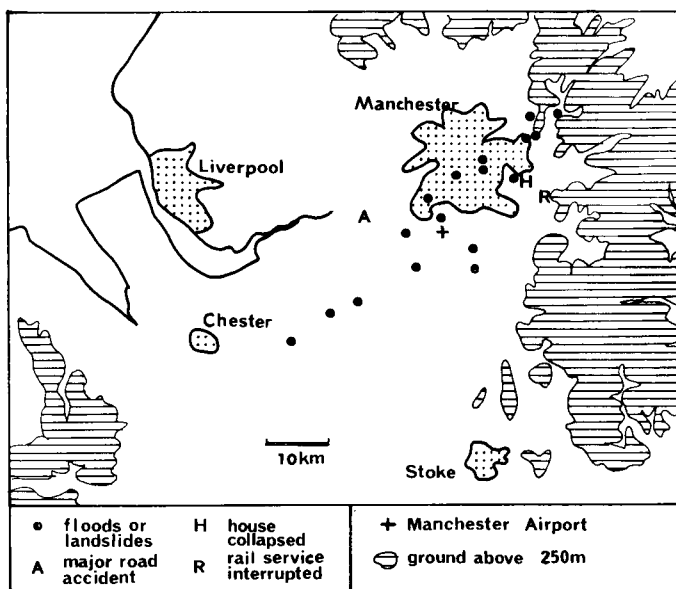


Figure 2. Location of floods and other incidents caused by heavy rain on the night of 5/6 August 1981, as collated from local newspapers.

2. Synoptic description

After a day or two of increasingly humid weather over France, the convergence associated with an intensifying upper trough caused storms to develop over a wide area and to move north-north-eastwards across England. The sequence of upper-air charts for midnight on each day from 4–7 August (Fig. 3) shows the changes that occurred at medium levels, represented by the 700 mb charts (approximately 3 km above sea level), and at high levels, represented by the 300 mb charts (approximately 9 km above sea level). At 0001 GMT on the 4th the air at medium levels was quite dry over England, moist air being evident chiefly over central France and Spain. By the early hours of the 5th an upper trough was approaching Ireland, preceded by a weak cold front, and the air at 700 mb had become moister over Biscay and western France. During the day a general backing of the airflow to a more southerly point occurred above 700 mb as the upper trough became sharper. The cold front was very weak as it crossed Ireland, giving only slight rain, and could not be easily identified at the surface.

The detailed surface analysis over the British Isles at 2100 GMT on the 5th is shown in Fig. 4. The main features are:

- (a) a slack, mainly cyclonic, north-easterly flow over England and Wales (with surface pressure rising slowly),
- (b) a tongue of hot, humid air over central England where the wet-bulb temperature exceeded 16°C, and
- (c) a cloudy region covering most of England and Wales, containing areas of unstable medium-level cloud and rain with some thunderstorms.

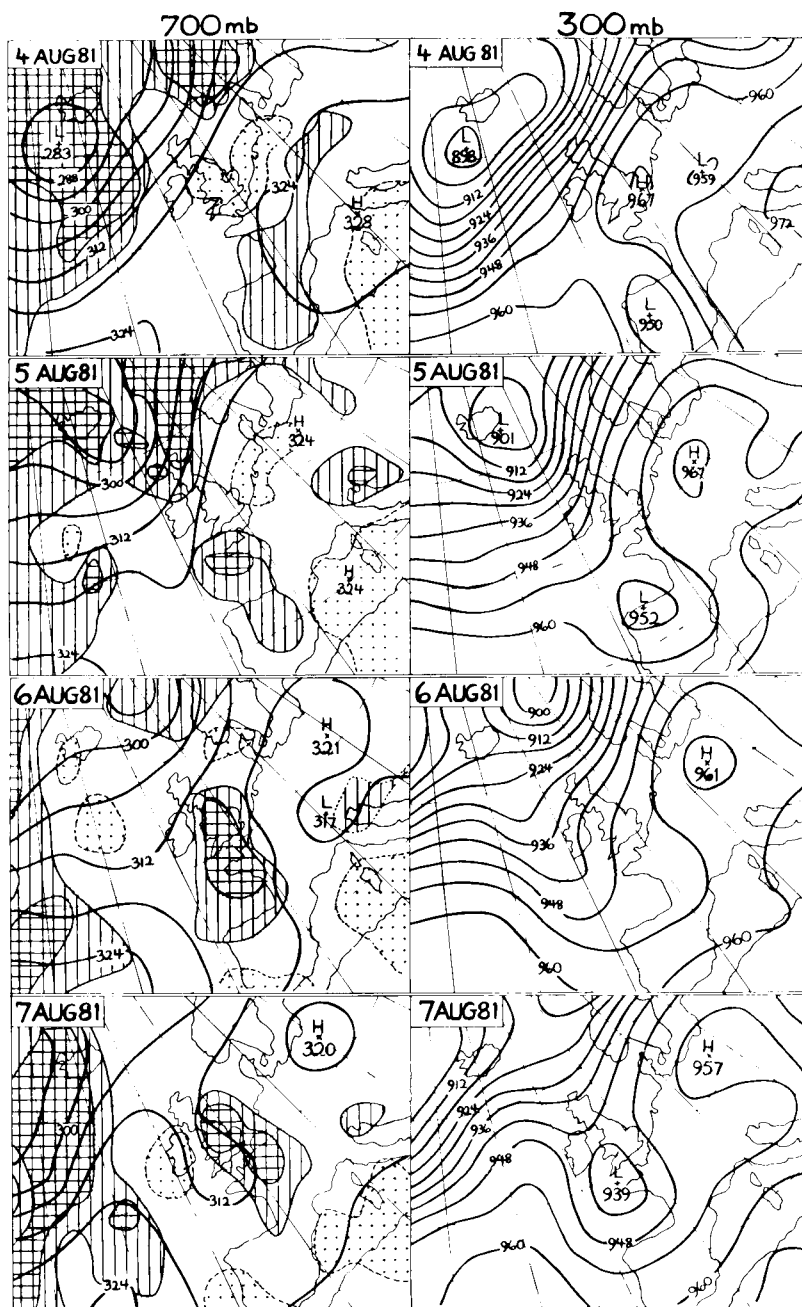


Figure 3. Upper-air analyses for 0001 GMT on 4, 5, 6 and 7 August 1981, showing the increase in relative humidity over England and north-west France at 700 mb and the formation of a sharp trough at 300 mb. Values in decageopotential metres. Relative humidity: cross-hatched $\geq 75\%$, hatched $\geq 60\%$ and dotted $\leq 30\%$.

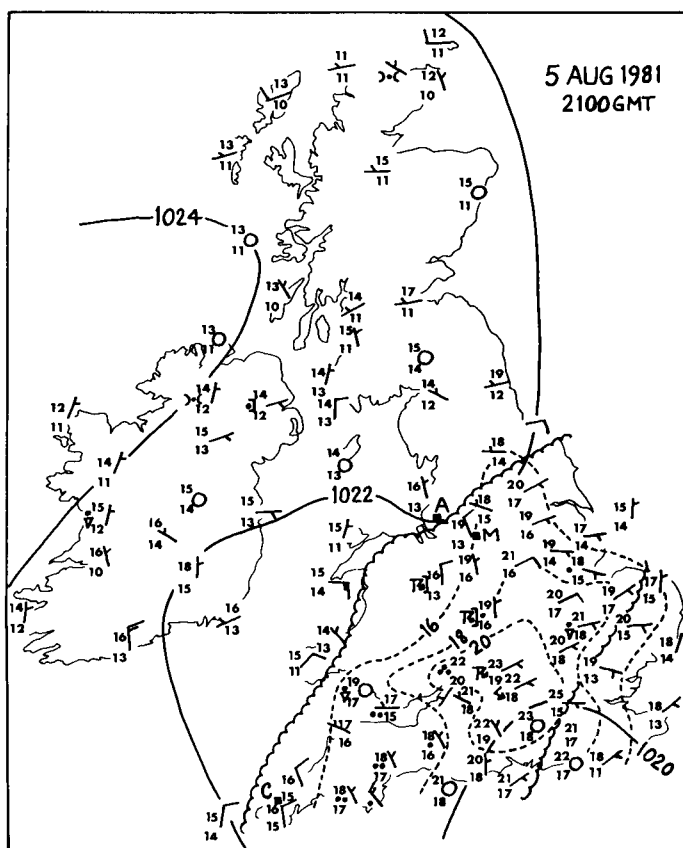


Figure 4. Surface wind, temperature, dew-point and significant weather at 2100 GMT on 5 August 1981. Continuous lines show mean-sea-level pressure (mb) and dashed lines show the region of highest wet-bulb temperature ($^{\circ}\text{C}$). Stations in England and Wales bounded by the wavy lines reported $\geq \frac{1}{8}$ cloud. Areas of unstable medium-level cloud were present within this cloudy region. The positions of Camborne, Aughton and Manchester Airport are marked with C, A and M respectively.

The nearest radiosonde station to Manchester is Aughton (Fig. 5). Here, the air was potentially unstable from 925 to 590 mb. The air at medium levels was dry because the main cloud mass was to the south-east; the Camborne ascent, which was probably more representative of the medium-level air associated with the Manchester storm, showed moist, potentially unstable air from 750 to 500 mb. The widespread release of that potential instability was responsible for the large area of cloud and thundery rain shown in Fig. 4.

Fig. 6 shows the distribution of rain at stated times during the 5th and 6th as observed by the radar network. Areas of thundery rain moved north-eastwards to reach the south-west of England by late afternoon on the 5th, while other storms developed over east Wales and the Midlands (Fig. 6(a)). During the evening, these storms moved north-north-eastwards towards northern England. The storms over eastern Wales, however, moved on a more northerly track towards the Shrewsbury area until 2100 GMT, when they began to move in a north-easterly direction towards Manchester. During the night new areas of thundery rain moved north across the Channel Islands and Cherbourg Peninsula towards

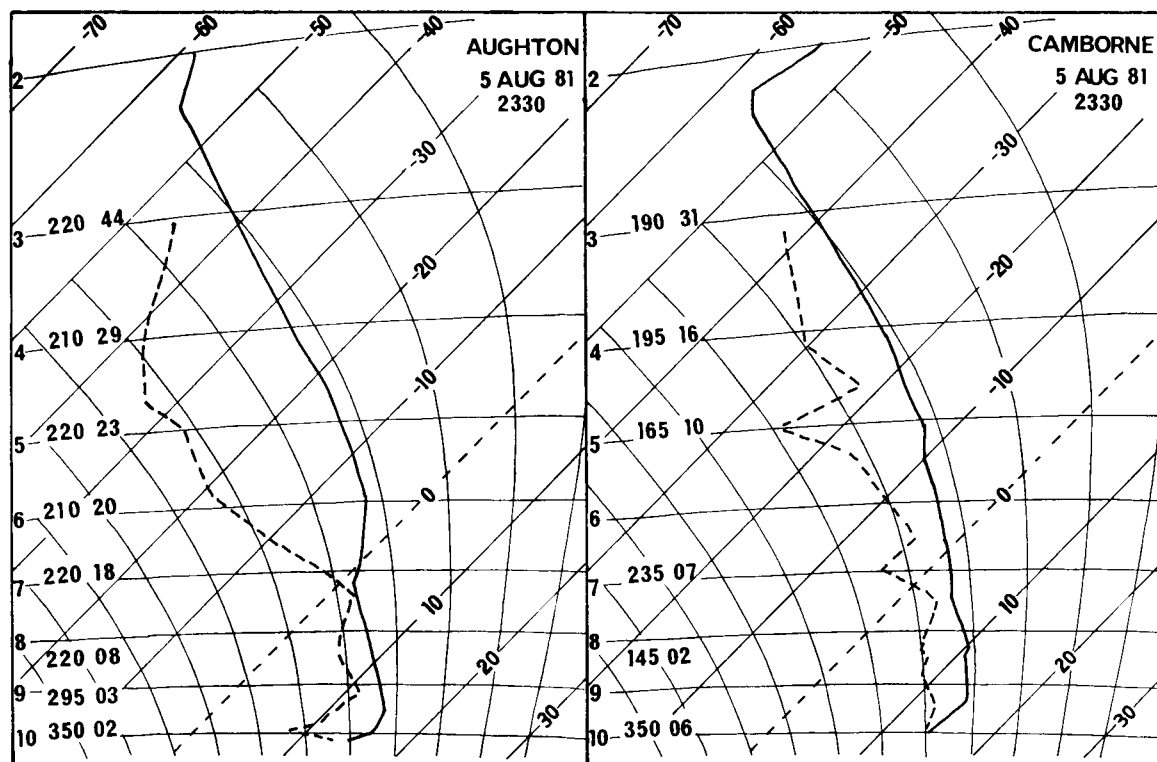


Figure 5. Tephigrams from the surface to 200 mb for Aughton and Camborne at 2330 GMT, 5 August 1981. Winds in degrees true and knots.

southern England (Figs 6(b) and (c)). These storms (Fig. 6(d)) were particularly violent over the London area around 0900 GMT. Gradually the more active storm areas moved northwards while the earlier storms died away to form large areas of persistent, but less intense, rain over the Midlands and northern England (Figs 6(e) and (f)). Drier weather extended north-eastwards across most of England during the night of the 6th/7th, but the upper trough was slow to clear the country and pockets of rain persisted over some northern parts throughout the 7th.

3. Rainfall over north-west England on 5–6 August 1981

3.1 Analysis of the rain-gauge data

Fig. 7 shows the rainfall totals over north-west England for the 24 hours ending 0900 GMT on the 6th. Two characteristics of the rainfall pattern are worthy of note:

- (a) the banded nature of the area of heavy rain, and
- (b) the small areas covered by the heaviest rainfall.

The strip of heaviest rain consisted of five main maximum fall areas (see also Fig. 1); two were orientated south/north near Shrewsbury and the other three were aligned south-west/north-east

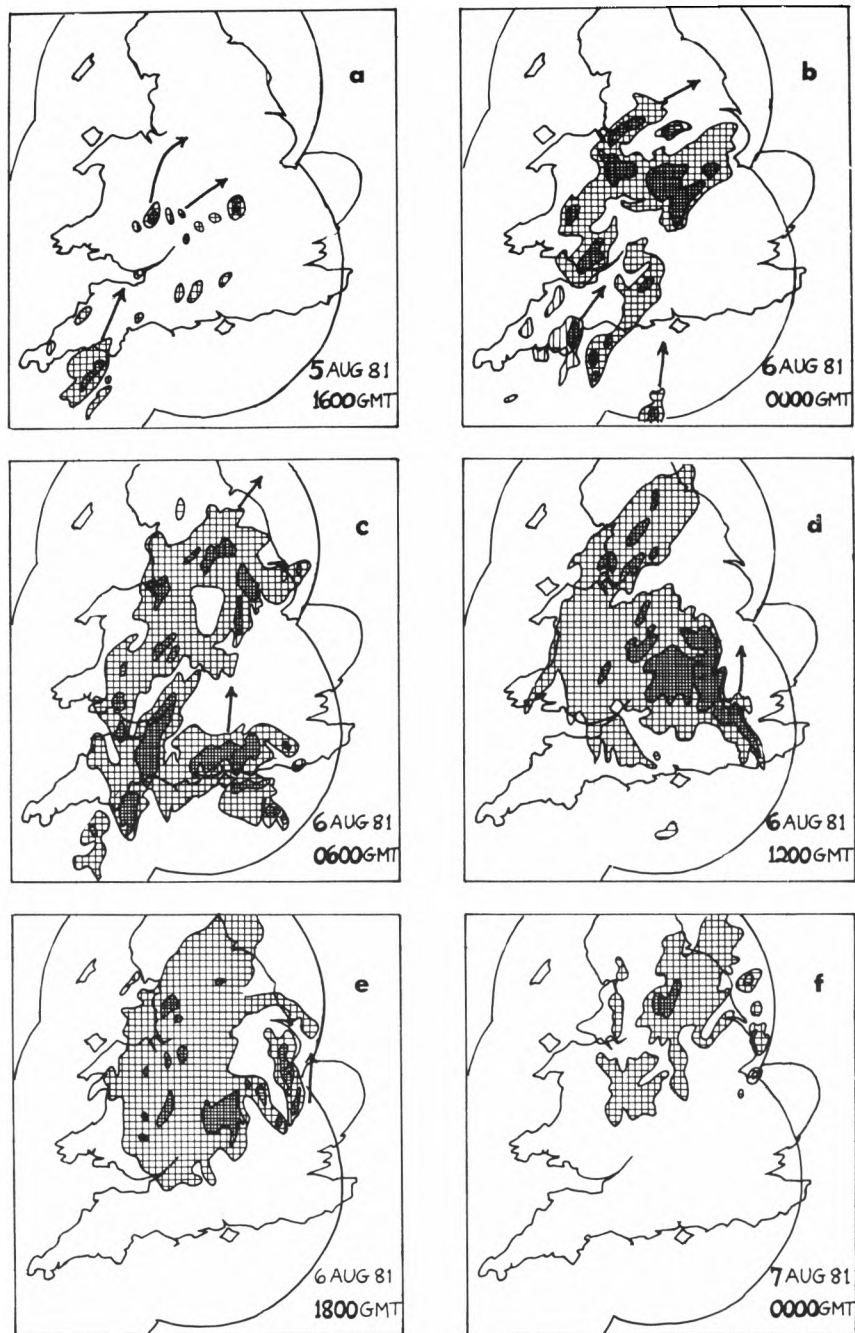


Figure 6. The cross-hatching (coarse and fine) depicts areas of rain shown by the radar network, effective within the circular boundaries. Fine cross-hatching shows rainfall rates exceeding approximately 4 mm h^{-1} . Arrows indicate movement during the interval from the current frame to the next frame, where this was not obscured by decay or new development.

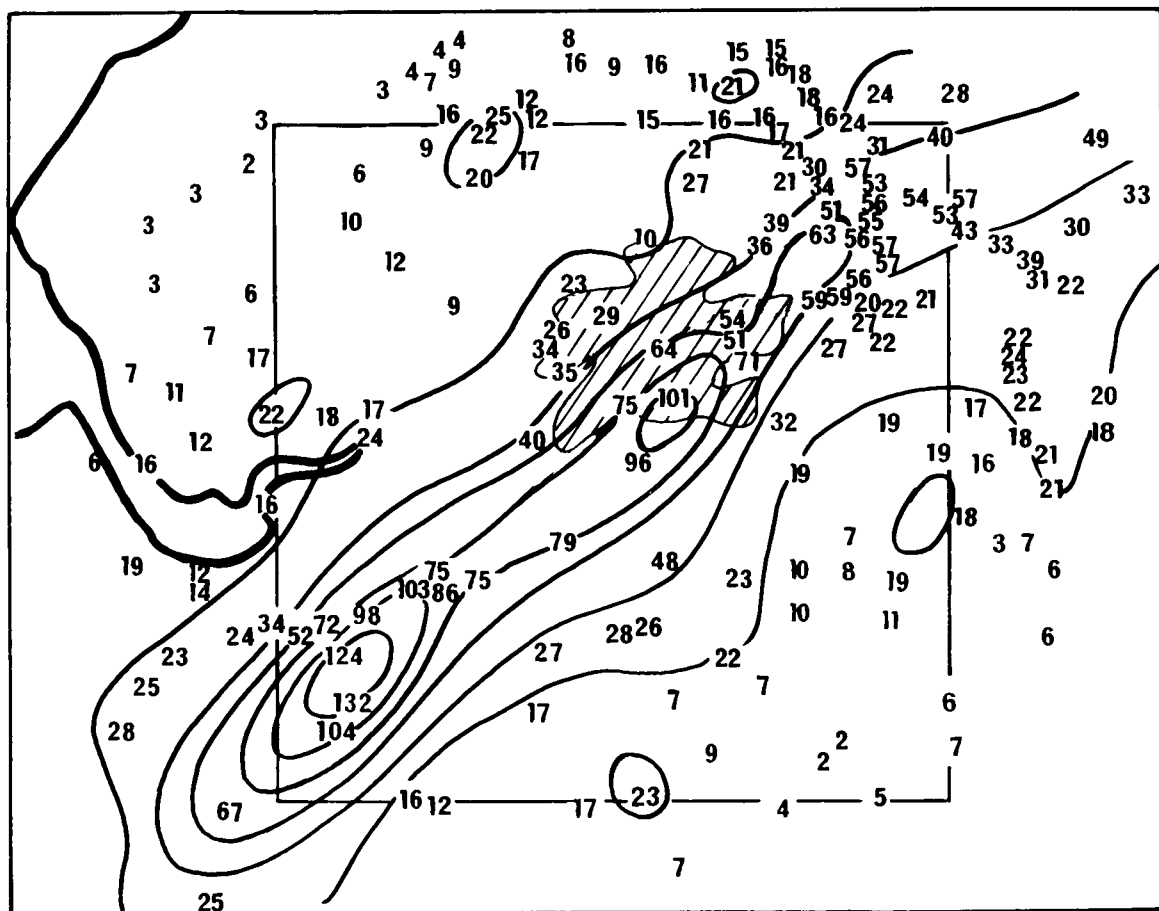


Figure 7. Rain-gauge totals (mm) for 24 hours commencing 0900 GMT, 5 August 1981. Contours at 20 mm intervals. Hatched area indicates Greater Manchester. The square locates the radar area used in Fig. 9. The totals of 101 and 96 mm were recorded at East Didsbury and Manchester Airport respectively. The highest total, 132 mm, occurred at Eaton Pumping Station.

towards the Pennines. The highest total of 132 mm was recorded at Eaton Pumping Station, 16 km east-south-east of Chester, but there were no data available from recording gauges in this area for resolving the rainfall for a duration of less than one day. However, the centre of the next maximum was situated to the south of Manchester where recording gauges were sited.

At Manchester Airport, most of the rain fell between 2200 GMT on the 5th and 0300 GMT on the 6th. The rainfall trace from the airport is shown in Fig. 8(a); the intense rain after 0100 GMT is well shown. The rainfall total for the five-hour event beginning at 2218 GMT was 89.8 mm. This corresponds to a return period of nearly 800 years. The characteristics of the rainfall at the airport were fairly typical of the rainfall in the surrounding area. However, East Didsbury, 7 km north-east of the airport, was nearer the centre of the maximum rainfall (Fig. 7); here, 85.3 mm of rain fell in 2 hours 40 minutes (Fig. 8(b)). This value corresponds to a return period of a little over 1000 years. Although the rainfall amounts from the Manchester storm were rare, much higher point totals have been recorded for similar durations; for example, 169 mm fell in 2½ hours at Hampstead, London, in 1975 (Keers and Wescott 1976).

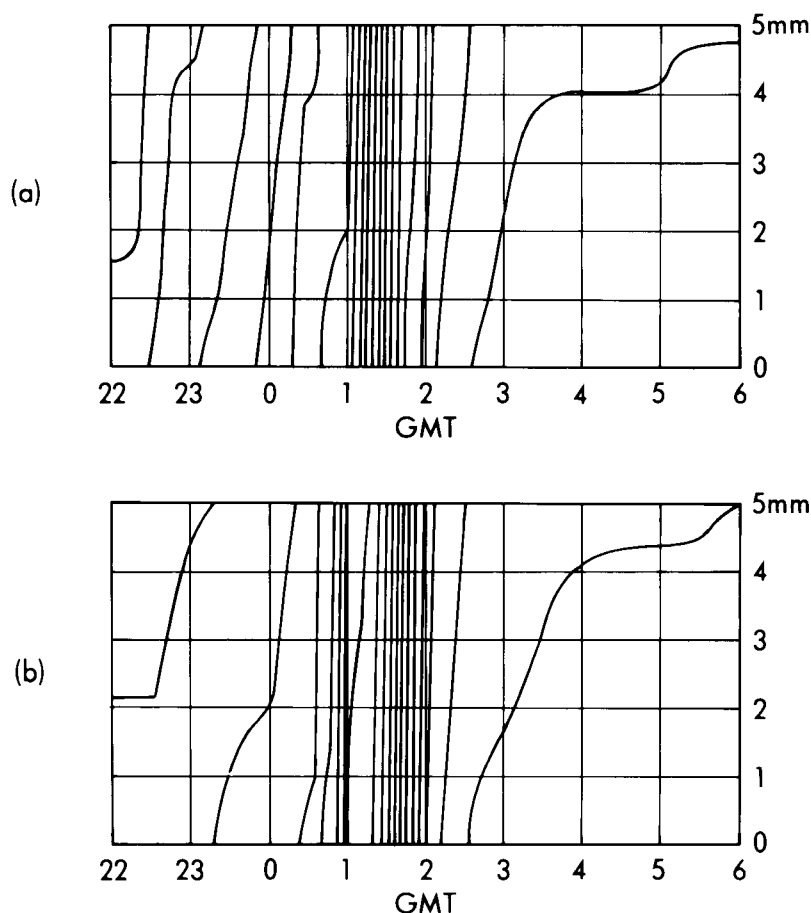


Figure 8. A copy of the rainfall trace at
 (a) Manchester (Ringway) Airport,
 (b) East Didsbury (Parrs Wood).
 The stations are about 7 km apart and are situated within the same maximum rainfall area (see Fig. 7). The abscissa is time, in hours GMT; the ordinate is rainfall in mm. One full-scale deflection corresponds to 5 mm.

3.2 Radar observation of the storms

This description of the storms is based on the radar data collected at Hameldon Hill from all four elevation scans (0.5° , 1.5° , 2.5° , 4°). Because of ground clutter, which affects the lowest beam in a north/south direction immediately to the west of Manchester, the shape and intensity of the storms are indicated more reliably by the 1.5° scan. In order to eliminate any large errors in the rainfall rates derived from the radar data (using the standard relationship $Z = 200R^{1.6}$, where Z is the radar reflectivity factor ($\text{mm}^6 \text{m}^{-3}$) and R is the rainfall rate (mm h^{-1})), a comparison was made between the five-minute radar data, integrated throughout the whole period of the storm, and the total rainfall measured around 0900 GMT. The ratio of radar to rain-gauge totals was mostly between 1.0 and 1.5 in the vicinity of the main rain-band. An overestimate is to be expected since Z will exceed $200R^{1.6}$ whenever the precipitation contains large water drops or hail (Battan 1973) and can be influenced by strong vertical air motions (Battan 1976). Some small areas of much higher ratios occurred to the south of the storms; these are

believed to have been caused by anomalous propagation (Battan 1973). In the following description of the progress of the storms, illustrated by Fig. 9, the rainfall intensities associated with cells A, B, C and D have been obtained by dividing the radar data by 1.0, 1.3, 1.1 and 1.4 respectively, while anomalous echoes have been eliminated.

Fig. 9 shows the position of the storms at 20-minute intervals across a 60×60 km square centred near Manchester Airport. The band of rain approximately 60 km long and 40 km wide was orientated in a north-east/south-west direction. The principal storm centres occurred on the south-eastern side of the band, producing steep rainfall gradients on this side, whereas an area of gradually diminishing rainfall rate extended over a 30 km range to the north-west of the storms. The general east-north-east progression of the envelope of rain belies the complexity of developments within it. Progression appears to have been caused by the development of new cells at about 40-minute intervals to the north-east of existing storms. Thus the cell labelled A in Fig. 9 remained some 40 km south-west of Manchester for about two hours, giving the heaviest rain (about 80 mm h^{-1}) around midnight. At this time the rain area appeared to split, with cell B moving east-north-east for a while to reach Manchester Airport by 0100 GMT while cell A drifted very slowly eastwards and weakened. Cell B became slow-moving near the airport and another cell, C, intensified some 20 km to the north-east. These cells in combination gave a 20 to 25 km long swathe of heavy rain exceeding 60 mm h^{-1} from 0100 to 0140 GMT. Cell D formed around 0100 GMT to the north-east of cell C and became the main centre by 0200, although it probably did not give rain heavier than 60 mm h^{-1} . Both cells B and C weakened quickly after 0145 GMT and cannot be identified as separate entities by 0210 GMT.

Comparison of Figs 7 and 9 shows that the three rainfall maxima in the daily totals coincide with the positions in which cells A, B and D were almost stationary.

4. Estimates of the areal rainfall associated with the Manchester storm

Hydrologists are particularly interested in rainfall amounts over areas, and radar has the potential for meeting this requirement. The snapshots provided by the radar at five-minute intervals were therefore used as a basis for calculating the highest amounts of rain that fell over areas consisting of one 5×5 km square, four squares (100 km^2) and nine squares (225 km^2). These were 99, 81 and 72 mm, respectively, in $2\frac{1}{2}$ hours. The corresponding totals for the Hampstead storm, which produced one of the highest point totals ever recorded in the United Kingdom, were 104, 56 and 35 mm (from Keers and Wescott 1976). Thus over 25 km^2 the totals from the two storms were similar, but over larger areas the rainfall from the Manchester storm was heavier. Remembering that the point rainfall from the Hampstead storm was much greater (section 3), it may be concluded that point rainfall from gauges whose spacing is comparable with or greater than the scale of rainfall variability can be a misleading indicator of areal storm rainfall. However, radar-derived data have the potential for providing more realistic values of catchment area rainfall, provided of course that the adjustment factors can be calculated accurately.

Similar considerations apply to hydrological design for which rainfall amount-area-frequency relationships derived from climatological records are used. To take the extreme case, in the design of hydrological structures that must have a high safety factor, the concept of Probable Maximum Precipitation (PMP) is used. This is the highest amount of rain that is likely to fall over the area and for the period appropriate to the catchment in question. According to the *Flood Studies Report* (Natural Environment Research Council 1975), the two-hour PMP for Manchester over 25, 100 and 225 km^2 areas is 143, 132 and 127 mm respectively. In the *Flood Studies Report*, PMP for this duration is used as a reference for computing PMP for other durations, so it is an important quantity to calculate correctly.

It is expected that PMP over a catchment on the ground would be produced from storm cells, like those in the Manchester storm, that remained quasi-stationary during their most intense phase. The

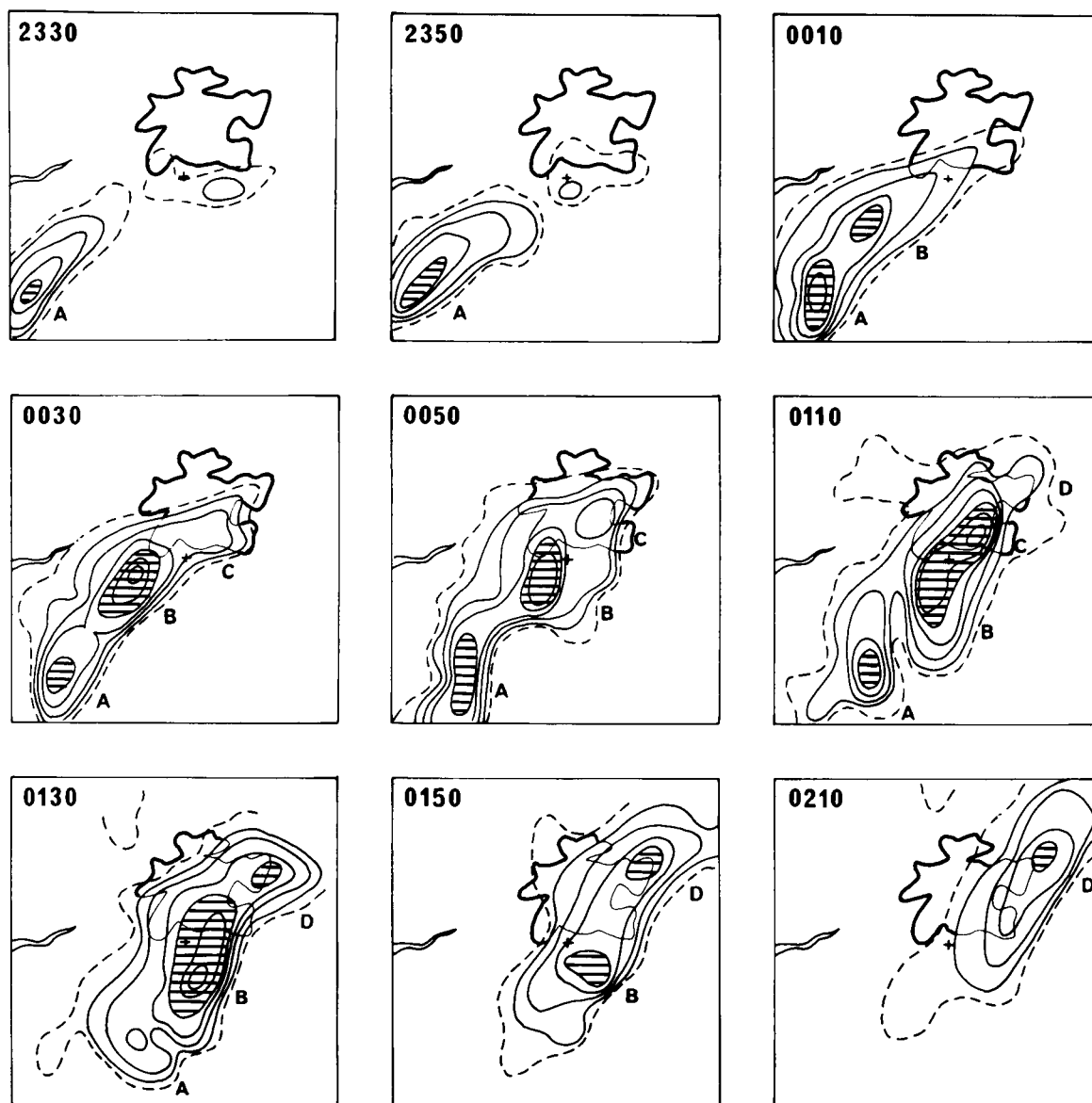


Figure 9. Progress of storms across a 60×60 km square centred near Manchester Airport (indicated by +). Contours are drawn at 5 mm h^{-1} (dashes), then multiples of 10 mm h^{-1} , with intensities over 40 mm h^{-1} shown by hatching. Letters identify individual storm cells. Solid outline shows the boundary of Greater Manchester. The radar is located at Hameldon Hill, which is 44 km north of Manchester Airport.

significance of the figures in the *Flood Studies Report* can therefore be assessed by using the radar data to calculate the rainfall from a cell as it moves along, i.e. in the Lagrangian frame of reference. The two-hourly totals for cell B (Fig. 9) were 145, 114 and 86 mm over 25, 100 and 225 km² respectively. Thus over 25 km² the observed total is similar in magnitude to the *Flood Studies Report* value of PMP.

During the hour when cell B was most active (0045 to 0145 GMT), the rainfall total over 25 km² of 83 mm was similar to that from other recent storms (Table I) that were studied using radar data. Thus, while it may be argued that the rainfall statistics over a particular catchment area are determined by the distribution of cell velocities as well as the rain that falls from the cells, the rainfall amount from cells like cell B may occur quite often and a larger sample of storms than that shown in Table I may reveal an even higher areal rainfall. Indeed, it is reasonable to envisage, given a favourable wind structure, two cells like cell B within a multi-cellular storm that deposit their rain over the same catchment area during their most intense phases. If so the *Flood Studies Report* PMP over 25 km² would be exceeded. Similar comparisons (see Table I) reveal that the *Flood Studies Report* PMP over 100 km² could be reached. Over 225 km², however, the PMP would not be reached, even though cell B produced much higher rainfall than the other storms studied — a fact that, given a larger sample, may add to the rarity of the Manchester storm.

Table I. *Hourly areal rainfall (mm) from storm cells in the Lagrangian frame of reference.*

Date	Location	Rainfall area		
		25 km ²	100 km ²	225 km ²
5 June 80	Darwen, Lancs.	60	37	24
20 May 81	East Pennines	83	51	30
1 June 81	Bournemouth	68	41	29
9 July 81	Derby	76	46	32
6 August 81	Manchester	83	66	51

The analysis of the Manchester storm shows how radar can broaden our knowledge of areal rainfall. Provided the radar data can be calibrated accurately, using 'ground truth' from gauges (as on this occasion), the data have potential for providing new insight into the catchment rainfall climatology, widely used for hydrological design.

5. Forecasting

The north-eastward movement and intensification of storms on 5 August were not well forecast. On the 4th a continuation of the dry weather was anticipated over most parts of England and Wales for the 5th and 6th. Though a risk of isolated thundery activity was recognized, associated with the vortex present on the 4th (see Fig. 3) moving north-eastwards across Biscay and northern France and weakening, this activity was expected to affect only south-east England and the Channel Isles. Early forecasts during the night of the 4th/5th told a similar story but when the Malvern radar network display in the Central Forecasting Office (CFO) at the Bracknell Meteorological Office showed echoes approaching the south-west around dawn on the 5th, a special synoptic review extended the risk area into much of southern England and South Wales. More widespread outbreaks of thundery rain were still only expected in the south-east following numerical guidance based on 0001 GMT data on the 5th which showed precipitation bounded by a line south-west/north-east through The Wash.

By the afternoon of the 5th, CFO were forecasting activity south-east of a line from the Severn to the Humber. Rectangle 10-level model forecasts based on 1200 GMT data gave good guidance with some large totals expected in the north-west Midlands overnight but unfortunately the output was four hours late arriving in CFO. By this time outbreaks were already occurring over Wales and these were being followed on radar.

The main reason for the thundery activity being more widespread than originally predicted was the failure to handle the complex evolution of the upper trough involving the north-eastward relaxation of the vortex over Biscay (Fig. 3), the disruption of the fast-moving Atlantic trough (positioned to the west of Ireland at 0001 GMT on the 6th) and the subsequent sharpening of its disrupted southern portion as contour heights rose rapidly upstream. The extension of this feature into Biscay considerably altered the flow pattern over the United Kingdom by the 6th and contributed to the widespread precipitation on that day, which was subsequently well forecast, but it appears to have occurred too late to contribute to the weather events over the United Kingdom on the 5th. The critical inflow of very moist, warm air at medium levels during the 5th appears to have been the result of a northward movement of a forward part of the Biscay vortex (as shown by the spread of medium-level cloud into south-west England and Wales) rather than north-eastward as predicted.

Although the broad-scale guidance from CFO did not provide an accurate forecast many hours in advance of this event, the availability of the real time Malvern radar composite displays in both CFO and at Manchester Airport did allow the development of the storms to be monitored closely. Using radar data at 15-minute intervals the local forecaster at Manchester Airport was able to modify the forecast for his area, in conjunction with CFO, as soon as it became evident that the radar was showing an extension of the storm development northwards. This led to the issue of a thunderstorm warning for Manchester Airport at 1937 GMT on the 5th. An alert was also passed to the duty hydrologist of the Mersey and Weaver Division of the North West Water Authority at 1955 GMT. By 2040 GMT Manchester Air Traffic Control had been briefed about the storms and warnings were then issued to aircraft, particularly light aircraft.

To have provided a more detailed forecast would have required foreknowledge that the storms which were over Shropshire at 2000 GMT would persist for several hours and veer to a more north-easterly track. Persistence is not always a reliable predictor since analysis of the radar data shows much variation in the duration of rainfall within storms. With regard to their movement, it is clear that winds above 600 mb had a stronger westerly component at Aughton than at Camborne (Fig. 5), though even at Aughton winds remained backed with respect to the general east-north-eastward displacement of the storm cells. Perhaps the stronger westerly components in the north contributed to the change of track observed after 2100 GMT. Such detail cannot be provided by current observational networks or operational numerical models with grid lengths of 50 kilometres or more, but may be provided eventually by remote sensing techniques and the development of numerical models with grid lengths of a few kilometres.

6. Conclusion

On the night of 5/6 August 1981, serious damage was caused in the Manchester region as a result of intense rain. Point rainfall amounts measured near Manchester during the storm occur on average only every few hundred years and, in this sense, the event can be described as rare. The banded distribution of heaviest rain at the ground as shown by the gauge observations can be explained by the north-eastward transfer of the main storm, as revealed by observations from the radar at Hameldon Hill. The radar analysis also provided new insight into areal rainfall amounts: the similarity in magnitude between the areal rainfall from this storm and the areal 'Probable Maximum Precipitation' in the *Flood Studies*

Report throws new light upon the current guidance given for engineering design purposes and further careful radar-based analysis of storms is needed.

Local forecasts of the event provided several hours warning of the thunderstorms over Manchester, but were unable to define the intensity of the rain which actually resulted. At present, radar and geostationary satellite imagery offer the only prospect of detecting the areas of development and for providing warnings with some lead time, even though this might be rather short on occasions. We hope that it will be possible in the future to use operational numerical models with a grid length of a few kilometres to forecast the preferred areas of development and rainfall amounts from storms caused by motions on the mesoscale.

Acknowledgements

The Hameldon Hill radar data were collected as part of the North West Radar Project which was jointly set up by the Meteorological Office, the North West Water Authority, the Water Research Centre, the Central Water Planning Unit and the Ministry of Agriculture, Fisheries and Food. We also acknowledge the kind provision of thermograph and anemograph data by Keele University. Thanks are also due to the Principal Meteorological Officer, Manchester Airport, and the Deputy Assistant Director (Central Forecasting) who provided details of the forecasts actually issued.

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Regional-scale interannual variability of climate — a north-west European perspective

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Summary

Climatic variability on space scales ranging from 10^7 km² (mainly North Atlantic and north-west Europe) to local areas (10 km²) within the United Kingdom (UK) is discussed with emphasis on relations between the characteristics of variability in space and time. A comprehensive study of monthly, seasonal or interannual variability has scarcely commenced so the bulk of our digested knowledge exists mainly on local and regional space scales. Even here, analyses have been dictated often more by practical than theoretical considerations, so our understanding of the causes of variability is, not surprisingly, meagre.

1. Introduction

The current state of knowledge about short period variability has progressed quite modestly since Craddock (1964) wrote: 'Research work concerned with the slower changes in the atmosphere is at the stage typified by Kepler rather than Newton in that its main task is that of assembling facts and recognising regularities and patterns rather than seeking explanations'.

Perhaps as (1981) emphasized by Hastenrath and Kaczmarczyk '... the characteristic time scales of climate and circulation variability, and the preferred frequency bands for spatial coherence [of such variability] have received little attention'.

2. Structure of the subject

Many empirical studies have been made of short period (a month to a few years) climatic fluctuations but the results are difficult to assess and to integrate. No unifying theory exists of regional interannual climatic variability or climatic variability from month to month, except to a limited extent that of the seasonal cycle. The analytical procedures vary greatly, geographical scope is usually limited and the purposes of analyses often reflect sharply-defined practical requirements. It is, above all, difficult at present to gain an appreciation of the spatial characteristics of time sequences of short period fluctuations. This reflects the difficulty of designing appropriate analyses though some use has been made of time series analysis in studies of longer term fluctuations.

Most studies could be grouped as follows (some combine several forms of analysis):

- (a) Case studies of individual 'events'.
- (b) Multiple case studies: 'superposed epoch analysis', 'analogue selection' in long-range forecasting (LRF), 'multivariate analysis'.
- (c) Time series studies.
- (d) Studies of the frequency or probability of 'events'.
- (e) Studies of associations of one type of data with another (correlation and regression).
- (f) Eigenvector analysis.

Analyses of types (e) and (f) will not be discussed in detail here, but Nicholls (1980), for example, gives a review of some applications to LRF.

3. What is the problem?

We need to explain or predict variations or 'spells' of weather like those illustrated below.

Example 1 — January 1963 (Figs 1(a) and 1(b))

January 1963 was persistently 'blocked' and very cold, as was much of the three months December to February, with a surface high north of Scotland. Winds were therefore mainly easterly over UK. The Iceland Low essentially disappeared and the jet stream was split between a branch south and another north of the block. The winter of 1962/63 was the coldest since 1739/40 in some places and blocking was generally more evident than usual over the Northern Hemisphere (Murray 1966, Namias 1963). (See also section 5.2.)

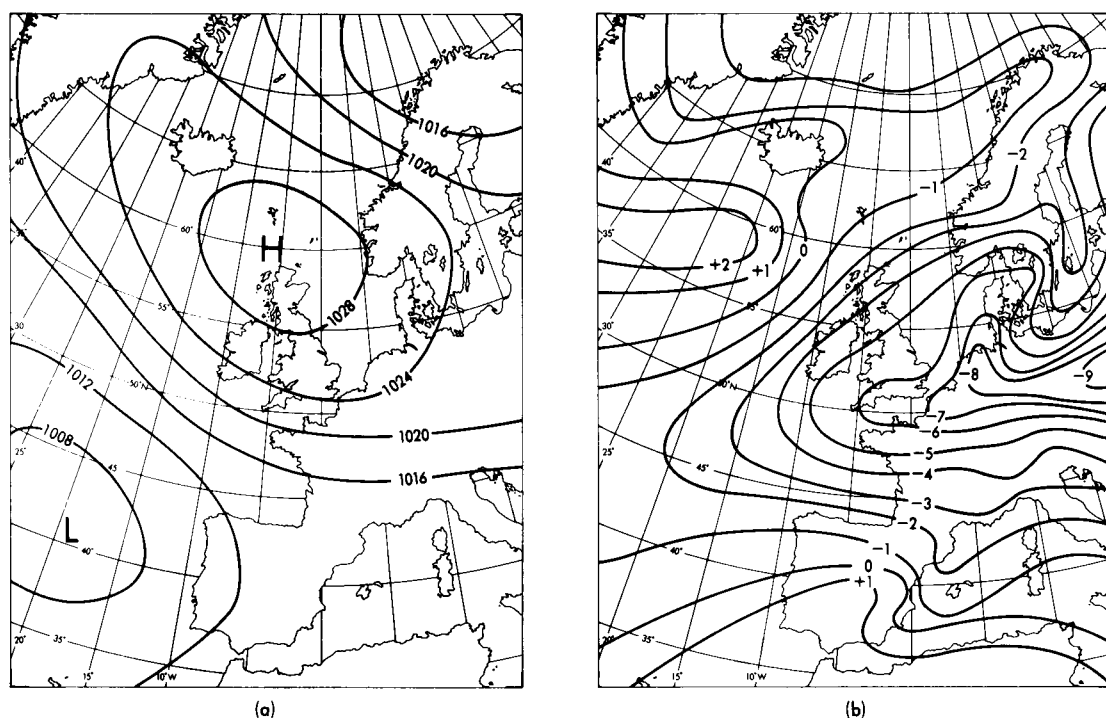


Figure 1. (a) Average pressure (mb) at mean sea level, January 1963.
(b) Average screen-level temperature anomaly (°C), January 1963. (Anomalies mainly from 1931–60 station averages.)

Example 2 — January 1974 (Figs 2(a) and 2(b))

January 1974 was stormy; the Iceland Low was exceptionally deep and persistent. This mild and westerly month in north-west Europe was an extreme example in the 'spell' of four such winters from 1971/72 to 1974/75 (Wright 1975, Painting 1976).

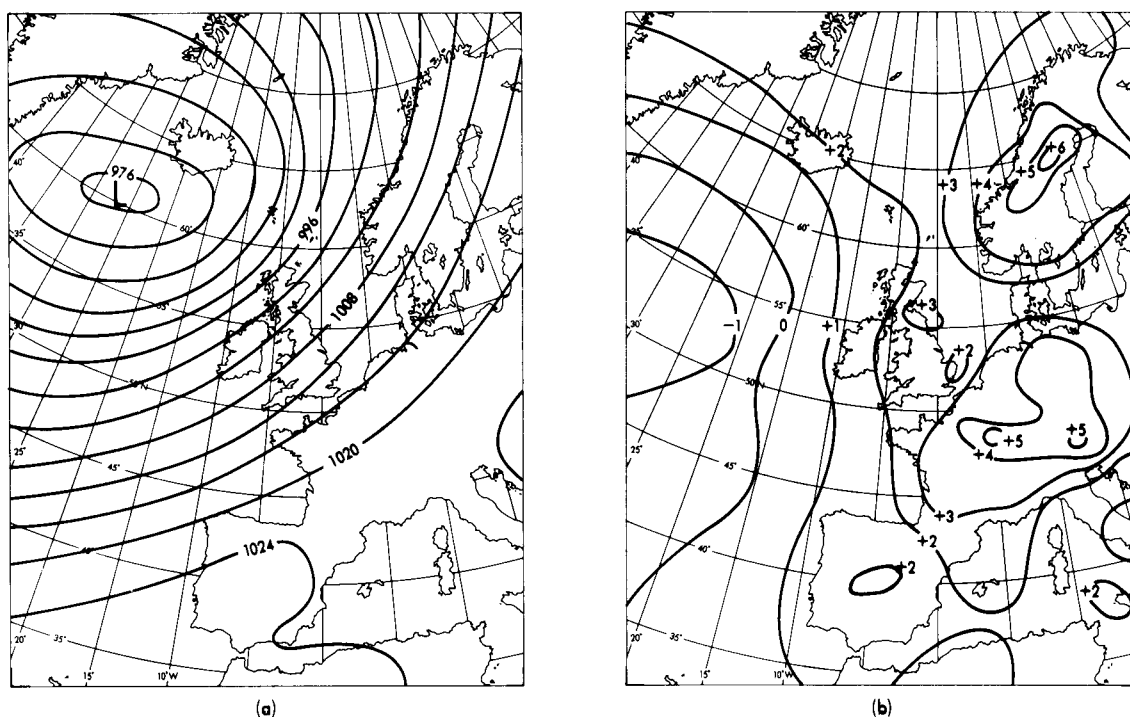


Figure 2. (a) Average pressure (mb) at mean sea level, January 1974.
(b) Average screen-level temperature anomaly (°C), January 1974. (Anomalies mainly from 1931–60 station averages.)

Example 3 — summer and autumn 1976 (Figs 3 and 4)

Summer 1976 was exceptionally dry and warm; the jet stream was persistently far to the north-west or north of the UK (Fig. 3), and frequently anticyclonically curved in UK longitudes. Consequently summer 1976 was one of the warmest in the last 300 years in parts of England, and exceptionally dry (Ratcliffe 1977, Miles 1977 and Murray 1977).

The transition to Autumn in 1976 was startlingly abrupt and in some ways contrary to the normal seasonal changes. The jet stream, from early September, became positioned persistently over, or south of, southern England (Fig. 4). Thus depressions frequently passed over, or were quasi-stationary near, southern England, (the jet stream tends to stay near northern Scotland in September). Autumn 1976 was the second wettest in many southern areas since at least 1727. (See also section 5.1.)

Example 4 — May 1975–August 1976 (Fig. 5)

Summer 1976 was the culmination of an even more exceptional 'spell'. The conditions shown in Fig. 3 were maintained with only short breaks (though the jet stream was generally slightly further south) during May 1975–August 1976 (Ratcliffe 1977, Miles 1977). Consequently May 1975 to August 1976 was the driest 16-month period in England and Wales (EW) since at least 1727. A Minister for Drought was appointed as the water supply dwindled and other consequences of the drought became severe (Folland 1978 gives summary). Fig. 5 shows the mean-sea-level pressure pattern and its anomalies over the

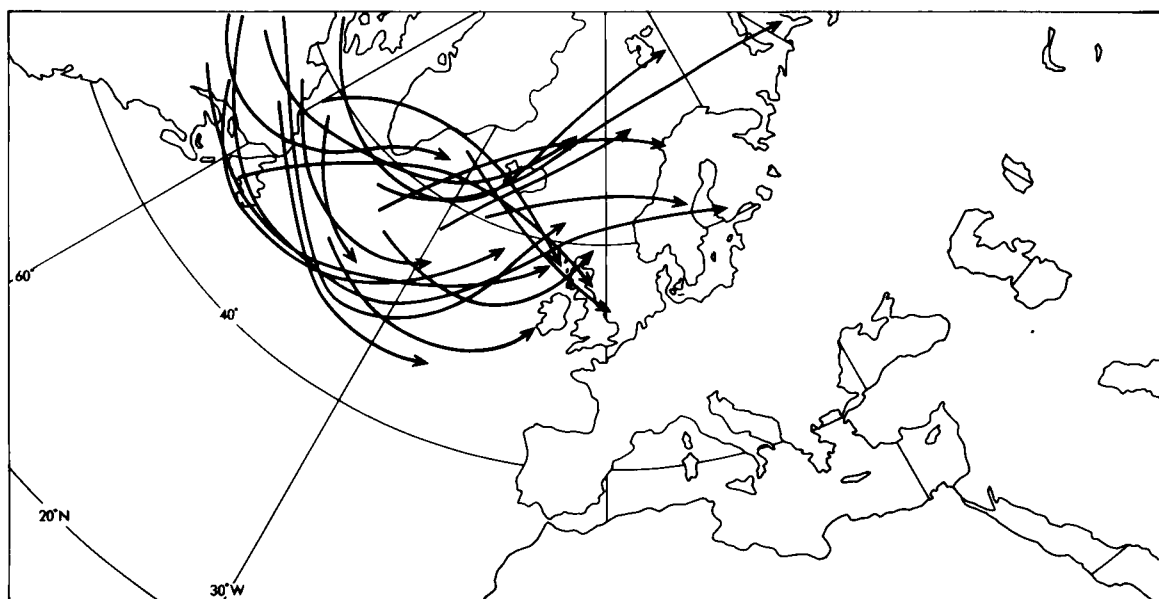


Figure 3. Average positions of mid-troposphere jet streams and their directions of flow for most five-day periods in summer 1976.

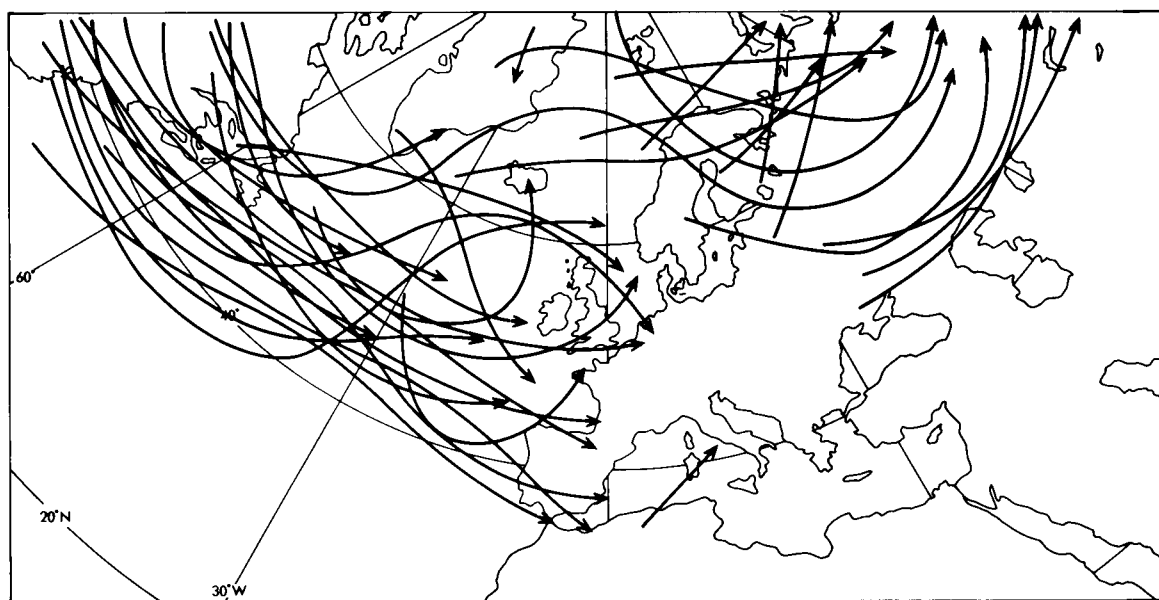


Figure 4. Average positions of mid-troposphere jet streams and their directions of flow for most five-day periods in autumn 1976.

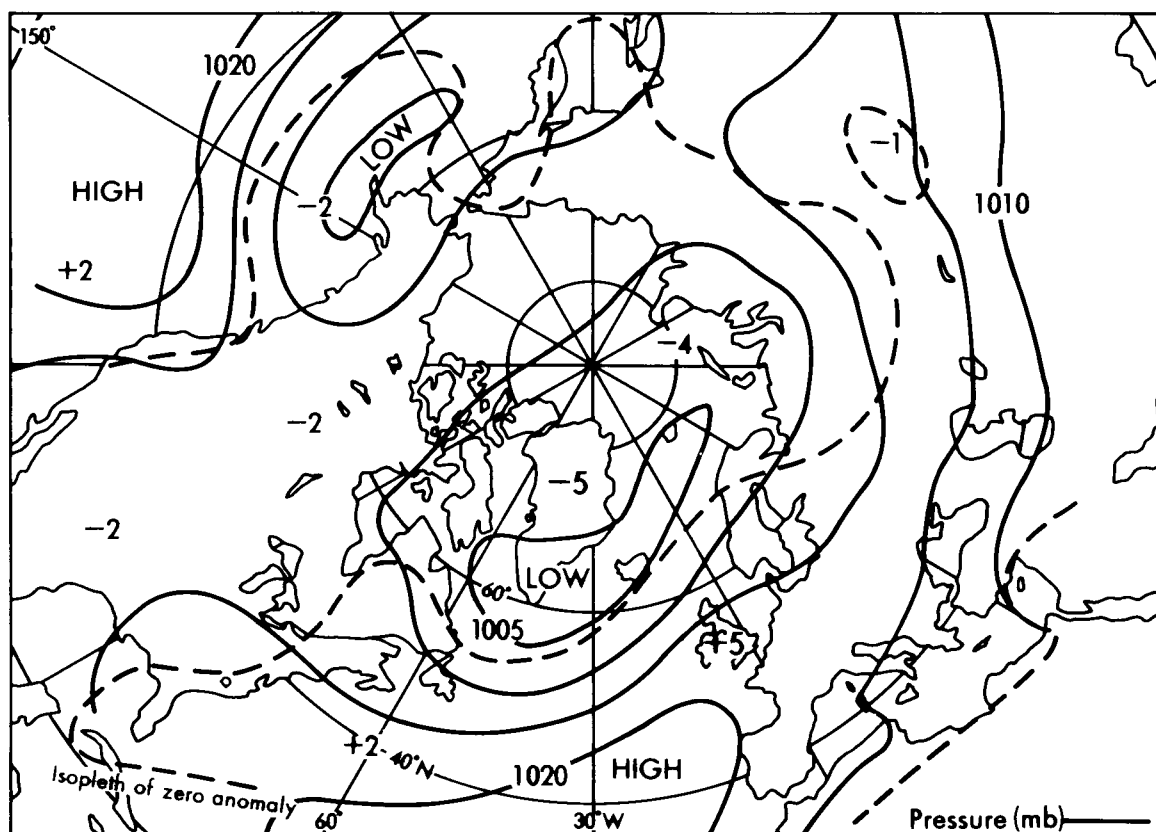


Figure 5. Average pressure (mb) at mean sea level and its most prominent anomalies from 1951-70 average, May 1975-August 1976.

period; the positive and negative anomalies near England and Greenland respectively are both exceptional being about three standard deviations (3σ) from average. The 500 mb geopotential anomalies were similarly placed so that, curiously, 1000-500 mb thicknesses were generally near average (see also section 5.1). Other exceptionally long 'spells' affecting the UK include the 1921 drought and the 1878-80 cold spell, both of surprising persistence and intensity.

A general discussion of long 'spells' is given in Lamb (1972).

4. A problem of interpretation

Many problems can arise in interpreting the unusualness or extent of weather anomalies from climatic data*. The variability of weather elements is difficult to define uniquely, as variabilities in time and space are intimately related. The problems mainly arise because variations at one point do not have the same amplitude or even phase, if sufficiently distant, as those at other points (Rodriguez-Iturbe and Mejia 1974 give a mathematical discussion for rainfall). Figs 6 and 7 give examples of the variation of the

*The word 'anomaly' is used in this paper to describe deviations of weather elements from their average at a given time of the year; the paper is mainly concerned with North Atlantic and north-west European area anomalies.

correlation coefficient (r) with distance, Fig. 6 for monthly summer rainfall at Kew with monthly summer rainfall at other points over EW and Fig. 7 in graphical form for temperatures averaged over about 2.2, 3.4 and 5 years between a number of stations distributed over Europe, adapted from Schönwiese (1979). Note the difference of space scale between the two examples for a given value of r ; monthly rainfall in summer over EW is much more poorly correlated at a given distance than is temperature over Europe when averaged over a few years. These diagrams also reflect the fact that the statistical structure of anomalies at points differs considerably from that over large areas. For example the $\pm 3\sigma$ anomalies in Fig. 5, which may each be expected to occur about once every 300 years on average (described as a 'return period' of 300 years), invite the question — climatic change? The perspective alters when it is realised that a $\pm 3\sigma$ point anomaly of surface pressure average over a year, for example, is likely to occur somewhere almost every year (Miles 1977).

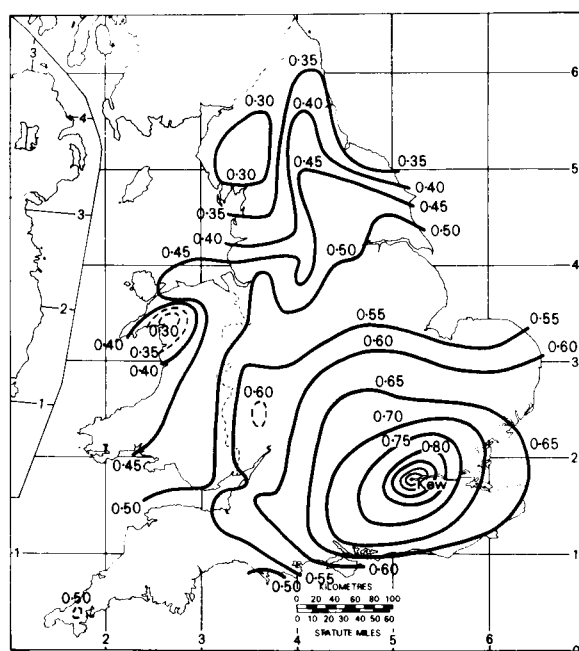


Figure 6. Correlation coefficient of monthly rainfall with that at Kew; summers 1911-70. Mean of June, July and August.

5. Two case studies

5.1 1975-76 drought (May 1975-August 1976, introduced in sections 3 and 4)

Fig. 8(a) shows that the 1975-76 drought covered much of western Europe (Fig. 8(a) actually covers October 1975-July 1976). Ratcliffe (1977) and Ratcliffe and Morris (1976) noted that the 500 mb mean jet stream near the UK appeared to move fairly steadily northwards between summer 1974 and summer 1976 (Fig. 8(b)). They considered that the northward movement may have been aided by a steady northwards and westwards recession (at a given season) of sea ice near east Greenland (Fig. 8(b)) that commenced after 1969. The recession was thought to be related to unusually stormy conditions in that region during the 'westerly' winters of 1971/72 to 1974/75 (mentioned in section 3). They suggested that the jet stream would tend to be moved northwards and westwards with the ice edge as a result of the

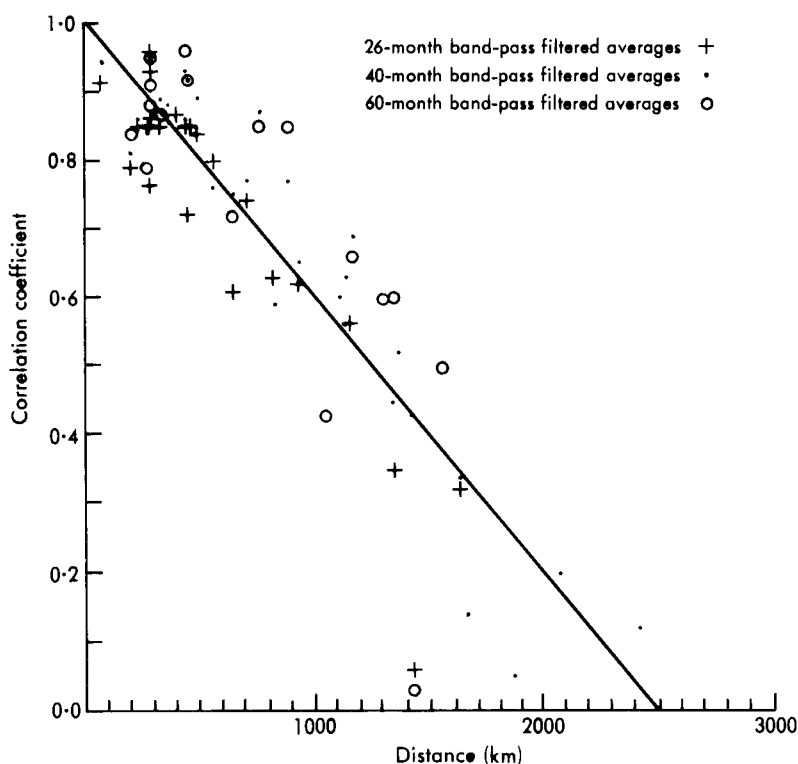


Figure 7. Inter-correlation of station temperatures measured in Europe for three averaging periods: 26 months, 40 months and 5 years.

accompanying movement of the strong (near surface) thermal gradient. Also noted was a sharp decline in Pacific sea surface temperatures (SST) north of 40°N and west of 150°E relative to those temperatures further south in most months from late 1974 to late 1976. The 1000–500 mb thickness gradient in mid-Pacific near 45°N was enhanced (at least in association) and 500 mb mid-Pacific zonal flow averaged 20% above normal during the drought period. Northern Hemisphere summers with noticeably strengthened 500 mb flow and those with weakened flow in this region were compared; on average the former were considerably drier and more anticyclonic over England and Wales. Similar effects were noted in winter; a study of the historical records indicated that anticyclonic tendencies were also strengthened in the presence of a stronger than normal east Canadian trough, as was observed in winter 1975/76. The generally westerly phase of the stratospheric quasi-biennial oscillation during the drought, at least until spring 1976, was also considered important in helping to maintain the east Atlantic jet stream in a northerly position (Parker 1982). Other factors were also considered (see Ratcliffe 1977). By summer 1976 some of the postulated influencing factors were waning or had disappeared; the persistence and great heat of the drought in the summer of 1976 was ascribed to anomalously efficient conversion of solar radiation to sensible heat as little evaporation would occur over the dry ground, so maintaining a strong local thermal ridge over western Europe. Finally at the end of the summer, with a decline in local solar heating, it was thought that the now altered hemispherical influencing factors forced a sudden change in the position of the jet southwards, so the drought ended very abruptly. These associations or ‘teleconnections’ have yet to be confirmed.

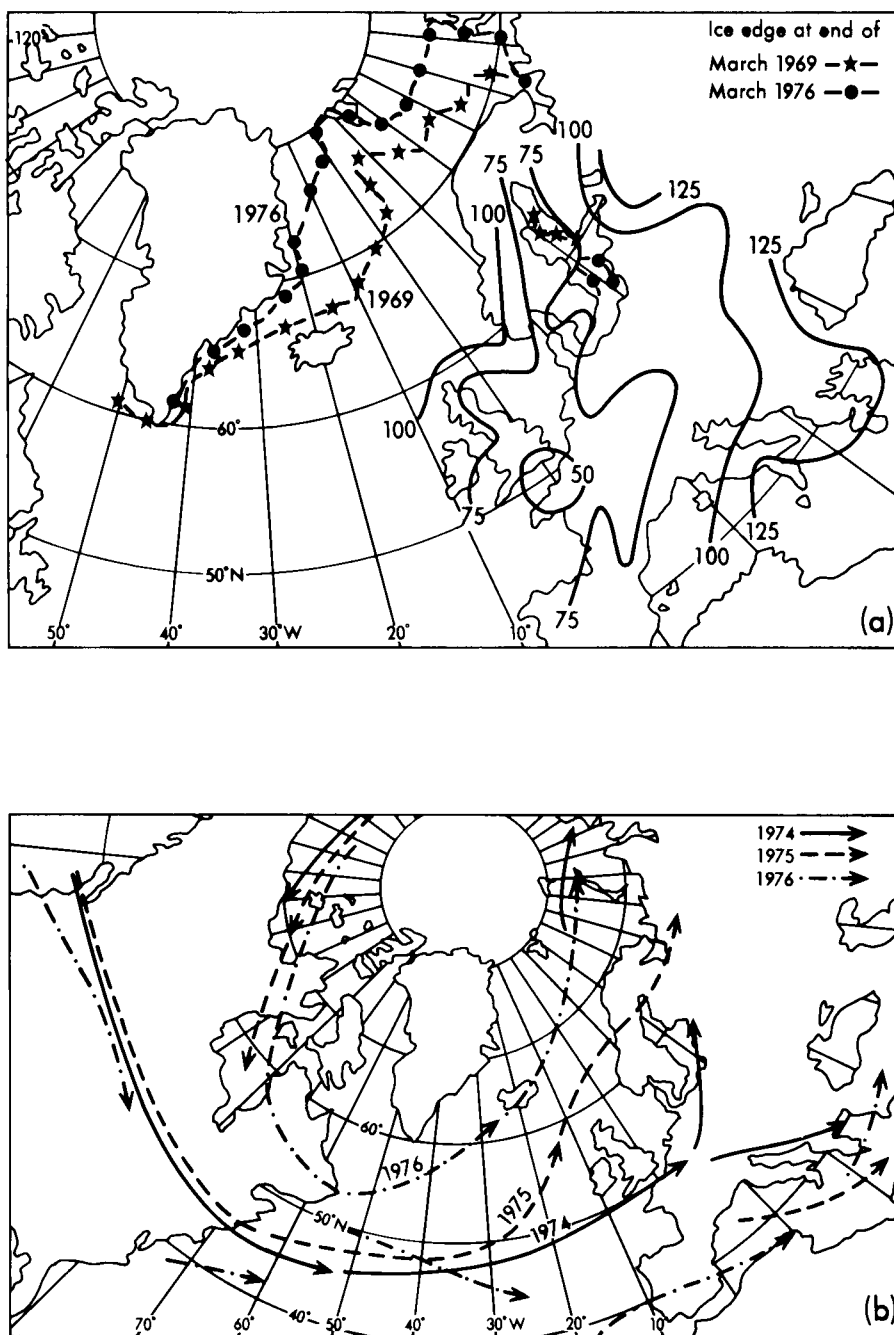


Figure 8. (a) Rainfall expressed as percentage of long term average in Europe, October 1975–July 1976, and position of ice edge March 1969 and March 1976. (After Ratcliffe and Morris 1976).

(b) The average position of the jet stream in the middle troposphere in July and August in the successive years 1974–76.

A similar, briefer, drought occurred in the period from August to November 1978 (Bader and Warrilow 1979). This drought also ended abruptly and was followed by a wet, cold winter with the jet stream again returning to a southerly position. Fig. 9 shows the positions of jet streams during autumn 1978, the size of the positive surface pressure anomaly and the area it covered, and the extent of the drought. The return period of the rainfall deficiency (average expected time, deduced from past records,

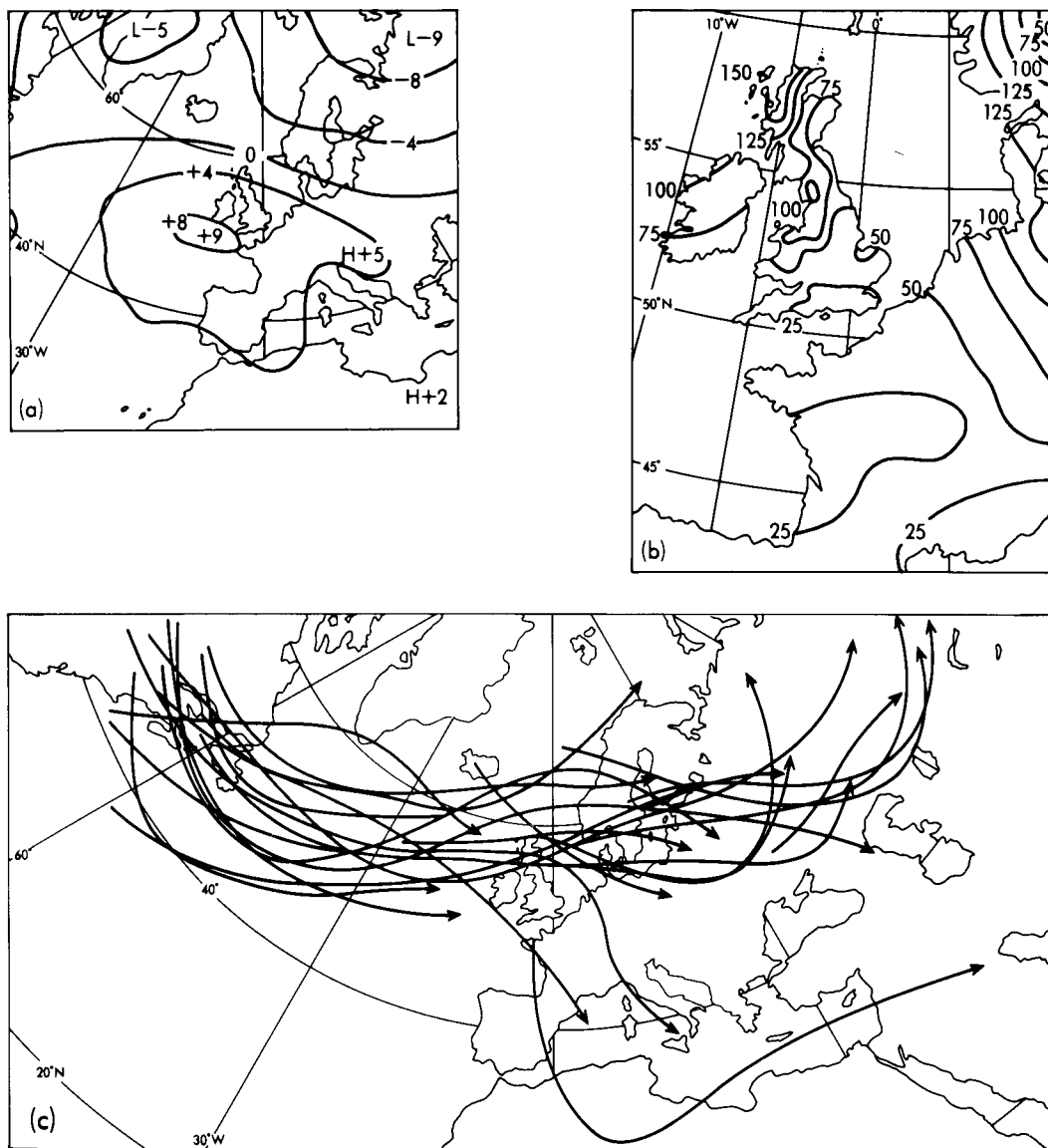


Figure 9. (a) Average pressure anomaly (mb) at mean sea level, September–November 1978. (Anomalies from 1951–70 averages.) (b) Total rainfall, expressed as a percentage of average September–November 1978. (Averaging period mainly 1931–60.) (c) Average positions of mid-troposphere jet streams and their directions of flow for most five-day periods in September–November 1978.

between rainfall deficiencies as or more severe than that under study) and its severe effect on the volume of two reservoirs in south-west England is shown in Fig. 10. This quite severe drought caused much concern to water engineers as it occurred so soon after the apparently very rare 1975–76 drought.

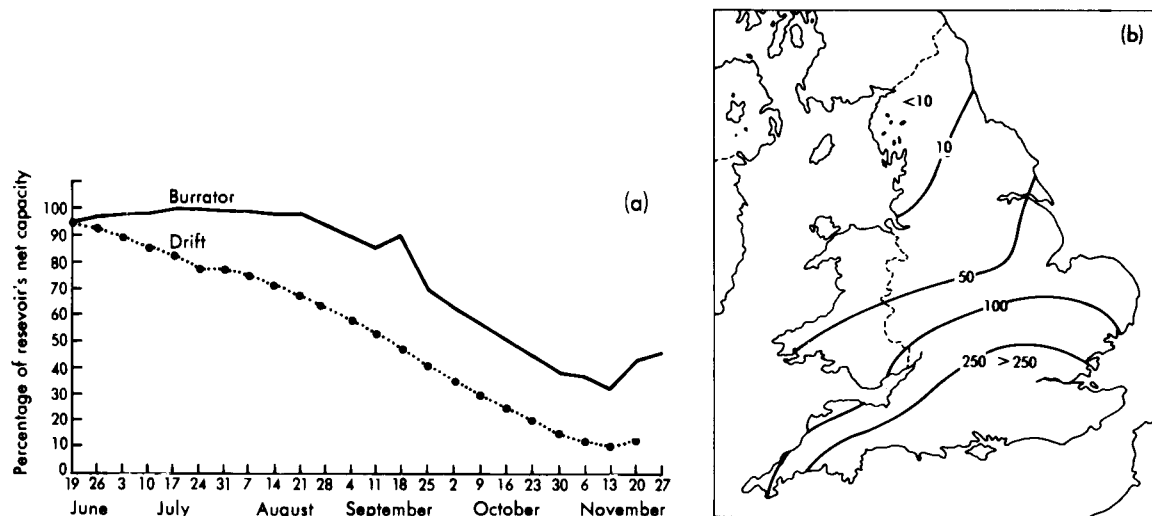


Figure 10. (a) The change in the volume of water in two reservoirs in south-west England, June–November 1978, measured as a percentage of the reservoir capacities.

(b) Autumn 1978 rainfall return periods (years) for England and Wales.

5.2 1962/63 winter: a case study involving the test of a hypothesis

Following on from previous work and, for example, the general ideas of Sawyer (1965), Rowntree (1976(b)) tested a hypothesis that widespread anomalously warm SST in the tropical North Atlantic helped to maintain the blocked, cold 1962/63 winter over the UK. Work using general circulation models had suggested that warm SST in the tropical North Pacific affected the winter-time mid-latitude Pacific atmospheric circulation (Rowntree 1972). Furthermore, in idealized numerical experiments on 'tropical forcing' Rowntree (1976(a)) confirmed the general possibility of such mid-latitude circulation effects, for example as a result of anomalous warmth or coldness in the tropical oceans, though significant forcing may be confined largely to the winter half-year. At this time of year the mid-latitude westerly circulation at upper levels often reaches as far south as latitude 15°N, above the trade winds. Rowntree noted that a wide expanse of the North Atlantic ocean surface waters between West Africa and South America was over 1 °C above average in January 1963 (area marked on Figs 11(a), (b) and (c)) with a maximum anomaly of 2.8 °C close to the West African coast near 17°N. These anomalies had mostly formed in Autumn 1962, before the winter circulation developed. The results of three pairs of experiments with and without the anomaly are shown in Figs 11(a), (b) and (c). Experiment 1 started from an isothermal atmosphere while experiments 2 and 3 started from real data, 29 December 1965, and differ only in model details. The results differ markedly, though experiments 2 and 3, especially, are in broad agreement. All experiment pairs show a maximum fall of pressure centred about 40° (experiment 1) or 25° (experiments 2 and 3) north of the anomaly. Experiments 2 and 3 show marked pressure rises near 60–70°N. In experiments 2 and 3, an easterly wind anomaly is evident near 60°N extending southwards over England though the observed anomalies implied by Fig. 1(a) are larger.

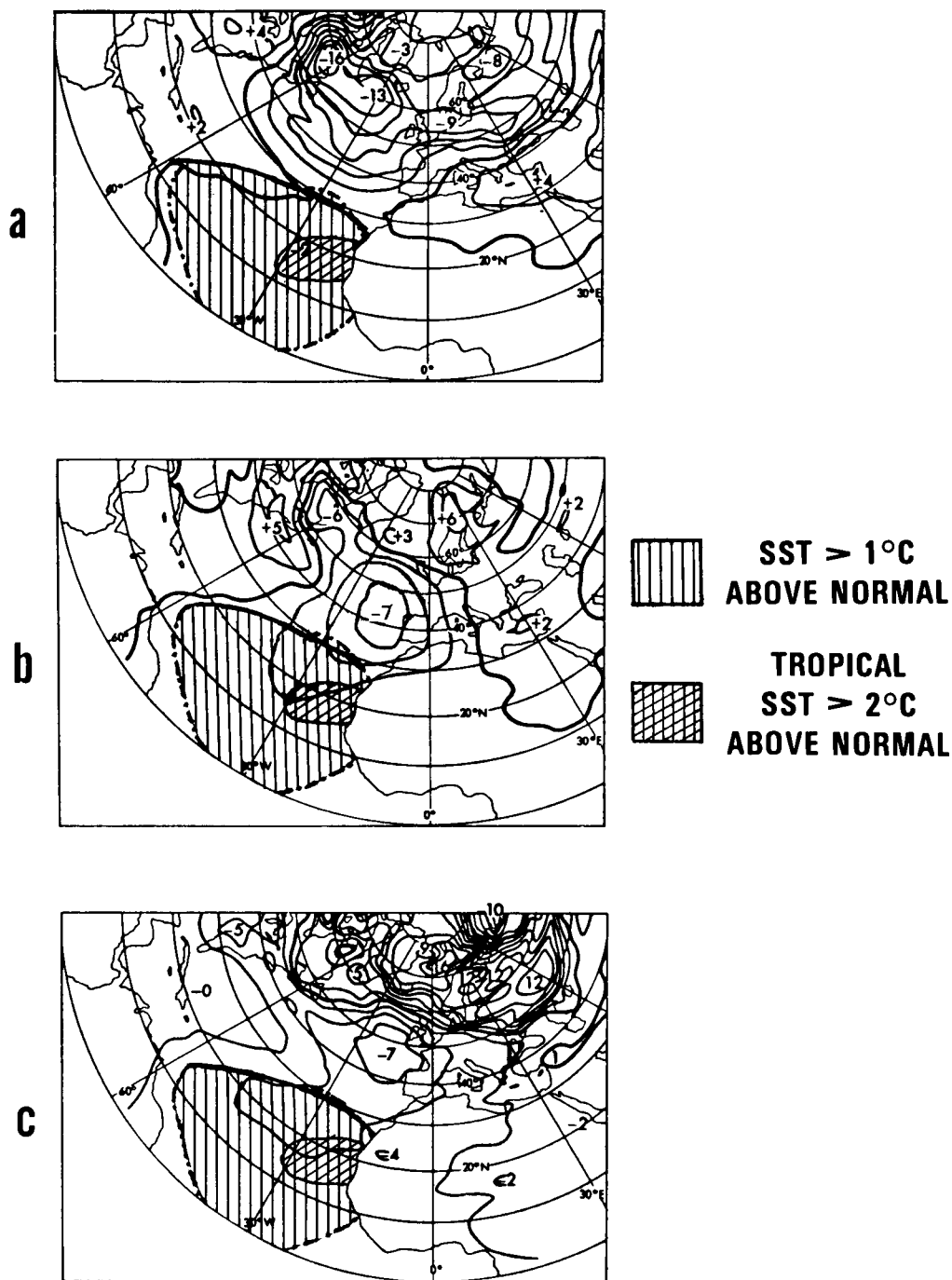


Figure 11. Difference in mean surface pressure (mb) averaged over days 41-80 of model integrations between surface pressure obtained with tropical Atlantic warming and the control experiment without the warming. (a) experiment 1 using isothermal initial data, (b) experiment 2 using initial real data, and (c) experiment 3 also using initial real data. Both (b) and (c) use initial data for 29 December 1965. SST averages taken from US Naval Oceanographic Office data.

The fall of pressure well north of the SST anomaly and the rise further north still could be regarded as manifestations of a forced standing wave in the meridional direction; model results (and the real data) showed that this wave-like effect extended high into the troposphere. Observed surface pressure data for the ten winters associated with the highest air temperatures at Mindelo, Cape Verde Islands (17°N, 25°W) and the ten winters with the lowest air temperature at Mindelo in the period from 1921–22 to 1969–70 were compared to the mean for the same period. Winter air temperature and sea temperature at Mindelo were thought to be well-correlated so the coldest winters at Mindelo should correspond to the coldest SST values and warmest winters to the warmest SST values. The average of the warm SST years gives a pressure anomaly pattern consistent with that of the 1962/63 winter though the pattern is much weaker (Fig. 12(a)). The average of the cold years gives an almost exactly reversed pattern in the North Atlantic (Fig. 12(b)), though it is again weak. This case study indicates the promise of the complementary use of modelling and observational studies, even though the results require further confirmation.

6. Superimposed chart analysis (SCA) and superposed epoch analysis (SEA)

SCA (sometimes called composite chart analysis) is illustrated by Rowntree's construction, discussed above, of two surface pressure anomaly charts each representing the average of winters selected according to their SST at Mindelo. In general SCA involves identifying and averaging one or more classes of fields of a variable selected according to their association with 'key' conditions. Differences between, and the consistency of, the data making up the composite charts can be studied. A related method is known as superposed epoch analysis, terminology usually reserved for analyses of recurrence tendencies in time series. Terms of the time series are classified according to the time elapsed since the occurrence of a key condition which recurs through the time series. The terms in each class are then averaged. The dates of the key conditions are called 'key dates'. Hypotheses are sometimes directly generated by the results of SEA or SCA. In Rowntree's analysis on the other hand SCA was used to support an independently arrived at hypothesis. However, in another well-known analysis by Ratcliffe and Murray (1970) SCA was essentially used to generate an 'a posteriori' hypothesis. Values of monthly mean-sea-level pressure over the North Atlantic and western Europe associated with monthly mean SST in an area near Newfoundland in the previous month were calculated and the result used to provide a long-range forecasting tool. The key conditions were the sign of the SST anomaly and the name of the calendar month of the year, giving a total of 24 SCA patterns. Difficulties can arise both with the assessment of the statistical reality of such results and with the objective selection of key conditions. Korevaar (1982) discusses, critically, difficulties encountered with objectively identifying SST patterns for use as key conditions in a subsequent extension by Ratcliffe of this work. Haurwitz and Brier (1981) provide a balanced critical discussion of the use of SEA, concentrating on a specific example of its use. Nevertheless, SEA and SCA can be valuable methods of exploratory analysis, well-illustrated together in a recent study by Rasmusson and Carpenter (1982) of variations in atmospheric wind circulation associated with different phases of the Southern Oscillation.

7. Time-series analysis

The full range of available time series techniques has perhaps hardly been used in meteorology. Meteorological time series are typically 'noisy'; nevertheless, a simple plot of the data against time is often useful and may be revealing. Fig. 13 shows a time series providing unexpected information. The largest 2-hour duration rainfalls (Jenkinson 1975, p. 31) recorded in each year (these would all be convective storms) were calculated for 22 stations in south-east England for a 20-year period, the 22

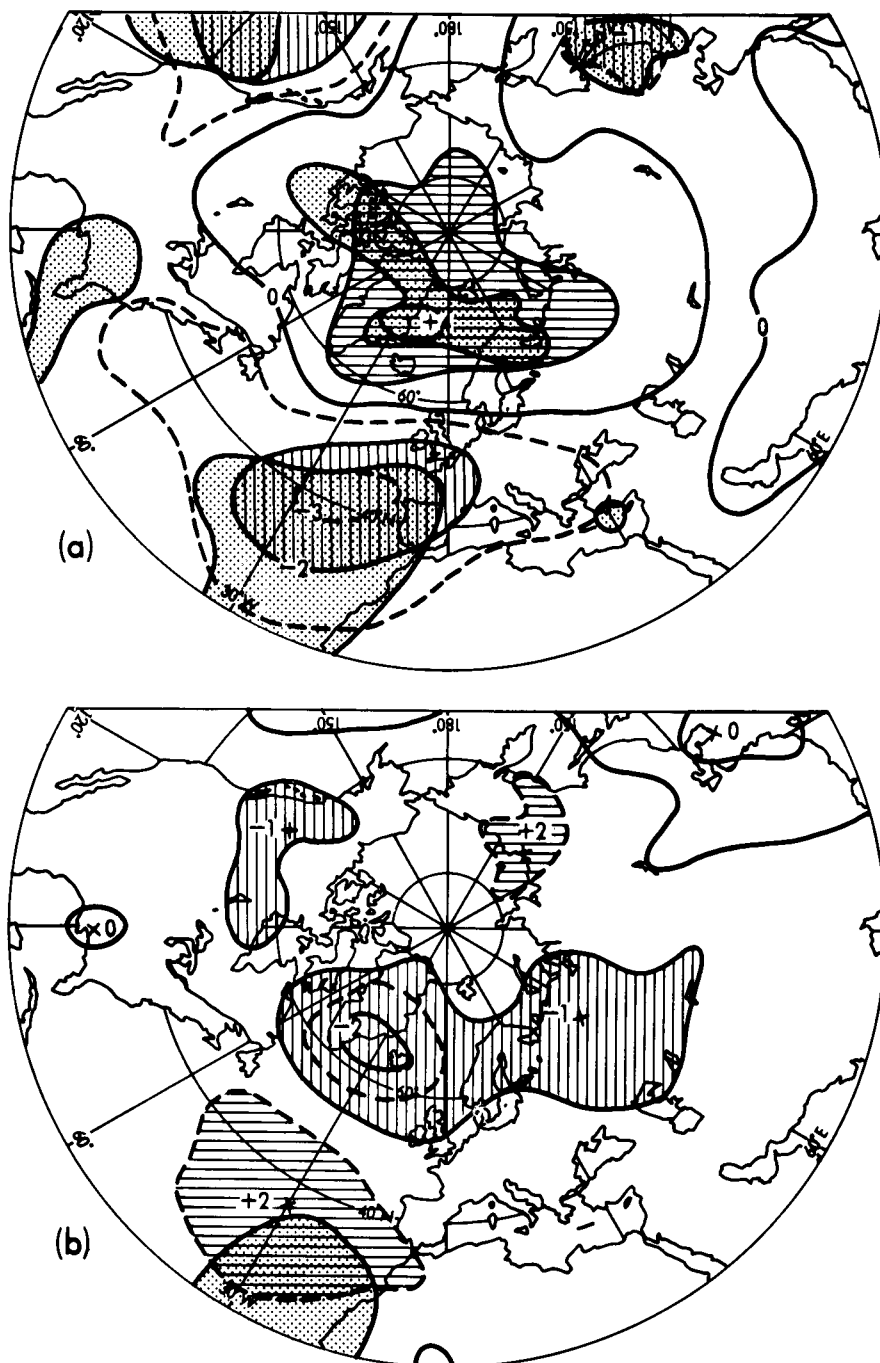


Figure 12. Average winter (December–February) pressure anomalies (mb) at mean sea level relative to 1921–22 to 1969–70 for (a) ten winters with highest air temperatures (b) ten winters with lowest air temperatures at Mindelo, Cape Verde Islands. Areas significant at 5% confidence level (Welch test) are stippled.

values observed in a given year were averaged and the averages plotted as a percentage of their median value as shown in Fig. 13. The time series is surprisingly well correlated from one year to the next for such an apparently transient phenomenon. Rainfalls of this type are of especial practical interest to urban drainage design engineers. (See section 8.2.)

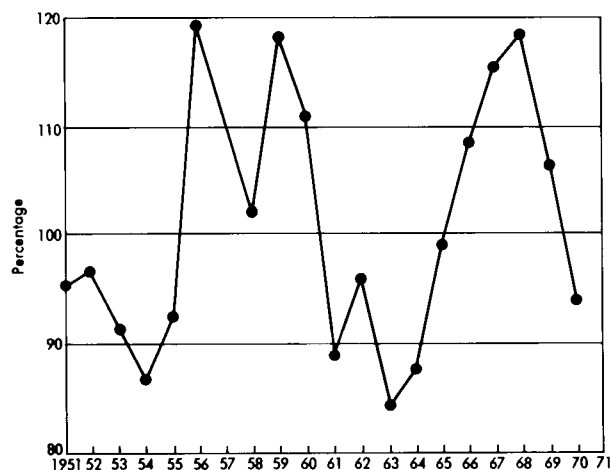


Figure 13. Two-hour annual maximum rainfall as a percentage of its median value for 22 stations in south-east England over a 20-year period.

More complex analyses are often needed. Power-spectrum analysis is one type where variation of a data series in time, for example the series of annual Central England Temperature (CET) 1659–1980 based on Manley (1974), is converted to variations of the data according to their frequency or wavelength. Cyclical or 'quasi-cyclical' recurrences can be identified; Fig. 14 shows a power spectrum of annual CET (Mason 1976). Wavelength near 2.1–2.4 years, 23 years and 90 years are particularly prominent. Such spectra can however be misleading; annual CET spectra calculated for independent, shorter periods show substantial variations. Filtering analysis is a way of studying the variations of data of a particular wavelength (frequency) range through time. Fig. 15 shows a study of the '23-year' wavelength filtered series of annual CET, where variations at and near this wavelength have been isolated. The amplitude of the series has varied greatly although the progressive decline with time of its amplitude may not indicate purely 'random' behaviour. Also shown is the lack of consistency of phase between these CET fluctuations and the 'Hale' or double-sunspot cycle often associated with climatic variability on this wavelength.

Many other forms of time-series analysis are used in meteorology, for example, the system mainly due to Box and Jenkins. See Gray (1976) for references and an application of these techniques.

It may be more valuable to study the time variation of whole fields of variables. A pioneering study was that of Sawyer (1970) who investigated the time variation of Northern Hemisphere 500 mb, 1000–500 mb thickness and surface pressure fields using filters. He contrasted the spatial behaviour of these parameters on synoptic or near synoptic time-scales (generally less than 15 days) and 'long-range forecast' time-scales (about 20–60 days). He found the ratio of the root-mean-square (r.m.s) 500 mb geopotential on the 20-day to 60-day time-scale to that on the synoptic and near synoptic time-scales was surprisingly large in some areas and spatially very variable, though Sawyer's investigation was limited to

a few years of data. Fig. 16 shows the results for the period 1961–63, where all seasons have been analysed together. A high ratio of r.m.s. variation on the 20-day to 60-day time-scale to that on the shorter time-scale is noticeable near UK. He also found a generally higher correlation between 500 mb geopotential, 1000–500 mb thickness and surface pressure anomalies on the 20-day to 60-day time-scale than the synoptic and near synoptic time-scales. Recently other workers have extended these analyses and show, for example, very high correlations between 500 mb geopotential variations and surface pressure variations over the north-east Pacific and north-east Atlantic on time-scales of about one month (e.g. Blackmon et al. 1979).

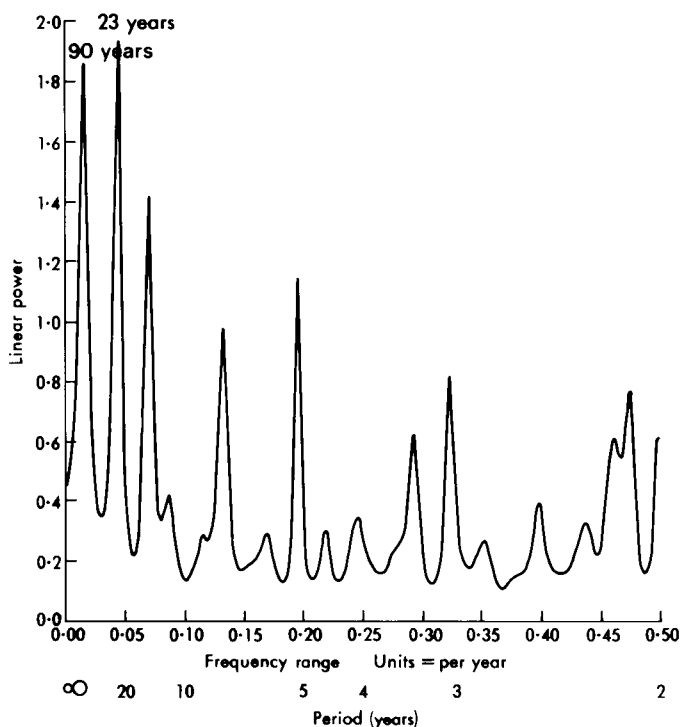


Figure 14. Maximum entropy power spectrum of Central England Temperature 1659–1974.

8. Practical application of studies of the probability or frequency of climatic events

Much of the application of climatic data to engineering and agricultural problems has involved this type of analysis. The numerical values from past data of a climatic variable are ranked and the return periods of the values, especially very large or very small values, are assessed for planning purposes.

8.1 Long duration rainfall — droughts and prolonged wet spells

Tabony (1977) provides a very detailed statistical model and computer programs (available in the Meteorological Office) for estimating the return periods of rainfall amounts in any one month up to any five-year period for any place or area in the United Kingdom. Fig. 17 illustrates a typical result from the

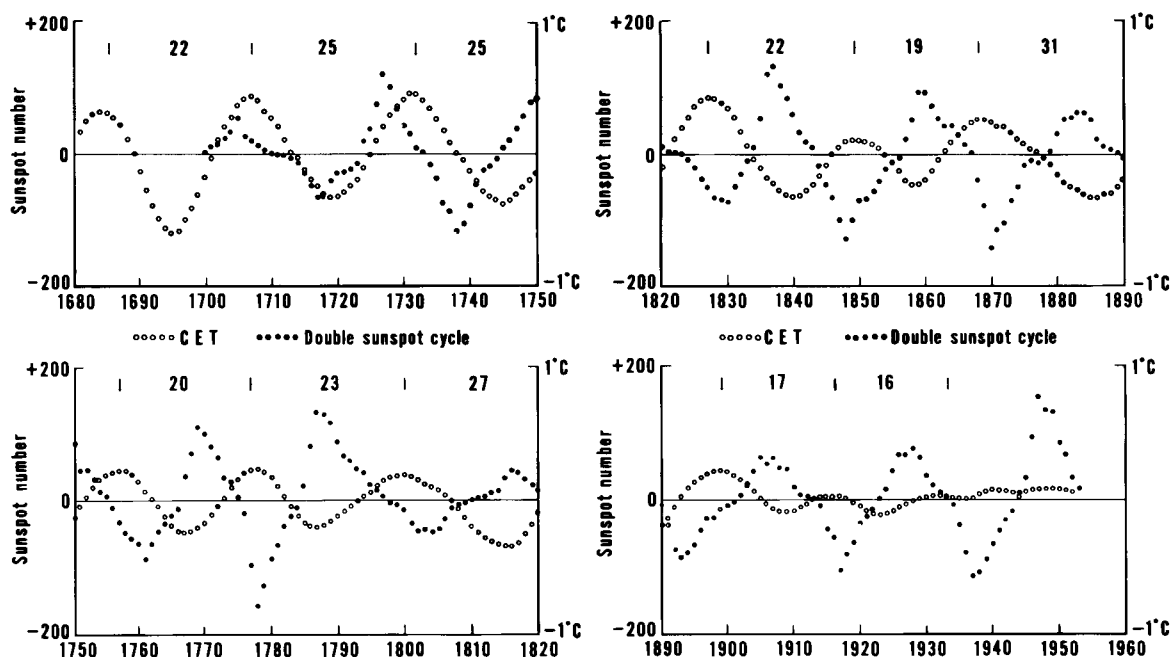


Figure 15. The '23-year' wavelength band-pass filtered series of annual mean Central England Temperature and the 'Hale' or double-sunspot cycle.

model and some of the problems concerning the mutual interaction of the spatial and time-scales of climatic 'events' which have to be considered for practical purposes. (See section 4 for an initial discussion). The pronounced geographical variation in the behaviour of rainfall may be reduced by expressing rainfall observed on a given time-scale as a percentage of its average value on that time-scale. For example, one month 'point', 'any rain-gauge' EW rainfall, has a markedly different frequency distribution from a series representing EW as a whole. Very rare dry events are drier at any point than events of equal rarity over EW as a whole while very wet events are wetter. This effect is less pronounced for events measured over longer time intervals and more pronounced over shorter time intervals. This difference of behaviour with varying time-scale reflects variations of the spatial correlation of rainfall; one-month rainfall is less well correlated at a given distance (it is more variable) than is 12-month rainfall, but it is better correlated than daily rainfall. The fact that point rainfall anywhere in EW having a 20-year return period tends to have a similar percentage of average value (the y-axis in Fig. 17) as 100-year rainfall over EW as a whole suggests that locally very dry areas will almost always be accompanied by much wetter areas elsewhere in EW. Thus the ability during droughts to transfer water over considerable distances within the area of EW could be valuable. The ratio of point to areal rainfall for a specified return period is often called the areal reduction factor, but better perhaps the areal adjustment factor (Folland, Kelway and Warrilow 1981).

8.2 Very heavy short duration rainfall

Fig. 18 shows a typical example of the shape of the frequency distributions for very heavy rainfall for several short durations, taken from the extensive work of Jenkinson (1975). This type of information is

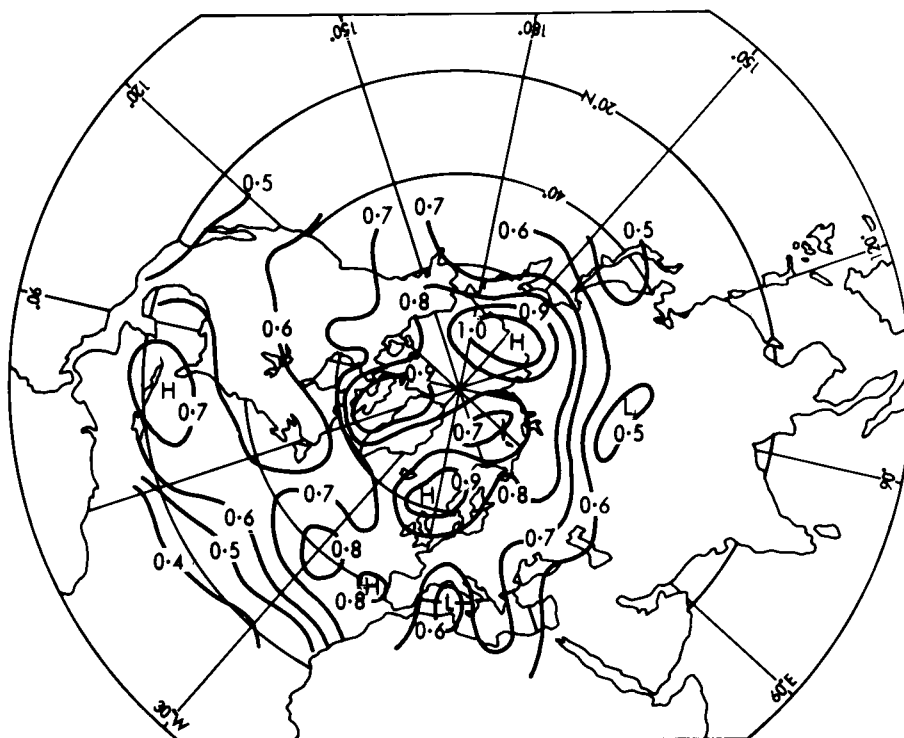


Figure 16. Ratio of root-mean-square amplitude of approximately 20-day to 60-day 500 mb geopotential fluctuations to root-mean-square amplitude on time-scales less than about 20 days; 1961-63.

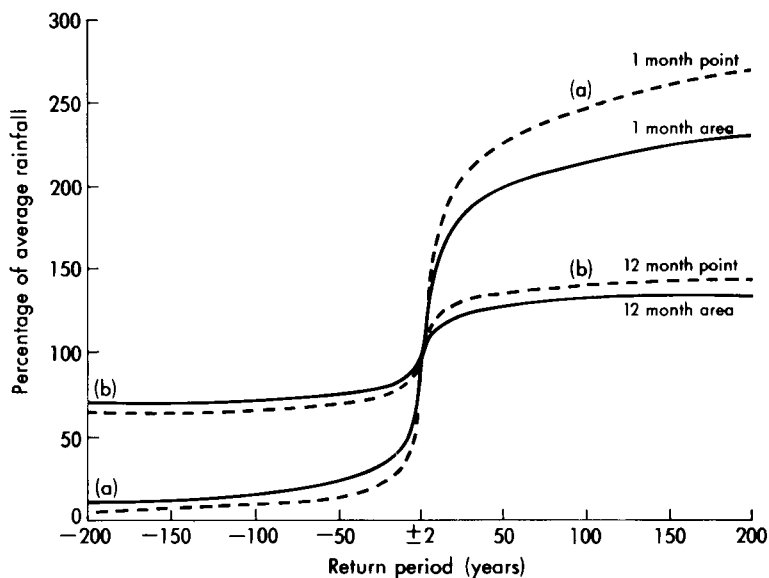


Figure 17. Percentage of average rainfall corresponding to various return periods for durations of 1 month and 12 months. Point curve for typical point in England and Wales; areal curve for England and Wales as a whole. Negative return periods represent deficiencies and positive return periods represent excesses. ± 2 represents a 50% chance of a wetter or a drier year.

used in dam, river flood protection, see *Flood Studies Report Volume I* (Natural Environment Research Council 1975) and sewer design for shortest durations, (see for example National Water Council 1981).

As can be seen from Fig. 18, short duration rainfall does not appear to converge to a maximum value as the return period becomes extremely large as might be expected on physical grounds. Most other variables for which long enough records are available do tend to converge toward a maximum, for example maximum daily temperature, whose value depends on the locality. Estimates of maximum possible rainfall are crucial in modern dam design where safety is the overriding factor; maxima are in fact estimated through the use of very simplified physical models. These difficulties of estimating statistically extreme rainfall have recently received attention (Warrilow in published discussion of the paper by Folland, Kelway and Warrilow (1981), same volume). It seems now that a key problem in the statistical calculations lies in a systematic change with return period in the average speed of movement of the rarer (convective) storms that contribute to the right-hand side of the curves in Fig. 18. Short duration heavy rain storms generally last considerably longer in the moving frame of reference of the rain storm than at an observing station rain-gauge, but it is likely that the heaviest rainfall totals measured by rain-gauges tend to result from the most slow-moving storms. A marked correlation between the speed of short-duration storms and measured rainfall is likely to violate seriously the assumptions underlying the extreme value analysis algorithms usually applied to short-duration heavy rainfalls. This aspect of the statistical interpretation of extreme climate data may be pertinent to the analysis of other meteorological phenomena.

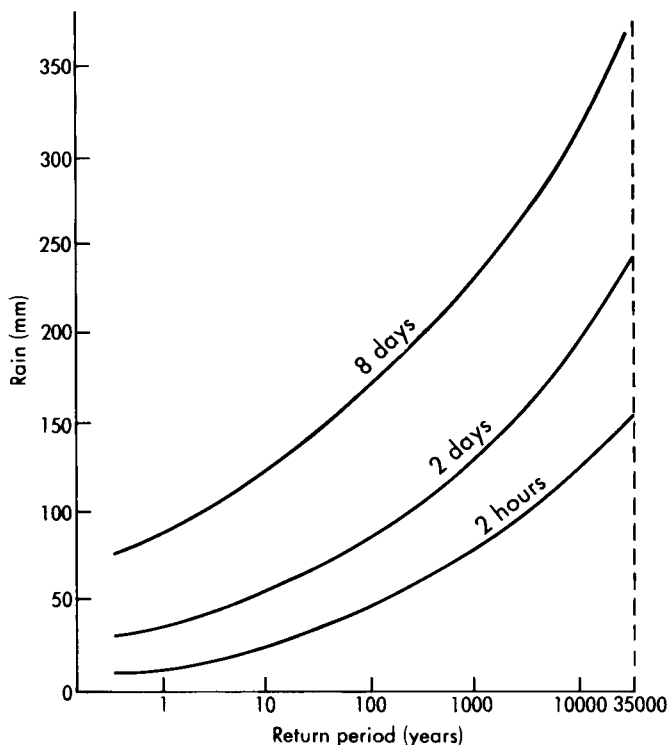


Figure 18. Typical relationship between rainfall total and return period at a point (south-east England).

8.3 An agricultural application

A contrasting application of climatic frequency data is shown in Fig. 19. Maize, a tropical grass, provides a very good source of winter cattle feed ('silage') but the climate of England and Wales is marginal to its success. Fig. 19 shows the percentage of years that a particular, very economic, form of silage can be successfully made from maize. In areas where more than two bad years in ten are likely to occur it may often not be economic to grow maize.

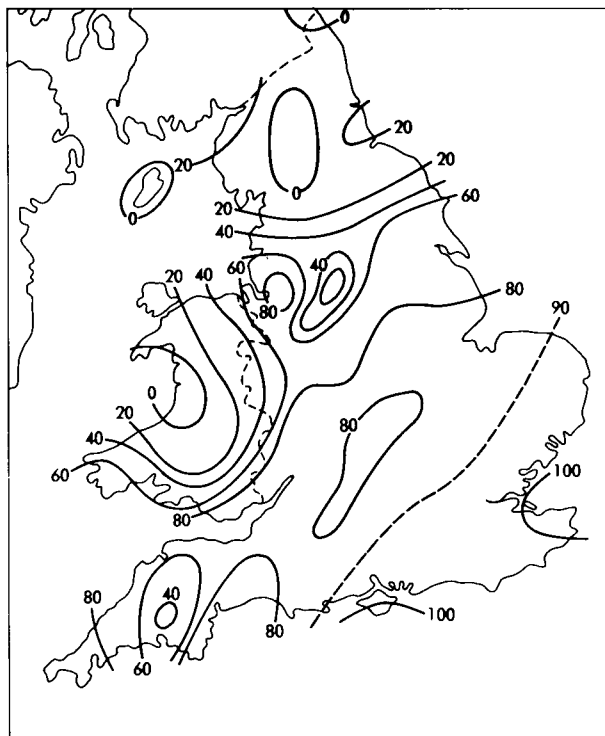


Figure 19. Percentage of years suitable for making Tower Silage from maize in England, Wales and the Isle of Man. (From Hough 1978.)

9. Conclusions

Prospects may soon improve for developing concepts about regional short-period climatic variability. Besides the greatly improved capability for integrating numerical atmospheric models, diagnostic data which allow daily atmospheric budgets of heat, moisture, momentum and radiation to be continuously monitored are becoming routinely available. The task is very challenging; long-range forecasting especially may depend for its development on some success in this field. The following words written a long time ago perhaps still apply:

Our knowledge of the properties of the atmosphere would therefore become of the highest utility to mankind, could the varieties of season, or recurrence of sudden changes of weather, be readily prognosticated. But this investigation is so intimately connected with circumstances which influence different climates, that a general table of prognostics can only be completed by the united labours and experience of the learned in every country.

Robertson (1808)

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Documentation of a Southern Oscillation index

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Summary

Monthly and seasonal values of the difference of mean-sea-level pressure between Tahiti (18 °S, 150 °W) and Darwin (12 °S, 131°E) are presented for the period from January 1935 to March 1983. A slight adjustment has been incorporated in order to take account of a change of observing time at Darwin. Extreme values of the pressure difference occurred from June 1982 onwards in association with anomalous behaviour of other elements of the Southern Oscillation.

1. Introduction

This paper attempts to satisfy the need for a tabulation of a Southern Oscillation index that is simple enough to be updated readily by any user. The mean-sea-level pressure-field index given by Wright (1977), although reliable, is not easily updated because it is based on principal component analysis. Similarly, areally-measured sea surface temperatures (Rasmusson and Carpenter 1982) and winds (Wyrtki 1980) are not simple to update and may also be analysis-dependent in data-sparse areas. Rainfall at Pacific islands may include local topographically forced components. The requirement for a simple but reliable index appears to be met best by the index recommended by Chen (1982) for diagnostic studies: Tahiti minus Darwin mean-sea-level pressure. The index is available throughout the period during which the Southern Oscillation can be studied most comprehensively, i.e. the period since the commencement of upper-air data, but for events before the opening of the Tahiti station in 1935, another index, such as Wright's (1977), must be used.

2. Tabulation and quality control of the monthly index

Monthly values of the difference in mean-sea-level pressure, Tahiti minus Darwin, are given in Table I for 1935 (the earliest year for which Tahiti data are available) to 1983 (March).

The sources of data were a magnetic tape from the USA National Climate Center, Asheville, NC up to December 1976, and CLIMAT monthly messages received at Bracknell over the Global Telecommunication System thereafter. CLIMAT messages were also used to fill in for the following data missing from the magnetic tape:

Tahiti: August and December 1961, and December 1974

Darwin: November 1961.

Australian annals were used to supply the following missing data:

Darwin: March, October and November 1973.

Two other values were missing: Darwin December 1974 and December 1976. The latter was filled by assuming a deviation from normal consistent with surrounding stations plotted on a routine monthly chart of mean-sea-level pressure anomalies. The former could not be filled in this way because the data for the entire Northern Territory of Australia were missing, probably as a result of the dislocation to communications caused by the tropical cyclone that struck Darwin in late December 1974. Therefore the value taken was the December normal plus the average of the deviation from normal of November 1974 and January 1975; the reliability of this procedure is open to question in view of the unusual nature of December 1974 with its tropical cyclone, but the seasonal mean (December to February) will be less seriously affected.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1935	5.6	3.4	6.0	2.5	0.6	0.7	0.7	1.8	3.2	3.9	3.3	2.5
1936	3.8	4.5	4.1	4.9	2.0	0.8	1.4	0.1	2.6	2.7	0.6	3.4
1937	6.2	3.3	4.9	2.4	1.4	1.4	-0.1	2.0	2.1	2.3	2.4	4.6
1938	5.8	5.1	3.1	2.6	3.1	3.2	3.6	3.5	3.4	4.8	3.0	6.0
1939	7.8	6.0	5.9	3.5	1.5	1.0	2.2	1.6	0.8	0.5	1.7	1.8
1940	4.4	3.7	2.0	1.2	-0.2	-1.2	-1.4	-1.2	-0.9	-0.1	1.9	-2.3
1941	2.4	1.3	2.0	1.0	0.8	-0.6	-2.2	-1.3	1.0	-0.4	1.5	1.8
1942	1.7	3.8	2.9	1.7	2.3	2.2	0.8	2.3	3.8	4.3	2.3	6.2
1943	6.4	6.8	4.7	4.0	2.0	0.2	1.4	2.9	3.3	4.4	3.5	1.8
1944	2.7	5.4	5.0	1.7	1.5	0.7	-0.4	2.2	2.8	1.5	1.9	4.3
1945	5.5	5.9	6.4	1.5	1.6	2.2	1.5	3.5	3.8	3.3	2.4	4.8
1946	3.9	5.5	3.6	1.2	0.2	0.0	-0.6	1.0	-0.3	0.9	2.7	2.4
1947	3.4	3.7	6.1	1.8	-0.1	1.5	2.4	2.8	4.3	2.6	4.3	4.5
1948	3.8	4.0	3.2	2.7	2.1	0.6	1.1	1.0	1.1	3.9	3.6	2.4
1949	2.9	5.0	5.0	2.5	0.9	-0.3	0.7	1.0	2.7	3.8	2.0	5.0
1950	5.5	8.2	7.2	4.3	2.6	4.5	4.2	3.6	3.5	5.7	4.8	8.0
1951	7.2	5.9	3.0	1.4	0.0	1.0	-1.1	0.8	0.4	0.9	1.6	2.1
1952	2.7	3.1	4.2	1.5	2.6	2.1	1.7	1.3	2.0	3.4	3.0	1.2
1953	4.9	3.3	2.9	2.3	-1.9	0.9	0.8	-1.0	0.1	2.8	2.5	2.6
1954	5.6	3.7	3.7	3.1	2.1	0.9	1.5	3.2	2.7	3.2	3.3	6.0
1955	3.4	7.7	4.4	1.7	3.1	3.1	3.7	3.9	4.8	5.5	5.3	5.3
1956	6.8	7.2	5.7	3.6	3.8	2.7	2.8	3.4	2.5	6.0	3.3	5.4
1957	5.5	4.1	3.6	2.4	0.0	1.0	1.2	0.3	0.7	2.8	1.2	2.9
1958	0.9	3.3	3.7	2.6	0.3	1.2	1.5	2.9	1.8	2.8	2.2	2.3
1959	2.7	1.7	5.6	3.0	2.1	0.5	0.3	1.0	2.4	3.6	4.7	5.1
1960	4.6	4.4	5.1	3.4	2.2	0.9	1.7	2.7	3.6	2.9	4.0	4.9
1961	3.9	5.9	-0.1	3.5	1.8	0.9	0.9	1.6	2.5	2.1	4.0	6.2
1962	8.0	5.4	3.5	2.3	1.2	2.0	-1.0	2.4	3.2	4.5	3.6	3.8
1963	6.0	3.3	5.1	3.1	1.9	-0.2	0.6	1.2	1.3	0.5	1.5	1.2
1964	3.7	4.3	5.3	4.0	2.5	2.1	1.8	4.0	4.7	5.1	3.3	2.9
1965	3.6	5.1	4.6	1.0	1.5	-0.3	-2.5	0.0	0.0	1.1	0.3	3.8
1966	1.9	3.8	1.5	1.6	0.5	1.3	0.9	2.4	2.0	2.5	3.0	2.8
1967	7.5	7.3	5.5	1.9	1.2	1.9	1.1	2.6	3.3	2.8	2.2	2.4
1968	5.3	6.6	3.4	2.0	3.5	2.7	2.0	1.7	1.9	2.6	2.4	3.8
1969	1.6	3.2	4.0	1.3	0.8	1.1	-0.1	1.0	0.6	1.0	2.9	4.2
1970	2.3	2.3	4.3	1.8	1.9	2.5	0.1	2.3	4.5	4.6	5.9	6.9
1971	5.0	7.9	7.5	5.1	2.8	1.5	1.2	4.0	5.0	5.8		

The tape values from 1955 to 1976 were compared with CLIMAT data as a cross-check; for earlier years, CLIMAT values were not available. The tape value for Tahiti for February 1965 was replaced by the CLIMAT value which agreed with the value in a national annal. Tape values for Darwin for October 1961, May 1972 and August 1972 were also replaced by CLIMAT values. The CLIMAT mean-sea-level values for Darwin for May and August 1972 appeared to be the correct ones in view of station-level pressures on the Asheville tape. The tape value for Darwin for October 1961 was climatologically unreasonable (6 mb below normal with no other values in 1882–1976 more than 3 mb below normal).

3. Adjustment for observing time

Up to 31 March 1939 the Darwin data were derived from $\frac{1}{2}$ (0017 + 0617 GMT) and thereafter from $\frac{1}{2}$ (2300 + 0500 GMT), (Smithsonian Institution 1947). An inhomogeneity will have resulted from the diurnal pressure cycle, but not from the semi-diurnal pressure cycle, because the data times remained six hours apart. The effect was estimated from data and graphs for many stations (not including Darwin) and regions, presented by Hofmeyr (1958). The necessary correction, based on a diurnal cycle amplitude of 0.85 mb with a maximum at 5 a.m. local time, was made by subtracting 0.2 mb from the Tahiti-minus-Darwin index for all months up to March 1939 inclusive. Table I includes this correction.

4. Seasonal index

The seasonal index in Table II is based on the values in Table I with northern winter being December to February and so on. The reader can use the means and standard deviations provided to create a normalized index. The skewness and kurtosis coefficients do not indicate any departure from a Gaussian distribution (Brooks and Carruthers 1953).

5. Behaviour of the index in 1982

During 1982 the Southern Oscillation entered the 'negative' phase with below normal mean-sea-level pressure at Tahiti, and above normal at Darwin. The lowest seasonal values of the series for northern summer, autumn and winter occurred in 1982–83 as did the lowest monthly values for August, September, November, and January to March, and the equal lowest monthly values for June and October. However, the associated episode of warmth in the equatorial Pacific Ocean has differed in major respects in timing and sequence from earlier events (US Climate Analysis Center, Diagnostics Branch, Special Climate Diagnostics Bulletin, 10 November 1982). In particular, the positive sea surface temperature anomalies developed during the southern winter rather than the southern summer which has usually been the season for this process. Also the anomalies were not preceded by equally large anomalies near the Ecuador–Peru coast. In addition it appears from preliminary upper-air data that the warming of the tropical troposphere normally associated with warm episodes of the equatorial Pacific Ocean (Hastenrath and Wu 1982) did not occur in 1982. This may be a consequence of an increase in global albedo as a result of the eruptions of El Chichon in Mexico in March and April 1982. The matter will be investigated and will be reported elsewhere.

Table II. Seasonal values of the difference of mean-sea-level pressure between Tahiti (18°S , 150°W) and Darwin (12°S , 131°E)

[illegible]

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NOTICES

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Analyses of moisture and convective activity from cloud, visibility and present weather reports

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Summary

Techniques have been developed to obtain analyses of the cloud water mixing ratio of stratiform clouds from cloud, visibility and present weather reports, and to identify and analyse convective activity. This paper describes two techniques and presents some examples of the analyses. One application of the work is in the enhancement of initial fields for the mesoscale numerical forecast model.

1. Introduction

A mesoscale forecasting system is being developed in the Forecasting Research Branch of the Meteorological Office for short-range (6-24 hours) forecasting for the UK area. Although the forecast model has been in existence for some time as a research tool (Tapp and White (1976) and Carpenter (1979)) effort has recently been concentrated towards producing an operational system. The most notable change introduced in recent years has been the inclusion of moist processes, the original model being dry.

In order to obtain greater detail in the initial data analyses for the mesoscale model, research has concentrated on techniques of extracting information from some of the elements of surface observations hitherto unused in numerical forecasts and interpreting them in terms of model variables. At present, initial fields for the mesoscale model are interpolated from data for the new 15-level fine-mesh model recently introduced into operational use. The fine-mesh model has a grid length of about 75 km compared with the 10 km grid length of the mesoscale model. Whereas an array of only 12 x 14 grid points cover the UK on the fine-mesh grid, there are 90 x 100 points on the mesoscale grid, see Fig. 1. It is hoped that the use of up to 200 surface observations hourly should enable mesoscale detail to be added to the interpolated fields. One such technique is the enhancement of model fields of moisture by an analysis of present weather, cloud and visibility observations to infer information regarding cloud water mixing ratio of layer clouds. Another is the analysis of present weather and cloud reports to identify areas of convective activity. The model may then be 'forced' to convect in these areas with an intensity in keeping with what has been observed.



Figure 1. 90 x 100 grid for mesoscale analyses.

This article describes these two schemes and gives examples of the kind of output that they make available to the model, (or, if used operationally, to the bench forecaster). The schemes inevitably depend on a considerable degree of empiricism, but results obtained so far are encouraging.

2. Cloud water mixing ratio of layer cloud

Cloud water mixing ratio (CWMR) and humidity mixing ratio (HMR) are the moisture variables used by the cloud and rainfall parametrizations of the mesoscale model. Values of CWMR can be estimated from observations of cloud, present weather and visibility. Observations within the mesoscale model grid are first selected from a given hourly data set within the operational synoptic data bank. Observations of cloud amount, cloud base, visibility and precipitation rate are interpolated on to grid points using an analysis program devised by Purser and McQuigg (1982), described in Section 4. This process spreads the information from the observing stations on to the entire mesoscale grid in a controlled manner.

Cloud amounts are used directly as reported; cloud bases are converted to metres and the station height added on before analysis. For visibility, only values within fog limits (i.e. less than 1000 m) are of interest since above this limit the CWMR is very small. Observed visibilities are converted to CWMR using a relationship based on Eldridge (1971).

$$\log_{10} W = -1.55 \log_{10} V - 5.46$$

where W is CWMR in kilograms of liquid water per kilogram of dry air and V is the visibility in kilometres. A visibility of 100 m corresponds approximately to the CWMR of stratus type cloud.

Conversion of present weather into a dynamical rainfall rate is achieved by assigning mean precipitation rates to present weather code values that indicate dynamical rainfall, using extensions to the specification of rainfall rate from the *Observer's handbook* (Meteorological Office 1982). The rates are shown in Table I.

Table I. Mean precipitation rates for dynamical rainfall

Present weather code	Mean rate (mm h ⁻¹)
50,56	0.05
51	0.10
52	0.15
53,57,58,60,68,70	0.25
66	0.35
54,61,71,77,79	0.50
55	0.75
59,62,72	1.00
63,67,69,73	3.00
64,74	4.00
65,75	7.00

Then, using the formulation described below, a cloud depth is computed from the precipitation rates.

The stratiform rainfall scheme used in the mesoscale model may be written

$$-\frac{\partial P}{\partial z} = M(z) \left\{ \alpha + \gamma P(z) \right\} \left\{ 1 - e^{-(M/M_0)^2} \right\}$$

where P is the rainfall rate, $M(z)$ is the CWMR and α , γ , M_0 are constants.

If this is discretized with constant Δz , and M is assumed independent of z , the total rate of rain at the bottom of a cloud may be written

$$P = \frac{\alpha}{\gamma} \left\{ (1 + \gamma \hat{M} \Delta z)^n - 1 \right\}$$

where $\hat{M} = M \left\{ 1 - e^{-(M/M_0)^2} \right\}$.

This formula may be inverted to give

$$H = \Delta z \frac{\log \left(\frac{P\gamma}{\alpha} + 1 \right)}{\log \left(1 + \gamma \hat{M} \Delta z \right)}$$

where $H = n \Delta z$, as an approximate relationship between rainfall rate and cloud depth (H). In the computations presented, $\Delta z = 500$ m, $M = M_0 = 0.5 \times 10^{-3} \text{ kg kg}^{-1}$, $\alpha = 10^{-4}$ and $\gamma = 1.0$.

The next stage is to combine the four analyses (cloud amount, cloud base, visibility and rainfall rate) to produce a three dimensional picture of CWMR. The computer program checks each grid point in turn, looking first for a cloud amount of five oktas or more. If this criterion is not satisfied, the CWMR remains set at zero, at all model levels, for that particular grid point and the program moves on to the next point. However, if the cloud amount criterion is satisfied, the program goes on to examine the precipitation analysis.

If the rainfall rate is less than 0.1 mm h^{-1} , a CWMR value for non-precipitating layered cloud (see Table II) is assigned only to the nearest model level above the cloud base. If a value greater than 0.1 mm h^{-1} is found, the cloud depth is computed, from the formula above, and the CWMR value for precipitating layered cloud (see Table II) is then assigned to all model levels throughout the estimated depth of the cloud. The final stage is to add the contribution of CWMR from the visibility analysis to the bottom level of the model, completing the picture described above.

These techniques can be reversed so that, if forecast CWMR data are available, values of rainfall rates, visibility, cloud base and cloud tops can be output.

Table II. *Assigned CWMR values, kg kg^{-1}*

No layered cloud/No precipitation/No poor visibility	Zero
Non-precipitating layered cloud	$5.0 \times 10^{-4} \times \text{cloud amount in oktas}$
Precipitating layered cloud	5.0×10^{-4}

Examples of the output from this scheme are shown in Figs 3, 4, 6, and 7 described in Section 5.

3. Analysis of convective activity

The purpose of this analysis is to identify areas of convective activity, of different intensity, in much the same way as a bench forecaster might pick out areas of interest from an hourly chart. Convective activity is by its nature a local effect whereas dynamical layered cloud and precipitation are of a more widespread and continuous nature. Hence, a different approach is required from that in the previous section.

The scheme uses a short scale of intensities, from zero to five, defined in Table III. It examines reports of present weather and cloud (both main and subsidiary 8-groups) to allocate an intensity to each observation. An observation containing none of this information is discarded. A zero intensity does not imply no weather or cloud, simply that any reported weather is not of a convective nature.

Table III. *Convective intensity definitions*

Intensity	Definition	Indicator
5	Thunderstorm at time of observation	ww = ≥ 95
4	Thunderstorm in last hour	ww = 29, 91-94
3	Moderate/Heavy/Violent shower at time of observation	ww = 81, 82, 84, 86, 88-90
2	Slight shower at time of observation	ww = 80, 83, 85, 87
	Adjacent showery activity	ww = 13-17
	Shower in last hour	ww = 25-27
	Cumulonimbus at time of observation	C = 9
1	No precipitation:	
	Altostratus reported	$C_M = 8$
	$\geq \frac{1}{8}$ cumulus reported	$N_S \geq 3$ when $C = 8$
0	Any other reports	Any other code figures

Notes

ww is Present weather code (Table 4677)

C is Cloud genus code (Table 0500)

C_M is Cloud genus code for 'medium-level' cloud (Table 0515)

N_S is Amount of cloud mass of genus C code (Table 2700) (World Meteorological Organization)

Observations are considered station by station and are first examined for the indicators described in Table III. An intensity value is then assigned to each observation. Where convective cloud is found, a cloud base height is also assigned, a background value of 4500 m being assigned where no information is available. When all observations have been examined the intensity field is analysed using Purser and McQuigg's scheme, as in the previous section, allocating a value to every grid point. These values represent a potential for convection, showing regions of activity, see Fig. 8. The next stage is to decide at which grid points, within a particular region of intensity, that type of convection, e.g. heavy showers, is actually occurring. To do this a statistical approach is adopted to introduce a random element into the distribution of showers.

This random effect is produced by calling up pseudo-random numbers from a subroutine within the computer (RNDM (X)), the distribution of variables being from the uniform distribution in the range 0 to 1. By varying the value of a test statistic, different chances of an occurrence can be modelled thus reflecting the different expectancies of convective activity. Test statistics currently used are shown in Table IV.

As an example, consider an area of heavy shower activity within which area all grid points will have been allocated an intensity of three at the analysis stage. A random number is then called up for each grid point. If that number is greater than 0.875, the appropriate test statistic for heavy showers, then a heavy shower is deemed to be occurring at that point. If the number is equal to or less than 0.875, then there is no shower at that point.

The test statistic varies according to the intensity at the grid point being considered. Hence if the intensity is four or five, the test value used is 0.9. All grid points analysed as having an intensity value of one are used as such at the next stage of the scheme with no randomization.

Table IV. *Chances of occurrence of convective activity*

Intensity	Definition	Chance	Test statistic
5/4	Thunderstorms	1 in 10	RNDM(X) > 0.9
3	Heavy showers etc.	1 in 8	RNDM(X) > 0.875
2	Showers	1 in 4	RNDM(X) > 0.75
1	Non-precipitating convective cloud	—	Any

In due course, the separation and occurrence of showers, cumulonimbus, etc., may be taken directly from satellite and radar observations.

The scheme then goes on to assign a cloud depth to each grid point at which convection is deemed to be occurring according to the intensity at that point. An empirical approach is used, based on general convective theory; values are shown in Table V.

Table V. *Cloud depths*

Definition	Depth
	<i>metres</i>
Thunderstorms	8000
Heavy showers etc.	5000
Light showers	3000
Cumulus reported, no precipitation	2000

The final stage of the scheme involves the analysis of cloud base heights, these being converted to metres and station heights added before analysis. The analysed height and depth fields are then combined to give a cloud top field. All these analysed fields are then available to the mesoscale forecast model so that there may be a forcing of the model towards the intensity and depth of convection reported.

4. Analysis scheme

The analysis routine used by both these schemes is described in detail in Purser and McQuigg (1982) and was designed specifically for mesoscale analysis. It uses a successive correction technique in which modifications to an initially uniform field are obtained using recursive filters. These filters permit a detailed control of the scales present in the final analysis. They have a one-sided exponential decaying shape and are applied twice in each coordinate direction giving an approximately Gaussian spread of the information. The initial magnitude of the adjustment at each scan is obtained by bilinearly weighting each observation at the surrounding four grid points. The smoothing is then governed by a range parameter which is initially set large enough to define the large scale pattern in areas of sparse data and is then progressively reduced to a specified limiting value subject to there being sufficiently dense data to describe these scales. For 'rough' information like cloud observations, the initial range is set to seven grid lengths (70 km) and the limiting range is two grid lengths (20 km). The final analysis will then consist of scales greater than a minimum ranging from 20 km in data-rich areas to 70 km in areas of sparse data.

The analysis scheme also contains a quality control facility based on comparison of an observation with the latest scan. The prime intention of this process is to reject spurious data. However, the discontinuous nature of some of the variables being analysed, such as cloud amount data, has led us to accept all observations reaching the analysis stage.

5. Output examples — 6 January 1983

The situation chosen to demonstrate the output from the schemes is that for midday on 6 January 1983. A cold front lay north-east/south-west across the UK from roughly the Wash to Portland Bill, see Fig. 2. The front was quite a good example of a cold front with much of the rain occurring to the rear of the surface frontal position. It was moving south-east at about 20 knots.

A descriptive picture of the situation can be built up from the output. Fig. 3 shows the presence of layered cloud ahead of, and in, the frontal zone with a sharp cut-off well to the rear.

Only those reports with cloud amount greater than five oktas of layered cloud are used in the analysis of layered cloud heights, Fig. 4. It can be seen from Fig. 3 that there are very few non-zero reports in the north-west of the chart. Consequently, information from these few reports is spread over a large area by the height analysis routine. Hence, the cloud height field must be used in conjunction with the cloud amount field; i.e. a height from Fig. 4 should only be regarded as valid where there is a significant (≥ 5 oktas) report of layered cloud. A point worth noting from the analysis is the low stratus in the warm air immediately ahead of the front and also in the Bristol Channel.

The analysis of convective cloud heights in Fig. 5 should also be used with care; a convective cloud height is only valid if there is convective activity at that point. The convective cloud height field is essentially flat, cloud base being quite uniform within the airstream, contrasting with the greater variability of the layered clouds.

Fig. 6 shows the analysis of rainfall rates. The frontal zone is well defined with pockets of moderate rain within a broad zone of slight rain. An observation of moderate continuous snow over the

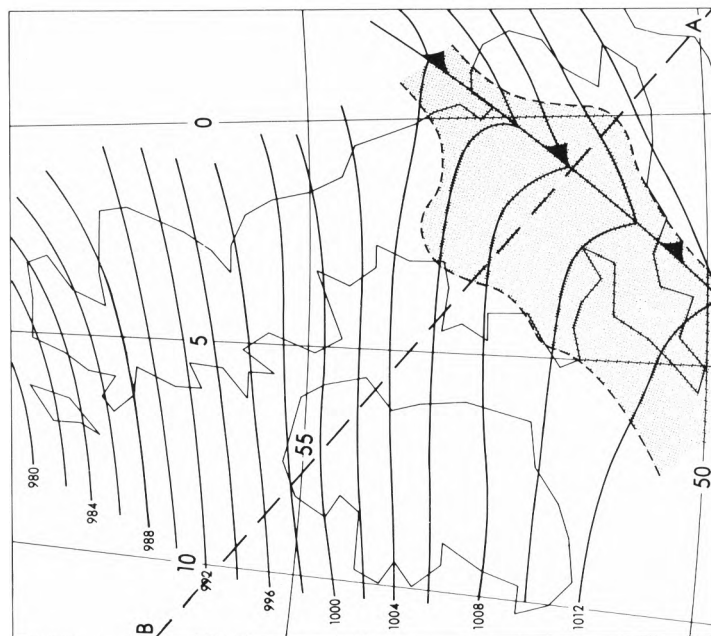


Figure 2. Synoptic situation, 1200 GMT 6 January 1983, with area of dynamic rain stippled. (For explanation of line AB see Fig. 7.)

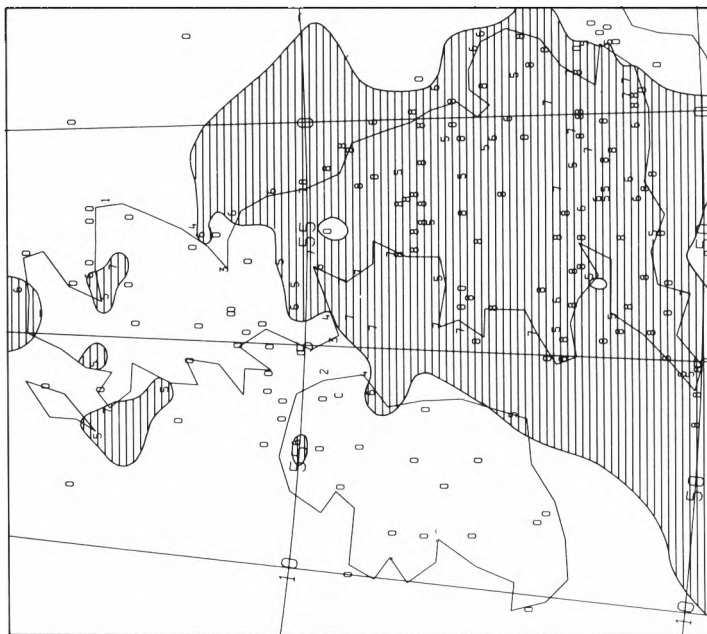


Figure 3. Analysis of layered cloud amounts for the lowest layer of five oktas or more, 1200 GMT 6 January 1983. (Cloud amounts plotted at observations.)

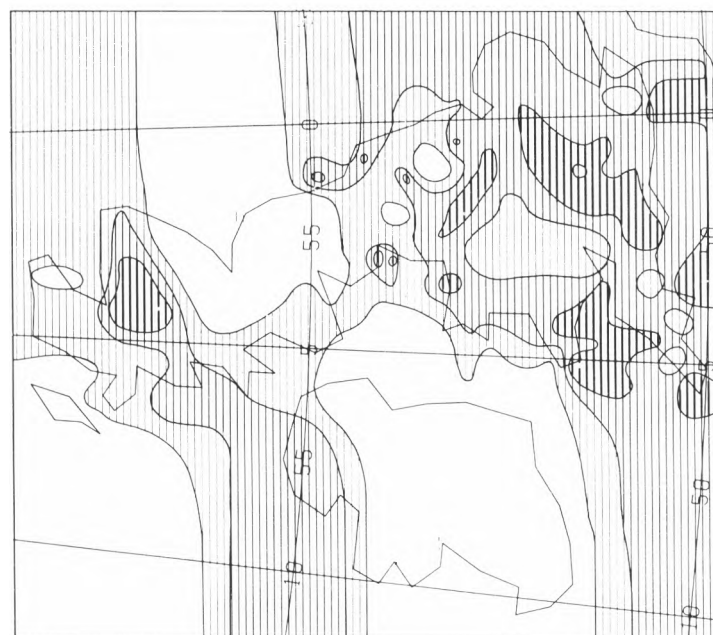


Figure 4. Analysis of layered cloud heights (metres) for the lowest layer of five oktas or more, 1200 GMT 6 January 1983. Dark: <400 m, Medium: 400-1200 m, Light: 1200-3200 m, No shading: >3200 m.

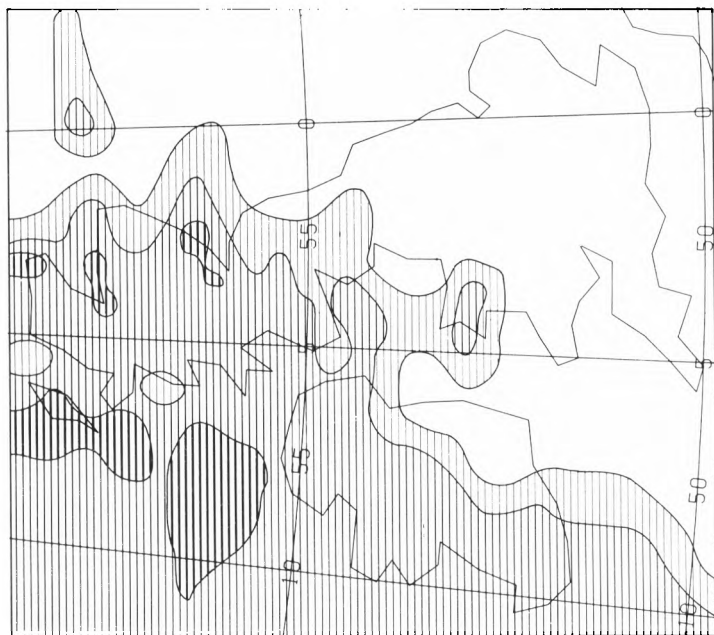


Figure 5. Analysis of convective cloud heights (metres), 1200 GMT 6 January 1983. Dark: <400 m, Medium: 400-1200 m, Light: 1200-3200 m, No shading: no convective cloud.

Cairngorms shows up as an area of dynamic precipitation with a rate greater than 3 mm h^{-1} . All neighbouring stations were reporting showers, highlighting the problem that these analyses are only as good as the observations on which they are based.

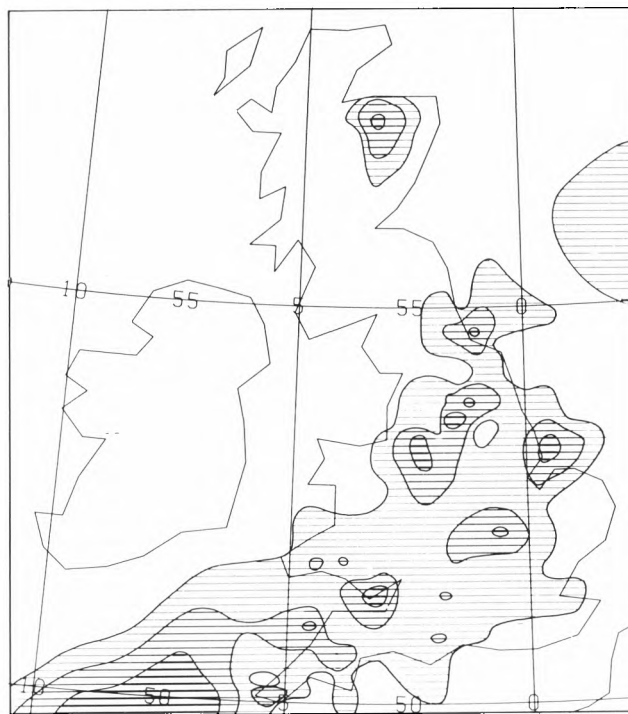


Figure 6. Analysis of hourly rainfall rates derived from present weather codes 50-79, 1200 GMT 6 January 1983. Dark: $> 3 \text{ mm h}^{-1}$, Medium: $1-3 \text{ mm h}^{-1}$, Light: $0-1 \text{ mm h}^{-1}$.

The vertical cross-section of CWMR Fig. 7 is a slice through the front and into the cold air, the line AB on Fig. 2. Thin non-precipitating layers are shown in the extreme south-east of England, thickening and lowering towards the frontal zone (grid points 65-70) and then thinning out to the rear of the front. There is a brief lowering of the cloud base over Shropshire before the cloud base lifts to medium and high cloud levels over the Irish Sea with no layered cloud reported in the genuine cold air over Ireland and westwards. This is a very good representation of the observations and it gives a good indication of the clearance of the upper cloud shield.

Fig. 8 shows the convective intensity analysis. The presence of quite widespread showers in the cold air is well illustrated as are areas of convection over high ground ahead of the main showery activity, North Wales and southern Pennines. Convection is just starting on the west coast of South Wales while that shown over Wittering is due to a report of four oktas of cumulus and slight continuous rain (with layered cloud above and below)! The shelter of the Cairngorms and Pennines is also illustrated.

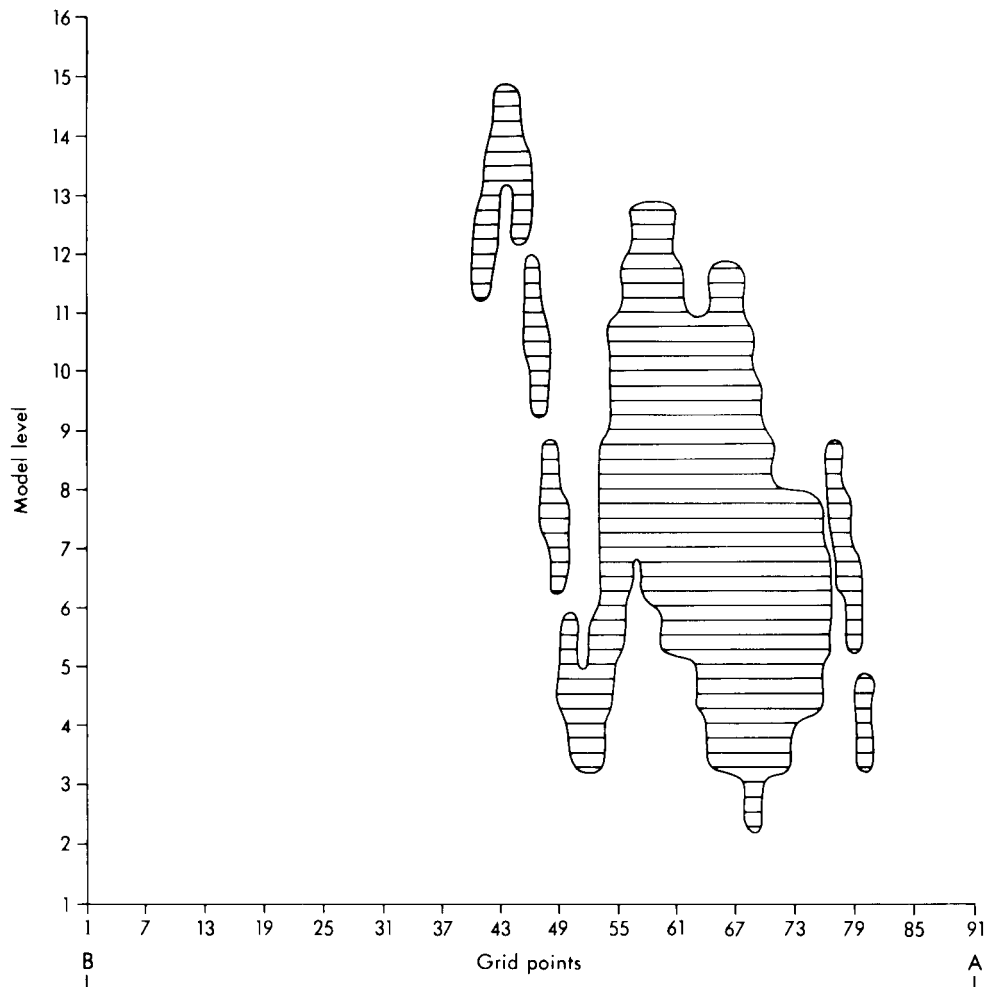


Figure 7. Analysis of cloud water mixing ratio, cross-section along AB — see Fig. 2.

6. Conclusions

Two areas of development of analyses on the mesoscale have been described. It is recognized that there are deficiencies in the schemes, not least of which is the problem of inconsistencies in reporting, but it is felt that the limitations imposed by these problems are greatly outweighed by the advantages of increased detail from the majority of accurate observations.

The work is relatively new and has yet to be incorporated into the mesoscale model, itself some way from an operational state. Further analyses, of such elements as pressure, temperature, winds, etc., can also be carried out using Purser and McQuigg's analysis scheme. It is hoped that as new sources of observational data become available, these too may interact with the model analyses. Satellite and

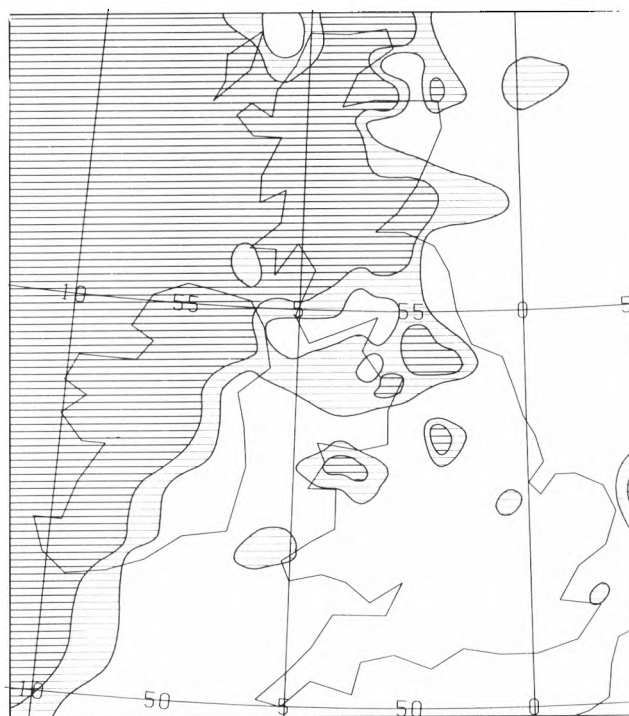


Figure 8. Analysis of convective intensity, 1200 GMT 6 January 1983. Light: non-precipitating convective cloud, Dark: showery.

radar data immediately come to mind for identifying more precisely cloud edges, cloud tops, individual thunderstorm cells, rainfall rates, etc. Only after testing and further improving these schemes within the full mesoscale model can their true usefulness be assessed.

Acknowledgements

We would like to thank Dr B. Golding for his help and guidance during the period of these projects.

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Global solar radiation measurements on 6 August 1981. A day of midday darkness

By R. J. Armstrong

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Summary

This article describes the effect on the solar radiation of the severe storms that hit southern England on 6 August 1981. The feature that distinguished this day from other days of violent thunderstorms, and made front page news, was the darkness that beset many areas, including London, in the middle of the day. From the solar radiation values provided by twelve sites the movement and intensity of the storms across southern and eastern England can be identified.

Introduction

August 6 was the first of three successive overcast days which followed the hottest spell of the 1981 summer, the fine weather being broken down by a series of organized thunderstorms. As a result of the intensity of these storms, 6 August 1981 has been designated as a day of meteorological importance for which various branches of the Meteorological Office are providing detailed reports on the different aspects of the weather. Other accounts and observations have been presented in the journals, such as Bader *et al.* (1983) Nicholson (1982), Elston (1982), Crane (1981), Austin (1981) and Goethuys (1982), as well as in many of the national daily newspapers. Previous storms that caused large reductions in the solar radiation have been described by Helliwell and Blackwell (1955) and Gildersleeves (1962).

The synoptic situation during this period can be regarded as ideal for thunderstorm development. After two days of convective activity over France and increasing moisture content over the Bay of Biscay, an upper trough developed and moved in from the Atlantic. The situation by the morning of the 6th was that of a pronounced upper trough near south-west England and a surface low over northern France (see Fig. 1). At 700 mb an area of moist air, with a relative humidity greater than 75%, stretched from northern France to cover most of England. The active storms crossed the south coast at about 0500 GMT on the 6th and moved north-east across south-east England and the east Midlands while earlier storms died away leaving a large area of persistent, but less intense, rain over the Midlands and northern England.

Measurements

Twelve stations (see Fig. 5 and Table I) were able to supply radiation data for the area of interest ranging from continuous records to hourly integrations. Four of these are Meteorological Office

Table I. *The location of the 12 sites that provided radiation data for this article*

Site	Latitude	Longitude	Site	Latitude	Longitude
Bracknell	51° 23'N	00° 47'W	Grendon Underwood	51° 54'N	00° 01'W
Brooms Barn	52° 14'N	00° 34'E	Hemsby	52° 41'N	01° 41'E
Crawley	51° 05'N	00° 13'W	London	51° 31'N	00° 07'W
East Malling	51° 17'N	00° 27'E	Rothamsted	51° 48'N	00° 21'W
Garston	51° 42'N	00° 23'W	Silsoe	52° 01'W	00° 25'W
Grafham Water	52° 17'N	00° 19'W	Wallingford	51° 36'W	01° 10'W

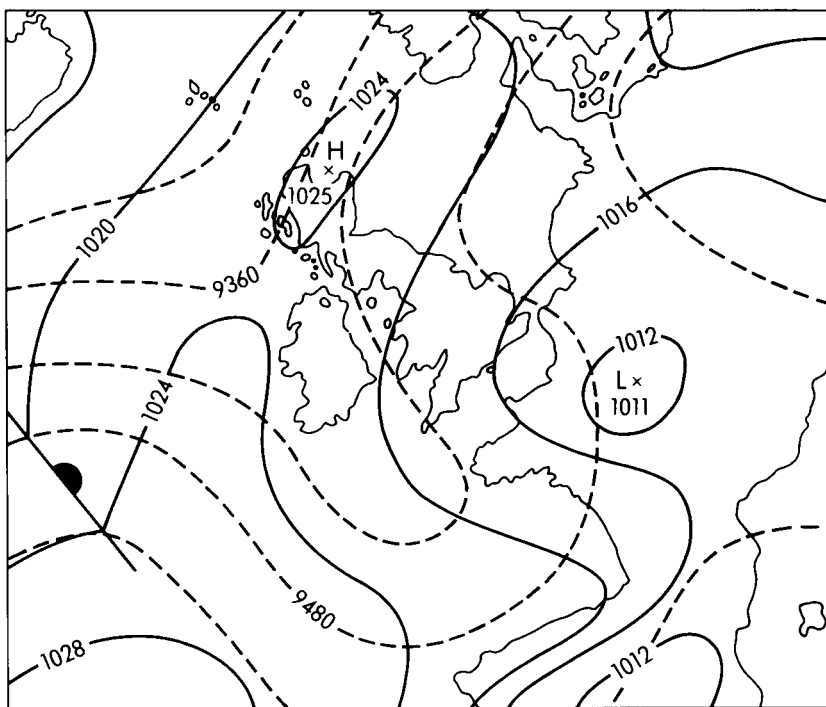


Figure 1. The synoptic situation for 1200 GMT, 6 August 1981. Mean-sea-level pressure (solid lines) in millibars, 300 mb geopotential (dashed lines) in geopotential metres.

stations, viz. Bracknell, Crawley, London Weather Centre and Hemsby, the rest being under the authority of other government departments or private research institutes, though forming part of a current network of 37 stations regularly supplying radiation data to the Meteorological Office.

The 12 stations concerned measure a range of solar radiation elements, though all record the global irradiance on a horizontal surface (i.e. the rate at which the radiant energy falls on a unit area of a horizontal surface) for the waveband 0.29 to 3.0 μm . The global solar radiation consists of two components: the diffuse or scattered radiation (measured at the four Meteorological Office stations and Silsoe); and a direct component (only recorded at Bracknell) measured normal to the sun's rays by a tracking pyrheliometer. Bracknell also measures the global solar irradiance on vertical surfaces facing north, east, south and west. These are of particular interest to engineers concerned with the heating of buildings. For the purpose of this article, the global solar radiation on a horizontal surface is the only variable considered.

The stations record radiation data by different methods: Meteorological Office stations use MODLE 3 (Meteorological Office Data-Logging Equipment, Mark 3) which logs values at one minute intervals on a magnetic tape. After computer processing the data are produced in graphical form. Two other stations (Rothamsted and East Malling) supplied a continuous chart record of the day's radiation. The remaining stations use voltage-time integrators which print the total at the end of each hour (except at Grafham Water where half-hour totals are printed). Additionally, Wallingford and Grendon Underwood supplied the times when their solarimeters did not record any radiation, and Garston

provided a small chart record of the day that indicates changes in the radiation level, but could not be quantified in absolute units. The minute values from the four Meteorological Office sites are processed in local apparent time (LAT); the difference between LAT and GMT depends on astronomical factors as well as the longitude of the station (solar noon or 1200 LAT is when the sun is due south of the station). For the purpose of this study the difference is small enough (i.e. less than 10 minutes) to be ignored.

Observations

Table II shows the daily totals of global irradiation on a horizontal surface (in W h m^{-2}) for the 12 sites with the long term means for August (based on up to ten years data). Each percentile (1%, 5%, 99%) indicates the number of occasions on which the given daily totals are not exceeded. Hence for Bracknell, Wallingford, Grendon Underwood and Garston the daily total on 6 August 1981 represents one of the three lowest radiation days to be expected in a ten-year period in August.

Table II. Daily totals of global solar radiation (W h m^{-2}) for the 12 sites together with the long term means for August (based on up to ten-years data). Each percentile (1%, 5%, 99%) indicates the number of occasions on which the given daily totals are not exceeded

Site	Daily total for 6 August 1981	1%	August percentiles 5%	99%	August average	Number of days used
Bracknell	603	702	1406	6843	4095	277
Crawley	1087	937	1614	6485	4074	61
London	1047	920	1502	6313	3929	211
Hemsby	1997	942	1435	7140	4136	31
Wallingford	310	591	965	6229	3722	186
Grendon Underwood	560	675	1072	6189	3731	186
Rothamsted	706	628	1141	6592	3742	278
Silsoe	956	577	1170	6738	3984	309
East Malling	2679	804	1399	6559	4012	307
Garston	650	680	1248	6477	3847	245
Grafham Water	1150	520	1148	6569	3652	155
Brooms Barn	2844	755	1147	7065	3688	62

Fig. 2 shows the mean hourly irradiances for the 12 sites. The extent of the storm clouds can be seen from the radiation values with periods of very low global irradiance (less than 5 W h m^{-2} on a horizontal surface) lasting for more than an hour at many of the sites. Such low levels of irradiance for such a long period indicate that the cumulonimbus must have been both very thick and horizontally extensive. Bracknell recorded only four minutes of direct irradiance greater than 10 W m^{-2} .

Fig. 3 shows the diurnal global irradiance curve for Bracknell. Evidence of a first storm can be seen by the irradiance values being below the level of detection between 0718 and 0733 LAT. Low values of irradiance continued until a second and more intense storm arrived at 0936 LAT, lasting for over an hour until just before 1100 LAT. Superimposed on Fig. 3 are the long term means for August (based on data from 1972–1981) represented by the 1%, 5% and 99% percentiles described above, as well as the 1972–1981 average for each hour.

Fig. 4 shows the diurnal irradiance curves for two other Meteorological Office stations. The two peaks in the morning at 0914 LAT at Crawley and 0953 LAT at London Weather Centre represent a clear spell between two storms, not clearly evident on the Bracknell output.

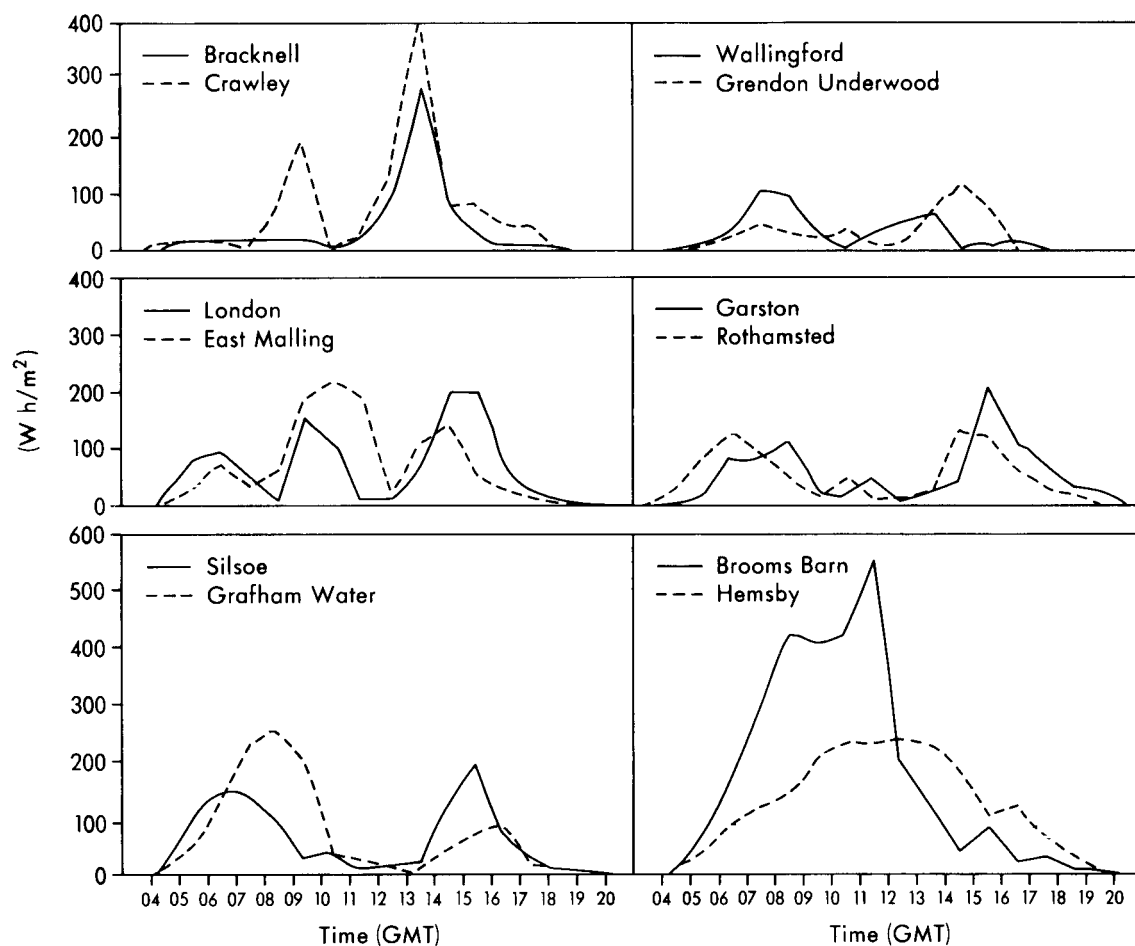


Figure 2. Hourly irradiations for selected sites on 6 August 1981.

Discussion

From the data provided by the twelve sites it has been possible to detect the periods of 'zero' radiation (i.e. global irradiance of less than 5 W m^{-2} on a horizontal surface), though for those stations that report hourly integrations, only approximate times could be estimated. The evidence suggests that two major storm systems moved south-west to north-east across south-eastern England and the east Midlands on 6 August 1981. The positions of the front edge of the main storm clouds, as defined by the time that the irradiance reached 'zero', have been plotted (Fig. 5(a)) for each hour: 0700 to 1000 GMT for the first storm and 0900 to 1600 GMT for the second storm, although beyond 1400 GMT the analysis is based on limited data. (See also Table III.)

The radiation data can provide information about the intensity (as inferred from the darkness) and extent of the storms. The first system was most intense over Crawley and London, lasting for a shorter period over Bracknell, while Wallingford showed no decrease in the radiation trace, this indicating the north-western extent. East Malling reached a minimum of 12 W m^{-2} in the radiation trace, suggesting the first storm was not as intense there as further west and this probably indicated its south-eastern

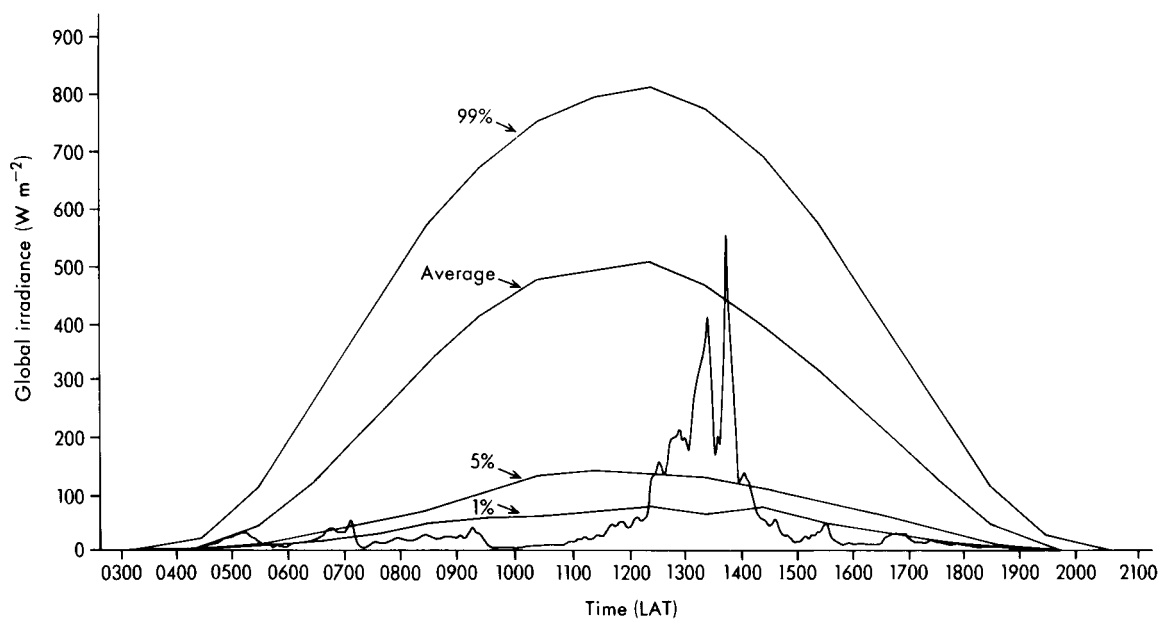


Figure 3. Diurnal radiation plot of Bracknell MODLE data for 6 August 1981 together with the average, 1%, 5% and 99% percentiles for August.

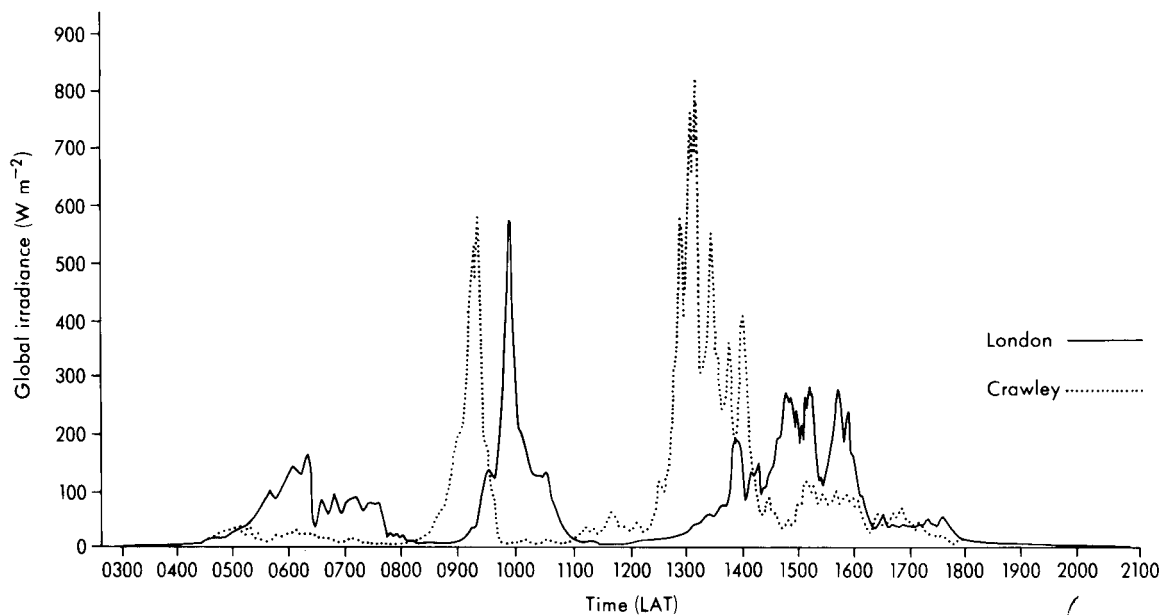


Figure 4. Diurnal radiation plots for two of the MODLE stations.

boundary. The darkness at Garston and Rothamsted lasted for about an hour, but by the time the storm reached Grafham Water the band of darkness was reduced in scale and there was no indication of significantly low values of irradiance at Brooms Barn. The period before the second system showed two distinct patterns: Crawley, London and East Malling had a relatively clear spell between the storms when it is obvious that the clouds broke for a short while, though no 'bright sunshine' was recorded at London or Crawley by Campbell-Stokes sunshine recorders; and Bracknell where the irradiance remained low all the time, never rising above 50 W m^{-2} until the end of the second storm.

The movement of the second and more intense storm system, lasting for more than an hour at over half the stations, was easier to detect, but because it affected all 12 sites the lateral extent could not be judged. It was still producing low irradiance values, though for a much shorter time, as it crossed East Anglia late in the afternoon, with Hemsby showing a pronounced dip in the irradiance trace for five minutes from 1548 GMT.

The Hydrometeorological Section of the Meteorological Office have studied the rainfall during this day and from radar data have been able to draw an outline of the main radar-echo area. Fig. 5(b) shows the outline at 0900 and at 1200 GMT. The shape of the echoes at 0900 looks rather like a semicolon; the lower part (comma shaped), which was more than 100 km long and less than 50 km wide, lies north-west to south-east. The most active area of the round part of the radar echo was near the eastern edge which moved northwards, just to the west of London about 0900 GMT, expanding in size to approximately 100 km across.

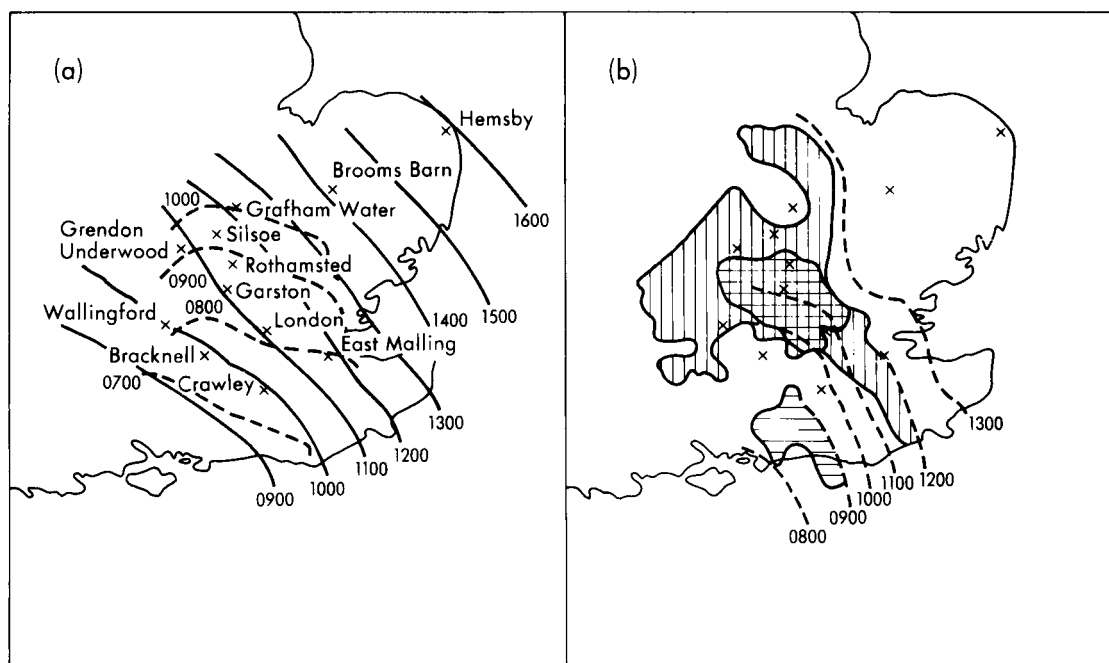


Figure 5. (a) The positions and times of the leading edge of the first storm system (dashed lines) and the second storm system (solid lines) as derived from radiation data. (b) The outline of the radar echo area at 0900 (horizontal lines) and at 1200 (vertical lines). The dashed lines show the positions and times of the leading edge of the second system as indicated by radar. All times are GMT.

Table III. *Estimated times (GMT) over each site for the two major storms, with minimum values of irradiance ($W m^{-2}$) recorded*

Site	First storm	Minimum	Second storm	Minimum
Bracknell	0727 to 0742	0	0945 to 1108	0
Crawley	0721 to 0816	1	0951 to 1109	1
Wallingford	—	—	1005 to 1130	0
London	0811 to 0905	0	1111 to 1217	1
East Malling	0755 to 0840	12	1200 to 1240	0
Garston	0845 to 0945	0*	1110 to 1230	0*
Grendon Underwood	0830 to 0930	20*	1040 to 1130	0
Rothamsted	0850 to 0948	8	1112 to 1248	6
Silsoe	0830 to 0930*	20*	1130 to 1230*	4*
Grafham Water	1000 to 1100*	10*	1245 to 1345	5*
Brooms Barn	—	—	1330 to 1445*	30*
Hemsby	—	—	1548 to 1552	2

* indicates that only an approximation could be made

The bright period between the storms at Crawley, London and East Malling can be explained by the passage of the northern part of the echo being followed by a gap, and then the comma-shaped part as it moved north-east. It was the comma-shaped storm that gave the heavy rainfall to places such as London at midday. Bader (personal communication) has plotted the leading edge of the radar echo associated with this storm as it moved across south-east England at each hour from 0800 to 1300 GMT (Fig. 5(b)) and this shows very good agreement with the position of the second storm as derived from the radiation data and shown in Fig. 5(a). The speed of the comma as estimated from the rainfall data was 25 km h^{-1} which again is in agreement with the calculated speed from the time at which the start of the 'zero' values were recorded at Crawley and then at East Malling. The speed of the top part of the semicolon was between 35 and 40 km h^{-1} . However, the speed calculated from the first 'zero' values at Bracknell and then at Rothamsted was slightly higher at 43 km h^{-1} . This could be explained by the fact that the storm was increasing in size during the morning of the 6th.

To achieve 'zero' values of global irradiance suggests that the clouds must have been both very thick and extensive. For example, the atmospheric transmission of solar energy at 1030 LAT, given by the ratio of the observed global irradiance (5 W m^{-2}) to the 'clear day' global irradiance (i.e. the 99% level) would be less than about $5/750$ or 0.7%. This is a much smaller value than the average observed overcast fractions (e.g. Haurwitz (1948) gave a figure of 10% for complete coverage by nimbostratus). It is also a much smaller transmission than for most models of radiation transfer through clouds; for example Liou (1976) gave a figure of 3% for a cumulonimbus cloud 4.5 km thick and Stephens (1978) formed parametrization relations for cumulonimbus clouds, the largest optical thickness (τ_N) considered being in the order of 5×10^3 which gave a transmission factor of 1%. He noted that if the sun's disc is not visible through a cloud then τ_N must be greater than 10 and gave the approximate relation of

$$\tau_N \approx 1.5W r_e^{-1}$$

(assuming uniform extended water clouds) where,

W = total liquid water content in a vertical path in g m^{-2} , and
 r_e = effective radius of droplet distribution in μm .

Therefore, if $r_e \approx 10 \mu\text{m}$, a typical figure for cumulonimbus, W must exceed $3 \times 10^4 \text{ g m}^{-2}$ if the transmission is to be less than 1%. The total liquid content, calculated from the Crawley 1200 GMT ascent with a wet-bulb potential temperature of 18°C and a parcel of air cooled along a saturated adiabat to 8 km, was $W = 3 \times 10^4 \text{ g m}^{-2}$, which agrees with the relation above. However, this calculation is an extreme simplification of the problem of determining the transmission of radiation through cloudy atmospheres and ignores many of the complications arising from multiple scattering, absorption and non-spherical ice particles.

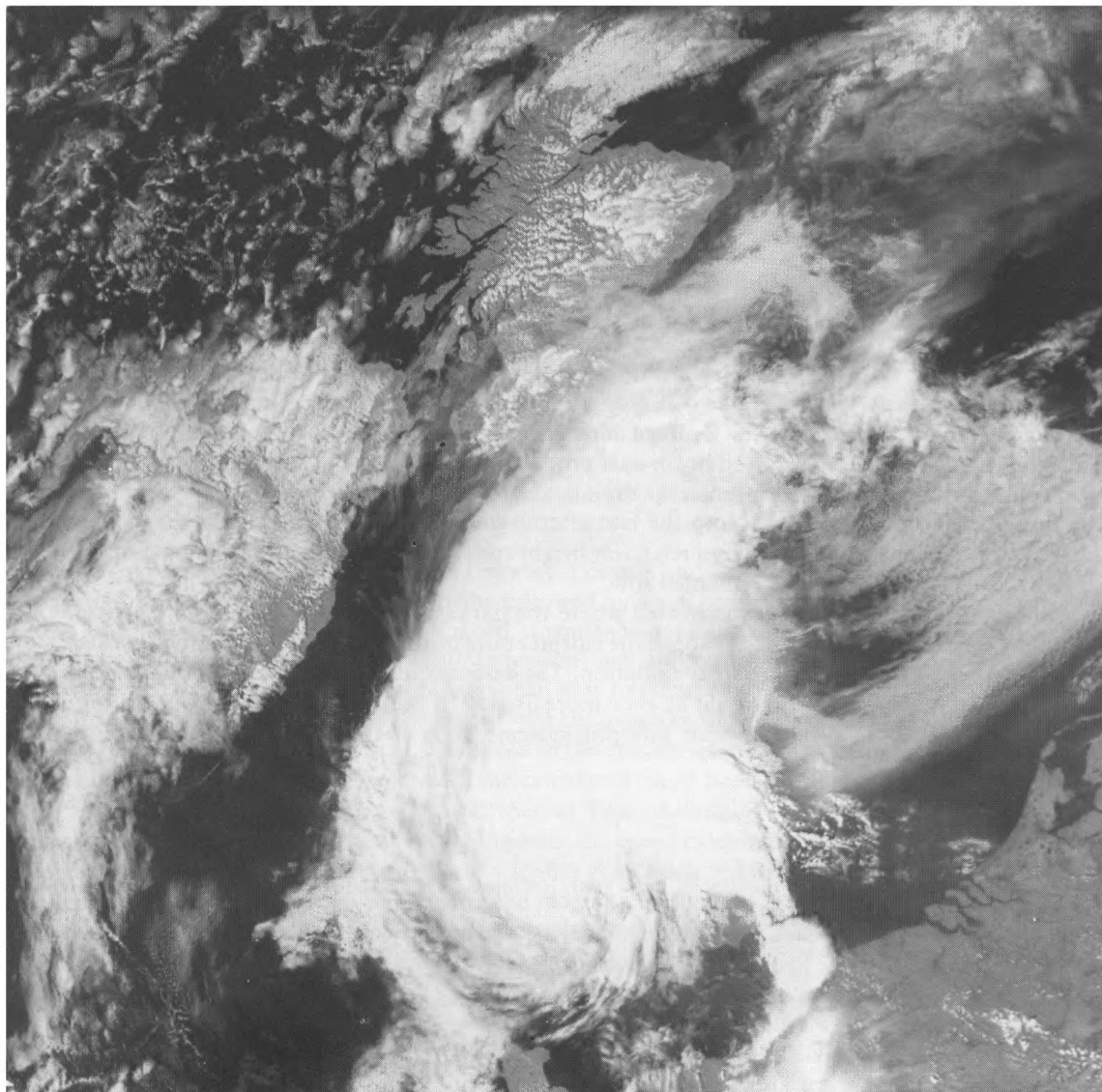
Conclusions

The storms of 6 August 1981 were of exceptional darkness and duration, which resulted in solar irradiance levels of less than the 1% percentile and rainfall intensities with return period of over 100 years in many places in south-eastern England. From the evidence provided by the radiation values of twelve sites there were two major storm systems: the first arrived at Bracknell at about 0730 GMT, moved north and weakened over Bedfordshire and Cambridgeshire. The second system arrived at Bracknell at 0945 GMT and moved north-east producing lower values of global radiation than the first and being associated with the spectacular thunderstorms and blackness of the sky widely reported in the Press. The storms lasted well into the late afternoon and probably dissipated over the North Sea after sunset. They were separated by a relatively bright spell in the east (e.g. East Malling) but in the west (e.g. Bracknell) the irradiance remained low.

Although the radiation values indicated where the darkest areas of the storms were, agreeing well with the rainfall data, the detailed shape of the storms could not accurately be determined because of the small number of sites recording solar radiation. The assessment of global radiation patterns in areas away from south-east England would be even more limited by the sparsity of the network, although the variation of radiation with large scale synoptic systems, such as fronts, could still be determined.

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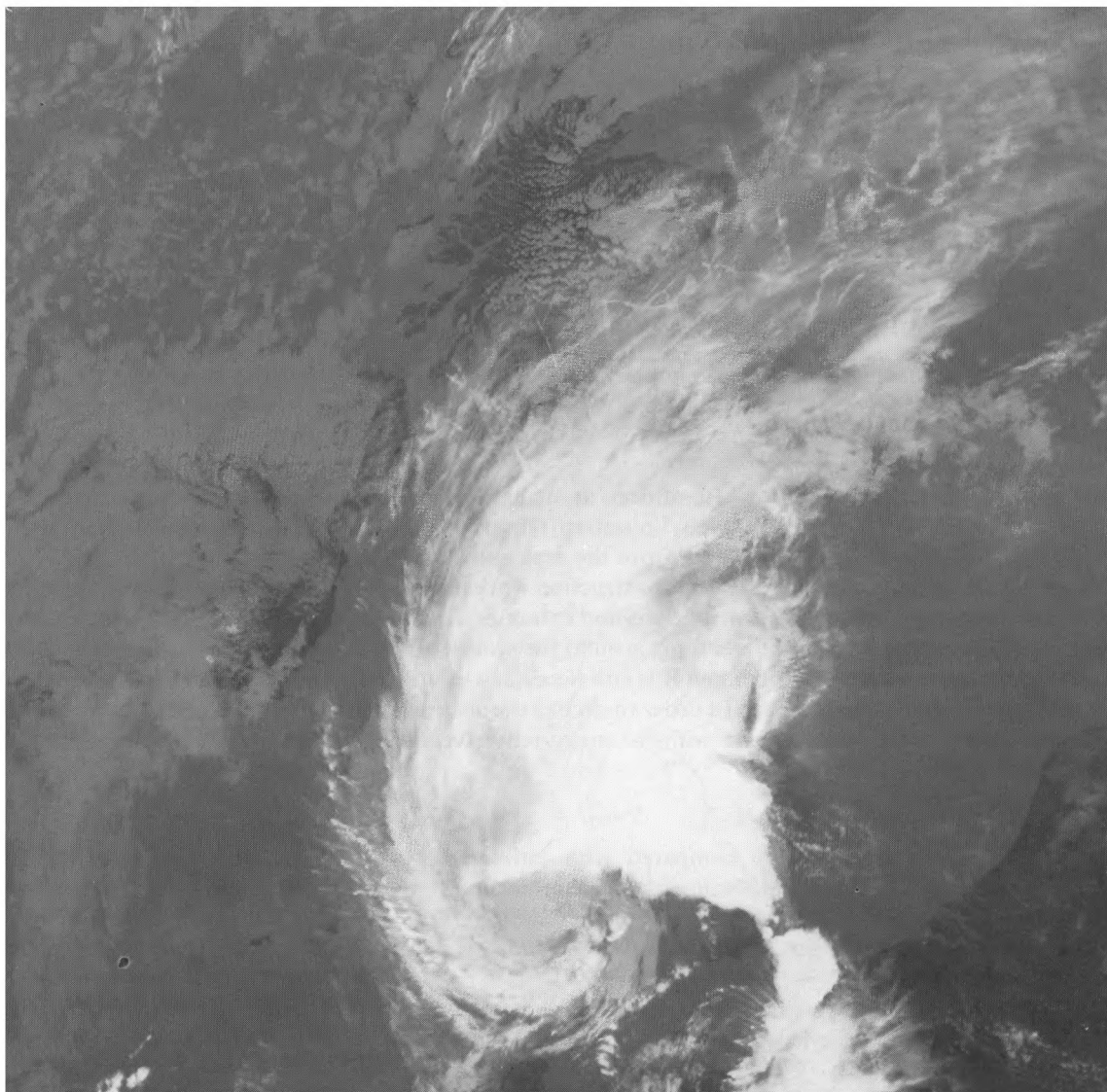
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Photograph by courtesy of Dundee University

(a)

Satellite (NOAA 7) photographs taken at 1402 GMT on 6 August 1981 (a) visual (b) infra-red. The horizontal boundary of the highest and thickest cloud, which caused the cut-off in radiation at the surface discussed in the paper by R. J. Armstrong on p 200, is clearly shown in the infra-red photograph. There is also a suggestion of a minor circulation at lower levels over Dorset; surface observations, however, showed only a minor trough.



Photograph by courtesy of Dundee University

(b)

Wave heights estimated by the Voluntary Observing Fleet compared with instrumental measurements at fixed positions

By Anne E. Graham

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Summary

Measured wave heights from twelve locations are compared with visual estimates made by the deck officers of merchant ships adjacent to the site. The methods of measurement and estimation are discussed together with the difficulties encountered in comparing the two different types of wave heights produced and in deriving extremes.

1. Introduction

For many years estimates of wave conditions at sea have been made by the deck officers of merchant ships. These merchant ships form the Voluntary Observing Fleet (VOF) which provides valuable meteorological and climatological data from the seas and oceans of the world.

In recent years the increase in offshore construction work has produced a need for knowledge of wave conditions including frequency distributions and extremes. Instrumentally measured wave heights are now available from a number of locations around the world, but generally these records are for short and often incomplete periods only and it is still necessary to utilise the many years of estimated data already archived on a global basis. In order to do this the accuracy of the estimates of wave conditions must be determined by comparison with the measured wave data.

2. Data sources

Measured wave heights were compared with estimated wave heights from the $2^{\circ} \times 2^{\circ}$ areas surrounding each site at which instrumental measurements were made. The positions of these 12 sites are shown in Fig. 1(a) together with Ocean Weather Stations (OWS) 'I' and 'J'. Fig. 1(b) shows the areas around each instrumental site, except for OWS 'L' which is an oceanic site and well exposed from all directions.

The instrumental data were of significant wave heights whereas the visually estimated data comprised wind wave and swell wave heights.

(a) Visually estimated wave heights

Visually estimated data were available for the period 1961–1978 and consisted of wind wave and swell wave heights, randomly distributed in space and time throughout the area.

(i) *Observations of wave heights.* The deck officer is required to report estimates of both wind wave and swell wave heights when it is possible to distinguish between the two. The actual instructions for making these estimates can be found in more detail in the *Marine observer's handbook* (Meteorological Office 1977), but briefly the estimate should be made from observation of at least 20 waves, the method depending on whether the length of the wave is longer or shorter than the length of the ship. It is noted that in general there is a tendency to overestimate the height of waves with short wavelengths and underestimate those with long wavelengths. At night or in poor visibility the observer has difficulty in observing wave heights and often will be unable to report on them.

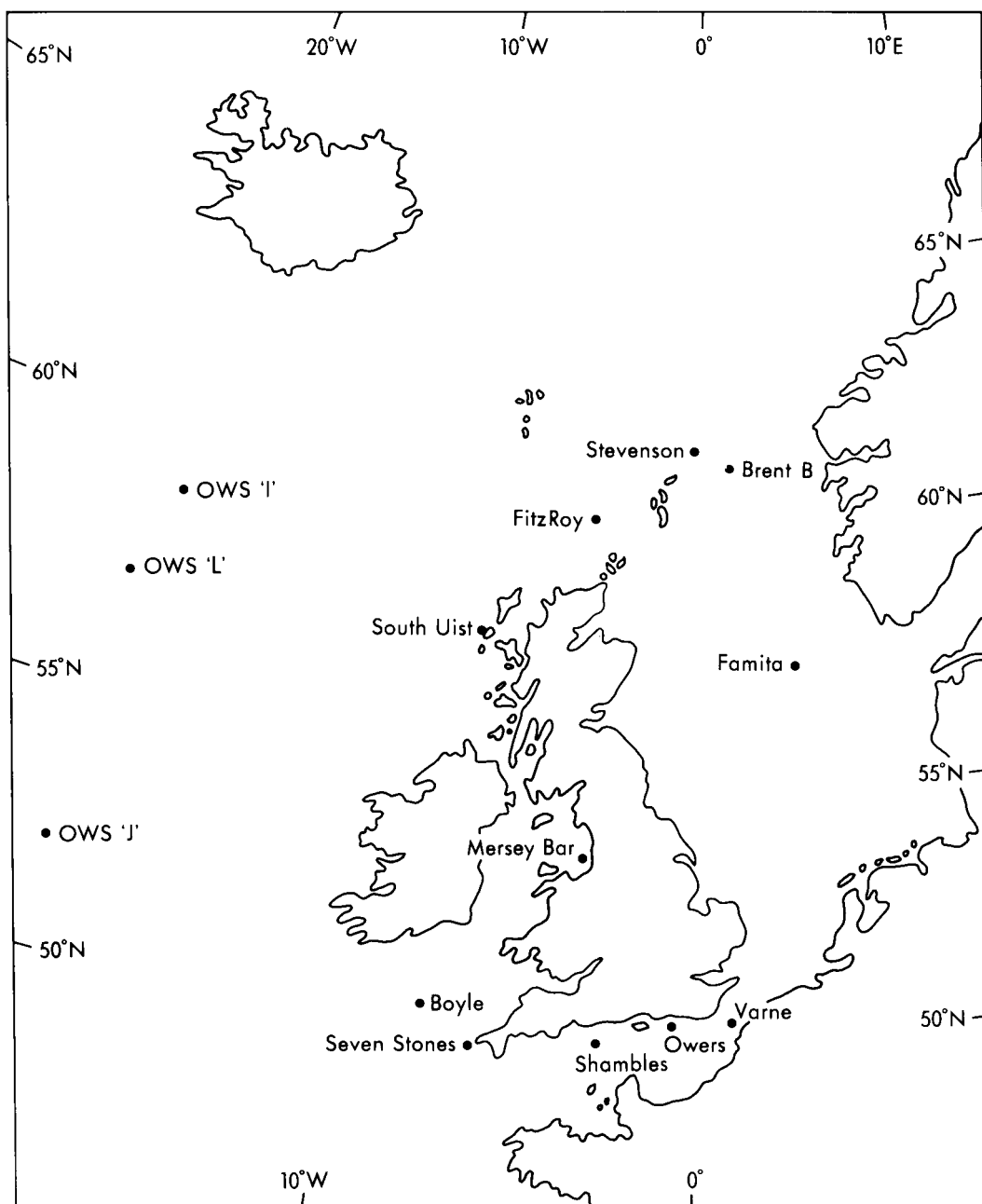


Figure 1(a). Positions of the fixed stations used in the analysis.

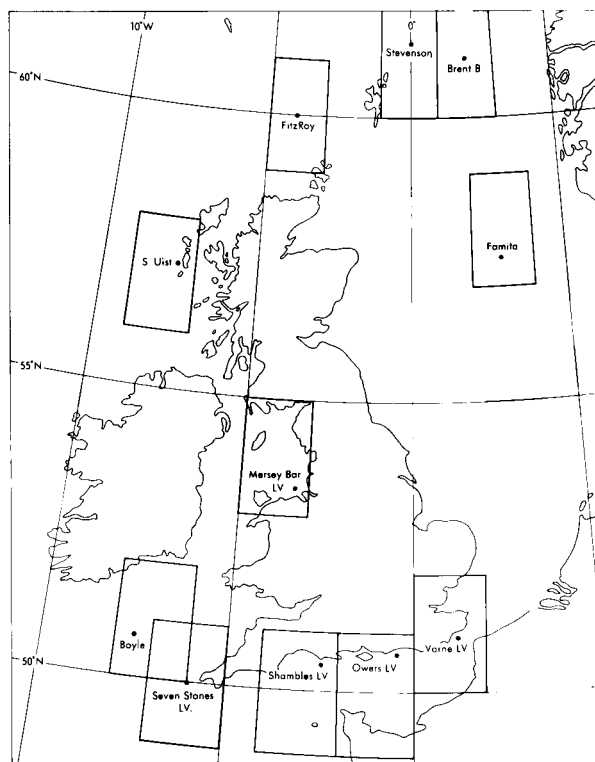


Figure 1(b). Positions of fixed stations and areas from which the VOF data were taken.

Visual estimates of wave heights are made in the same way by observers on board ships at the OWS. The data sets of wave heights from the OWS consist of regular observations made at the same location. A comparison of such data with the randomly observed data from the VOF was made for the three OWS, 'I', 'J' and 'L'. For OWS 'L' the regularly observed estimates could also be compared with the instrumentally measured wave heights available at that site.

For comparison with the measurements of significant wave heights it is necessary to combine wind wave and swell wave estimates since it is this combination of all wave conditions that equates with the significant wave. An equivalent significant wave height, here called the resultant, R , can then be found using a formula derived by Nordenstrøm (1971):

$$R = 1.68c^{0.75}$$

where

$$c = \{(\text{wind wave})^2 + (\text{swell wave})^2\}^{1/2}$$

Consequently, only those occasions when both wind wave and swell waves had been reported were used in the analysis.

(ii) *Coding of wave heights.* The period covered by the VOF data used in this study was 1961–1978; this period includes a change of coding practice on 1 January 1968.

The observer is required to report the estimated wave height to the nearest half metre using a code figure, but before 1968 the wave heights were reported using code figures 0–9 only. This required an addition of 50 to the estimation of the wave direction for wave heights greater than 4.5 m. (See Table I(a).)

Table I(a). *Wave height code table pre-1968*

Code figure	Height		Code figure	Height	
	metres	feet		metres (50 added to wave direction)	feet
0	< 0.25	< 1	0	5	16
1	0.5	1.5	1	5.5	17.5
2	1	3	2	6	19
3	1.5	5	3	6.5	21
4	2	6.5	4	7	22.5
5	2.5	8	5	7.5	24
6	3	9.5	6	8	25.5
7	3.5	11	7	8.5	27
8	4	13	8	9	29
9	4.5	14	9	9.5	30.5

Note. The range of heights covered by a number is half a metre; e.g. number 3 applies to waves whose heights are between $1\frac{1}{4}$ m and $1\frac{3}{4}$ m (4 feet and $5\frac{3}{4}$ feet).

From the beginning of 1968 code figures 01–49 were used (see Table I(b)). This did not involve changes to the report of wave direction for any height.

The wind wave and swell wave height distributions were examined for the pre- and post-1968 periods, but no evidence was found that there had been a marked reduction in reports of five metre wave heights before the code change compared with those made afterwards. The major difference between the pre- and post-1968 distributions is the lower number of observations in the former period. In 10 of the 12 areas the pre-1968 observation count for the resultant wave heights was less than half that for post-1968, and just over half for the remaining two. The pre-1968 period covers only 7 years whereas 11 years of data were available post-1968. This could account for some, but not all, of the discrepancy.

Another change in the coding practice was that before 1968 the same code was used for both wind waves and swell. The first wave group reported referred to the wind waves, and subsequent groups to swell. Since 1968 one code has been used for the wind waves and a different one for swell, with two or more groups being used in the event of more than one swell wave train. This may have encouraged the reporting of a separate swell wave and may account for the increased number of resultant waves in the post-1968 period.

(b) *Instrumental wave heights*

The wave height derived from instrumental recordings is known as the significant wave height, h_s . Originally this was defined as the mean height of the highest one third of waves sampled. It is now defined (Tann 1976) in terms of the variance m_0 of the sea surface elevation such that:

$$h_s = 4\sqrt{m_0}.$$

Table I(b). *Conversion table (feet/metres) with reference to height of waves as used after 1 January 1968.*

Feet	Metres	Code figure	Feet	Metres	Code figure
1	0.3	1	41	12.5	25
2	0.6	1	42	12.8	25
3	0.9	2	43	13.1	26
4	1.2	2	44	13.4	27
5	1.5	3	45	13.7	27
6	1.8	3	46	14.0	28
7	2.1	4	47	14.3	29
8	2.4	5	48	14.6	29
9	2.7	5	49	15.0	30
10	3.1	6	50	15.2	30
11	3.3	7	51	15.5	31
12	3.7	7	52	15.8	32
13	4.0	8	53	16.1	32
14	4.3	9	54	16.5	33
15	4.6	9	55	16.8	34
16	4.9	10	56	17.1	34
17	5.2	10	57	17.4	35
18	5.5	11	58	17.7	35
19	5.8	12	59	18.0	36
20	6.1	12	60	18.3	36
21	6.4	13	61	18.6	37
22	6.7	13	62	18.9	38
23	7.0	14	63	19.2	38
24	7.3	15	64	19.5	39
25	7.6	15	65	19.8	40
26	7.9	16	66	20.1	40
27	8.2	16	67	20.4	41
28	8.5	17	68	20.7	41
29	8.8	18	69	21.0	42
30	9.1	18	70	21.3	43
31	9.5	19	71	21.6	43
32	9.7	19	72	21.9	44
33	10.1	20	73	22.3	45
34	10.4	21	74	22.6	45
35	10.7	21	75	22.9	46
36	11.0	22	76	23.2	46
37	11.3	23	77	23.5	47
38	11.6	23	78	23.8	48
39	11.9	24	79	24.1	48
40	12.2	24	80	24.4	49

Wave heights can be measured using several kinds of device. Those involved here are the waverider buoy (WRB) and the shipborne wave recorder (SBWR).

The WRB contains an accelerometer which measures vertical displacement as the buoy rides the waves. Thus, it records the variability of the sea surface elevation about the mean sea level.

The SBWR consists of two pairs of accelerometer and pressure units. These are located one on each side of the ship, approximately on the pitch axis. When the waves are of longer wavelength than the length of the ship the accelerometers measure vertical displacement as in the WRB. For waves with wavelength shorter than the length of the ship, the pressure units detect variations in pressure as the waves pass by.

The precise method of obtaining the significant wave heights from the recording device depends on the agency responsible. As an example, for wave recorders belonging to the Institute of Oceanographic

Sciences, the waves are recorded over an approximate 15-minute period every three hours. Significant wave heights are then calculated using the Tucker-Draper method (Tann 1976).

Table II lists the stations with measured wave data together with the period of measurement and number of observations. The corresponding numbers of resultant estimated wave observations for the 18-year period 1961–1978 are also shown.

Table II. *Availability of measured wave data and estimated data used in the analysis*

Station	Type of measurement	Period of measured data	Number of measured observations	Number of estimated observations during 1961–78
Famita	SBWR	1969–77	8566	8183
OWS 'L'	SBWR	1975–77	5188	2835
Seven Stones LV	SBWR	1968–78	24369	11899
Mersey Bar LV	SBWR	1965–66	2919	1475
Shambles LV	SBWR	1966–68	2920	12302
Varne LV	SBWR	1965–66	3146	9465
Owers LV	SBWR	1968–70	4426	10535
Stevenson	WRB	1973–76	6028	5520
Stevenson	SBWR	1973–76	5370	5520
FitzRoy	WRB	1973–76	4589	2972
FitzRoy	SBWR	1973–76	5008	2972
Boyle	WRB	1974–77	7175	6032
Boyle	SBWR	1974–77	7029	6032
South Uist (Offshore)	WRB	1978–80	9342	1665
South Uist (Onshore)	WRB	1978–80	3714	1665

For three of the sites there are two data sets, one from WRB measurements and one from SBWR measurements. These three sites are Stevenson, FitzRoy and Boyle, manned by ships sponsored by the United Kingdom Offshore Operators Association (UKOOA).

At the South Uist site there are two data sets of WRB measurements, one from a position 10 miles off shore in 42 m of water and the other 5 miles off shore in 14.5 m of water.

3. Analysis of data

(a) *Distributions of resultant estimated wave heights*

As with most meteorological data used for climatological purposes some quality control is necessary. The normal sequential checks and areal comparisons are difficult for ships of the VOF because of their random distribution in space and time. Comparison of the wave heights with the corresponding wind speed estimates provides a rather crude method of quality control, but one which eliminates the more obviously incorrect wave heights.

However, there were still several values in each data set producing a distribution with a long 'tail' of higher wave heights. In each case this tail consisted of resultant wave heights derived from estimates made in the post-1968 period. The most likely reason for this is the larger sample of wave heights present in the longer post-1968 period, allowing a greater likelihood of sampling more high waves.

The percentage frequency distributions of the resultant wave heights for each site are shown in Figs. 2(a)–2(f). With the exception of OWS 'L' with the mode at three metres, all the distributions have the mode at two metres and contain some zero wave heights.

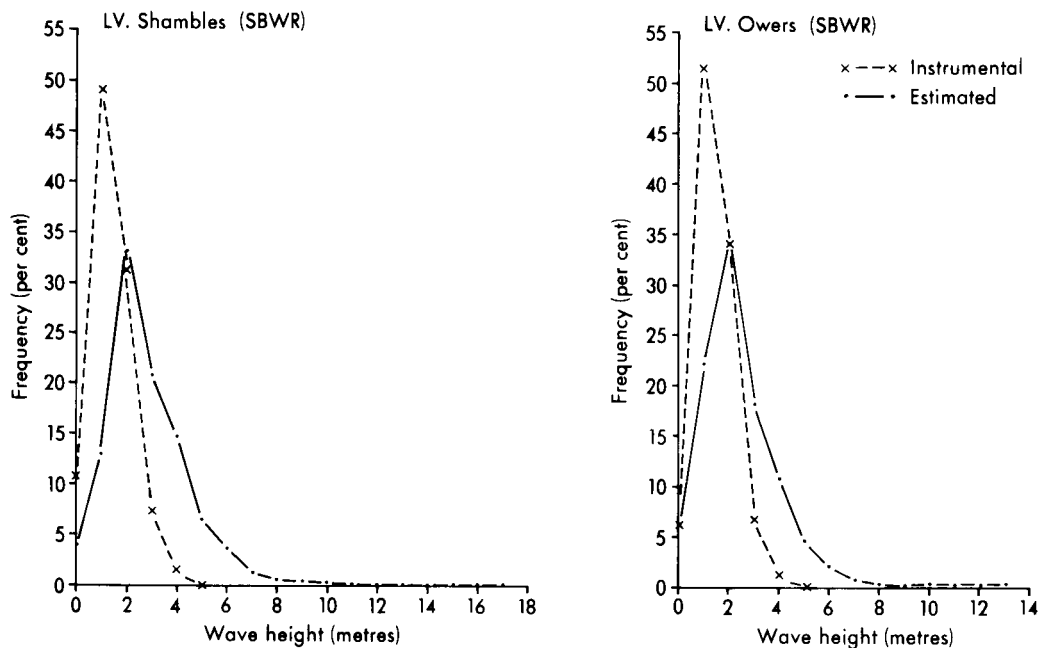


Figure 2(a). Wave-height frequency distributions for LV Shambles and LV Owers compared with those for co-located VOF ships within the $2^\circ \times 2^\circ$ area around the fixed position.

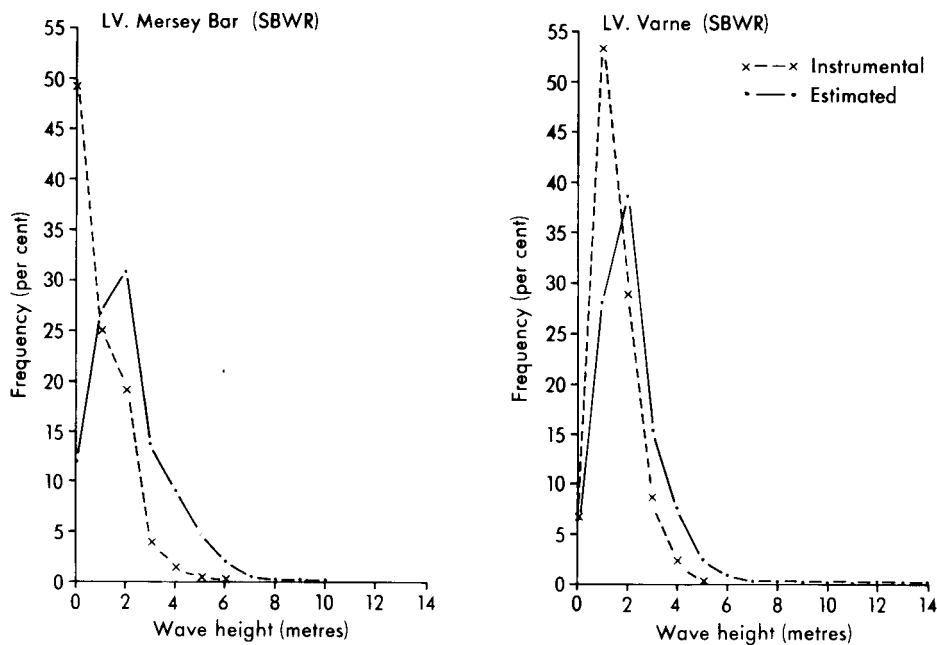


Figure 2(b). Wave-height frequency distributions for LV Mersey Bar and LV Varne compared with those for co-located VOF ships within the $2^\circ \times 2^\circ$ area around the fixed station.

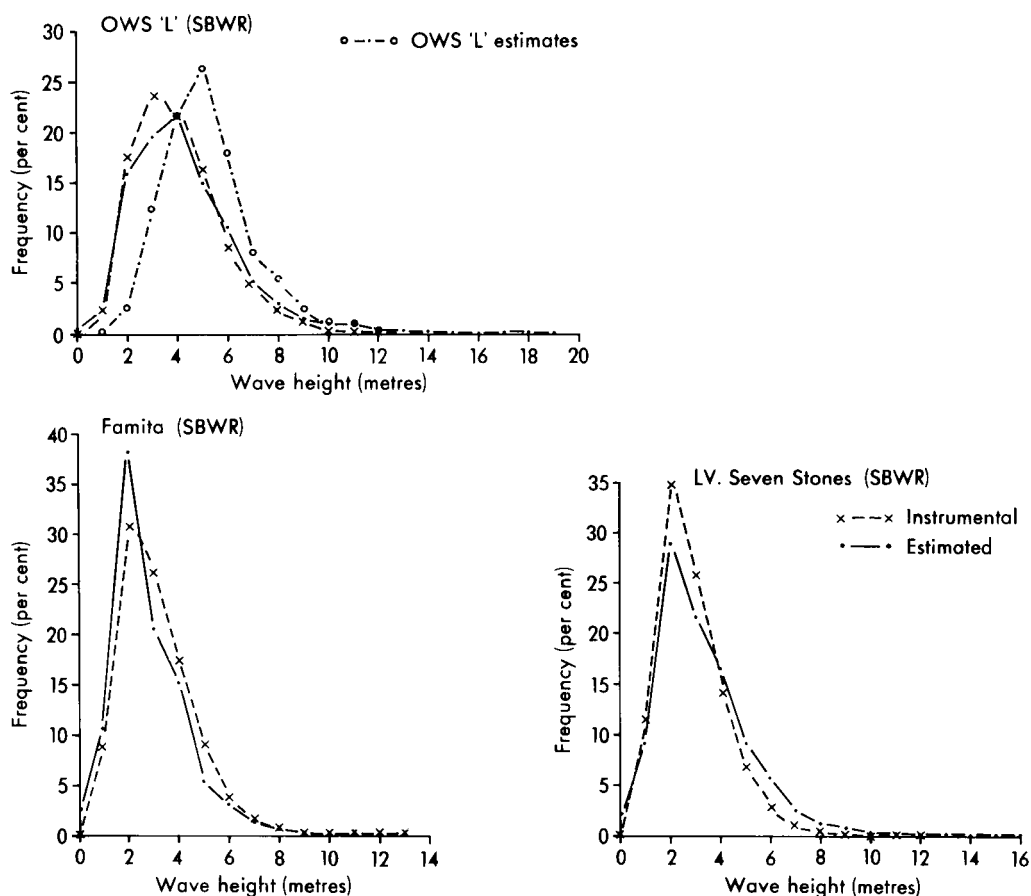


Figure 2(c). Wave-height frequency distributions for OWS 'L', LV Seven Stones and Famita compared with those for co-located VOF ships within the $2^{\circ} \times 2^{\circ}$ area around the fixed position.

(i) *Visual estimates of wave height by OWS observers.* There are three data sets available for comparison at the OWS 'L' site: the measured (SBWR) significant waves, the estimates made by the VOF in the surrounding area, and those made by the OWS observers. Fig. 2(c) shows the percentage frequency distributions of the wave heights in these three data sets. The distributions of measured wave heights and the resultant waves derived from the VOF estimates agree reasonably well, but that for the OWS estimates is rather different having a mode of five metres. Visual estimates from OWS 'I' and 'J' were examined to check that the difference was not due to the short period of data available from OWS 'L' (1975–1979). The distributions of resultant wave heights from OWS 'I' and 'J' spanned the period 1961–1975 and the corresponding VOF estimated wave heights the years 1961–1978. Fig. 3 shows that for these locations also the OWS mode is higher than that of observations from the VOF. Examination of distributions of simultaneously observed data showed the same difference, thus eliminating the possibility that it is due to the comparison of regularly observed with randomly observed data.

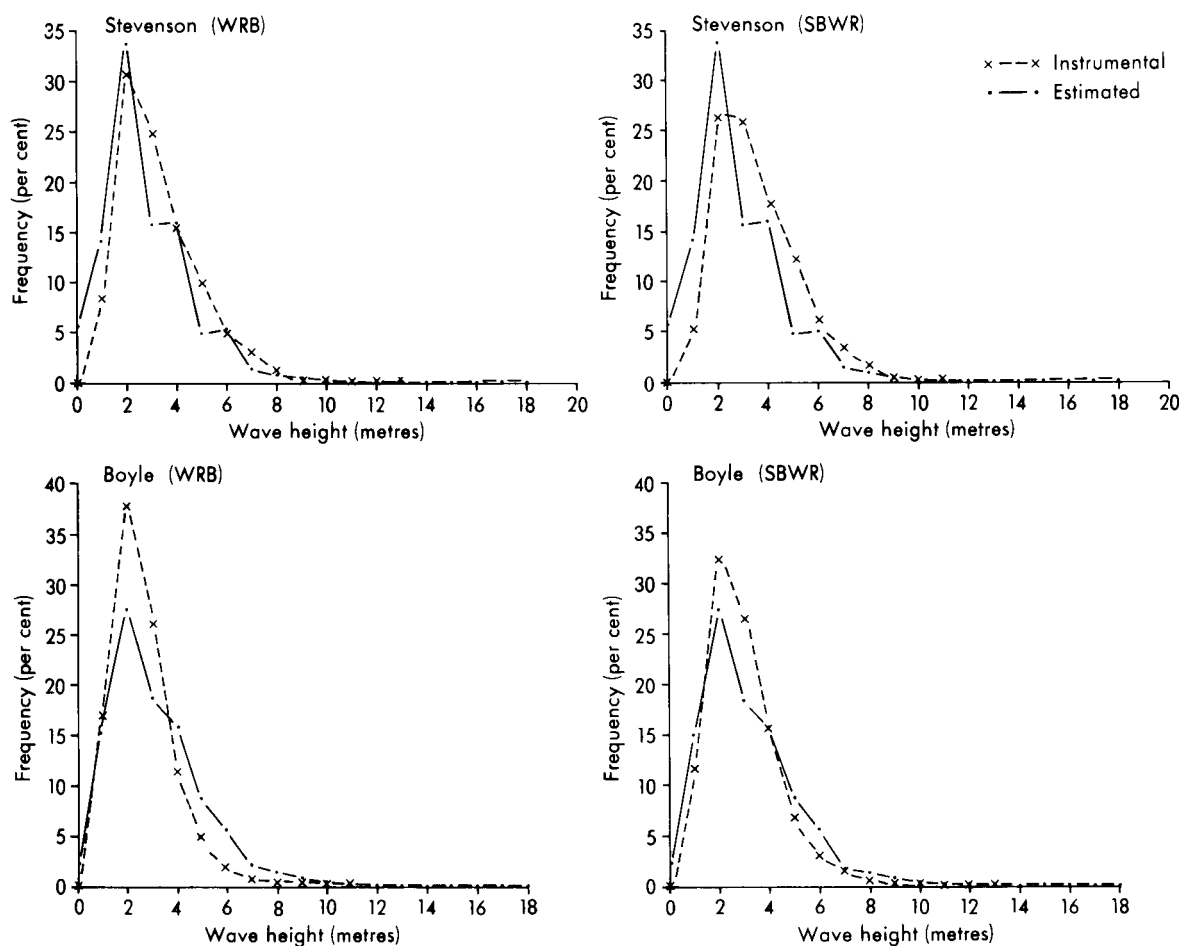


Figure 2(d). Wave-height frequency distributions for Stevenson and Boyle compared with those for co-located VOF ships within the $2^{\circ} \times 2^{\circ}$ area around the fixed station.

Informal discussion with observers from the Meteorological Office who have worked on ships manning OWS indicates that the opinion of the deck officer is usually sought when estimating wave height. Consequently, this difference is unlikely to be due to the inexperience of the observers of conditions at sea.

Another possible explanation is that the ships at the OWS do not usually steam in wind speeds below Beaufort force 5. When this wind speed is exceeded the ships need to steam to remain on station. When 'stationary' the ship will be subjected to much more pitching and rolling than when steaming. It is possible that wave heights are overestimated when the ship is stationary and this could explain the low percentages of zero and one metre heights and also the shift in the peaks of the distributions. The point at which it becomes necessary to steam to stay on station will vary with the state of the sea, and so Beaufort force 5 is only an estimate. Unfortunately, there is no indication of whether or not the ship was steaming when an observation was made and so this explanation cannot be tested.

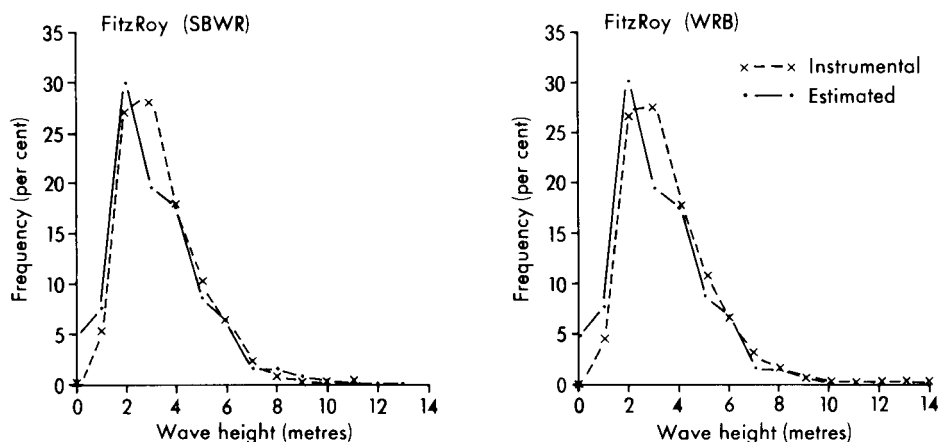


Figure 2(e). Wave-height frequency distributions for FitzRoy compared with those for co-located VOF ships within the $2^{\circ} \times 2^{\circ}$ area around the fixed station.

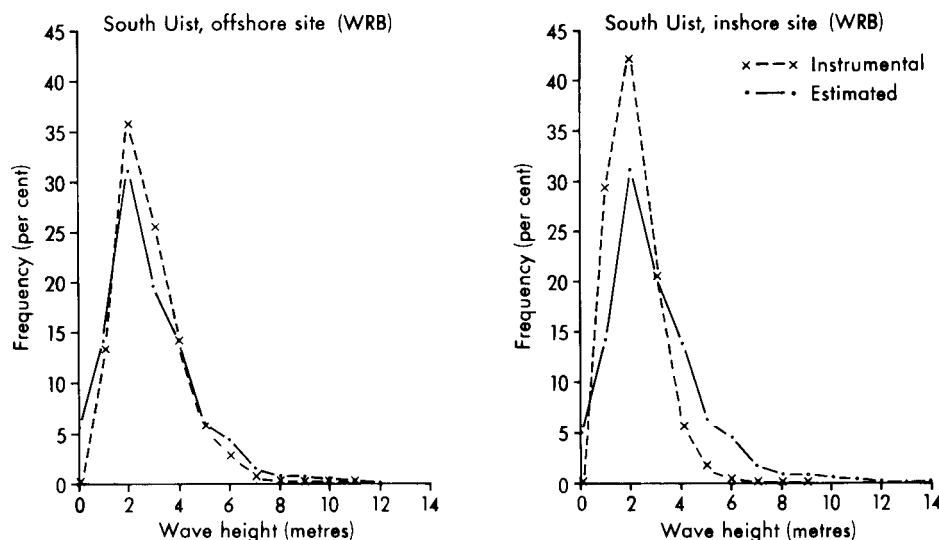


Figure 2(f). Wave-height frequency distributions for South Uist compared with those for co-located VOF ships within the $2^{\circ} \times 2^{\circ}$ area around the fixed station.

(ii) *Period of VOF data used.* The resultant wave height distributions derived from estimates made by the VOF all cover the period 1961–1978. The distributions of measured data with which the resultant waves were to be compared covered varying periods as shown in Table II. Values for Brent B are not shown since the WRB data is still subject to confidentiality rules. Because of the short periods of measured data involved, the number of resultant waves available in the equivalent periods was too small for reasonable comparison, and so for each data set the distribution of waves from the whole period of VOF data was used. The similarity of the wind climatologies at the sites for both the short and long periods indicated that such comparisons were reasonable.

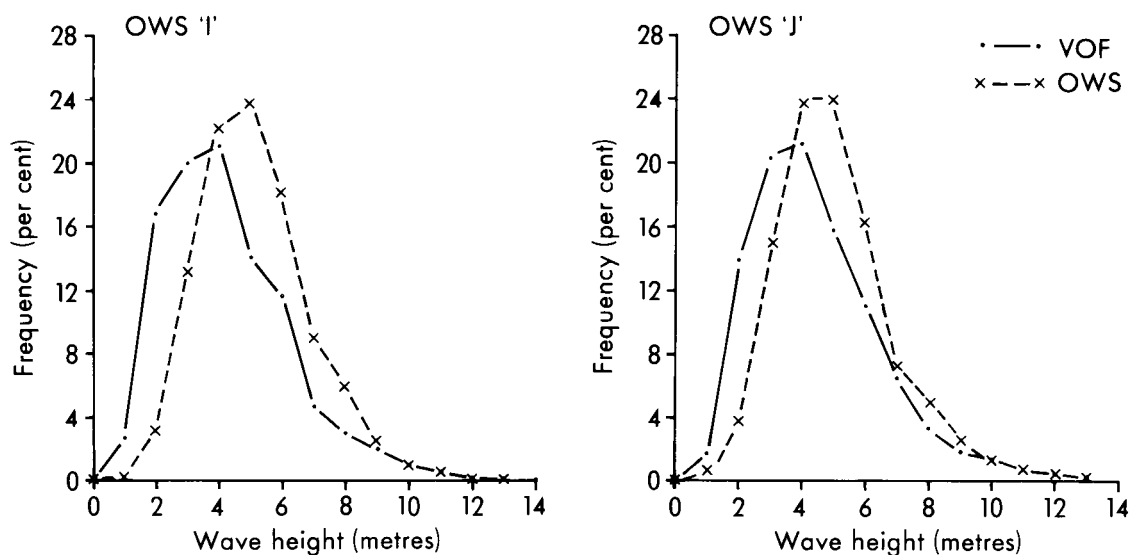


Figure 3. Wave-height frequency distributions for OWS 'I' and OWS 'J' compared with those for co-located VOF ships within the $2^{\circ} \times 2^{\circ}$ area around the OWS.

(b) Distributions of instrumental significant wave heights

The percentage frequency distributions of instrumentally measured significant wave heights are also shown in Figs. 2(a)-2(f). The four light-vessels (LVs) Shambles, Varne, Owers and Mersey Bar have distributions with rather different characteristics from the others. Here the measured data are compared with estimates made over a large area. Many of the estimates will have come from comparatively more exposed positions (see Fig. 1(b)). The data sets for these LVs cover very short periods, one year for each except Owers which covers almost two years. The other LV, Seven Stones, is in a more exposed position, as are the two South Uist sites, although both are fairly close inshore. The South Uist site five miles from the coast does show a slightly higher percentage of low wave heights as would be expected.

For Seven Stones LV and the two South Uist sites there were no zero wave heights recorded and the mode of each distribution occurs at two metres. At all sites, except for the four LVs already discussed, no zero wave heights were recorded. The distributions for Famita, Stevenson (WRB) and Boyle (both SBWR and WRB) also have the mode at two metres. Except for OWS 'L', the remaining sites have produced distributions of significant wave height with no clear peaks, but similar percentage frequency of occurrence for wave heights of two and three metres. For OWS 'L' there was a low percentage frequency for wave heights of one metre with the mode at four metres. OWS 'L' is the only oceanic position considered in this study and the higher modal wave height reflects the different regime.

All of these data sets cover only short periods of time. There are only two with more than four years of data; Seven Stones LV, 1968-1978, but with data for the whole of 1970 and twenty other complete months missing; Famita has data covering a period of nine years, but the bulk of the measurements were made during the winter months and only 32% of the possible total number of observations were available.

Figs. 2(a)-2(f) show that the distributions of instrumentally measured and visually estimated wave heights differ at all sites. The bulk of the observations agree reasonably well, but large differences occur in the lower and higher ranges. The greatest discrepancies occur at the LVs Shambles, Varne, Owers and Mersey Bar. The VOF data for these locations were taken from the surrounding area, often from more exposed positions some distance from the instrumental site.

(c) *Extreme-value analysis*

For the design and planning of offshore structures it is necessary to have an estimate of the extreme sea conditions likely to be experienced during the expected lifetime of that structure. Extreme values are estimated by fitting a distribution to the available data, and extrapolating the tail of the distribution to the value having a cumulative probability of exceedance corresponding to the return period required. This gives the value expected to be exceeded, on average, once in N years, where N is the return period.

Many distributions used to estimate the extreme values require the identification of annual maxima. This means that long periods (more than ten years) of regularly observed data are required. Consequently, these methods cannot be used for estimating extreme wave heights from the distributions shown in Figs. 2(a)-2(f) since the measured data available cover only a few years and the estimated data are not regularly observed. The method used here to estimate extreme wave heights was to fit a 3-parameter Weibull distribution to the whole spectrum of data.

In practice, when fitting a Weibull distribution to wave heights, it is often necessary to alter subjectively the boundaries of the frequency distribution of the data. This is particularly so when dealing with data collected from the VOF which are random and therefore may give an irregular and unrepresentative distribution in the higher frequency ranges. It has already been noted that, even after some quality control to remove the obviously incorrect wave heights, there is still a long tail of greater wave heights. Where some subjective alteration appeared to be required the estimated extreme values were very similar to those estimated from the unaltered distribution.

This problem did not occur with the distributions of measured wave heights; these were quite smooth throughout the ranges used.

4. Results

The 1 in 50-year extremes derived from the significant and resultant wave height distributions are shown in Table III. The whole 18-year period of data was used for the resultant wave height analysis. The extremes estimated from the significant wave heights measured by SBWR were converted to the equivalent WRB height (Graham *et al.* 1979).

The results for the four LVs, Shambles, Varne, Owers and Mersey Bar are not comparable because of the difference in the distributions due to the large area from which the VOF data were taken which covered more exposed seas than those at the LV sites. It is probable that the same reason also accounts for the large difference in estimated extremes at the 'inshore' South Uist site.

In every other case the extremes estimated from the distributions of resultant wave heights are higher than those derived from the significant wave heights. The mean difference is five metres. This represents considerable difference in the 1 in 50-year extreme wave height between the resultant wave height distributions and the measured waves. However, it is important to remember that the measured data sets cover only very short periods and it may be that more extreme situations would be sampled over longer periods reducing the apparent over-estimation of the extreme conditions derived from the visual data. The variability of the percentage frequency of occurrence of wave heights is illustrated in Fig. 4. This figure shows the percentage frequency of occurrence of wave heights in two ranges for ten years of data from the LV Seven Stones. It is apparent that the choice of data from the years 1972-1974 would indicate different long term characteristics from those derived from data from the years 1975-1978.

Table III. *1 in 50-year extreme values for all data sets of measured wave heights and the corresponding VOF resultant wave heights*

Station	Extremes derived from significant waves	Height metres	Extremes derived from resultant waves
Famita	13		16
OWS 'L'	17		19
Seven Stones LV	12		17
Mersey Bar LV	8		12
Shambles LV	5		17
Varne LV	5		16
Owers LV	5		15
Stevenson (WRB)	14		21
Stevenson (SBWR)	13		21
FitzRoy (WRB)	14		16
FitzRoy (SBWR)	14		16
Boyle (WRB)	12		20
Boyle (SBWR)	12		20
South Uist (Offshore)	11		15
South Uist (Onshore)	9		15

Extreme values were also derived from the distributions of resultant wave heights obtained from visual estimates made by OWS observers. The 1 in 50-year extremes are shown in Table IV together with the extremes estimated from the corresponding VOF data. Despite the shift to a higher modal wave height the extremes estimated from the OWS resultant wave heights are lower than those from the VOF resultants. The 1 in 50-year extreme value of 17 metres derived from the instrumental data at OWS 'L' indicates that the OWS resultant distribution underestimates the extremes.

Table IV. *1 in 50-year extreme values for OWSs and VOF resultant waves*

Station	Extremes derived from OWS resultant waves	Height metres	Extremes derived from VOF resultant waves
OWS 'L'	15		19
OWS 'I'	15		19
OWS 'J'	14		19

5. Conclusion

With a few exceptions, the measured significant wave heights that are available cover very short periods of time and so, despite the high quality of the measurements, their use is limited both climatologically and especially for the estimation of extremes.

The main advantage of the estimated data is that they cover long periods of time and are available for all sea areas. Individually, these data are of much poorer quality being far less accurate than measurements of wave height. However, the bulk of each distribution is probably sufficiently accurate to give an estimate of the general wave climatology. Unfortunately, because of the difficulties in estimating sea and swell separately, many of the resultant wave heights will be incorrect representations

of conditions at the time of observation. The distributions are markedly affected in the higher wave height ranges and consequently difficulties are again created in the estimation of extremes.

Obviously, neither the instrumentally measured data available at present, nor the visual estimates are sufficient for current needs if used separately. Where possible both kinds of data should be used to give the most complete picture. When the visual estimates of wave height are the only source of information available they should be used with caution, bearing in mind the differences known to exist between estimated and measured data especially the tail of high wave heights of doubtful accuracy. Instrumental records should equally be used with caution because of the short length of record and their incompleteness.

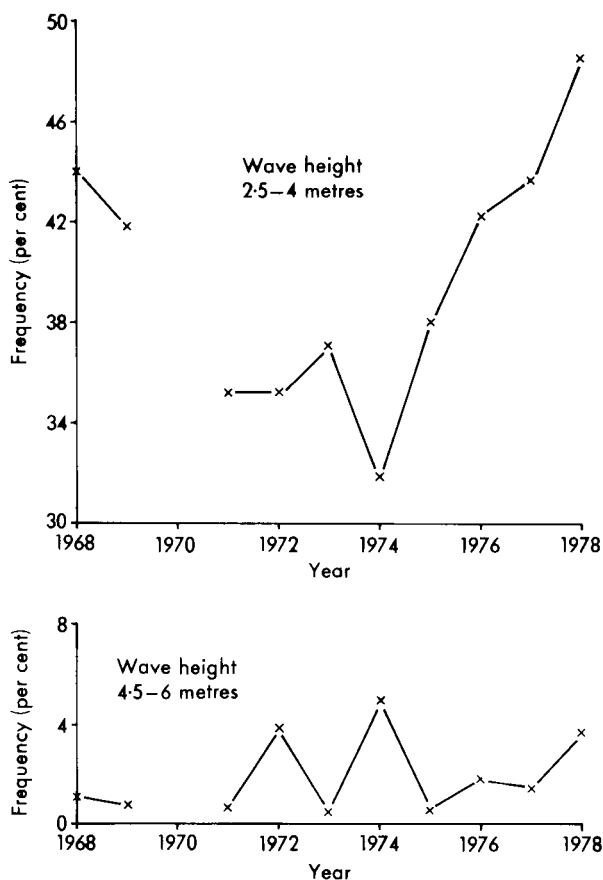


Figure 4. Percentage frequency of waves in each year at LV Seven Stones for wave heights 2.5-4 m and 4.5-6 m inclusive.

Earlier work comparing visually estimated wind speeds with instrumental measurements concluded that the winds reported by the VOF can be used with confidence to derive a wind climatology where no reliable measured data are available (Graham 1982). The National Maritime Institute is developing a wave climate model by combining visually estimated wind speeds and wave heights, together with measured wind and wave data and wind-wave relationships.

However, such a modelled wave climate does not provide a solution to the problem of estimating extreme wave heights. Extremes do not occur in average conditions and therefore cannot be described by models based on average relationships.

6. Acknowledgements

This work is part of a wave climate synthesis project carried out in collaboration with the National Maritime Institute with the support of the Maritime Technology Committee.

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World Meteorological Organization Commission for Agricultural Meteorology (CAGM) Eighth Session, Geneva, 21 February — 4 March 1983

By N. Thompson

(Meteorological Office, Bracknell)

The need to increase food production, both to keep pace with the rising world population and to raise food intake to proper levels of nutrition, is providing mankind with one of its greatest challenges. Since the last meeting of the Commission in Sofia in 1979 the general trend of agricultural output has continued upwards, but in some countries the production per head of population has actually fallen in recent years. With this background, one of the most important objectives in world agricultural meteorology now is to transfer effectively the experience that continues to be accumulated in developed nations to those countries suffering food shortages and lacking at present the knowledge and organization to reap the full benefits that application of agricultural meteorology can confer.

This theme dominated the Eighth Session of the Commission and is reflected in the resolutions passed for work in the next intersessional period. For example, of the seven Working Groups established to report on various topics within this period, all but one (the President's Advisory Group) have terms of reference that include specifically the agricultural and technical problems of Third World nations; a different response from the Commission in the present circumstances would have been unthinkable.

The topics which will be studied by the Working Groups, and by a number of specialist rapporteurs who were also appointed at the meeting, range from applications of remote (satellite) sensing to agriculture through to the benefits to be derived from quantifying the experience behind, and further developing the methods of, microclimatic manipulation and management which are features of traditional farming; successful completion of all of these tasks will bring very large benefits to the poorer countries in particular.

In view of the great emphasis on Third World problems at the meeting, it is appropriate to record that the Commission unanimously supported a resolution which indicated in some detail the important role that agrometeorology has in developed nations also; all present recognized that without the progress which continues to be made in the better-endowed countries, and without the efforts that these countries make to adapt and transfer this technology to less fortunate nations, the prospects for world food security would be bleak indeed.

The United Kingdom delegates were Mr C. V. Smith, who was elected to the President's Advisory Working Group, and Dr N. Thompson, who was appointed Chairman of the Working Group on Agrometeorological Aspects of Operational Crop Protection Measures.

Review

Carbon dioxide review: 1982, edited by William C. Clark. 210 mm × 280 mm, pp. xix + 469, *illus.* Oxford University Press, 1982. Price £22.50.

The 'Carbon dioxide review: 1982' is intended 'to appeal to a wide cross-section of scientists, policy advisers, news analysts and informed citizens', and 'seeks to provide for experts on various aspects of the CO₂ question a useful introduction to their disciplinary neighbours'. The articles, generally by

experts in the relevant fields, were written during the second half of 1981. The book is well laid out and the diagrams are clear. Each chapter is preceded by a short summary, and the longer articles are followed by two or more short commentaries by other specialists in the appropriate field.

The first section, 'Perspectives', commences with a rather too detailed summary of how man is increasing the concentration of atmospheric CO₂ and the possible effects, including changes in climate. The second chapter considers five past climate studies and attempts to assess why they were (or were not) successful.

The main section, 'Issues', includes chapters on climate modelling, and the biological and chemical response of the oceans. Both are well written, but include a fair amount of technical detail. An article on the first detection of climate change due to increasing CO₂ is less technical and very readable. The essay on the possible effects due to increasing minor atmospheric constituents is confusing as the commentators correctly dispute the method used by the authors. However, the results still give a qualitative impression of the changes in surface temperature that could occur following increases in other trace gases. The remaining chapters, on an ice-free Arctic, the effects on agriculture, and future increases in CO₂ due to man's activities, are of a more speculative nature.

Part 3, 'Notes', comprises short informative articles on the measurement of atmospheric CO₂ concentrations, the role of the earth's vegetation in the carbon cycle, the possible release of methane hydrate in high latitudes, and the relative unimportance of the enhanced production of CO₂ from synthetic as opposed to natural fuels.

Finally, under 'Data', a useful guide is provided to recent publications and data on the carbon cycle, climate, and on carbon dioxide released by the activities of man.

I found the Review easy to read and up to date. There are many references, including a list of the more important papers published in the last few years. I recommend this book to those who wish to know more about various aspects of the increase in atmospheric CO₂ and its consequences.

J. F. B. Mitchell.

Obituary

We regret to record the death on 12 March 1983 of Mr A. Gray, Higher Scientific Officer, who was a member of the Climatological Services Branch.

Alec Gray joined the Office as an Assistant (Scientific) in October 1941. A member of the RAF Meteorological Branch from 1943 to 1947, he served during the War and for the following couple of years at a variety of forecasting outstations. In August 1947 he was sent on loan to the Bermuda Meteorological Service returning two years later to become an Instructor at the Meteorological Office Training School where he studied for, and in 1951 obtained, the Intermediate B.Sc. of London University. In August 1951 he was promoted to the forecasting grade of Assistant Experimental Officer and was further promoted to Experimental Officer in 1956.

Apart from three years in the Middle East, when he worked at Habbaniyah and Nicosia, Alec Gray's forecasting career was largely spent at Acklington with occasional spells of duty at other UK outstations. In October 1969 he was posted to the Climatological Services Branch (Met 0 3) at Bracknell. While in Met 0 3, he was responsible for dealing with enquiries on overseas climatology and made the job very much his own. His help and advice were much in demand by a wide range of business and commercial interests and covered anything from requests for data for designing air-conditioning plants in Riyadh to information relevant to the forward buying of commodities.

Alec Gray had a somewhat earthy, but colourful, sense of humour; his craggy face, usually with a pipe clenched between his teeth, was a familiar sight in the Library and the Technical Archives Office. He — though not always his pipe — was well liked and respected by his colleagues. His two great interests outside work were his garden and his dog.

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NOTICES

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The WPL Profiler: a new source of mesoscale observations

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Summary

A ground-based system being developed at the Wave Propagation Laboratory in Boulder, Colorado, is able, unmanned, to provide atmospheric profiles up to tropospheric heights. The output from this system is continuous in time and thus is potentially a useful source of information for short-period forecasters.

1. Introduction

A system to obtain frequent atmospheric profiles, known as the WPL Profiler (Little 1982), is being developed at the Wave Propagation Laboratory in Boulder, Colorado, under the overall direction of Dr C. G. Little. This article is a summary of a more detailed paper study made in order to familiarize the Meteorological Office with the potential capabilities of the Profiler (James 1983).

2. Background

There is currently much interest in very-short-range forecasts (0 to 12 hours ahead). However the existing upper-air observational networks are largely geared to providing input data for synoptic scale models which are designed to produce forecasts for periods of multiples of 12 hours ahead.

Forecasters in the UK produce local forecasts using hourly surface observations, 12-hourly radiosonde profiles, and satellite images, all interpreted in the light of the general synoptic situation. The UK Weather Radar Network pictures are now becoming more widely available and provide frequent information on weather patterns associated with precipitation. In fact, radar rainfall pictures and half-hourly satellite images from Meteosat are the principal inputs to the FRONTIERS† system which is intended to produce simple very-short-range forecasts by extrapolation (Browning 1979, 1980; Browning and Collier 1982).

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†The acronym FRONTIERS embodies the following key elements: Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite images.

Mesoscale dynamical models are also being developed for short-period forecasting but the principal restriction on their use is the lack of suitable observations. The observations for very-short-range forecast models must be available rapidly and on a fine enough mesh so that important mesoscale features are not missed.

One possible source of such information is the TOVS (Tiros Operational Vertical Sounder) temperature sounding data from the polar-orbiting Tiros-N series of satellites. The Satellite Meteorology Branch of the Meteorological Office are planning to process such data in near real time (Eyre and Jerrett 1982). Information is available over an area within 2 500 kilometres of the UK every six hours. The horizontal resolution of the data is 40 and 200 kilometres for the infra-red and microwave sounders, respectively. The satellite measurements allow vertical temperature profiles to be estimated at points on a 40 kilometre mesh and the derivation of thickness and thermal wind charts over a large area (for example see Fig. 6, Eyre and Jerrett 1982). A problem with polar orbiter data is that, although they are of good horizontal resolution, they are only available at intervals of six hours from a pair of satellites. In addition the resolution is worse (200 kilometres) in the cloudy areas where much of the interesting weather occurs because the infra-red sounder cannot penetrate cloud. Geostationary satellite sounding techniques developed in the USA (Smith *et al.* 1982) are able to provide data at one-hour intervals but they are restricted at present to infra-red soundings in clear or partly cloudy conditions. Further problems with satellite data are that the vertical resolution and accuracy of the temperature and humidity data become worse near the surface, and that information on the wind field is inadequate.

3. The WPL Profiler

The WPL Profiler is an alternative system to obtain frequent atmospheric profiles. The Profiler is a ground-based system consisting of three elements; a clear-air Doppler radar, a six-channel vertically pointing microwave radiometer and a set of surface sensors that monitor surface pressure, temperature and humidity. The Doppler radar measures a wind profile above the Profiler site and the radiometer provides information which can be processed to produce temperature and approximate humidity profiles. The wind, temperature, and humidity profiles are available continuously in time. A unique feature of the system is that information from the radar sub-system can be used to improve the temperature profiles obtained from the radiometer measurements alone.

3.1 *The clear-air Doppler radar sub-system*

The Doppler radar is used to obtain wind profiles under all weather conditions. 'Clear-air' radars observe the very weak returns from inhomogeneities in refractive index present in the air on a scale of half the radar wavelength (see James 1980). The refractive index of air in the upper troposphere is almost entirely dependent on temperature and so clear-air radars detect fluctuations mainly in the temperature field. The radar used is very sensitive in comparison with conventional Doppler weather radars. This sensitivity is achieved by using a large antenna (100 by 100 metres in the case of the Profiler VHF radar developed originally by the Aeronomy Laboratory) and by integrating the returned signal for periods of up to two minutes to make a single velocity measurement. The large antenna is constructed from simple arrays of wires and has no moving parts. Observations are made at a number of different ranges simultaneously; the Profiler radar makes measurements with a height resolution of 1 kilometre at heights of between 2 and 20 kilometres. The radar is normally used to look simultaneously in three different directions, vertically and 15 degrees from the zenith in two orthogonal directions (e.g. East and North). Provided strong wave motions are not present these measurements allow both horizontal and vertical air motions to be calculated.

Other important information can be obtained from the radar measurements. It has been found that a very much stronger signal is observed by the vertical beam (compared with the oblique beams) from stable layers in the stratosphere (Gage and Green 1979). This increased signal results from specular reflection from regions of large refractive index gradient caused by strong vertical gradients of temperature in these stable regions. This allows the height of the tropopause to be measured remotely and continuously from the surface. In addition tropospheric stable layers, in particular the inversion at the top of the boundary layer, give enhanced signals in the vertical beam. The strength of such signals is related to the strength of the inversion; thus the radar is able to detect and measure the height of stable layers and give an indication of their static stability. In any new system every effort should be made to decrease the minimum range to one kilometre or less so as to increase the frequency with which the boundary layer top is detected.

3.2 The radiometer sub-system

The Profiler uses a six-channel passive microwave radiometer to provide temperature, water vapour and liquid water observations. Four of the channels are at frequencies between 52 and 58 GHz, on the side of an oxygen absorption band. These four are used to give temperature information. The other two channels are used to provide water vapour and liquid water observations. One is near the peak of a water vapour absorption line at 21 GHz and the other at 31 GHz is removed from any absorption lines but is sensitive to continuum absorption by liquid water. The atmosphere is relatively transparent between 20 and 30 GHz and as a consequence these two channels are able to measure the total column water vapour and liquid.

Individual radiometer channels are sensitive to the atmospheric temperature over a range of heights; the exact sensitivity is described by the weighting function, see for example, Eyre and Jerrett (1982). In the case of the four temperature sounding channels the weighting functions are relatively broad (>100 mb) and none is sensitive to the temperature above 400 mb. In order to recover a useful temperature profile from the radiometer measurements a technique termed inversion is used. The inversion technique employed in the Profiler system is statistical inversion. A climatological set of radiosonde ascents is assembled and for each ascent the measurements the Profiler would have made are calculated. Next these synthetic measurements are correlated with the original radiosonde profiles to form a cross-correlation matrix. This matrix describes statistically how changes in a radiosonde ascent relate to changes observed by the Profiler. When new Profiler measurements become available the cross-correlation matrix can be used to estimate the atmospheric profile. This technique is a form of multiple linear regression. The method is improved by dividing the climatological data set according to the time of year.

Further improvement is achieved by utilizing information from the radar. The climatological data set can be divided according to the height of the tropopause: one set would contain tropopause heights between 10 and 11 kilometres, the next heights between 11 and 12 kilometres etc. By measuring the tropopause height with the radar, the appropriate climatological data set can be used in the inversion. A similar method can be used to handle the boundary layer inversion. Further refinement can be achieved by modifying the calculated profiles in the light of radar measurements of the heights and strengths of other tropospheric inversions.

4. Examples of some results

Fig. 1 shows time changes of the wind observed with the Profiler radar. The diagram shows a series of wind profiles at one-hour intervals over a two-day period (Ecklund *et al.* 1979). Height is shown vertically and the eastward and southward components of the wind are shown separately. Horizontal

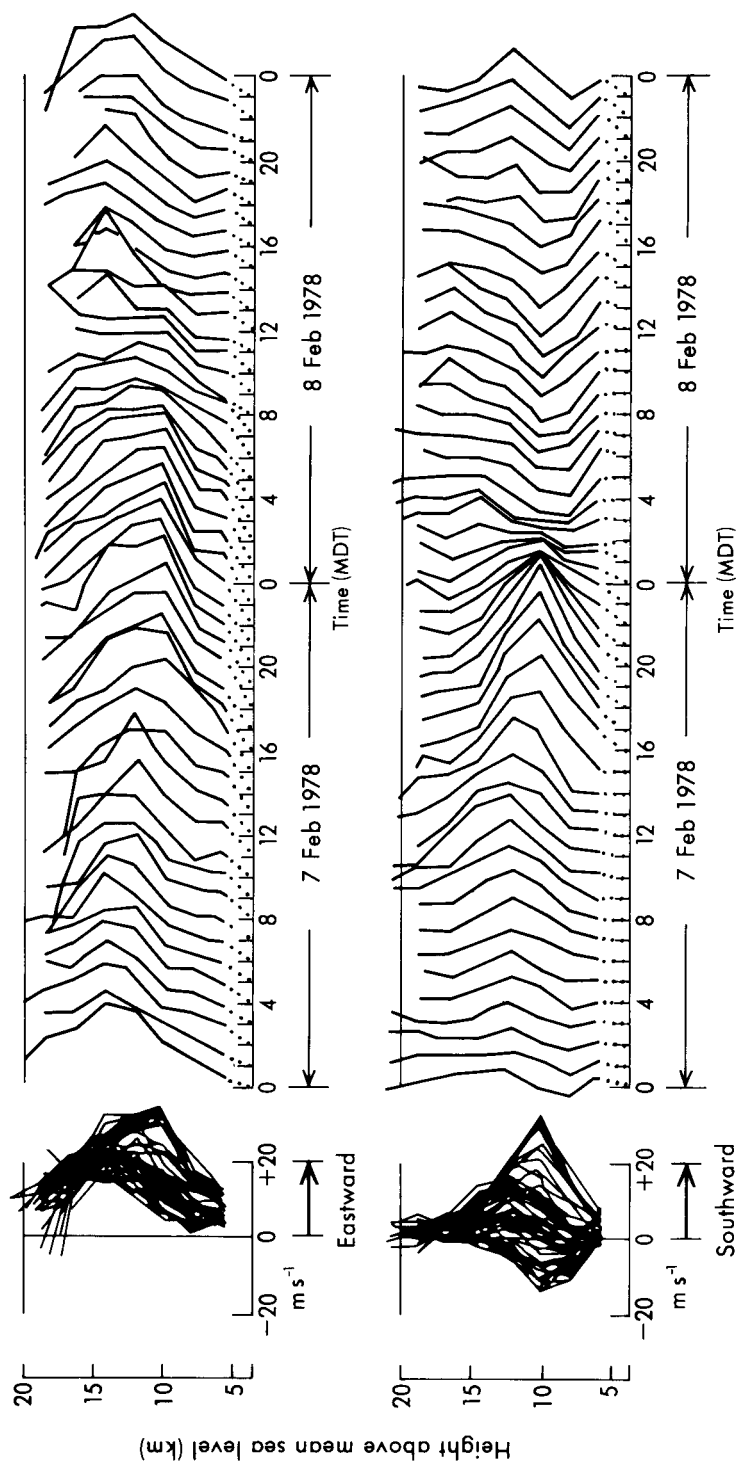


Figure 1. A series of wind profiles from the Profiler radar at one-hour intervals over a two-day period. Height is shown vertically and the eastward and southward components of the wind are shown separately. Horizontal displacement of the solid lines indicates the wind speed at a particular height.

displacement of the solid lines indicates the wind speed at a particular height. The wind was generally obtained up to a height of 17 to 18 kilometres. Wind changes over periods short compared with the interval between 12-hourly radiosondes are very apparent on this occasion.

Fig. 2 shows a time sequence of Denver Profiler measurements in comparison with radiosonde measurements (Little 1982). These results were obtained using the brightness temperatures from the six radiometers together with surface measurements (surface pressure at Denver averages 840mb); no use was made of radar data in this case. Measurements of 700, 500 and 300 mb geopotentials are shown over a four-day period. It was cloudy during the latter half of this period and it was raining lightly on the last day, but this did not appear to affect the accuracy of the results. The comparison draws attention to the value of the fact that, whereas radiosondes are generally launched at fixed intervals of time the Profiler output is essentially continuous. At 700 mb there is very good agreement, detailed comparisons show that the Profiler measures the 700 mb geopotential with a r.m.s. (root-mean-square) difference relative to the radiosonde, of less than 5 geopotential metres (gpm). On the fourth day the Profiler measured an increase in the 700 mb geopotential of 50 gpm in just two hours. Thus one immediately learns of changes in geopotentials and also the time rate of change of the geopotential. This information helps to locate mesoscale features, like fronts, precisely. At 500 mb the Profiler has a r.m.s. difference, relative to the radiosonde, of about 15 gpm and large and real changes are followed by the Profiler (the radiosonde measurements of geopotentials are rounded to the nearest 10 gpm). At greater heights the Profiler becomes progressively less accurate, the difference in measurements of the 300 mb geopotential by the two methods being about 32 gpm (without the benefit of radar data). However the Profiler output is following the general decrease in 300 mb geopotential shown by the sonde measurements as well as showing some structure on a short time-scale. Comparison of Profiler measurements with radiosonde measurements is complicated because radiosondes are carried by the wind and thus the two systems do not sample the same volume of the atmosphere. In addition radiosondes themselves are subject to errors. In an experiment where pairs of radiosondes were launched on single balloons it was found that the paired measurements gave r.m.s. differences of geopotentials of 19 gpm at 500 mb and 27 gpm at 300 mb (Hoehne, 1980). This would suggest that the Profiler measures geopotentials up to 400 mb with an accuracy comparable with the radiosondes used in the USA.

Fig. 3 shows the Profiler r.m.s. retrieval error as a function of height (Westwater *et al.* 1983). The retrieval error was again evaluated by comparison with radiosonde ascents. The solid line gives the r.m.s. 'error' when using radiometer measurements alone, i.e. without radar data, the dashed line shows the improvement obtained when using the radar-measured tropopause height together with the radiometer measurements. Knowledge of the tropopause height improves retrievals at levels between 500 and 100 mb, the improvement being as large as 2°C at the tropopause itself.

5. Conclusions

The Profiler has the following characteristics:

- (a) It has no moving parts.
- (b) It is cheap to operate, and easy to maintain.
- (c) Its output is continuous.
- (d) It operates unmanned.
- (e) It provides almost all-weather operation. Wind measurements are possible in all conditions; temperature and humidity profiles begin to deteriorate at rainfall rates greater than about 3mm/h (C. G. Little private communication).
- (f) It provides profiles of wind and temperature routinely to tropopause heights.
- (g) It is able to measure separately the integrated water vapour and liquid water.

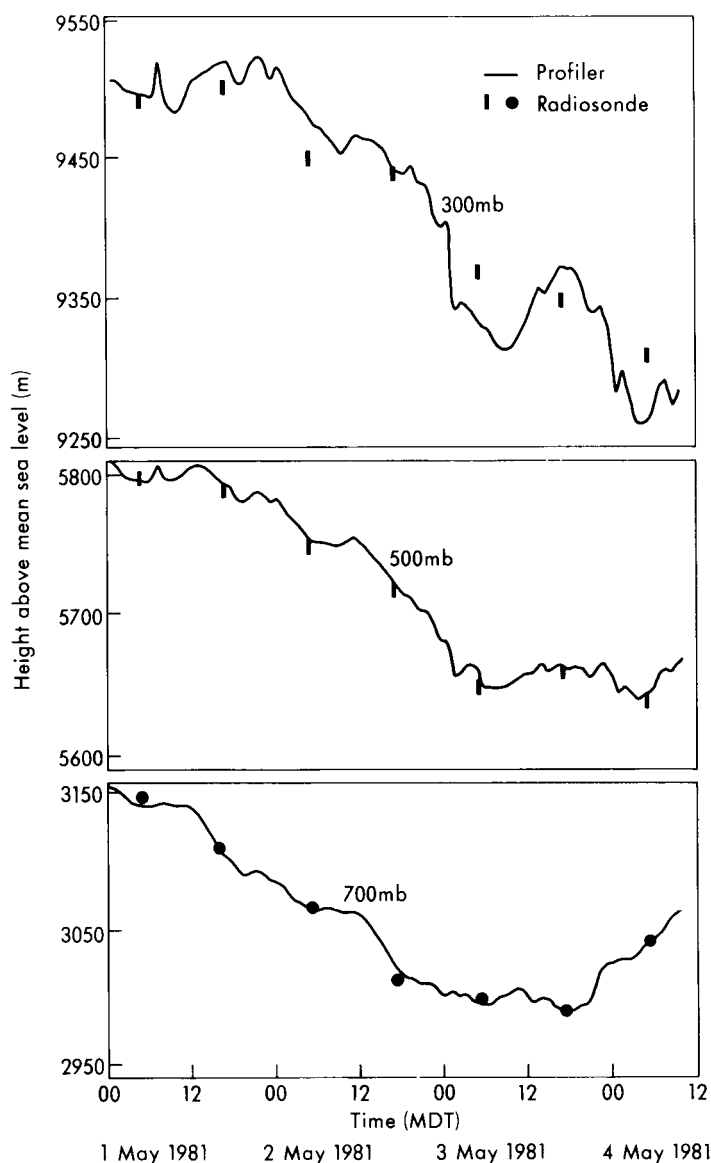


Figure 2. A time sequence of Denver Profiler measurements (without the benefit of radar data) in comparison with radiosonde ascents. The surface pressure at the Profiler site averages 840 mb. The figure shows measurements of 700, 500 and 300 mb geopotentials* over a four-day period. The radiosonde measurements are at 12-hour intervals and are shown as dots or rectangles, the Profiler measurements are shown as continuous lines. Times are shown as Mean Denver Time.

*It will be noted that the y-axis is labelled as 'height above mean sea level (m)'. The reference from which this diagram is taken fails to distinguish between 'geopotential', 'geopotential altitude' (as defined in e.g. the WMO 'International Meteorological Tables'), and 'geometrical altitude' i.e. height above msl, the first quantity being a specific energy and the last two lengths. Probably the numerical differences involved are negligible. Similar remarks apply to Fig. 3.

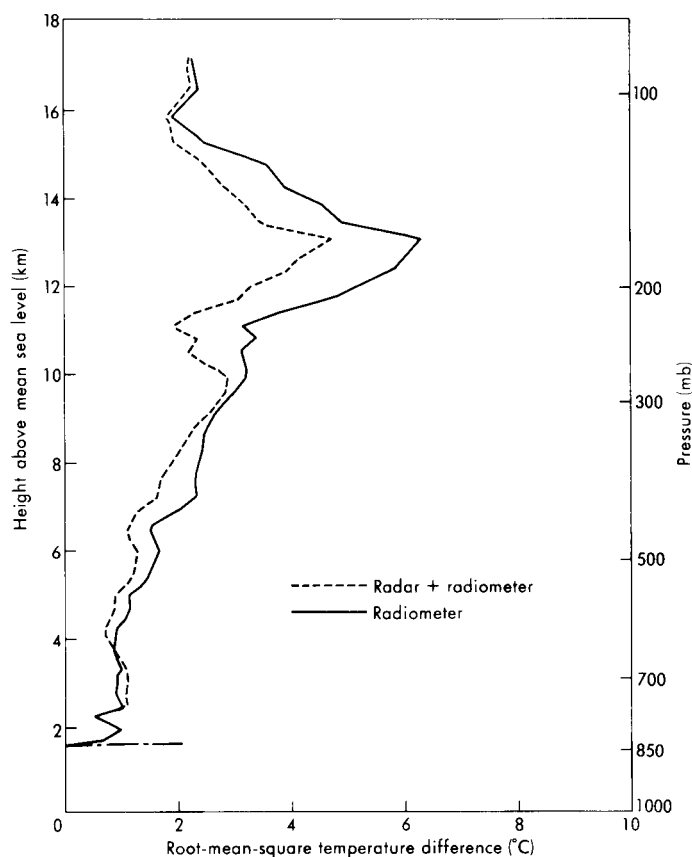


Figure 3. The root-mean-square retrieval accuracy of a Profiler system obtained by comparison of the Profiler output with 21 radiosonde ascents over an 18-day period. Comparative curves are shown with and without the benefit of knowledge of the tropopause height as measured by the radar. The fine structure apparent in the curves is a consequence of the limited sample available.

- (h) It monitors the height of the tropopause and significant inversions.
- (i) Its resolution is around 100 mb at low levels but becomes worse with increasing height. However the heights of significant features such as the tropopause and inversions are measured with much better resolution.
- (j) It is able to give an indication of the stability of layers.
- (k) It can also give an indication of the strength of turbulence at a particular height.

Profiler systems will not be able to replace conventional radiosondes entirely, as the vertical resolution of the Profiler is poor in comparison and they are unable to obtain accurate temperature measurements above the tropopause. D. C. Hogg (private communication) has estimated that the cost of a Profiler system in the USA is equivalent to only about four years operation of a conventional radiosonde site; thus it is not unreasonable to consider the possibility of building a network of Profilers to provide observations for very-short-period forecasts. Profiler systems, with their good time resolution and their best accuracy at low levels, can be regarded as complementary to satellite sounding systems, which have good spatial coverage and have their best accuracy at higher levels.

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Long-range transport of air pollution

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Summary

A general review is given of the known facts on the long-range transport of air pollution and its influence on 'acid rain' and of the present state of theoretical and practical investigation of the various problems involved. These include the nature of emissions, the amount of local deposition, the estimation of trajectories and lifetimes of airborne pollutants and their chemistry, relative amounts of dry and wet deposition, and background concentration. An account is given of computer modelling and observational studies being carried out by the Meteorological Office and of possible future developments.

1. Introduction

Oden (1968) was the first to relate reductions in freshwater fish populations in southern Scandinavia to the airborne transport and deposition of air pollutants originating perhaps hundreds or thousands of kilometres away. Similar fears have since been expressed in other parts of Europe (e.g. Scotland: Harriman and Morrison 1980), in the Appalachian mountains of the USA and in large areas of Canada (Harvey 1980). In fact there are many other sensitive areas of the world which might be at risk at equally large distances from major sources of pollution.

At the 1982 Stockholm Conference, Professor Ulrich described an alarming degree of forest 'dieback' in Germany and cautiously postulated that this might be due to root damage, followed by rot penetration, originating from the toxic action of inorganic aluminium released within the soil from its natural bound state under the influence of 'acid rain'. At present, hard evidence in support of this hypothesis is not available and other possible causes do exist. Nevertheless, it does remain a possibility and, if true, a deeply worrying threat to the European and American environment.

Since the original suggestion that ecological damage was being caused by man-made airborne pollutants, two major international collaborative experiments have taken place in Europe. The first (1971–76) involved most of the western European countries and was carried out under the auspices of the Organization for European Co-operation and Development, OECD (OECD 1977). The second (1977–) brought in many of the east European countries, including the USSR, in recognition of the truly international character of the problem, and was mounted jointly under the auspices of the Economic Commission for Europe, the United Nations Environment Programme and WMO (Eliassen and Saltbones 1982). This second experiment is called EMEP (the European Monitoring and Evaluation Programme) and is operated by three Centres responsible to a Steering Committee formed of delegated members from the participating countries. One of the Centres, the Chemical Co-ordinating Centre in Lillestrøm, Norway, under Dr Ottar, is responsible for overseeing and collating appropriate air and precipitation measurements on a daily basis at a large number of sites across Europe, remote from local sources, and inferring total deposition fields. The other two Centres — the Meteorological Synthesizing Centres — one in Oslo under Dr A. Eliassen, the other in Moscow under Dr A. Pressman, are involved in developing and running mathematical models which use estimated emission fields based on statistical data supplied by the governments of the countries involved, and meteorological observations of low-level winds, rainfall and mixing depths to simulate the atmospheric transport and loss processes that should link the emissions to the observed depositions (Fig. 1 outlines the various processes that occur). Similar monitoring and modelling programs have been under way in Canada and the USA since about 1977.

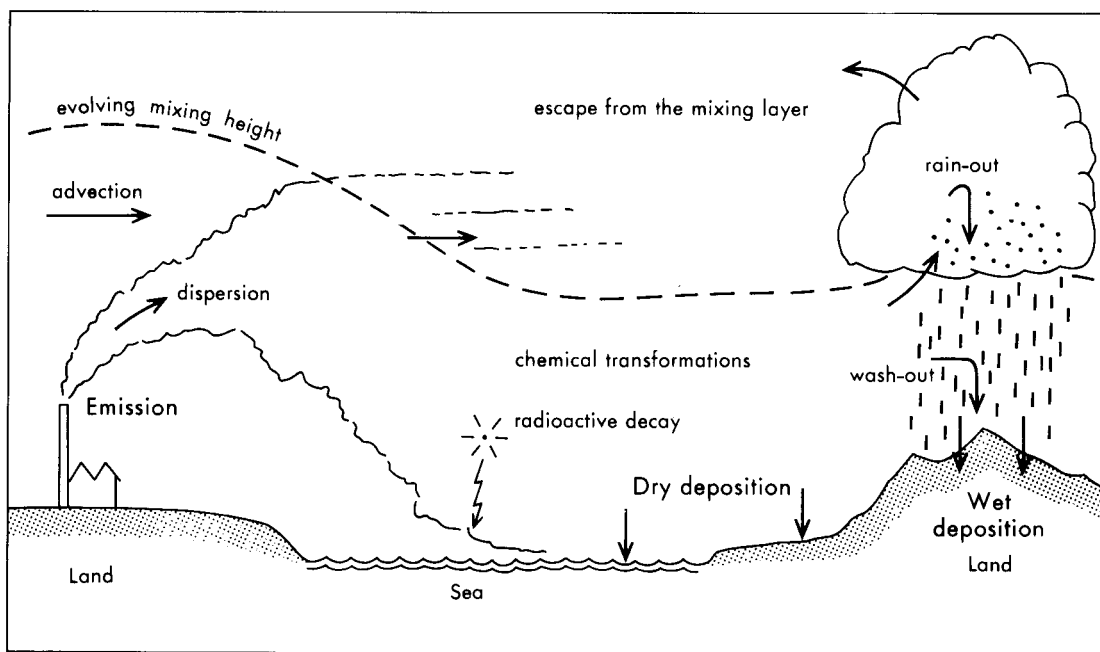


Figure 1. Processes involved in the deposition of atmospheric pollutants.

In addition to this work aircraft sampling flights (sometimes using specially released tracers) have been mounted in the UK since 1971, (see Smith and Jeffrey 1975), in Norway and in the USA to answer very specific questions concerning the physical and chemical behaviour of the pollutants involved in the acid rain problem.

2. Some basic problems

(a) Emissions

Long-term average emissions of sulphur dioxide are reasonably well known in northern and western Europe, in Canada and in the USA. Elsewhere emissions are not well documented. On shorter time-scales, the position on emissions is less satisfactory as data become increasingly uncertain everywhere.

For other acid-rain components, emissions are considerably less certain although estimates have been made for some components such as the oxides of nitrogen.

(b) Local depositions

Some fraction of the emission will be deposited locally, depending on the height distribution of the sources, local topography and atmospheric climatology. Typically, about 10% of the sulphur dioxide emitted within a 150×150 km square is deposited within the area itself. Similarly an analysis of measured depositions implies that about 30–40% of the UK's emissions of sulphur dioxide are deposited within the UK.

(c) *Trajectories*

Trajectories can be obtained using the winds and temperatures given by data-analysis methods used in operational numerical weather forecasting models. The accuracy of such trajectories is, at best, modestly good in simple synoptic situations and over relatively uniform terrain with adequate meteorological station coverage. This is confirmed by results from the North Sea plume-sampling flights that will be referred to later. In more complex situations, more important errors are sometimes evident with serious consequences for the prediction of single pollution events. Nevertheless, these errors are not thought to be of major significance for the estimation of long-term (e.g. annual) deposition fields.

(d) *Lifetimes of airborne pollutants*

All the evidence supports the belief that common industrial pollutants like sulphur dioxide (or SO_4^{2-}) have mean atmospheric lifetimes of the order of a few days and can travel in that time several thousands of kilometres. The lifetimes of reactive gases are affected by the rate of chemical conversion and by 'dry deposition' rates to the underlying surface. Resulting aerosol particles (like sulphate) normally have only small dry deposition rates and their lifetimes are usually determined by the frequency of interception by rain belts. The lifetime of any individual 'quantum' of pollution in the air is therefore highly variable.

(e) *Air chemistry*

Both dry deposition and the uptake of pollution into precipitation depend on the composition of the pollution itself, including the relative proportions of primary and secondary pollutants (e.g. SO_2 and its oxidized form, SO_4). The chemical changes inherent in these proportions often depend on a great number of complex processes within the air which in practice may require basic information totally beyond our capacity to achieve with any kind of precision. It may be postulated that in so far as long-term deposition fields are concerned such knowledge is unnecessary. The total sulphur depositions in Norway, for example, are determined principally by the total amount of sulphur in the air and the long-term rainfall patterns. Oxidation and removal rates are often very rapid in precipitating cloud. Statistical variations in rainfall distribution and intensity on the one hand and in the pollution mixture on the other are virtually self-cancelling except in short-lived single events.

(f) *Dry and wet deposition estimates*

Dry depositions are not measured directly but are inferred from air concentrations assuming so-called velocities of deposition. These are known from field experiments for certain common air pollutants, such as sulphur dioxide, and over such surfaces as short grass. Aircraft sampling studies have also assessed the deposition velocity of SO_2 over the sea and over typical mixed agricultural countryside. Values for other surfaces are largely unknown but where they are sufficiently extensive a balance tends to be achieved between the true velocity and the air concentration which yields a deposition rate which is insensitive to the precise nature of the surface.

The influence of local sources, altitude of the monitoring station and local topography all tend to affect measured air concentrations and hinder validation of model results.

Wet depositions can also be strongly influenced by monitoring-site characteristics and by the presence of mountains which modify airflow, enhance rainfall and change the collection efficiencies of pollutants by precipitation within the boundary layer.

Modelling of wet deposition may also be in error owing to spatial and temporal smoothing of rainfall data from widely separated meteorological observing stations when these data are projected on to the trajectory (Smith 1981a). This source of error is inherent in depositions over all time-scales but is

especially important in single-event depositions when peak values experienced at a point may be of vital importance. Standard meteorological data are incapable of yielding the information necessary for assessing large episodic depositions from large convective storms, for example.

(g) Background concentrations

Measurements confirm that air entering Europe having spent considerable time over the Atlantic contains sulphate not apparently originating in sea-water. Concentrations are low but are sufficient in many western areas, remote from large SO₂ sources, to constitute a significant fraction of the annual total of sulphur wet deposition. In Norway, for example, some 25% is thought to be of this kind. It is reasonable to suppose that much of this sulphur originates from the USA and Canada and has undergone really long-range transport, and has been isolated from prolonged surface deposition by rather low-level marine inversions.

3. Modelling and experimentation

(a) Long-term and short-term depositions

The links between acid rain and ecological damage are imperfectly understood and are often circumstantial and conjectural. Nevertheless, the observed damage is so extensive and potentially long lasting that even conjectures have to be considered seriously. Thus accepting for the while that such links do in fact exist, we are faced with the job of assessing the true nature of the transport and deposition problem. Unfortunately, such an assessment is at present only partial. For example, the relative importance of the following is still not clear:

(1) Long-term depositions (LTD) and average concentrations of the various acid components in the precipitation. These factors may degrade the natural buffering capacity of soils at rates which depend on soil character.

(2) Short-term episodic decompositions (STED) containing high concentrations of acidity which, when LTD have degraded the soil beyond some critical limit, may directly effect living organic members of the ecosystem or indirectly do damage through the release of toxic material (such as aluminium) previously safely 'locked' within the natural soil state.

(b) The nature of models

Many models have been developed which attempt to include the emission, advection, diffusion, chemical change, loss from the boundary layer and deposition processes which affect industrial air pollutants. Which model is best for a potential user depends on his intended use, an assessment of the model's validity and the availability of appropriate meteorological data and computer facilities.

Models can be subdivided in a variety of ways which can only be touched on very briefly here. Three of them are as follows:

(1) Models that use statistics of winds, mixing heights and precipitation. Resulting deposition fields may have validity but only in the very long term. They are simple and very economical to run. They can also be surprisingly successful when compared with 'observed' fields.

(2) Models that use day-by-day meteorological data but through the use of much parametrization still have only rather long-term validity. The EMEP models are of this type.

(3) Complex models that are essentially extended mesoscale models taking account of topography and the three-dimensional equations of motion. They require considerable non-standard meteorological data and a highly sophisticated computer facility. The Ontario Ministry of the Environment in Canada is attempting to develop a model of this type. It is difficult to believe such a

model should be run except to study discrete events of exceptional scientific interest or public concern.

An alternative way of subdividing models is in terms of their mathematical nature: whether they are Lagrangian models or Eulerian models. Both have positive advantages and disadvantages which we shall not attempt to describe here. Other subdivisions can be made in terms of vertical resolution and the way vertical dispersion is modelled.

(c) *A very simple statistical model*

A model of type (1) above has been developed within the Meteorological Office. It is extremely simple and efficient to run on a computer, producing deposition fields in a minute fraction of the time required by the EMEP models. The model when applied to Europe assumes a single wind-rose (based on certain UK wind direction frequency statistics) applicable all over Europe and assumes airborne pollution travels in straight lines. Dry deposition occurs at a constant rate. Wet deposition can be represented with various degrees of simplicity; the simplest being to assume that the probability of rain is independent of wind direction and is constant along the track. Under these assumptions the predicted and observed fields are correlated: for dry deposition the correlation coefficient $r = 0.87$ and for wet deposition $r = 0.77$. If, on the other hand, the sporadic nature of rain is recognized using Smith's (1981b) simple probability approach, the probability of rain is allowed to depend on wind direction as observations suggest and, if grid values of dry and wet deposition are modified according to the actual annual rainfall, then the dry-deposition correlation rises to 0.90 and the wet-deposition correlation to 0.83. Amongst the most valuable aspects of the model are its ability to provide inter-country budgets of sulphur pollution (see Table I) and its versatility, so the sensitivity of the results to changes in the parameters or to other ideas can be quickly and economically tested.

(d) *Episodes (STED)*

As already noted, the development of models capable of dealing with single-event depositions, especially of episodic proportions, is a formidable problem. Perhaps the simplest approach at this time is to examine the EMEP data for occasions of high episodic concentrations of sulphate in precipitation

Table I. *A budget of annual total depositions (grams of sulphur per square metre per year) given by the EMEP Meteorological Synthesising Centre-West's Lagrangian trajectory model when applied to 1978-79.*

The budget gives the estimated contributions to the average deposition in one country arising from other countries. Only a selection of countries is given and these are ranked in order of deposition magnitude. It is interesting to note that Czechoslovakia receives over 12 times as much sulphur deposition as Norway. Note that the figures quoted for the USSR refer only to the area of that nation within the analysis area of the model — very roughly that part within Europe.

Receiving country	Area (10 ³ km ²)	Emitting country												Total
		Czech.	GDR	Belg.	FRG	Poland	Neth.	UK	France	USSR	Norway	Others	Undec.	
Czech.	128	4.5	1.8	0.1	1.0	0.9	0.1	0.3	0.4	0.1	0	2.1	0.8	12.2
GDR	108	0.6	5.5	0.1	0.9	0.3	0.1	0.2	0.2	0	0	0.4	0.3	8.6
Belgium	30.5	0	0.1	2.6	0.9	0	0.2	0.7	1.1	0	0	0.3	0.4	6.3
FRG	250	0.2	0.6	0.2	2.7	0.1	0.1	0.3	0.5	0	0	0.4	0.4	5.6
Poland	313	0.5	0.8	0	0.1	2.2	0	0.1	0.1	0.1	0	0.8	0.3	5.1
Neth.	41	0.1	0.2	0.5	1.3	0	1.2	0.8	0.4	0	0	0.3	0.3	5.1
UK	244	0	0.1	0	0.1	0	0	3.3	0.1	0	0	0.1	0.4	4.2
France	544	0	0	0.1	0.2	0	0	0.2	1.4	0	0	0.3	0.4	2.7
USSR	3363	0.1	0.1	0	0.1	0.1	0	0	0	1.3	0	0.3	0.4	2.5
Norway	324	0.03	0.08	0.01	0.07	0.04	0.01	0.15	0.04	0.03	0.07	0.14	0.27	0.94

and to consider the meteorological situations which gave rise to them, and to assess in broad terms where the pollution originated. This has been done for a group of stations in the 'sensitive' area of southern Scandinavia. Frequently these episodes occur when a blocking high over central Europe begins to weaken and fronts start to penetrate across Scandinavia drawing air from the industrial areas to the south, which over the previous days has become highly polluted. Fig. 2 shows a sector analysis for episodes and all depositions within the area for the years 1977–80. An episode is here defined as a concentration in rain exceeding 4 mg of sulphur per litre, with the condition that at least 1 mm of rain should have fallen. The sectors were chosen to cover the main industrial countries, i.e. UK, Netherlands, Federal Republic of Germany, German Democratic Republic, Poland and the USSR. The episode 'bar' simply gives the percentage number of occasions when the air originated from within the sector. The all depositions 'bar' is not quite the same in this figure: it represents the fraction of sulphur originating from each sector to the *total* deposition.

The episode values may be contaminated by dry deposition on the collecting funnel during the previous dry spell. Although in principle the funnel should be washed daily, a correlation appears to exist between the apparent wet deposition and $\Sigma \text{SO}_2/R$ (where ΣSO_2 is the sum of the sulphur dioxide concentrations over the preceding dry days and R is the rainfall). However, the correlation may be

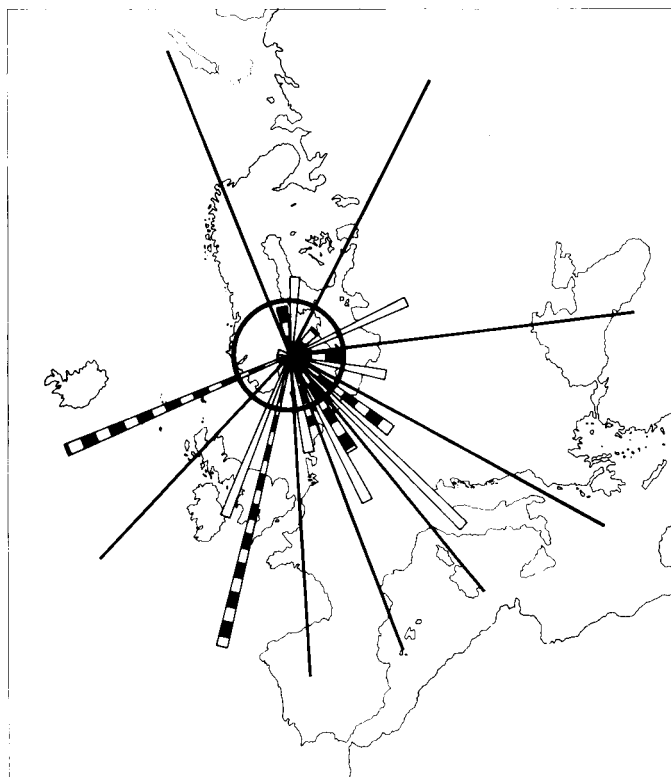


Figure 2. Sector analysis for southern Scandinavia 1977–80. White bars represent frequency of wet deposition. Striped bars represent all depositions. See text for explanation.

entirely spurious since an equally good correlation exists between the concentration in the collected rainwater and the current sulphate-in-air concentration, and the latter may be reasonably correlated with ΣSO_2 .

4. Meteorological Office/Central Electricity Research Laboratories (CERL) flights

A collaborative program between the Meteorological Office and the Central Electricity Research Laboratories (CERL) is currently in operation to study the plume from Eggborough Power Station in South Yorkshire. The Meteorological Research Flight Hercules aircraft has been instrumented to measure winds and other relevant meteorological data and to monitor pollutants during flight. Special sorties are made whenever the meteorological situation seems satisfactory and the aircraft is available. Fifteen flights have so far been made and analysis of the data is proceeding. To assist in the interpretation (particularly necessary since the plume is not isolated from other source plumes) tracers are injected into the stack effluent: sulphur hexafluoride is injected continuously during flights and sometimes PB2, a freon, is injected intermittently to act as time markers for Lagrangian studies. The following questions are being tackled: (a) oxidation rates of SO_2 to sulphate, (b) loss rates to the surface and out of the upper boundary to the troposphere above, (c) the history of sulphur drawn into precipitating clouds, (d) the accuracy of forecast trajectories, and (e) the origin intensity and influence of atmospheric mesoscale motions on plume behaviour.

5. The future

The Meteorological Office has an important role to play in the future of this study, although ultimately the exact nature of the role must depend on the consensus view of ecologists, and others, on whether or not industrial pollutants *are* causing grave damage to the environment at long range. If that becomes their viewpoint then it is likely that certain actions will be taken that will not involve the Office. For example, it is likely that desulphurization of flue gases will become more common, and that greater emphasis will be placed on energy generation from non-polluting processes (e.g., nuclear power etc).

Nevertheless, some alleviating actions may well involve the Office in research and daily operation. Three examples are as follows:

(a) *The reduction of the emission of other components in the pollutant mix.* If meteorologists and atmospheric chemists can demonstrate that another more easily and cheaply controlled pollutant holds a key role in the atmospheric sulphur cycle and its elimination could very significantly reduce depositions within Europe, then this might provide a very useful strategy. The Office would be involved in modelling the chemical interactions within the framework of atmospheric transport to see if such control would or would not be effective.

(b) *The reduction of depositions within Europe by increasing effective source heights.* A comprehensive study is required of the effectiveness of increasing the height to which hot plumes can rise under the action of their own buoyancy or motion with a view to maximizing the insulation of the pollution from ground-deposition processes. Over the last few decades the UK has followed a policy of building high stacks for large emitters with the view of controlling nearby ground-level concentrations and this policy has been eminently successful. However, the UK has sometimes been accused of thereby increasing the amount travelling out of the country and increasing its deposition in sensitive areas. A rather simple analysis I carried out some years ago indicated that in 1969 (the last year for which data on current stack heights were available) if all the high stacks were deliberately reduced to medium-height stacks (about 80 m high) the resulting average nearby surface concentrations would increase by *at least* 35% whereas the long-range transport would decrease by only some 10%. In fact, some of this 10% from high stacks

actually gets well above the mixing layer and may not be available for deposition within Europe. A more detailed analysis based on today's chimney height figures and occasional aircraft sampling flights might be advantageous in meeting the accusations of the critics of the high-stack policy and might point to the effectiveness, or otherwise, of pursuing this policy even further.

(c) *Emission control.* It is possible that power stations could have additional supplies of low-sulphur fuel that could be used whenever meteorological forecasts predicted travel of the effluents to specified sensitive areas. At other times cheaper and more readily available fuels, containing more sulphur, would be consumed. A pilot study of this possibility was made in 1974 when the quality of three-day weather forecasts was significantly less than it is today. Considering the sum of the time of travel of a typical plume from, for example, the UK to Norway, the time required to enact a fuel switch and the time to produce a trajectory forecast following the collection of weather observations, we find that three-day forecasts would probably be required. If success were identified as a trajectory error of less than 250 km at a range of 1000 km (corresponding to the distance between the UK Midlands and central southern Norway) then the 1974 study indicated that only about a 45% success rate could be achieved. This was deemed unsatisfactory at that time. Perhaps a new study should now be carried out to see if the situation has significantly improved. For the present and the immediate future, it is imperative that the Meteorological Office and CERL collaborative flights should continue with a determination to answer the questions posed earlier in this paper. The modelling work should also be exploited to its full potential, particularly if many of the air-chemistry processes can be grossly simplified for LTD purposes, and incorporated into the simple model described earlier. The physical, chemical and meteorological character of episodes also needs to be investigated in greater depth with a view to understanding the significance of these relatively uncommon events to the whole problem of acid-rain damage.

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Noctilucent clouds over western Europe during 1982

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Table I summarizes the observations of noctilucent cloud (NLC) over Western Europe during 1982, as reported to the Department of Meteorology, University of Edinburgh.

The times given in the second column of the Table do not necessarily indicate the duration of the display, though appearance and disappearance times are referred to in the Notes where known. In the third column brief notes of the displays enlarge on the facts listed in the other columns — NLC forms discernible, tropospheric cloud conditions, photographs and sketches available. Co-ordinates of the observing stations and selected details of elevation and azimuth appear in the remaining columns.

Routine hourly observations were made at 12 Meteorological Stations in the United Kingdom and at Reykjavik in Iceland when darkness permitted. Observers at these stations provide information of sky conditions during all hours of darkness; the significance of 'negative' nights, i.e. when an observer can state with confidence that there is no NLC, is obviously great when trying to assess the total number of appearances of NLC. Each year, however, we note with appreciation that in many instances NLC is recognized when quite large amounts of tropospheric cloud — in fact, up to seven-eighths (oktas) — are present.

As in most previous years a high incidence of tropospheric cloud seriously interfered with observation of the NLC. The interference in 1982 was in fact probably at a record high level, as evidenced by the fact that, on average for the UK observing stations, cloudiness exceeded six oktas on 22 of the 30 'peak NLC' nights from mid-June to mid-July; while on only one of these nights was the average tropospheric cloud at the stations less than four oktas.

Nevertheless, during the season some extensive and bright displays were seen by observers at widely separated stations in the network, and in many instances photographed. In all, 37 occurrences of the clouds are listed; latitudes of observing points varied from 50°N to 65°N, and longitudes from 27°E to 07°W. Mr Parviainen, Finland, recorded in great detail by means of notes, sketches and photographs, the many displays of NLC he observed. It is difficult to do justice in this brief report to his work and to that of the many other contributors.

Time-lapse photography was carried out at the Department of Meteorology, Edinburgh, throughout the season, providing a record of nightly conditions there. Dr Michael Gadsden at Aberdeen ran a photometer, on nights when skies were good enough for photometry, at 20° elevation in the plane containing the directions of the zenith and the sun.

Noctilucent cloud data have been collected, collated and published by the Department of Meteorology, Edinburgh, since 1964, financed by an annual grant, originally from the Royal Society and in later years from the Meteorological Office. The efforts of many observers have contributed to the lists; we offer most grateful thanks for their help over the years. The data are filed in the Department of Meteorology and will continue to be held there, available to any who wish to consult them. Information in future should be sent to the Director of the Auroral Section of the British Astronomical Society (Mr R. J. Livesey, 46 Paidmyre Crescent, Newton Mearns, Glasgow G77 5AO).

Note

A summary for the whole period of the survey will appear in a later edition of *The Meteorological Magazine*.

Table 1. Displays of noctilucent clouds over western Europe during 1982

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max. elev. degrees	Limiting azimuths
1982						
23/24 May	2400	Patches of NLC visible between tropospheric cloud, W and E of N. Easterly patch bright with band formation. Almost complete cloud cover before and after this observation from Kinloss.	57.5°N 03.5°W	2400		345-015
9/10 June	2200	Small patch NLC visible between tropospheric cloud (6/8). Cloudy conditions later.	56.5°N 07°W	2200		
13/14	2400-0200	Aldergrove and Tírree reported clear conditions and no NLC at 2300. At 2400 NLC seen clearly to N; display extended NW to E by 0100, in zenith as viewed from Tírree. Newcastle reported band and wave formation. Faint patches still visible Tírree at 0200.	56.5°N 07°W 55°N 01.5°W 54.5°N 06°W	0100 0200 0050 0145	90 — 10 14	090 045 340-040 335-075
14/15	0100	Clear conditions and no NLC visible 2300, 2400 and 0200. At 0100 billow formation NLC visible above tropospheric cloud.	56.5°N 07°W	0100	8	350-010
15/16	0100	Faint patch of NLC visible from Tírree after tropospheric cloud clearance. No NLC visible at 0200 in clear conditions. (Almost complete cloud cover down E side of N Britain.)	56.5°N 07°W	0100		
20/21	0100	Possible NLC visible at Boulmer in tropospheric cloud breaks.	55.5°N 01.5°W	0100		330-050
21/22	2010	Weak display visible at Rønne — through binoculars only.	55°N 14.5°E	2010	25	340
22/23	2200	Photograph taken by Mr Beeston in N London clearly shows NLC bands. No other report — N Britain cloud covered.	51.5°N 0°	2200	10	360
25/26	2315-2340	Report from Udny (Aberdeenshire) of NLC at very low elevation. (Report of red glow seen at Fiane — 59°N 09°E — high in S sky at 2038 thought unlikely to be NLC.)	57°N 02°W	2330	2	360
29/30	2330-0100	Faint bands of NLC visible on Edinburgh film.	56°N 03°W	2400		020
30/1	2200-2230	Very bright patch of NLC seen and photographed by Mr Andersen at Wildbjerg; its extensive spread was seen through tropospheric cloud. Faintly visible area of NLC in NE direction. Display also seen by Mr Ebers at Hitzacker (W. Germany), and Mr Bouma of Groningen who photographed the clouds at 2206 when brightly visible above tropospheric cloud bank.	56°N 09°E 53°N 11°E 53°N 06.5°E	2210 — 2206	15 — 15	360 — 360
1/2 July	2400-0145	The three reporting stations viewed the NLC through tropospheric cloud breaks — both Kinloss and Edinburgh (film) recording high elevation.	57.5°N 03.5°W 56°N 03°W 54.5°N 06°W	0100 2400, 0100 2400	26 20 7	010-040 — 020-030
2/3	2105-2350	Display seen by Mr Olesen from aircraft over Czechoslovakia and E. Germany, en route Rome/Copenhagen. Observed in Finland first as faint irregular bands to high elevation. At maximum of display (around 2240) bands and billows spread into SW and SE sectors. At 2300 N-S oriented bands seen E-SE. Observations ceased 2350 with NLC fading into the dawn.	60°N 22.5°E 50°N 10.5°E	2200 2230 2300 2130	40 120 140	315-360 225, 135 135 ?—045
3/4	2350-0115	Reported by Kinloss as possible NLC. From Udny NLC seen at very low elevation. Faintly visible on film at Edinburgh through tropospheric cloud breaks.	57.5°N 03.5°W 57°N 02°W 56°N 03°W	2400 2350 0100	— ½ —	315-360 350-355
4/5	2115-0215	Bright display visible in Finland (Mjösund) almost to S horizon; in Denmark (Alrø) — very bright in tropospheric cloud breaks; and in E Britain to high N elevation. The widespread display seen in Finland was patterned by band and billow formation over the whole extent. Bands, billows and delicate structure were seen at Edinburgh to 50° elevation. At Aberdeen photographs were taken every 15 minutes from 2345 to 0215.	60°N 22.5°E 57.5°N 03.5°W 57°N 02°W 56°N 03°W 56°N 03.5°W 55.5°N 01.5°W 55°N 14.5°E 55°N 01.5°W 54.5°N 01.5°W	2210 2230 2250 2310 0130 0200 2310 2250 2310 2327 2310 0025 0200 2215 2300 0130	140 160 165 140 9 13 40 25 30 50 30 30 30 7 3	225-110 135 135 250-110 360-020 350-040 345 340-060 320-050 340 360 340-010 340-020 340-045 360 010
6/7	2145-2240+	Medium bright display visible Mjösund, with faint forms beyond zenith, brightest in NNW. Bands and wave forms. Maximum of display 2225. Observations suspended because of fog conditions.	60°N 22.5°E	2200 2215 2225 2235	80+ 90 90+ 90	315-045 300-090 300-090 270-030

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max. elev.	Limiting azimuths degrees
7/8	2045–2310 0001–0100	Bright display seen Mjösund with long bands in N–SW direction; spreading through NW and NE sectors past zenith; fog and moonlight possibly obscuring fainter areas. At Rønne the display was very bright and to high elevation. Photographs taken Aberdeen 0033 & 0053.	60°N 22.5°E	2105 2135 2145 2200 2245 57°N 02°W 0001 55°N 14.5°E 2105	40 90 100 110 120 — 55	315 270–090 270–090 290–090 045 340–135
8/9	2048–2350	With almost complete cloud cover in Mjösund it was impossible to assess the extent of the display. Only NW was clear; but occasional breaks in tropospheric cloud in NE and E disclosed no NLC. The very bright display was observed for 3 hours at Alrø, where Mr Olesen took a series of colour and black and white photographs.	60°N 22.5°E 56°N 10°E	2220 2250 2120	8 15 45	315 315 290–045
9/10	2300–2320	Weak display observed at Alrø.	56°N 10°E	2312	5	020–045
10/11	2050–0208	In Finland seen as medium bright small scale display mainly in E sky. Described as very bright from Kirkwall and Tiree. 23 fine prints taken at Malin Head record the details of the display, which was still bright and extensive in last photograph (0208).	60°N 22.5°E 59°N 03°W 56.5°N 07°W 55.5°N 07.5°W	2050 2100 2150 2210 0115 2300 2400 0100 0200 2400–0208	90 90 90 90 — 10 13 14 14 12	045–090 270,090 250 350–090 030–090 315 310–340 330–030 330–040 330–070 315–045
11/12	2200–2330 0300–0330	NLC bands and billows visible Tiree, Wick and Kirkwall, in NW sector. Later sighting from Wick of veil in NE. No NLC visible 2400 in clear conditions Tiree and Wick.	59°N 03°W 58.5°N 03°W 56.5°N 07°W	2300 2200 2300 0300 2205 2230 2300	— 15 15 20 6 7 6	290 315 300 045 320–360 345 305–330
13/14	2150–2215	Faint small scale display of weak bands in N seen Mjösund. Possible sighting at the same time queried by Boulmer. Aberdeen reported auroral display 2320 to 0150, and queried possible NLC at 0150.	60°N 22.5°E 57°N 02°W 55.5°N 01.5°W	2150 2200 2215 0150 2200	10 12 15 15	360 360 360 300–020
16/17	2230–2315 2400–0209	Wispy bands reported Kinloss and Dyce, faintly visible on film from Edinburgh, and to low elevation but bright from Boulmer. In Denmark display weakly visible showing band and veil structure.	57.5°N 03.5°W 57°N 02°W 56°N 03°W 56°N 10°E 55.5°N 01.5°W	2400 0038–0209 2230 2255 2400 0100	11 10 10 12 5 5	350–030 360–020 360 360 350–020 010–020
18/19	2140–0200	Picturesque, small display seen Mjösund, still visible after 2330 when observations ceased. Band and billow formation. Faintly visible on Edinburgh film.	60°N 22.5°E 56°N 03°W	2140 2200 2230 2300 2330 2230	— 18 30 30 30	315–045 340–020 340–045 360–045 315–045 360
19/20	2230 0200–0220	NLC bands, medium brightness, visible Northumberland. Faintly visible earlier on Edinburgh film.	56°N 03°W 55.5°N 01.5°W 55°N 01.5°W	2230 0200 0200	— 15 7	— 355–005 335–005
21/22	2100–0230	Display seen from very varied locations, medium brightness in Britain and very bright in Finland. Many brighter bands against veil background. In Denmark display bright, showing band and billow structure with red coloration near horizon. Photographs taken at Alrø and Wildbjerg.	60°N 22.5°E 57.5°N 03.5°W 56.5°N 07°W 56°N 03°W	2100 2125 2205 2330 0100 2230 2305 2325 0030 0050 56°N 09°E 2210 56°N 10°E 2110	8 15 10 9 6 9 6 6 5 3 — 15	360 360–045 360–045 350–025 330–010 010–040 360–030 345–020 355–015 355–015 340–045
22/23	0300	Diffuse band of NLC visible Tiree. Clear conditions and no NLC 2200–0200.	56.5°N 07°W	0300	14	030–038

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max. elev.	Limiting azimuths degrees
24/25	2220–0230	'Best display since 1978' according to Mr Parviainen, though maximum (2330) occurred when sky brightening. At 0030 the display covered whole sky except low NE where obscured by rising sun. Mr Hapgood, travelling in roughly the same latitude, recorded the appearance of the NLC in the NE, developing towards the zenith until dawn, with marked wave structure after 0200. Mr Parviainen provided 20 photographs of the display taken at Mjösund, and Mr Hapgood sent details of the 20 he took some 300km to the west, at Gävle, in Sweden.	61°N 17°E 60°N 22.5°E	2245 2400 0100 2220 2235 2315 2335 0005 0020 0030	20 – 10 20 30 90 90+ 140 180	360 045 045 360,045 315–045 360–090 270–090 250–090 135–225
25/26	2100–0100	Another 'great display' as seen Mjösund to maximum elevation 22°, with very bright area on eastern tip (045°). Sumburgh and Wick reported the NLC area at high elevation when observed at 0100.	60°N 22.5°E 60°N 01.5°W 58.5°N 03°W	2100 2125 2145 2230 0050 0100	20 20 20 22 35 30	360 315–360 315–020 300–045 350–040 360
26/27	2030	Diffuse NLC visible through widespread breaks in tropospheric cloud at Fiane.	59°N 09°E	2030		
27/28	2100–2150	Very faint small scale display, soon obscured by tropospheric cloud.	60°N 22.5°E	2100 2120 2140 2150	10 15 10 15	360 315,360 360 360
28/29	2150–2225	Very faint NLC showing no development during observing time.	60°N 22.5°E	2150	10	360
29/30	2245–2335	Clear sky at 2200. Quiet display of short duration; band and billow formation in NW sky, becoming faint at 2335.	60°N 22.5°E	2245 2305 2315	40 16 30	315–360 360 315
30/31	0200–0400	At Håstrup, Denmark, short lived appearance of medium brightness NLC. NLC not visible in clear conditions at Tirree until 0300, when two narrow bands in NNW moved slowly into NNE.	55.5°N 10°E 56.5°N 07°W	0200 0300 0400	20 12 14	340–045 340–360 020–030
3/4 Aug	2145–2315+	Relatively bright display on a very cold night in N Finland. When observations began, NLC already bright in N sky; greatest extension 315–090 at 2230; maximum brightness 2250.	65°N 27°E	2155 2205 2245 2305	40 20 22 18	345–070 315–090 360–070 360–045
14/15	2100	Silvery bands reported from Benbecula, with N–S origination to maximum elevation 7°.	57.5°N 07°W	2100	7	315
17/18	2040–2115	Possible short sighting of NLC at high elevation.	59°N 09°E	2100	90	

Photographs

22/23	June	2200	London
29/30		2330–0100	Edinburgh Met. Dept
30/1		2206	Groningen
		2225	Wildbjerg
1/2	July	2400–0145	Edinburgh Met. Dept
2/3		2200–2300	Mjösund
3/4		0001–0115	Edinburgh Met. Dept
4/5		2210–2300	Mjösund
		2310–2325	Edinburgh (Cammo)
		2315–0145	Edinburgh Met. Dept
		2345–0215	Aberdeen
		2330	Edinburgh (Joppa)
6/7		2200–2230	Mjösund
7/8		2130–2300	Mjösund
		0033, 0053	Aberdeen

8/9		2048-2330	Alrø
10/11		2120-2200	Mjösund
		2355-0208	Malin Head
13/14		2200	Mjösund
16/17		2230-2300	Edinburgh Met. Dept
18/19		2230-2300	Mjösund
		2230-0200	Edinburgh Met. Dept
19/20		2230	Edinburgh Met. Dept
21/22		2125-2215	Mjösund
		2152-2205	Alrø
		2200-0230	Edinburgh Met. Dept
		2210	Wildbjerg
24/25		2300-0030	Mjösund
		2326-0022	Gävle
		0230	Edinburgh Met. Dept
25/26		2330-2400	Mjösund
27/28		2130	Mjösund
29/30		2330	Mjösund
3/4	August	2145-2315	N. Finland

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Meteorology and crop-spraying

By N. Thompson

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Summary

Adverse weather can seriously degrade the effectiveness and safety of crop-spraying and, in particular, may lead to damaging spray drift. This paper provides a brief review of meteorological factors of importance in crop-spraying, and gives quantitative descriptions of spray drift and the related off-target uptake and deposition of pesticides in both vapour and drop forms.

1. Introduction

Crop-spraying has advanced within the last two decades from a relatively minor activity on most arable farms to one of the most frequent and important of the various field operations in British agriculture. Two of the major reasons for this are: first, the recognition of the economic benefits of using sprays to reduce agricultural losses caused by pests and diseases and, second, changes in farming practices which demand much greater use of herbicides than hitherto; examples of the latter are the substitution of minimum cultivation techniques for ploughing, and the increase in acreage of winter cereals.

Many of the pesticides* are phytotoxic (damaging) to neighbouring crops which are not targets for the spray. Also, some (e.g. growth regulators and herbicides) are effective or safe only when applied at a

*Pesticide is the collective term for sprays used against insect pests, plant pathogens and weeds; it is now also applied to hormone-based plant growth regulators.

particular growth stage of the plants being protected or controlled. Meteorological factors therefore play an important part in a number of aspects of spraying; they determine, for example, whether spraying at the appropriate time can be carried out successfully or whether there is a significant risk of pesticide drifting on to, and damaging, sensitive off-target crops, either through drifting spray drops at the time of application or from pesticide which volatilizes at some time after application.

A number of studies (e.g. Adams 1980, Spackman and Barrie 1981) have confirmed that in some years the periods for spraying that are best in biological terms often do not coincide with optimal meteorological conditions. Then, for example, farmers may be forced to spray on occasions when the soil is so wet that damage is caused to the soil structure by the spraying vehicle, with consequent penalties in terms of crop yield. Alternatively, spraying may take place in conditions where excessive drift occurs, with the possibility of damage to sensitive plants growing outside the target area. The magnitude of drift is linked very closely to meteorological factors, and the remainder of this paper describes how recent work within the Meteorological Office (Thompson 1983, Thompson and Ley 1982) has led to progress in quantifying the spray drift hazard.

2. Some factors contributing to damaging spray drift

(a) *Vapour drift*

Most phytotoxic pesticides have low volatility, and at the time when they are often widely applied (in spring) temperatures are usually low enough for only insignificant quantities of pesticide to volatilize after application. However, some very effective pesticides which contain esters are much more volatile, and for them up to about 40% of the amount applied has been found to volatilize within a few hours of application in warm conditions with temperatures around 25 °C (Maybank *et al.* 1978). Vapour pressure, and hence rate of evaporation, of many pesticides decreases by a factor of around 4 for each 10 °C decrease of temperature (e.g. Burkhard and Guth 1981), so in Britain it might be expected that around 10% of the pesticide applied with these formulations would volatilize on the warmer spring days.

Another important aspect of vapour drift is that the wind direction may change between the time of application of the pesticide and the period in which damaging drift occurs. In order to avoid direct drift damage (i.e. by drops), the operator would not spray in the vicinity of sensitive off-target plants while the wind was blowing directly towards them; however, he would be unlikely to abandon an attempt to spray because of a forecast of a potentially damaging wind shift *after* completion of the task.

Thus, the combination of wind shift and high temperatures in the period after application, and the use of pesticides with high vapour pressure, are usually responsible for damaging vapour drift.

(b) *Drop drift*

At present most crop-spraying involves the use of a hydraulic system in which the pesticide, diluted around 100 times with water, is ejected through spray jets mounted on a boom about 0.5 m above the plants. The hydraulic pressure is typically 250 kPa, which forces the liquid from the jets at around 20 m s⁻¹ in a thin fan-like sheet. The sheet breaks up into drops with a wide size-spectrum, entraining air in the process so that the drops decelerate more slowly than if they had been ejected singly from the sprayer. In the absence of wind there is clearly no drift; conversely, an increase of wind produces an increase of drift, for two main reasons. Firstly, a stronger wind will disrupt the spray sheet and its entrained air more quickly, so that drop trajectories become controlled solely by atmospheric turbulence and drop fall-speeds at a height above the surface (called the effective release height) which is greater than in light winds, leading to a potentially larger source of drifting drops. Secondly, in stronger winds a larger proportion of the emitted drops have fall speeds which are small compared to the

turbulent updraughts and downdraughts in the atmosphere, and so behave more like neutrally-buoyant particles which can drift long distances before impacting on the surface.

Therefore, the most damaging drop drift usually occurs when spraying takes place in windy conditions, with the general direction of airflow from the target area towards the sensitive non-target plants.

3. Quantifying spray drift

(a) Vapour drift

The factors of importance here are (i) the source strength (amount of pesticide volatilizing), (ii) dilution, by atmospheric turbulence, of the vapour as it moves downwind, (iii) relation between rate of uptake of pesticide by plants and the vapour concentration in the air around the plants and (iv) the relationship between phytotoxicity and dose for the pesticide and plant species in question: the first three are strongly controlled by meteorological factors, and the last may also involve a dependence on weather, through temperature or an earlier weather-induced stress (e.g. through frost or soil moisture shortage).

There are considerable difficulties in estimating the rate of volatilization of a pesticide applied in known amounts to a target area. Thus, the pesticide may be distributed initially, in poorly-defined proportions, between foliage and the underlying soil. Volatilization from the soil will be influenced by adsorption, soil moisture and temperature. Loss of pesticide to the atmosphere from foliage will be determined by leaf temperature, wind speed, rate of absorption into the leaf tissue, form of the dilutant and physical nature of the deposit (e.g. its surface area). Both foliage and soil surface temperature may depart significantly from screen temperature, especially if the soil is dry. For these reasons it is not usually possible to provide a reliable estimate of rate of volatilization of the applied chemical; however, on the basis of earlier comments, a quantity of the order of a few percentage of that applied is likely to evaporate on the day of application when the more volatile formulations are used.

The treatment of the dilution of the vapour as it moves downwind is more straightforward. Areas sprayed in arable farming are usually several hectares in size, and so without much loss of generality the effects of lateral dispersion on dilution can be ignored. It is convenient to idealize the source as a series of long, adjacent cross-wind strips of unit alongwind length and then, following Pasquill (1974), the near-surface concentration of vapour, C , produced by a single source strip emitting Q units $s^{-1}m^{-2}$, at a distance x downwind is approximately

$$C(x) = \left(\frac{2}{\pi}\right)^{1/2} \frac{Q}{\bar{u} \sigma_z(x)} \quad \dots \quad (1)$$

This assumes that the distribution of vapour concentration in the vertical, about an axis at ground level, is Gaussian with standard deviation $\sigma_z(x)$, and that the mean speed of movement downwind is \bar{u} . The vapour concentration when contributions from all the source strips are included is then

$$C(x) = \left(\frac{2}{\pi}\right)^{1/2} \frac{Q}{\bar{u}} \int_x^{x+X} \frac{dx}{\sigma_z(x)} \quad \dots \quad (2)$$

with X the alongwind length of the sprayed area. $\sigma_z(x)$ is a function of atmospheric turbulence as well as x , and so varies with wind speed, atmospheric stability and aerodynamic roughness of the underlying

surface. Pasquill (1961) presented graphs showing how $\sigma_z(x)$ is related to distance and stability. The graphical data are described more conveniently in the present context by power-law relations which for fairly unstable (Pasquill's class B), near-neutral (class D) and fairly stable (class F) cases are approximately:

$$\left. \begin{aligned} \sigma_z(x) \text{ (B)} &= 0.12 x^{0.89} \\ \sigma_z(x) \text{ (D)} &= 0.10 x^{0.81} \\ \sigma_z(x) \text{ (F)} &= 0.055 x^{0.52} \end{aligned} \right\} \dots \dots \dots (3)$$

Substitution of equation (3) in equation (2) allows the calculation of vapour concentration at different distances from source areas of specified size.

The rate of uptake of vapour by plants depends on numerous factors apart from vapour concentrations adjacent to the plants. However, an estimate of this rate for most field crops may be obtained from the assumption that the vapour enters the plants through the leaf stomata*, and is then completely absorbed into the plant tissue; postulation of this mechanism for uptake of sulphur dioxide for example (Fowler and Unsworth 1979) leads to calculated rates of uptake in close agreement with measured values. A simple resistance analogue provides a method for developing the necessary theory in the case when the plants form a dense canopy completely covering the ground. Then the vapour concentration difference between that just above surface ($C(z)$) and that at the absorption sites in the leaves ($C(0)$) produces a flux density of vapour (F) which is controlled by two resistances in series:

$$F = (C(z) - C(0))/(r_a + r_c). \dots \dots \dots (4)$$

Here r_a is the average resistance to the transfer of vapour from the reference height z to the surface of the plant foliage; it may be estimated from wind speed, surface roughness, stability and molecular diffusion coefficient of the vapour (Monteith 1973 and Chamberlain 1974), and for short crops in near-neutral conditions has a value around 200 s m^{-1} when the 10 m wind is 2 m s^{-1} . r_c is the average resistance, per unit ground area, for the transfer of vapour from the leaf surface through the stomata. It has not been measured directly for pesticides, but can be deduced from the typical observed value of around 40 s m^{-1} for water vapour transfer through this pathway. This is done by applying a correction factor resulting from the smaller molecular diffusion coefficient of pesticides; most have molecular masses of around 300, compared to 18 for water vapour, and so r_c has a value around $40 (300/18)^{1/2}$ or about 150 s m^{-1} . Substituting these values for r_a and r_c in equation (4), and putting $C(0) = 0$ in view of the assumed perfect sink for the vapour within the leaf tissue, leads to a vapour flux density

$$\begin{aligned} F &= u_g C(z) \\ &\approx 3 \times 10^{-3} C(z) (\text{units } \text{m}^{-2} \text{ s}^{-1}). \dots \dots \dots (5) \end{aligned}$$

Here u_g is the *deposition velocity*, which in this case takes a value equivalent to the whole vapour cloud sinking towards the surface at 3 mm s^{-1} . The treatment may be modified slightly to apply to isolated individual plants, for which the rate of uptake is found to be several times larger than for the same plants when grouped to form a dense ground cover.

*Stomata are small pores in the leaf surface which permit the exchange of water vapour and carbon dioxide between plant and atmosphere.

The vapour concentrations calculated from equation (2) and (3) may be used with equation (5) to provide daytime estimates of likely rates of pesticide vapour uptake by plant canopies downwind from sprayed areas of typical size (Table I); no values are given in the Table for night-time because stomata are then usually closed. It is seen that in conditions typical of a warm, fairly sunny day the rate of uptake of vapour is calculated to exceed 1% of the source strength out to distances of at least 200 m. The larger uptake in near neutral conditions has to be set against the lower source strength then expected because of the lower temperatures found in these conditions.

Table I. *Estimated rate of uptake of pesticide vapour by a short, dense plant canopy: the vapour is assumed to be emitted from a broad field, 200 m long in the alongwind direction, at a rate of 1 unit $\text{m}^{-2}\text{s}^{-1}$ and to move downwind at 2 m s^{-1} .*

Downwind distance from field edge (m)	Rate of uptake (units $\text{m}^{-2} \text{s}^{-1}$)	
	Moderately unstable	Near-neutral
5	0.055	0.087
10	0.046	0.076
20	0.038	0.065
50	0.027	0.046
100	0.020	0.034
200	0.013	0.023
500	0.007	0.013
1000	0.004	0.008

The results indicate that for a case where 10% of the pesticide deposited on a target subsequently volatilizes, the uptake within about 200 m of the target can exceed 0.1% of the target dose. This figure may be considered in the light of the results from a number of experimental studies (e.g. Way 1964) in which sensitive plants have been sprayed by damaging pesticides to provide an indication of the magnitude of the dose required to cause some injury. Data given in Table II indicate that a number of horticultural crops can be damaged by very low doses. For the conditions under which Table I was constructed it is seen that when 10% of the applied pesticide volatilizes, then for lettuce affected by the herbicide 2,4-D for example, damage might be expected out to around 100 m from the field; if 20% of this herbicide volatilized, the distance of hazard would increase around threefold. These results are not

Table II. *Minimum damaging doses of herbicide (as percentage of normally applied dose) for various crops.*

Herbicide	Minimum damaging dose	
	0.1 – 0.4%	0.4 – 1%
MCPA	Outdoor lettuce, tomato	turnip
2,4-D	Outdoor lettuce	tomato, turnip, swede, cabbage, cucumber
Mecoprop	Outdoor lettuce, turnip, tomato	

inconsistent with some reported cases of herbicide drift damage. Thus there is some prospect that, provided sound methods are established for estimating the magnitude of the vapour source strength, and the necessary relationships between dose and damage are known for different plant species, meteorological treatments may be used to establish the weather conditions under which spraying can take place near sensitive plants without a subsequent risk of damage from vapour drift.

(b) *Drop drift*

A typical conventional hydraulic sprayer produces a drop-size spectrum with a volume median diameter around $250\ \mu\text{m}$, but the spectrum is broad so that as much as 10% of the spray volume may be carried by drops less than $100\ \mu\text{m}$ in diameter. Many factors additional to drop size affect drift; the most important are probably

(i) height distribution of each drop-size fraction when the drops have decelerated from their initial high ejection speeds to speeds where their subsequent trajectories are determined solely by fall speed and atmospheric flows,

(ii) wind speed and atmospheric turbulence,

(iii) rate of evaporation of the drops, and

(iv) the collection efficiency of the underlying surface for each drop size involved.

There are many interactions between these various factors, of which one of the most important is between (i) and (ii); it is well established that the number of drops which become potential drift (fail to be deposited immediately after release) increases with increasing wind speed in the case of conventional sprayers (e.g. Courshee 1959).

A qualitative picture of the drop-size range which is liable to drift may be obtained by comparing drop fall speeds (Table III) with typical vertical turbulent velocities in the atmosphere. Spraying usually takes place in daytime conditions with mean 10 m wind speeds less than about $5\ \text{m s}^{-1}$, when root-mean-square (r.m.s.) vertical velocities are typically less than about $0.5\ \text{m s}^{-1}$. Drops with fall speeds around or significantly larger than these turbulent velocities will have their trajectories largely determined by mean wind and gravity; drops for which the r.m.s. velocities significantly exceed their fall speed will behave more like neutrally buoyant particles, and be likely to drift. On this basis, drift will usually be negligible for drops larger than about $150\ \mu\text{m}$, unless spraying takes place with wind speeds greater than $5\ \text{m s}^{-1}$ or with a release height substantially greater than about the 0.5 m usually employed.

Table III. *Fall speeds of water drops in still air.*

Drop diameter	Fall speed
μm	m s^{-1}
20	0.01
30	0.03
50	0.07
100	0.25
150	0.48
200	0.71
250	0.93
300	1.15
400	1.60

There have been numerous experimental studies of crop-spray drift, but because of the large number of variables involved, and their mutual interactions, it has not been possible to derive from the results general expressions quantifying drift in terms of the variables. An inherently more satisfactory method of estimating the magnitude of spray drift is to construct mathematical models based on the underlying physics that may be applied after validating them against the results of limited numbers of field experiments. Until recently such models usually invoked a diffusing, sedimenting plume, with surface deposits determined from the geometry of intersection of the plume and the surface (e.g. Bache and Sayer 1975). However, these models are not able to represent satisfactorily all the processes involved,

and more recently 'random-walk' methods have been used to provide a more comprehensive description of drop drift (Thompson and Ley 1982, 1983).

Before describing results from the latter class of models, it must be pointed out that at present there appears to be no satisfactory method for describing simply the dynamics of drops in the period immediately following emission from hydraulic sprayers; it is necessary therefore to assume, rather than calculate, effective release heights of the drops whose trajectories are being modelled.

The random-walk model assumes that the trajectories of individual drops, away from the immediate influence of the spraying system, can be represented by a connected series of discrete displacements determined partly by a correlation between successive drop velocities and partly by a random selection from a Gaussian distribution of turbulent air velocities. Considering the vertical component of drop motion (the treatment is extended readily to three dimensions) and ignoring initially the drop-fall speed, we find the appropriate description is provided by the equation

$$w_{i+1} = \alpha w_i + \eta_{i+1} \sigma_w (1 - \alpha^2)^{1/2}, \quad \dots \quad (6)$$

where w is the vertical velocity of the drop, i is the number of the time step, η is a random variable with zero mean and standard deviation of unity, and σ_w is the r.m.s. vertical velocity. α is related to the Lagrangian time-scale (τ_L) of turbulence and the length of time step (Δt) used; provided that $\Delta t < \tau_L$ and, with several lesser assumptions, it may be shown that (e.g. Hall 1975)

$$\alpha = \exp(-\Delta t / \tau_L). \quad \dots \quad (7)$$

Introducing the fall speed (v_s) of the drop, and noting that the z axis is orientated upwards, leads to

$$w_{i+1} = \alpha (w_i + v_{si}) + \eta_{i+1} \sigma_w (1 - \alpha^2)^{1/2} - v_{si+1}. \quad \dots \quad (8)$$

The treatment is valid only for drops with a settling speed small enough for them to respond adequately to the velocity fluctuations in the surrounding air, but this is not a restrictive condition in the present context since, according to Smith (1959), this will be the case for $v_s < 2 \text{ m s}^{-1}$ (corresponding to water-based drops less than about $450 \text{ } \mu\text{m}$ in diameter).

Since the drops are usually water-based, their fall speeds change with time unless the air is saturated. The drops contain about 1% pesticide, whose evaporation may usually be neglected, and so decrease to about one fifth of their original diameter when all the water is lost. It is convenient to assume that mass transfer takes place from the drops as if they are pure water until only pesticide remains and it appears that this simplifying assumption adequately represents the evaporation of water-based sprays in many cases (Wanner 1980). On this basis the temperature of the drops is close to the wet-bulb temperature of the air (Ranz and Marshall 1948); following these last authors, the rate of change of drop diameter with time is approximately

$$\frac{d}{dt} d_\mu = -0.36 (\Delta p / d_\mu) \{ 2 + 0.124 (v_s d_\mu)^{1/2} \}, \quad \dots \quad (9)$$

where d_μ is the drop diameter in μm , and Δp (Pa) is the saturation deficit at the wet-bulb temperature ($\Delta p \approx 67 \times \text{wet-bulb depression}$).

Evaluation of the boundary layer variables contained in equation (8), and in the equivalent expression for alongwind motion, is carried out using similarity theory and flux-profile relations for non-adiabatic conditions (Ley 1982, Ley and Thomson 1983, Dyer 1974, Panofsky *et al.* 1977).

Application of the equations to the estimation of drop deposition on the underlying surface, and of numbers remaining airborne, at different distances from the source requires, in both cases, some assumptions about how the drops are trapped when they meet the underlying surface. It is found that the results are relatively insensitive to the height at which the drops are assumed to be deposited within the plant canopy, but are affected by the efficiency of collection. It is satisfactory therefore to assume that the trapping surface for the drops is at the top of the plant canopy; the possibility of less than complete capture of the drops when they first cross this surface (Lawson and Uk 1979) is accounted for by introducing partial absorption in the model, with the absorption coefficient ranging from one for large drops (diameter $> 100\ \mu\text{m}$) to values close to zero for very small drops. The model may then be used to calculate drift of drops and surface deposit densities for any distance from the source, although in crop-spraying applications it is convenient to limit this distance to a few hundred metres. It is necessary to follow the trajectories of a large number of individual drops (up to 10^4) in order to reduce statistical variability of the calculated deposits at longer distances to a level where reliable smooth curves of deposit density against distance can be drawn.

Quantitative estimates may then be obtained indicating the effects on drift of changing any of the meteorological or source variables, but for brevity only the effects on drift of varying effective release height, wind speed and rate of evaporation will be described here. Fig. 1 shows estimates of surface deposit densities at various distances from a long cross-wind line source of strength 10^4 drops per metre, for two drop sizes and a range of wind speeds and effective release heights. Except very close to the source, the effect of an increase in release height is seen to be an increase in drift deposits at all distances. In very light winds most of the $100\ \mu\text{m}$ drops fall out close to the source, but when winds are moderate or fresh the deposit densities are roughly proportional to effective release height. A smaller, but still marked, dependence of deposit density on release height is seen also for $50\ \mu\text{m}$ drops. The large increase of drift deposit with increasing wind speed which is evident for the $100\ \mu\text{m}$ drops is not observed for the $50\ \mu\text{m}$ size, because the smaller drops, with fall speeds only one quarter of those for $100\ \mu\text{m}$ drops, behave more like neutrally buoyant particles, even at wind speeds as low as $2\ \text{m s}^{-1}$. As discussed earlier, an important consequence of an increase in wind speed is an increase of the effective release height of the drops, which in turn widens the size spectrum of those drops liable to drift. Thus, directly or indirectly, wind speed is seen to exert a very large influence on drift; this is in accord with the experience of spray operators who believe that spray drift of phytotoxic chemicals becomes unacceptably large in many cases when $10\ \text{m}$ winds increase above about $5\ \text{m s}^{-1}$.

Drop evaporation also has a significant influence on drop drift, but a difficulty here is that the collection efficiency of the surface on which the drops are deposited decreases as the drops shrink in size, but in a way which is at present not quantified. The physical nature of the underlying surface will be important here (Lawson and Uk 1979), and the wind speed as well; however, in the absence of an accepted relation it will be assumed that collection efficiency (β) decreases linearly from 1.0 for $100\ \mu\text{m}$ drops to 0.1 after complete evaporation of water, with the corresponding range from 0.5 to 0.05 for drops which are initially $50\ \mu\text{m}$ in size. The results using these assumptions are compared in Fig. 2 with those for non-evaporating drops, and for drops with the absorption coefficient remaining constant in size as the drops shrink in size; the results are given for a wind speed of $5\ \text{m s}^{-1}$, effective release height of $0.5\ \text{m}$ and (for cases with evaporation) a relative humidity of 50% at 20°C . It is seen that, beyond a few hundred metres, the deposit densities of evaporating drops are substantially larger than for non-evaporating drops, and are also nearly independent of the lower boundary assumption. This unexpected latter result must however be viewed in conjunction with the numbers of drops airborne in the different cases (Table IV). Partial absorption leads to a larger number of the drops remaining airborne, particularly at longer distances. However, the estimated increase in the airborne fraction from this cause would be completely inadequate to compensate for the small absorption coefficient (about 0.1) if those drops, when reflected, became distributed in the vertical in the same way as those still

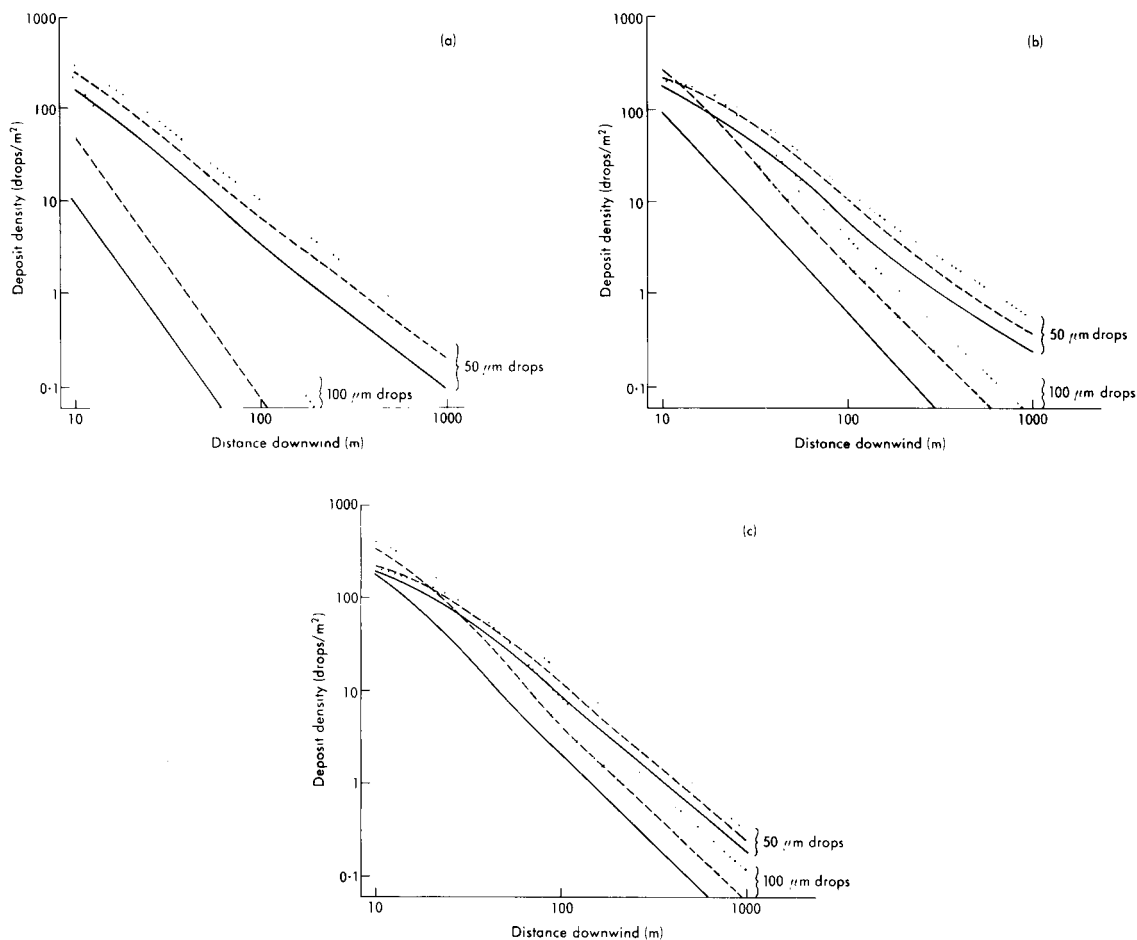


Figure 1. Estimates of surface deposit densities at various distances from a long cross-wind line source of strength 10^4 drops per metre, for two drop sizes ($50\text{ }\mu\text{m}$ and $100\text{ }\mu\text{m}$), three effective release heights (0.2 m —, 0.5 m ---, and 1.0 m ) and a range of wind speeds (a) 2 m s^{-1} (b) 5 m s^{-1} and (c) 10 m s^{-1} .

Table IV. Percentage of drops remaining airborne at different distances from source: an effective release height of 0.5 m , and a wind speed of 5 m s^{-1} , are assumed.

Drop size (μm)	Assumed conditions	Percentages airborne			
		at 10 m	50 m	100 m	500 m
50	a	63	28	20	12
	b	69	44	37	27
	c	81	72	67	58
100	a	24	3.8	2.0	0.5
	b	30	10	8	5
	c	29	12	11	8

- a = non-evaporating drops with constant β (collective efficiency)
 b = evaporating drops with constant β
 c = evaporating drops, with β decreasing with decreasing drop size

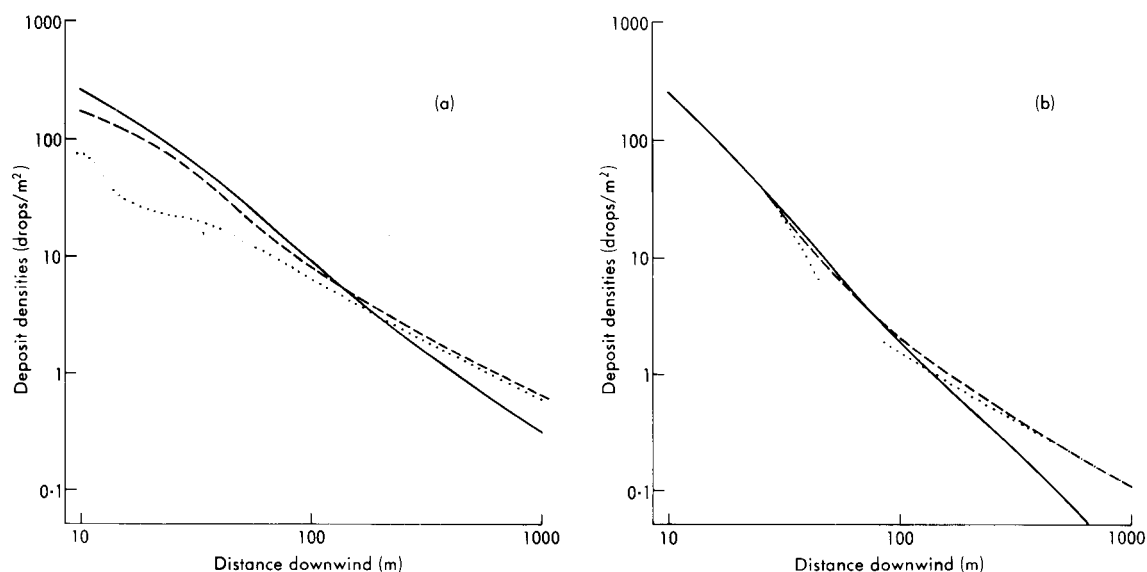


Figure 2. A comparison between surface deposit densities, in unstable conditions, of non-evaporating drops ———, evaporating drops (collection efficiency, $\beta = 1$) ---- and β decreasing with decreasing drop size ····, for drops that are initially (a) 50 μm and (b) 100 μm .

unreflected. On the other hand, reflected drops are likely to remain close to the surface for some time, and perhaps undergo further partial reflection, because of the small scale of atmospheric turbulence at these low heights. Reflected drops produce, therefore, a substantial increase in drop numbers near the surface, and in the context of deposit densities this appears largely to compensate for the low absorption coefficient; some measured distributions of drop numbers with height given by Lawson and Uk (1979) provide support for this idea. Nearer the source the proportion of reflected drops is much smaller and a reduced absorption coefficient therefore leads to a substantial reduction in surface deposit.

4. Concluding remarks

It is clear that meteorological factors have a considerable influence on the safety and success of crop-spraying on any particular occasion. It has been shown in this paper how knowledge of the relations between the structure of atmospheric turbulence near the surface on the one hand and simple meteorological parameters such as wind speed on the other allows the development of quantitative treatments of spray drift in both vapour and drop form with the help of simple models of turbulent flow. At present the full potential of such studies cannot be realized because of uncertainty in the precise nature of the sources of vapour or drops, a difficulty which is unlikely to be resolved easily; in spite of this the meteorological treatments are clearly able to give useful information on how drift varies with changes in meteorological variables. As more information becomes available on the characteristics of pesticide sources producing the drifting material the goal of estimating drift and drift hazard over the whole range of meteorological conditions normally experienced in crop-spraying should become attainable.

Although little has been said in this paper about the problem of spraying in wetter periods with only small soil moisture deficits, here too the application of meteorologically-based models provides useful

information on the number and duration of those periods in which spray vehicles are likely to be able to move over the land without damaging its soil structure. The approach required involves simulation of the variations of soil moisture with time at different depths in the soil by use of models of evaporation from the soil surface, and of water flow in soil, in conjunction with standard meteorological observations. The methods applied here are clearly very different from those used in estimating spray drift, indicating the great scope for application of physical principles, and those of atmospheric physics in particular, in problem-solving in agricultural meteorology.

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Concorde forecasts and the new 15-level model

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Summary

A global 15-level numerical model recently replaced the 10-level model at Bracknell and its behaviour in relation to the preparation of 100 mb flight forecast charts for Concorde aircraft has been monitored. Results so far are favourable, although a few dynamical problems have emerged.

1. Introduction

The 10-level model used at Bracknell for the past decade was not suited to produce forecasts of 100 mb temperature to be used in the preparation of flight forecast charts for Concorde. Temperatures were consistently too high in troughs and too low in ridges and the analysis did not even fit the reported temperatures from radiosonde stations (Atkins 1982). However, at the beginning of September 1982, the 10-level model was replaced operationally by the new 15-level model. This followed a period of trials lasting over six months during which time both models were run and the results assessed in various ways.

The development of the new model has been described by Gilchrist and White (1982) showing that the 10-level geopotential analysis has been replaced by an analysis of wind, temperature and surface pressure fields, moulded by a six-hour period of assimilation. Also, since the new model extends up to near 20 mb, instead of 100 mb for the 10-level model, it should be more suitable for producing temperature and wind forecasts at 100 mb. Assessments have been carried out by the author and although they were made on an irregular basis, it has become clear that there has been a marked improvement on the 10-level model although some consistent faults have been noted.

The form of the output from the 15-level model, run on the Cyber 205 computer, is virtually unchanged from the 10-level model and the times of receipt also remain about the same.

2. Analysis of the 100 mb temperature field using data assimilation

A considerable improvement has been noticed on the 100 mb temperature analysis mainly because the 10-level model temperatures were deduced from the thickness of 100 mb layers and the top such layer was 200–100 mb. A typical example of a comparison between the analysis of the two models and the analysed radiosonde reports is shown in Fig. 1. The improvement is seen in an objective verification of the 100 mb temperature analyses in August 1982 using observations over an area including Europe, the Atlantic and parts of America. The root-mean-square errors for the two models were as follows:

10-level model	2.1 °C
15-level model	1.5 °C

3. Behaviour of the 15-level model at 100 mb

The 24-hour forecast 100 mb geopotential contour patterns are mostly good. There is a tendency to forecast low values of geopotential although this does not necessarily affect the shape of the pattern and

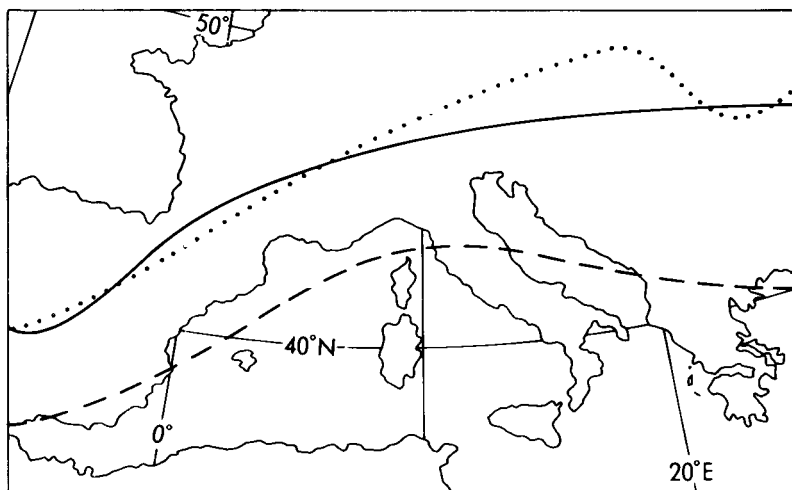


Figure 1. A comparison between the analysis of the 10-level model (dashed line) and the 15-level model (dotted line) of the -56.5 degrees Celsius isotherm (the International Standard Atmosphere) at 100 mb, for 00 GMT 21 July 1982. The full line shows analysed radiosonde temperatures.

hence the wind field. The model is also liable to move troughs and ridges a little too far east but this has only a minor effect on a 24-hour forecast. A more serious problem does occur on a few occasions when the model extends an upper trough excessively with consequent effects on the temperature and wind fields. Fig. 2(a) is an example of the error which can arise in the 24-hour forecast, while Fig. 2(b) shows the corresponding error in the forecasts of temperature (deviations from the International Standard Atmosphere); temperatures are seen to be as much as 5 degrees Celsius too high on the 24-hour forecast. Fig. 2(c) shows that, in addition, the area of maximum winds lying directly over the Concorde route at validity time, was displaced southwards off the route. Nevertheless, the 15-level 100 mb geopotential contour patterns are of an acceptable standard to be used generally in the preparation of the flight forecast charts, as indeed were the fields from the 10-level model.

4. The 15-level model forecasts of 100 mb temperature fields

Seventy-five assessments were made of the 24-hour forecast isotherms and these showed conclusively that there has been a marked improvement on the 10-level model forecasts. The forecasts were marked as poor when the error was assessed to be at least 4 degrees Celsius over at least 400 nautical miles of the flight route. Of the 75 forecasts checked, only 7 were marked as poor and 5 of these were related to excessive troughing. However, the success rate of the new model means that the computer forecasts of the 100 mb temperature can be used with a high degree of confidence in the preparation of the flight forecast chart. Little confidence was held in the 10-level model which necessitated the effort to find a method to obtain an acceptable forecast (Atkins 1982). A typical comparison between the 10- and 15-level model forecasts and the analysis for the same validity time is seen in Fig. 3. Objective verification against observations of the 100 mb temperature forecasts from T+24 hours to T+48 hours, for August 1982, when both models were running in parallel, is shown in Table I. The verification area includes Europe, the Atlantic and parts of America. These figures confirm the subjective assessments that the new 15-level model 100 mb temperature forecasts are better than the 10-level model.

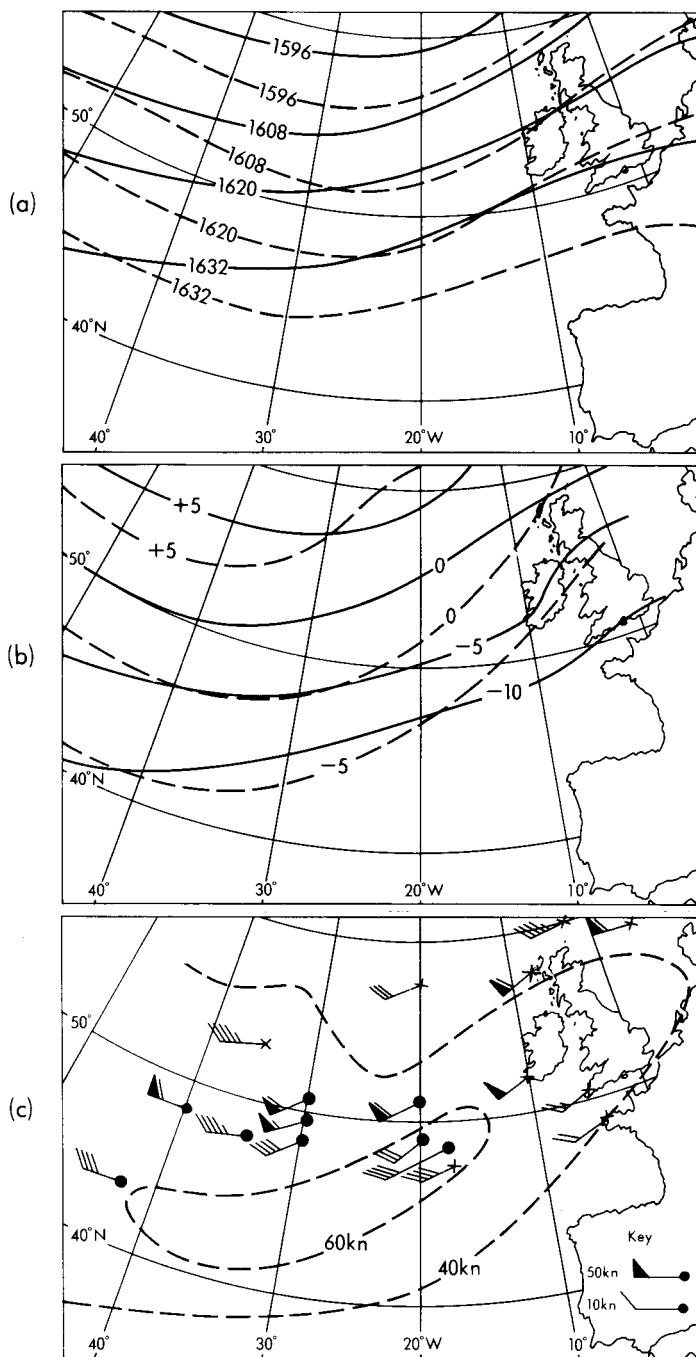


Figure 2. Comparisons between 100 mb charts for 00 GMT 20 October 1982. (a) The analysed geopotential contour chart (full lines) and the 15-level 24-hour forecast (dashed lines). Values in decapotesl metres. (b) The analysed isotherms (full lines) and the 15-level 24-hour forecast (dashed lines). Values in degrees Celsius as a departure from the International Standard Atmosphere. (c) The 15-level 24-hour forecast isotachs (dashed lines) and actual reports. Radiosonde stations for the same validity time are marked X, Concorde reports with a flight level near 100 mb, 3 to 6 hours earlier, are indicated by ●.

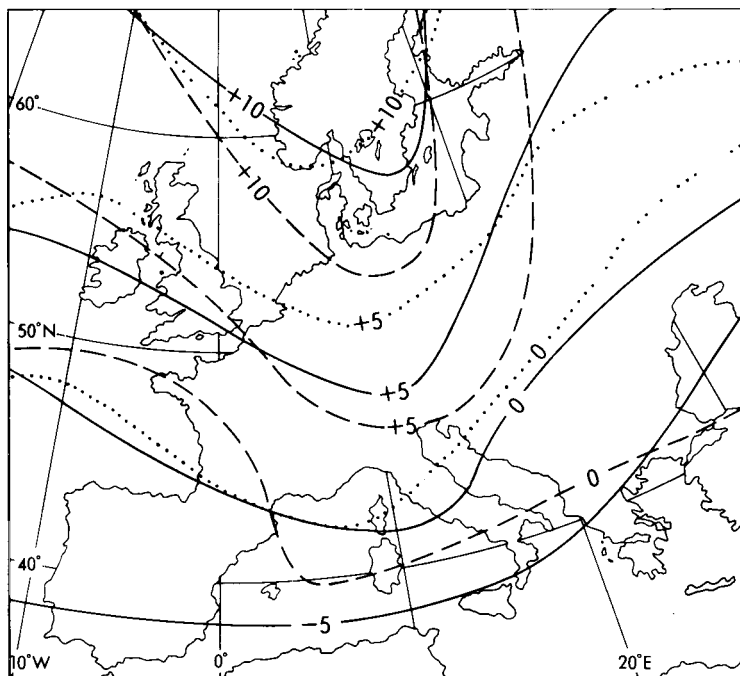


Figure 3. A comparison between the analysed 100 mb isotherms for 12 GMT 21 August 1982 (full lines) and the 24-hour forecast 10-level model (dashed lines) and the 15-level model (dotted lines) of the same validity time. Values in degrees Celsius as a departure from the International Standard Atmosphere.

Table I. *The root-mean-square error 100 mb temperature (degrees Celsius) forecast, verification against observations for August 1982. The mean error is given in brackets.*

	T+24	T+36	T+48
10-level model	2.2 (-0.5)	2.4 (-0.6)	2.6 (-1.0)
15-level model	1.8 (0.2)	2.4 (0.2)	2.1 (0.1)

5. The 15-level model forecast of 100 mb wind fields

Apart from the fault of excessive troughing mentioned above, the 100 mb wind fields are generally good, with areas of maximum wind strength well generated. However, anticyclonic winds in particular can be a little too strong, by about 10 kn, but it is possible for the forecaster to modify the numerical product. An example is given in Fig. 4 when the 80 kn isotach was deleted from the 15-level 24-hour forecast before issue. As can be seen from the verifying observations this proved to be a correct decision.

6. Concluding remarks

(a) The 100 mb temperature analysis has been improved with the introduction of the 15-level model and the chart analyst can accept the computer product with reasonable confidence even in data-sparse areas.

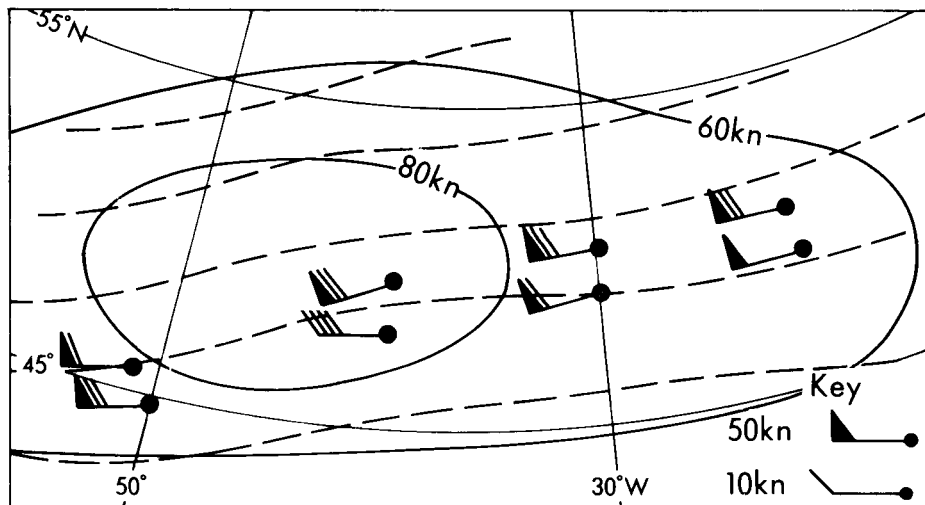


Figure 4. The 15-level 24-hour forecast of 100 mb isotachs for 00 GMT 10 December 1982 (full lines) and all the Concorde actual reports with 4 hours of that time with flight level near 100 mb. The 24-hour forecast 100 mb contour flow is indicated by the dashed lines and is similar to the subjective analysis for the same time. In the event, the 'anticyclonic' 80 kn isotach was deleted before issue.

(b) The 15-level model has produced a marked improvement on the 24-hour 100 mb temperature forecast. Temperatures may be up to 5 degrees Celsius too warm due to excessive troughing but, if this is taken into account, the standard of forecasts should be high.

(c) Subjective modification of the 15-level forecast isotachs can be beneficial.

(d) The 15-level model is still in its early stages and changes are continually being made to improve it. When the problem of excessive troughing has been overcome it might be possible to computerize the flight forecast chart so that a 12-hour forecast with data time 00 GMT could be used for the early morning forecast, perhaps issued a little later. At present the data time goes back 16 hours.

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Notes and news

Dr G.O.P. Obasi (Nigeria) appointed Secretary-General of WMO

The Ninth World Meteorological Congress, meeting in Geneva in May of this year, appointed Dr Godwin Olu Patrick Obasi (Nigeria) as Secretary-General of the World Meteorological Organization (WMO) for a period of four years commencing 1 January 1984.

Dr Obasi was born in Nigeria in 1933 and joined the Nigerian Meteorological Department in 1956. Subsequently he studied at McGill University, Montreal graduating in Mathematics and Physics and then at the Massachusetts Institute of Technology where he gained a Master's degree with distinction, a doctorate in meteorology and the Carl Rossby award for the best doctoral degree thesis. In 1963 he returned to the Nigerian Meteorological Service.

In 1967 he went to Kenya as Senior Lecturer at Nairobi University under the WMO/UN Development Programme, subsequently becoming Professor and Dean of the Faculty of Science. Returning to Nigeria in 1976, he was appointed Adviser to the Federal Government in Meteorological Research and Training and Head of the Nigerian Institute for Meteorological Research and Training and in 1978 he joined the WMO Secretariat in Geneva as Director, Education and Training Department. He has served as member or chairman of several important national and international scientific committees and working groups including being Chairman (1976–78) of the Nigerian National Committee for the West African Monsoon Experiment and Chairman (1965–67) of the Working Group on Tropical Meteorology of the WMO Commission on Atmospheric Sciences.

He is married and has six children.

He succeeds the present Secretary-General, Dr Aksel C. Wiin-Nielsen who has held the post since 1 January 1980.

Obituary

We regret to record the death on 29 March 1983 of Mr J.L.F. Irwin (Assistant Scientific Officer) of the Operational Instrumentation Branch (Met O 16). Mr Irwin joined the Office in 1971 and had worked from then on in the Radiosonde Calibration Plant. He was a keen morris dancer and was a member of the Yately Morris Men. He was also a musician with the Mayflower Morris Group.

THE METEOROLOGICAL MAGAZINE

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NOTICES

It is requested that all books for review and communications for the Editor be addressed the Director-General, Meteorological Office, London Road, Bracknell RG12 2SZ and marked 'For Meteorological Magazine'.

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Photograph by G. A. Corby

Retirement of Sir John Mason CB, FRS

Sir John Mason retires from the Meteorological Office on 30 September 1983 after filling the post of Director-General for 18 years. His term of office was characterized by a remarkable range of major

developments and innovative changes, mostly accomplished as a direct result of his own enthusiastic drive and formidable determination to advance the interests and prestige of the Meteorological Office. Any regrets he may have on taking his departure can justly be tempered by the knowledge that he leaves behind a smooth-running and magnificently equipped institution which is truly in fine fettle.

John Mason came from Norfolk, as revealed to the sensitive ear by the lingering traces of an East Anglian flavour in his accent, and remained there until completion of his grammar school education. His academic training continued at University College, Nottingham, but was interrupted by the Second World War when he was commissioned and served in the Far East in the Radar Branch of the Royal Air Force. Returning from the war to London University, he graduated in physics with 1st class honours in 1947, later adding a London M.Sc. and D.Sc., and began a brilliant academic career at Imperial College amongst the stimulating group which included P.A. Sheppard, E.T. Eady, R.S. Scorer and F.H. Ludlam. In 1957 John Mason became the Royal Society's Warren Research Fellow and during 1959-60 visiting Professor of Meteorology at the University of California. After his return from the USA he was appointed Professor of Cloud Physics at Imperial College and established a group which under his leadership quickly achieved a high reputation for its scientific excellence.

By 1965, the year in which he was both elected a Fellow of the Royal Society and appointed Director-General of the Meteorological Office, John Mason was already internationally renowned in his specialized field of cloud physics. Apart from his overall eminence in the science he had become well known around the world for his courage and scientific integrity in challenging sensational but dubious claims of success in rain-making and by exposing questionable evidence or untrustworthy analysis. In consequence, he was often consulted (and still is) by those with power and influence who find themselves faced with awkward decisions in the controversial field of rain-making.

However, in the rather different and staid corridors of the Scientific Civil Service back in 1965, the newly-appointed Director-General of the Meteorological Office seemed to some a very youthful, even perhaps brash, successor to his sedate predecessors. If to be bold and audaciously imaginative is to be brash, then the description fitted: but events soon proved wrong any who may have feared a clumsy or incautious regime due to inexperienced direction. John Mason quickly established himself as a very shrewd scientific administrator and forceful organizer with a great capacity for getting things done and shaping circumstances for the benefit of the Office.

When he took over, the Meteorological Office was of course already an old-established and reputable institution. It had recovered from the traumatic effects of the enormous concentration on forecasting for military aviation during the Second World War; scientific research had been steadily expanded from almost nothing to a substantial total effort; and the Office was fully settled into its fine new headquarters at Bracknell. The white hope of forecasting, namely numerical prediction, was about to become a routine operational activity using the recently commissioned KDF9 computer (the Office's second large machine).

Of the countless achievements of John Mason's Director-Generalship the most significant have probably been the impressive enhancement of the material resources available to the Office, the many auspicious acts of reorganization and modernization introduced to meet changing requirements, the great emphasis placed on research both fundamental and practically oriented and, perhaps most important, a genuine heightening of the scientific standing of meteorology and the Meteorological Office.

The gains in material resources available to the Office have been considerable, for example: the giant computers such as the IBM 360/195 installed in 1971 (augmented in 1975 by the IBM 370/158 as a 'front-end' processor) and more recently the CDC Cyber 205, commissioned in 1981, which have provided massive computer power for both operational work and research and which have been the envy of many less fortunate meteorological services; the progressive automation over several years of

the Bracknell telecommunications centre; the striking improvements in accommodation as exemplified by the Richardson Wing at Bracknell which houses the main computers, telecommunications and Central Forecasting Office (incidentally the wing was formally opened by the Prime Minister, Edward Heath, in 1972), the splendid new building and facilities at the Experimental Site, Beaufort Park and the first-rate training college at Shinfield Park; also other outstanding assets such as the powerfully equipped Hercules aircraft of the Meteorological Research Flight and the fine facilities at Malvern for research in radar meteorology. Such costly resources are not bestowed at the drop of a hat by a benevolent Treasury. They have to be fought for through many stages of a sometimes lengthy bureaucratic process and the irresistible appeal of John Mason's persuasive advocacy has frequently been a decisive factor in securing the best possible for the Office.

Although John Mason encouraged meteorological research in universities, especially where they had some unique expertise to offer, he considered that inevitably the Meteorological Office had to be the primary seat of meteorological research in this country. Indeed, he believed with great conviction that the service-type activities undertaken by the Office would stagnate and fail to respond to new requirements unless good and appropriate research was vigorously pursued in parallel. Accordingly, he took steps to expand and develop the activities and projects on both the Services and Research sides of the Office whilst at the same time encouraging a healthy interchange of ideas and staff between the two sides, to the mutual benefit of both.

On the Services side a major organizational change was an additional Deputy Directorate for communications and computing created in 1970 to meet the paramount need for an organization like the Meteorological Office to make optimum use of the latest computer technology and potential in its operations and research. Additionally, extra emphasis was placed on the need to take into account the cost effectiveness of meteorological services and much effort was devoted to publicizing the benefits which could accrue in many industries and enterprises from an intelligent use of tailor-made meteorological advice and forecasts. Particularly relevant areas for these efforts were the North Sea oil and gas industries, Concorde operations and ship routeing services. As a result of these and many other efforts almost one third of the cost of operating the Meteorological Office is now recovered from customers of the various specialized services provided. On the equipment side a major development was the introduction into service of a new, automated radiosonde system of very advanced design, developed within the Meteorological Office.

As to research, John Mason established a new branch for research in cloud physics soon after taking office, whilst another new research group for specialized studies in geophysical fluid dynamics was subsequently set up and the effort in several areas was expanded, notably in numerical forecasting and in dynamical climatology (general circulation research). Major national projects were Scillonia and the Dee Weather Radar Project, whilst internationally during the 1970s the Global Atmospheric Research Programme (GARP) was steadily brought to fruition. An important landmark in the latter programme was the GARP Atlantic Tropical Experiment which John Mason personally promoted through his chairmanship of the International Board of Management and by committing substantial UK resources to the experiment itself, conducted in the tropical Atlantic in 1974. He also assiduously fostered satellite meteorology, in particular by conceiving and following up the idea of the UK contribution to Tiros-N and by applying his good scientific sense and statesmanship to furtherance of the Meteosat programme.

Reference to these international activities is a reminder that as Permanent Representative of the UK at the World Meteorological Organization (WMO), John Mason has, throughout his term as Director-General, been very active and influential in the affairs of WMO and many amongst the meteorological community around the world will sorely miss his presence and wise counsel at future Congresses and meetings of the WMO Executive Committee.

John Mason knew only too well that, given reasonable facilities, the excellence or otherwise of an organization like the Meteorological Office depends almost entirely on the quality of its staff. He rightly valued brains and scientific ability as of paramount importance. There is no doubt that around the universities of the country his many talks and lectures, delivered with his own special brand of infectious enthusiasm and given added magnetism by his own eminence, have done much to make meteorology an attractive discipline amongst the brightest science graduates and have resulted in a steady intake of high calibre staff which augurs well for the future of the Meteorological Office.

One might remark here that, although it may not have been evident to those who knew him only superficially, John Mason had a genuine concern for his staff and their welfare and was distressed when a staff member or his family was in trouble, perhaps from illness, bereavement or otherwise; however busy, he always felt impelled to offer what help or comfort lay within his power. Indeed, behind the brisk, extrovert exterior there is a kindly, sensitive inner man who likes to recharge his spirit occasionally by a solitary tramp over the countryside or by hearing an orchestral concert.

One would expect the task of managing the Meteorological Office to be so demanding and exacting that the Director-General would have no reserves of time or energy for other activities, but those who have worked close to John Mason will know that his drive, stamina and capacity for work are absolutely prodigious. He has always seemed to live and breathe science, especially meteorology, with an intensity which never flags and his work-style exemplifies perfectly the paradox that exceptionally busy people are the very ones who always appear able to take on even more!

To list all John Mason's extramural activities would take considerable space but we may perhaps mention as examples his substantial efforts over the years in support of the British Association for the Advancement of Science, culminating in his Presidency of the BA for 1982–83; his services as President of the Royal Meteorological Society, 1969–70 and as President of the Institute of Physics, 1976–78; his Chairmanship of the Council of the University of Surrey, 1970–75 and his acceptance of the Pro-Chancellorship of that University in 1979. However, his most significant contribution of this kind (and probably the one which has given him the greatest personal satisfaction) has since 1976 been his work for the Royal Society in his capacity as Treasurer and Senior Vice-President — an office which is by no means a mere sinecure but is a tough and responsible job, the performance of which decisively affects the scientific well-being of the country.

Throughout his career John Mason has also been a prolific contributor to the journals with some hundreds of scientific papers and articles to his credit, as well as the major textbooks on cloud physics and rain-making for which he is justly celebrated.

As a public speaker he is persuasive, eloquent and entertaining and naturally has always been in great demand. As well as undertaking many of the prestigious, commemorative lectures in the world of science (e.g. the Kelvin, Bakerian, Thomson, Hugh MacMillan, Symons, Halley, etc.) he has been tireless in his willingness to speak on any occasion which presented an opportunity to publicize meteorology or to promote the interests of the Meteorological Office. He has indeed been a splendid ambassador for the subject dear to his heart.

Not surprisingly the academic and scientific world has showered John Mason with honours and awards, for example the Charles Chree Medal and Prize of the Physical Society, the Rumford and Bakerian medals of the Royal Society, the Institute of Physics Glazebrook Medal, the Royal Meteorological Society's Symons Memorial Gold Medal and others, not to mention a number of Honorary Doctorates bestowed by universities anxious to show their esteem. The ultimate accolade, his Knighthood, came in the 1979 Birthday Honours List.

It is appropriate to make the point here that, in the writer's opinion, John Mason's wide-ranging commitments, far from lowering his effectiveness as Director-General of the Meteorological Office, did in fact enhance his contribution. Even the staff, to varying extents, basked in the reflected glory of their

illustrious chief's eminence and their morale was thereby enhanced. But, more important, the stature of the Director-General himself was strengthened amongst those with whom he had to deal in his official work, insofar as his scientific distinction ensured respect for his views and aspirations and gave added power to his elbow in the official business of the day, whether negotiating for resources or whatever.

It is of course well known that John Mason could on many occasions have moved on to pastures more green, more lucrative and more prestigious. Fortunately for the Meteorological Office, he had over the years come to have a special pride in, indeed affection for, the Office and undoubtedly he derived great pleasure and satisfaction from presiding over its welfare and progress. Happily these considerations won the day and were sufficiently strong to keep him in post as Director-General.

Apart from being a milestone for the Meteorological Office, the end of John Mason's term is naturally an important juncture in his own career but it surely cannot herald his retirement into oblivion, the very thought of which seems manifestly absurd. Whenever one meets him, he appears as ebullient as ever; whatever one discusses arouses keen interest and a shrewd comment; and if one touches a spot which is scientifically or meteorologically sensitive, the gleam in his eye is as fresh and bright as ever. Fortunately he also continues to enjoy undiminished energy for life and zest for work.

One can only conclude that there must be many spheres in which his unique talents, experience, judgement and leadership could be applied to good effect.

We wish him well in whatever new activity or challenge he takes up and hope that he will achieve great success and satisfaction. On a more personal level, we extend to Sir John and Lady Mason our sincere best wishes for all possible health, contentment and good fortune in the future.

G.A. Corby

Sir John Mason as seen by the Chairman of the Meteorological Committee

By The Earl of Halsbury, FRS

(Chairman of the Meteorological Committee, 1971–82)

From the start we met as experienced committee men in the field of scientific administration. Each of us knew what the other was supposed to be for. From the outset the relationship between Director-General and Chairman was established on a basis of doctrinal orthodoxy. All we had to do therefore was to get acquainted, make friends and discharge our functions without getting in one another's way.

Knowing it would be fatal, I never attempted to set up as an amateur meteorologist and was content to exploit my mathematical physics up to but not beyond the point where I could comprehend what the meteorological equations stated and thereafter take an interest in the difficulties in solving them by numerical methods. It seemed the least I could do by way of tribute to and interest in the work of my colleagues, and by pursuing it no further I was left free to admire the professional skill of John Mason in his own field, a skill that set the tone for all the work that went on under his overall command.

I shall never forget his brilliance as an expositor, first heard in the course of his Bakerian lecture at the Royal Society in 1971. I remember thinking how much I would like to emulate his quality when speaking in Parliament: fluent, word perfect and unhesitating without a note of any kind.

As an administrator he was the kind of tough, driving chief executive that every Ministry would like to see in post. As a policy-maker and decision-maker he was, in political terms, dry as opposed to wet: definitely not one of the bleeding heart brigade, he had no use for sob stuff or hard luck stories.

Granted that he had the confidence of his MinisTRY, what did the MinisTER need an advisory committee for? What was the function that we fulfilled that John could not discharge himself? Chiefly, I think, providing the Minister on occasion with informed lay views on problems with political, that is to say Governmental and Parliamentary overtones: for example, did such and such an activity give the tax payer good value for his money.

In order to enable us to weigh in with advice on demand, we had as a matter of routine to familiarize ourselves with the broad outlines of everything that went on by receiving regular reports, department by department and topic by topic in rotation. On these occasions we met the DG in another of his aspects, as compère waiting in the wings and intervening only occasionally to restore balance into whatever might be getting out of perspective in the cut and thrust of discussion.

I have left till the end a final aspect, that of friend. We got through twelve years work together without a disagreement or a misunderstanding. What else but friendship could emerge from such an association and what would life be without it?

A synoptic case-study using a numerical model

By E. McCallum, J.R. Grant

(Meteorological Office College, Shinfield Park)

and B.W. Golding

(Meteorological Office, Bracknell)

Summary

Conventional analysis is supplemented by results from a numerical model to give increased understanding of the airflow through a system causing an area of extensive frontal rain over England on 22 June 1982.

1. Introduction

The conventional approach in studying synoptic systems involves analyses of synoptic charts and tephigrams. The information gleaned by this approach is limited because the data, especially upper-air information, are rather sparse. Inclusion of radar and satellite data in the analyses has resulted in a greater understanding of the dynamics of these systems, but realistic evaluation of vertical velocity over a large area remains difficult. As mass ascent leads to cooling, condensation, clouds and formation of precipitation, it is essential to evaluate this parameter. This is possible by using a numerical model which can produce fields of vertical uplift derived from the basic equations of motion. Unfortunately, in most models the analysis and initialization procedures result in rather smoothed fields which are inadequate for detailed studies. This problem may be overcome by using forecast fields which are less smooth and have a better dynamical consistency of the mass and wind fields. However, the vertical velocities obtained in this way should be treated with caution since they are based on a model which imperfectly simulates atmospheric processes.

It is an object of this study to use both model and observational data in a complementary way to help in the understanding of the dynamics of a particular synoptic system. The observational evidence will be presented in the first part of the paper in the form of charts and diagrams. In the second part diagnostic fields and trajectories from a model forecast will be studied and compared with the 'conventional' findings. The particular synoptic system being investigated in this case-study occurred on 22 June 1982 and was responsible for widespread rainfall over large parts of England and Wales.

2. Synoptic analysis

During the period 21–23 June 1982 the upper-air pattern was dominated by a blocking anticyclone centred near Iceland (see Fig. 1). Cool air from northerly latitudes flowed over Scotland around this high pressure area, while further south a relatively strong zonal flow carried surface features from the Atlantic over France and southern areas of England. Two warm occlusions crossed southern England during 20–21 June, merged and became slow moving over the north Midlands (shown as OA on Fig. 2). This resulted in a quasi-stationary convergence zone over northern England separating the relatively cool dry air over Scotland from warm moist maritime air over southern England. Prolonged widespread rain fell in northern England on the 21st as a result of this area of convergence and consequential forced ascent.

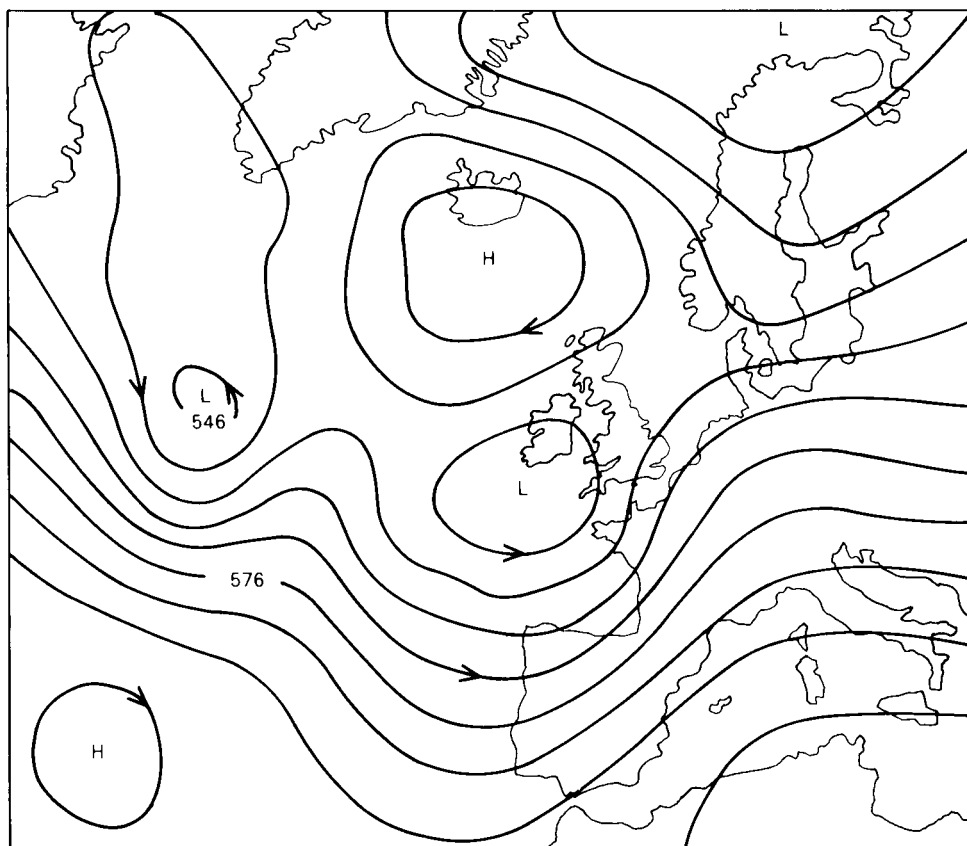


Figure 1. Contours at 500 mb (in standard decageopotential metres) for 1200 GMT on 22 June 1982.

On the 21st a deepening depression centred 250 nautical miles west of Corunna moved quickly north-east, ahead of a sharpening thermal trough, and was centred 80 nautical miles south of Ireland by midday on 22 June (see Fig. 2). At this time the vortex was moving north-eastwards at only 8 knots. The associated fronts swept across southern England during the morning of the 22nd, becoming slow moving near the line of the old occlusion OA later that afternoon. From detailed British Isles charts, radar data and satellite information it was calculated that at 1200 GMT the warm front WB and occlusion OB were moving north at 7 knots. Cold front CC over southern England was moving east at 17 knots while a second cold front or trough CD near Cherbourg progressed east at 22 knots. The infrared satellite picture for 1355 GMT (Fig. 3) shows two parallel cloud bands curving down over France associated with the two cold fronts. CC represents the back edge of the extensive cloud mass and precipitation area, with generally lower cloud tops apparent on CD. However, the cloud on CD is enhanced in places by convective instability due to strong midsummer surface heating and local convergence. Otherwise, this second cold front is largely a low-level feature with little organized precipitation, but with a marked drop in surface dew-point behind it. The features of the two fronts exhibit similar characteristics to the split cold front model of Browning and Monk (1982).

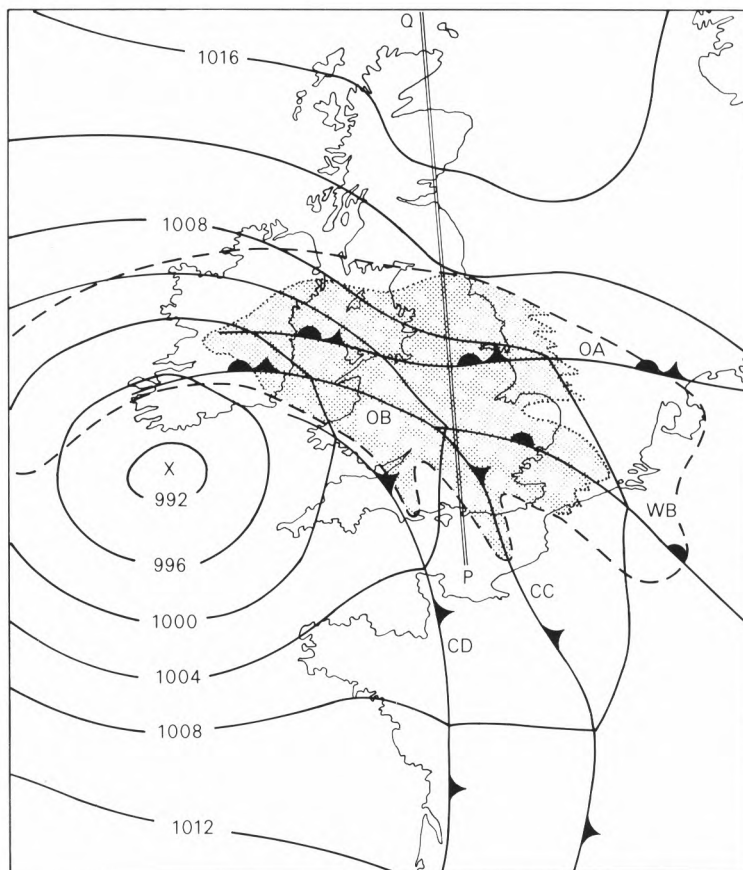
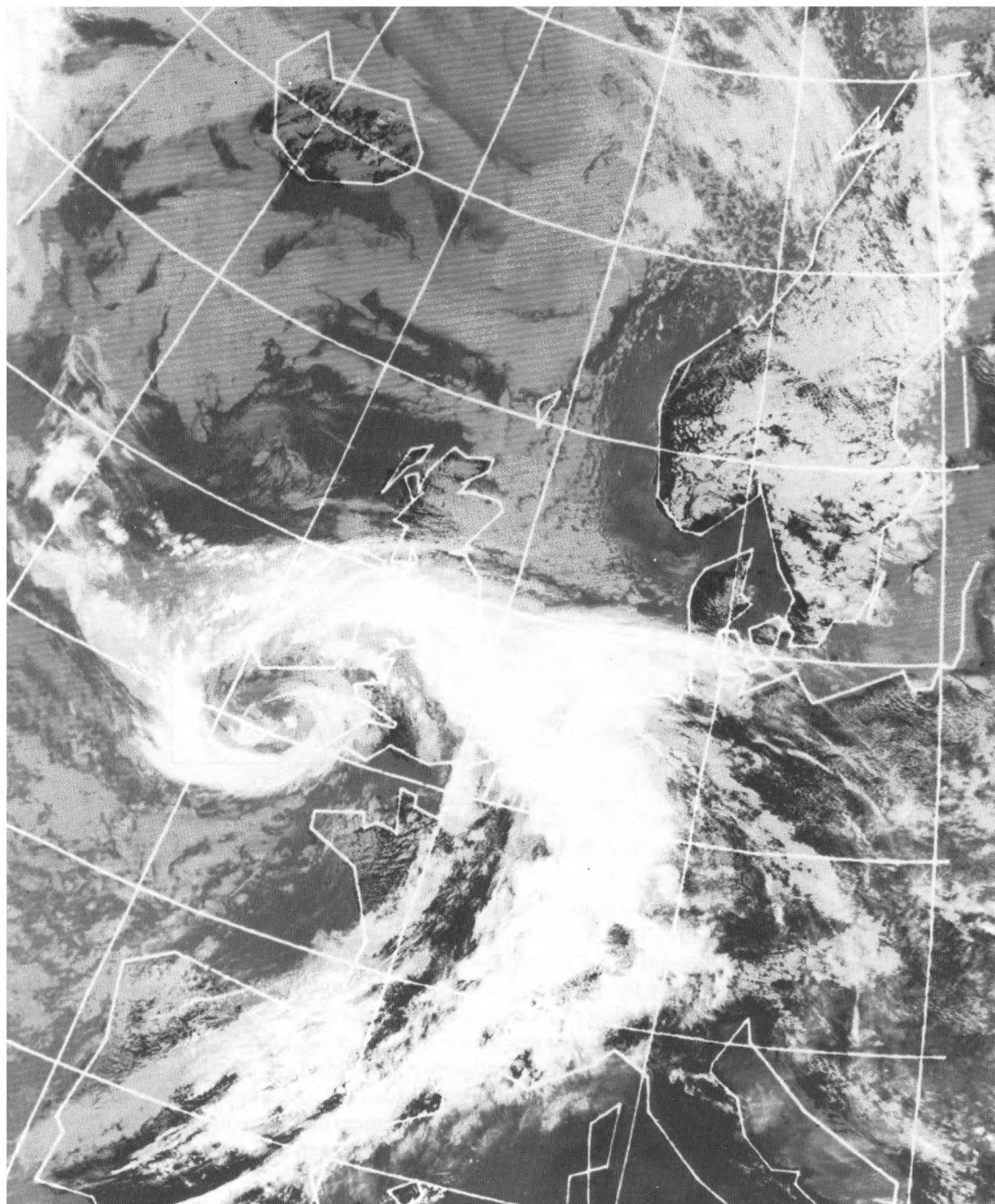


Figure 2. Surface analysis for 1200 GMT on 22 June 1982. The shaded area includes stations reporting moderate or heavy rain at the 1100, 1200 or 1300 GMT observation. The dashed line encloses the area of slight rain. The line PQ denotes the cross-section shown in Fig. 4.

A good deal of very warm moist air was brought north in the southerly flow ahead of these cold fronts and as this was forced to rise over the Midlands and northern England, large amounts of rain were produced. This warm front and occlusion rain reinforced the rain already falling in the old convergence zone, producing an extensive precipitation area which is depicted in Fig. 2. The heaviest and most persistent rain was in northern and eastern England with Silpho Moor in North Yorkshire reporting 94.2 mm in the 24-hour period commencing 0900 GMT on 22 June. Indeed seven other Yorkshire stations reported over 70 mm of rain that day with orographic enhancement adding to its intensity. The satellite picture (Fig. 3) shows the mass of cloud causing the rain over northern and eastern England as well as the swirl of cloud associated with the vortex south of Ireland.

A cross-section was taken almost north-south along the line PQ in Fig. 2, coinciding with the Pennine Chain (see Fig. 4). Examination of the values of wet-bulb potential temperature (θ_w) revealed a major frontal zone between 8 °C and 10 °C, having an average slope of 1:125. This was interpreted as an amalgam of the two warm occlusions which crossed the country on 21 June, and labelled OA on Fig. 2.



Photograph by Courtesy of Dundee University

Figure 3. Infra-red satellite picture for 1355 GMT on 22 June 1982.

The warm front arriving on the 22nd had θ_w values of 12 to 14 °C, but its structure was complicated by the presence of potential instability between 850 mb and 700 mb. The release of this instability in the form of 'generating cells' (see Marshall and Gordon 1957) was a major factor in the formation of enhanced mesoscale precipitation areas apparent on radar output.

For wind components parallel to the plane of the cross-section and relative to the motion of front OB/WB it is possible to estimate values of vertical motion if the following assumptions are made:

- (a) air parcels maintained their own θ_w values.
- (b) the thermal pattern of the front was unchanged.

This gives a band of ascending air over Aughton and Long Kesh, associated with the old occlusions, with maximum vertical velocities of around 8 cm s⁻¹ below the 800 mb level. Another cell of rising air associated with the warm air behind front WB (θ_w 14 to 16 °C) is found above 600 mb over the Midlands with maximum uplift of around 12 cm s⁻¹ at 400 mb. The calculated vertical velocity field below 700 mb between Hemsby and Long Kesh is complicated by the presence of potential instability. This highlights the difficulty of this approach and casts doubt on the results obtained.

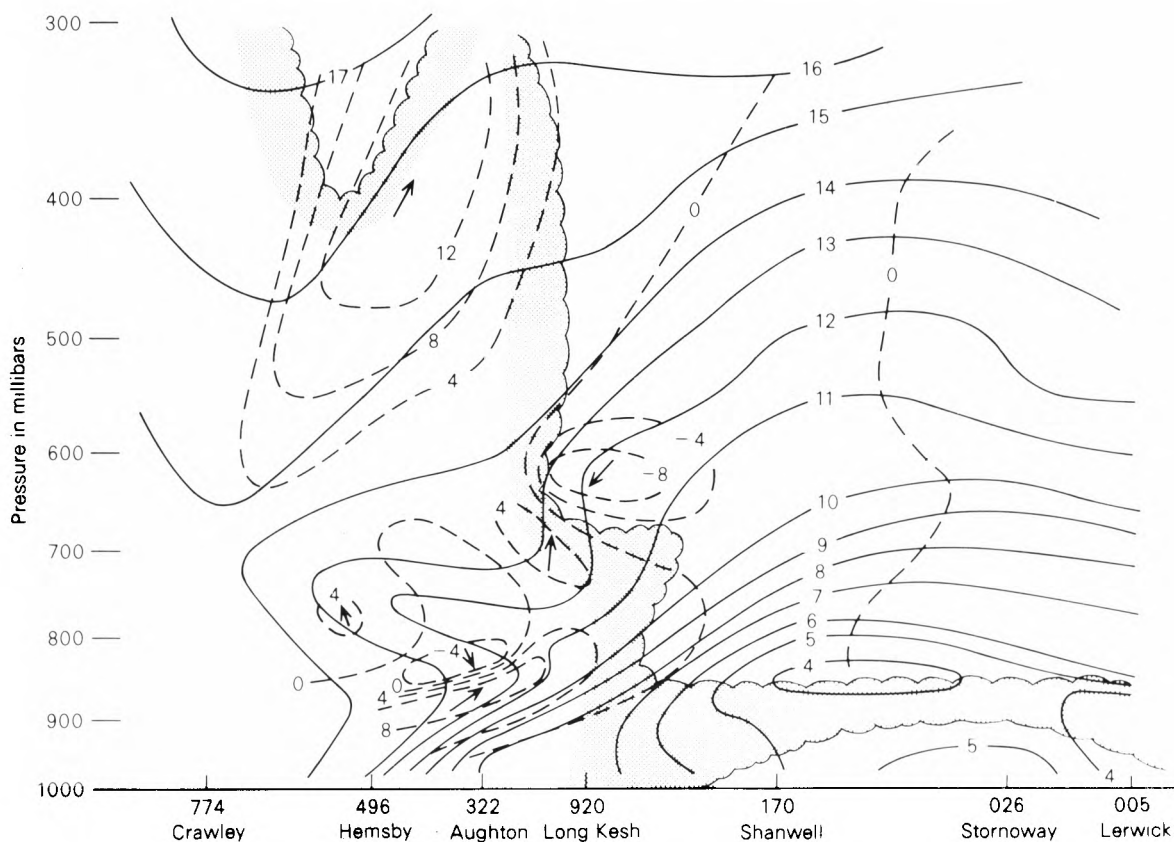


Figure 4. Cross-section along the line PQ shown in Fig. 2, for 1200 GMT on 22 June 1982. Solid lines represent wet-bulb potential values (θ_w) at 1 °C intervals. Dashed lines are isopleths of vertical motion in cm s⁻¹. The scalloped line denotes dew-point depression of less than 5 °C and is interpreted as the envelope of significant cloud. Station index numbers are shown above the radiosonde station names.

Fig. 5 shows a moist isentropic analysis (after Harrold and Nicholls 1968) based on midday data for the 14 °C wet-bulb potential temperature surface. This surface was taken as indicative of the movement of the warm air associated with front WB. The wind arrows represent airflow in knots relative to the front OB/WB and show the air rising up the isentropic surface over central southern England and the Low Countries. It was also found that analysis of the 8 °C θ_w surface showed general descent of the cool air at lower levels over Scotland and Northern Ireland.

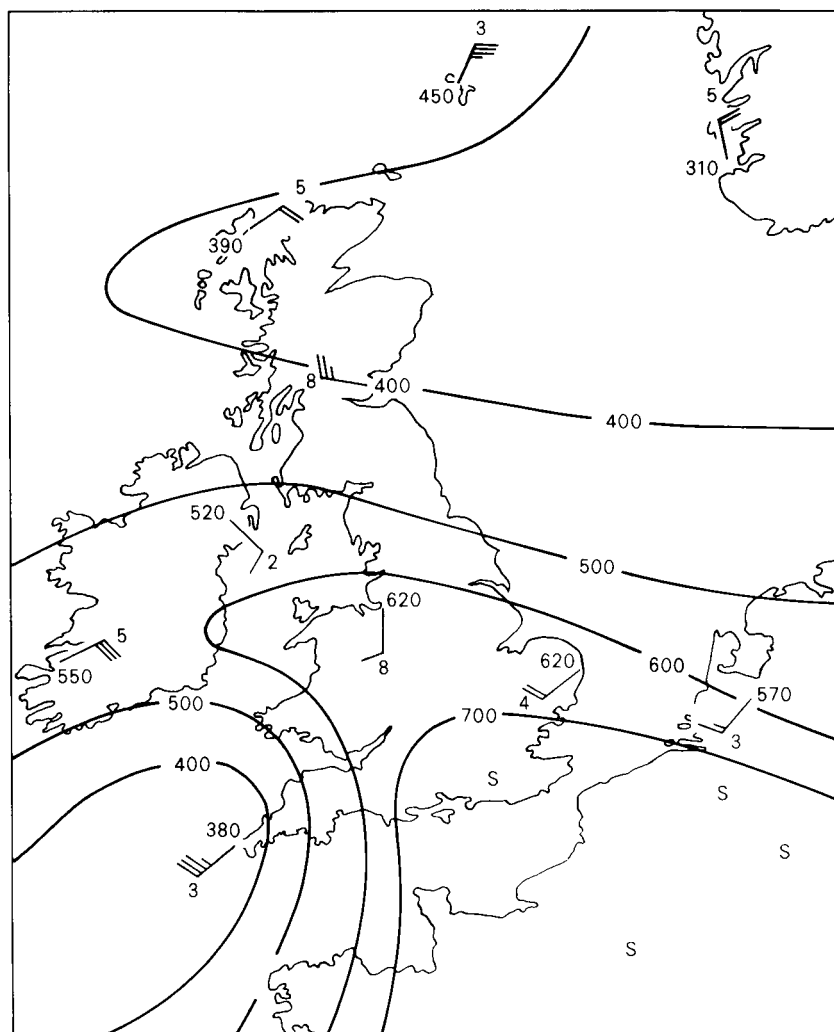


Figure 5. Moist isentropic analysis for the 14 °C wet-bulb potential surface at 1200 GMT on 22 June 1982. Solid lines show the height of the surface (mb). Stations with the surface at station level are marked S. Winds (kn) plotted at the radiosonde stations are relative to the motion of the warm front WB and are for the pressure levels (mb) shown.

3. Model simulation

The model simulation was made with the fine-mesh version of the Meteorological Office 10-level model (Benwell *et al.* 1971, Burridge and Gadd 1977, Gadd 1978a, b, 1980) which was in operational use at the time. The model has a 100 km grid length on a polar stereographic projection of the North Atlantic and western Europe. In the vertical, it has ten constant pressure levels at 100 mb intervals with the lowest at 1000 mb. The effects of orography are introduced through the 1000 mb geopotential tendency equation and by blocking the airflow where the surface intersects the lowest levels. The model has a comprehensive suite of sub-grid-scale parametrizations including condensation (leading to rainfall), solar radiation, surface fluxes of heat and moisture, surface friction and deep convection. Boundary values were fixed for the study presented here, but this did not affect results over the area of interest. The model has a time step of ten minutes; and contour height, wind velocity and humidity mixing ratio were obtained at every time step for use in trajectory and diagnostic computations.

The 12-hour model forecast for 1200 GMT on 22 June (see Fig. 6) produced a good qualitative description of the surface pressure field although the absolute pressure values were too high. However, the general shape and pressure gradient, important aspects from a forecasting point of view, were well represented. The area of moderate rain was also well predicted as can be seen by comparing Fig. 6 with Fig. 2. It is therefore reasonable to assume that since the forecast gave good guidance in this example, the model represented atmospheric processes reasonably well and so its diagnostic fields can be used to supplement observational information.

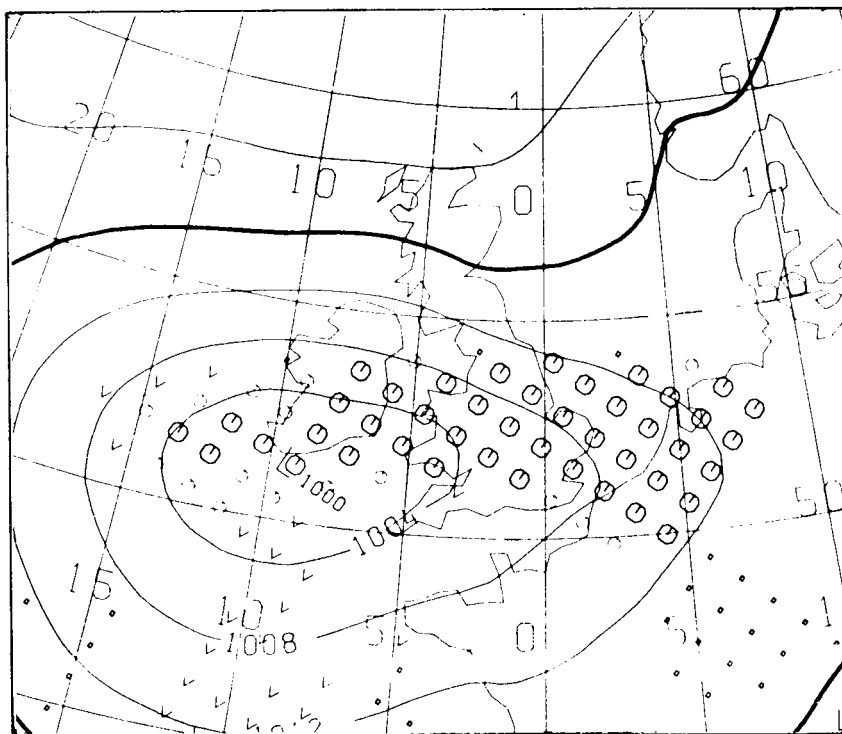


Figure 6. Twelve-hour forecast from the fine mesh version of the Meteorological Office 10-level model, valid for 1200 GMT on 22 June 1982. Frontal rain: ⊙ 0.5 to 4.0 mm h⁻¹, ○ 0.1 to 0.5 mm h⁻¹, ◦ trace Showers: ∨ 0.5 to 4.0 mm h⁻¹

Fig. 7 shows the 500 mb vertical velocity field with a general area of uplift of 8 cm s^{-1} over the Midlands and a maximum of 13 cm s^{-1} at $51^\circ\text{N } 3^\circ\text{E}$. This is at the junction between ascent in the conveyor belt ahead of the front CC and the general uplift associated with warm front WB, and corresponds to the steepest ascent noted in the isentropic analysis of Fig. 5. The region of ascent on front CC agrees well with the observed cloud in Fig. 3 and with the subjective analysis in Fig. 2. The effect of moisture plays a crucial role in the rate of vertical motion within the system. This is seen if Fig. 7 is compared with a corresponding dry run depicted in Fig. 8. The absence of moisture greatly reduces the vertical uplift with an innocuous 2 cm s^{-1} over the Midlands contrasting with 8 cm s^{-1} on the moist run.

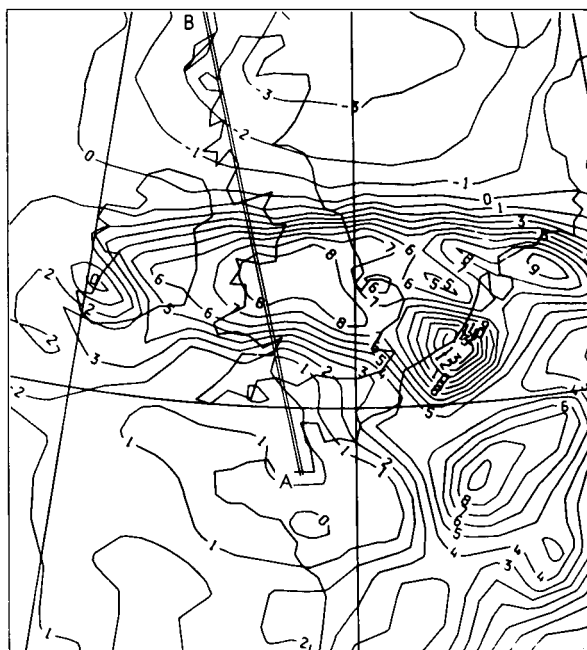


Figure 7. Twelve-hour forecast 500 mb vertical velocity in cm s^{-1} , valid for 1200 GMT on 22 June 1982. The line AB denotes the line of the cross-section shown in Fig. 9.

The vertical structure of the wet-bulb potential temperature field from the model forecast is shown in Fig. 9. The cross-section is taken along the line AB in Fig. 7 which is close to the line of the manual analysis shown in Fig. 4. The location of the strong θ_w gradient and its slope agree well between the diagrams, although the low-level values are generally two degrees higher in Fig. 9 with a weaker contrast between Hemsby and Aughton. Higher up there is some evidence of the double structure analysed in the hand-drawn section, shown by the space between the 12°C and 13°C isentropes in the Shanwell to Stornoway section. The model forecast only hints at an area of potential instability at 700 mb between Hemsby and Aughton compared with its conspicuous presence in the hand-drawn section.

Also shown in Fig. 9 is the vertical velocity from the model forecast, dominated by a cell of maximum ascent (almost two grid lengths wide), leaning northwards with height. This area of ascent corroborates the vertical velocity field obtained from the conventional analysis and corresponds well with the area of thickest cloud depicted in Fig. 4. The edge of the thickest cloud also fits closely with the zero vertical

isotach (in both the conventional analysis and the machine forecast) which separates rising air over England from sinking air over Scotland. This is supported by the satellite picture which shows the edge of the significant cloud over the Borders.

Airflow through the system is illustrated by examining trajectories of air parcels which show the air motions relative to the ground. A detailed description of the method and its application to the study of baroclinic wave development has been given by Golding (1981). In Fig. 10 the 1200 GMT positions at 950 mb are marked by dots, while the arrowheads show the position 12 hours later, with the final pressure level printed alongside.

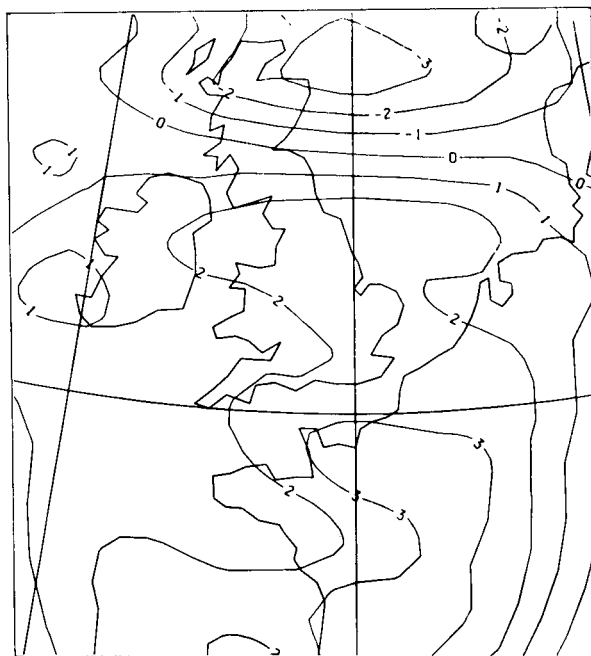


Figure 8. Twelve-hour forecast 500 mb vertical velocity, without moisture, in cm s^{-1} , valid for 1200 GMT on 22 June 1982.

To get an idea of the motion of the air over a 24-hour period reverse trajectories were also computed. Fig. 11 is an attempt to represent the low-level airflow at 1200 GMT in a simplified schematic manner with rising air shown by thickening arrowheads and descending air by arrows which thicken towards their tails. Two regions of flow can be identified. In the north, parcels move westward and descend slowly. In the south, parcels initially move northwards but on reaching the front they ascend rapidly and turn to the left to flow westwards above air from north of the front. This pattern is typical of the mature warm fronts analysed by Golding (1981).

Fig. 12 represents the flow of air at 750 mb for 1200 GMT. A gross distinction can still be drawn between ascent in the south and descent in the north. A further general division may be made into parcels which ultimately travel westwards and those which travel eastwards. Within the area of ascent there is considerable variation in intensity and two regions are marked within which parcels ascend very rapidly, many having an average vertical velocity greater than 4 cm s^{-1} over 12 hours or more.

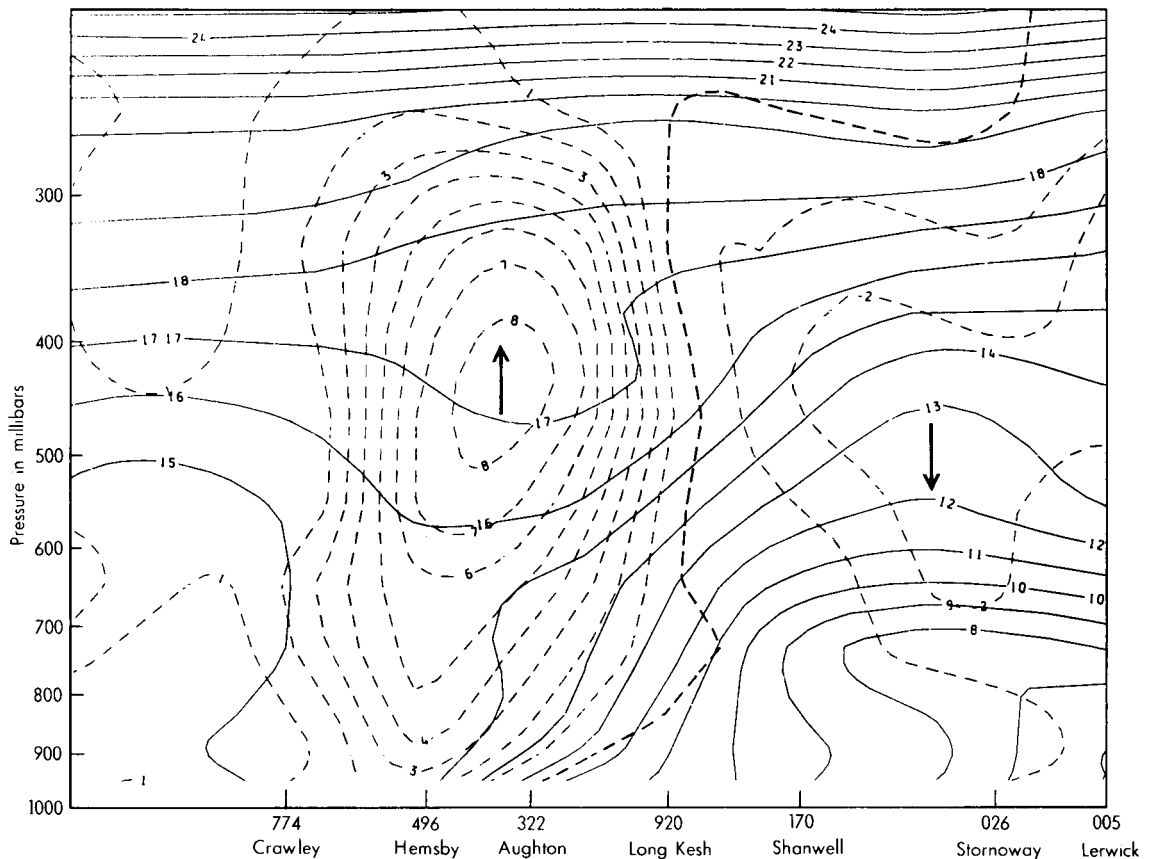


Figure 9. Cross-section along the line AB in Fig. 7 at 1200 GMT on 22 June 1982. Solid lines are wet isentropes in $^{\circ}\text{C}$ and dashed lines mark vertical velocity in cm s^{-1} . For comparison with Fig. 4, radiosonde locations are marked at the bottom along with their station index numbers.

At 450 mb (Fig. 13) the pattern is similar except that the demarcation line between eastward and westward flow lies further west. The most striking feature is the sharp discontinuity between rapidly rising parcels from the south and non-rising or sinking parcels from the north. The only area of disagreement with Fig. 5 is in the south-west, where the computed trajectories show parcels ascending rapidly during north-eastward motion and then turning westwards over Wales, whereas the isentropic analysis at this particular level shows descent. This is because the motion of this part of the system (the eastward moving front CD) was not taken into account in the hand analysis. This highlights a danger of isentropic analysis when the motion of the complete system is complex.

Fig. 14 is a cross-section from the model forecast along the line AB in Fig. 7, for the 24-hour period from 0001 GMT on the 22nd to 0001 GMT on the 23rd. The initial and final positions of the parcels are denoted by arrowtails and arrowheads respectively. The most striking feature is the narrowness of the band of parcels involved in the cell of strong ascent. Comparison of Fig. 14 and Fig. 9 indicates that parcel trajectories rise less steeply than the isentropes, although studies of 0600 and 1800 GMT model data confirm that the parcels conserve their θ_w values. This apparent discrepancy is accounted for by minor changes in the θ_w pattern itself and is largely due to the slow northward movement of the warm front.

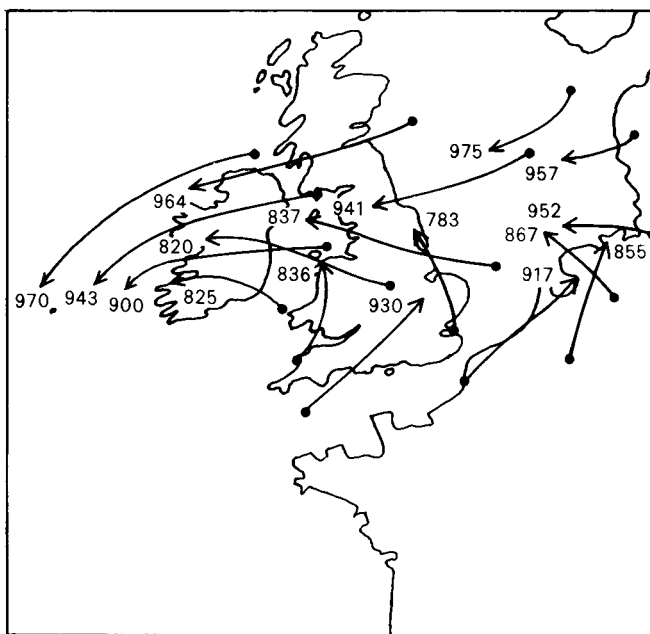


Figure 10. Twelve-hour trajectories for parcels of air initiated at 950 mb at 1200 GMT on 22 June 1982. Arrowheads mark the final positions with the pressure (mb) indicated alongside.

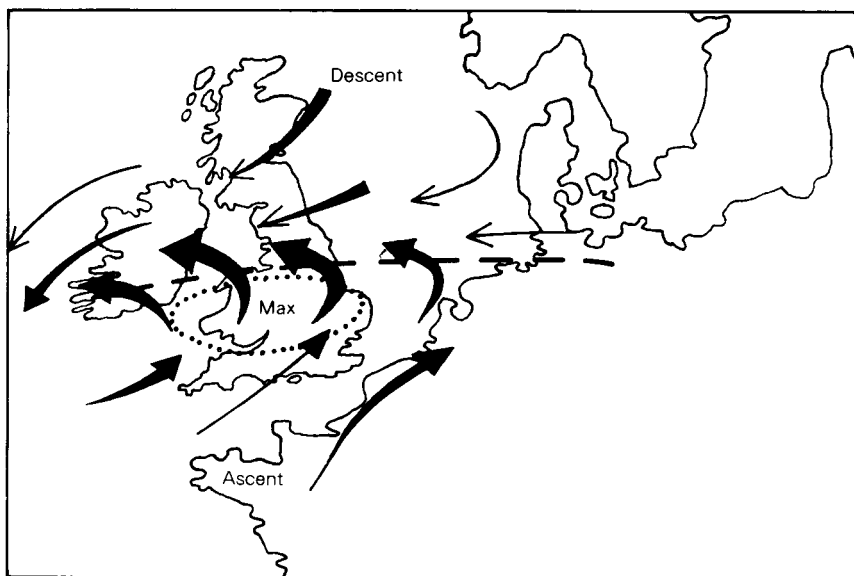


Figure 11. Schematic diagram of the airflow near 950 mb at 1200 GMT on 22 June 1982. Rising air parcels are indicated by arrows which thicken towards their heads and descending parcels by arrows which thicken towards their tails.

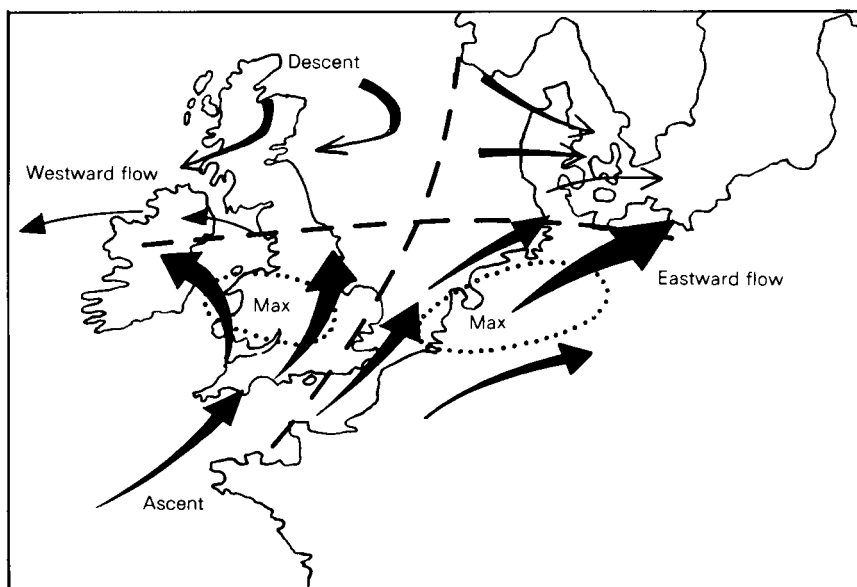


Figure 12. Schematic diagram of the airflow near 750 mb at 1200 GMT on 22 June 1982. Rising air parcels are indicated by arrows which thicken towards their heads and descending parcels by arrows which thicken towards their tails.

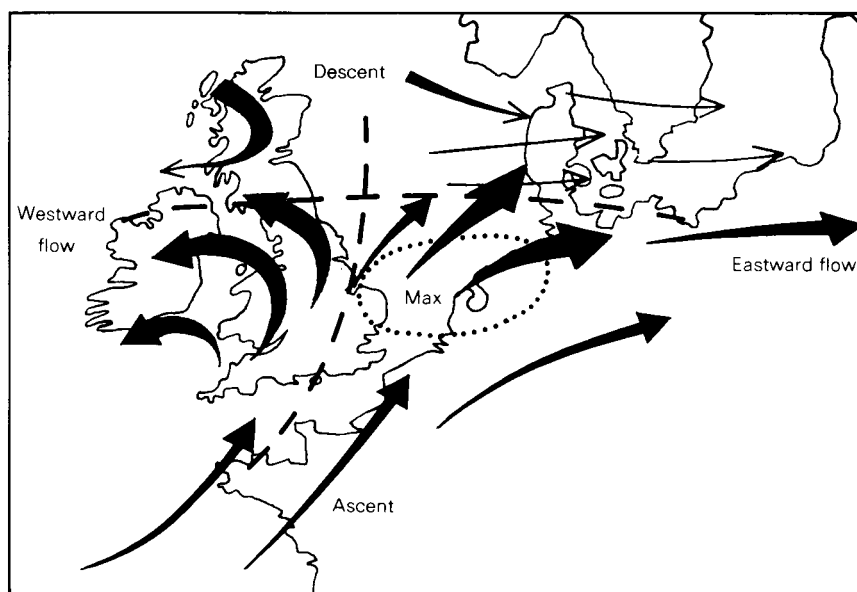


Figure 13. Schematic diagram of the airflow near 450 mb at 1200 GMT on 22 June 1982. Rising parcels are indicated by arrows which thicken towards their heads and descending parcels by arrows which thicken towards their tails.

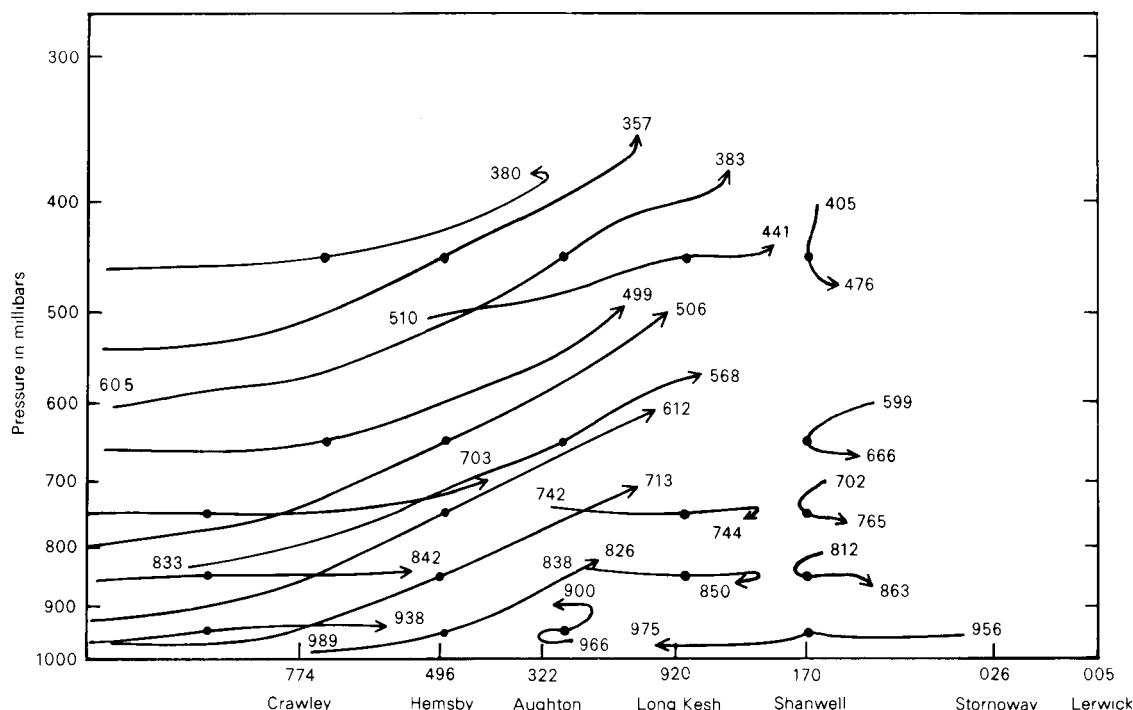


Figure 14. Twenty-four hour trajectories in the plane of the cross-section in Fig. 9. Positions at 1200 GMT on 22 June 1982 are marked by dots while the start and finish points have appropriate arrows with the pressure (mb) marked alongside. Radiosonde stations, with their index numbers, are marked at the bottom for comparison with Fig. 4.

4. Conclusion

An attempt has been made in this article to study the airflow through a synoptic scale system, responsible for widespread rainfall over a large part of England on 22 June 1982. From both conventional hand drawn studies and model data, it is apparent that the main mechanism producing the rain was the mass uplift of warm moist air from the south over cold air covering northern Britain.

The results from the numerical model emphasize the importance of latent heat release in substantially increasing the vertical motion compared with that found in the dry run. However, they fail to highlight the intricate detail of the system including the presence of potential instability depicted in the hand-drawn study. The release of this instability was undoubtedly responsible for heavy bursts of rain reported within the main rain band. Its presence made manual calculations of vertical velocity even more difficult, probably accounting for some of the discrepancy in the absolute values obtained by the different methods. In general though, the regions of ascent both in cross-section and plan view show good agreement. The only area of disagreement was found in the south-west of the UK and this emphasizes the difficulty of moist isentropic analysis when the motion of the complete system is complex, as is often the case.

These results supplement each other in aiding our meteorological understanding of this particular system. The model enables flow patterns to be visualized in a way which would be impossible using

observations alone. This ability to look in detail at the three-dimensional structure of synoptic systems makes numerical models valuable in meteorological teaching and research, as well as in their conventional role as a forecasting tool.

Acknowledgements

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An analysis of noctilucent cloud over western Europe during the period 1966 to 1982

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Summary

A statistical analysis of noctilucent cloud observations received at the Edinburgh Data Centre from 1966 to 1982 shows a somewhat higher elevation for the upper border of the clouds than has been previously suggested. The range in solar depression over which the clouds were visible and their distribution in latitude are more restricted than in earlier surveys. The median date for peak frequency of occurrence of the clouds is found to be 4 July. An inverse relationship between annual sunspot number and corresponding frequency of noctilucent cloud occurrence is suggested but not definitely confirmed.

1. Introduction

Noctilucent cloud is an upper atmospheric phenomenon of considerable beauty most frequently observed during the long summer twilight of high latitudes. Such clouds form close to the mesopause at a height of about 82 km when the conditions of temperature and humidity are favourable. However, they do not become visible until obliquely illuminated by sunlight from below the horizon and, even then, only when the solar depression lies within the critical limits of 6° and 16° . The 1962 discovery that noctilucent clouds are largely composed of ice crystals (at heights where the water content had previously been judged to be too low for cloud formation) caused a resurgence of interest in this phenomenon that led to the setting up of World Data Centres around 1964. In this review we analyse and summarize the observational data that have been lodged with the West European Centre in Edinburgh and have been published in the form of annual reports, first by Paton (1967 to 1973) and subsequently by McIntosh and Hallissey (1974 to 1983). It is particularly appropriate to make this summary at the present time as the work of the Data Centre has just been concluded. For a comprehensive résumé of experimental and theoretical aspects of noctilucent cloud, in contrast to our summary of observational data, the reader is referred to the recent excellent review by Gadsden (1982).

2. The observational data

The data for this survey came from the annual reports of the West European Data Centre in Edinburgh for the period 1966 to 1982 (cited above) during which full observational information is available in respect of

- (i) date and time of observation,
- (ii) individual observer's latitude and longitude, and
- (iii) maximum elevation of the cloud in the direction of the sun at the time of observation.

The corresponding reports for 1964 and 1965 were omitted from this survey because they contained insufficient detail to allow for corroboration.

A total of 1680 observations with the above information were received in this 17-year period; a further 126 incomplete reports were also received, but these were rejected for inclusion in this study as

they did not contain sufficient information for the mathematical criteria of acceptability to be applied. Each of the complete observations was screened for reliability by determining if it satisfied the conditions necessary for the illumination of noctilucent cloud from the observer's site at the time of the observation. This was done by testing whether the observed maximum elevation of the cloud (h), the solar depression at the time of the observation (d) and the height of the cloud (H) satisfied the mathematical relationship between these three interdependent parameters and whether the resulting values of d and H lay within the ranges normally accepted for noctilucent cloud. The details of the procedure, which is a modification of the 'one-sided' methods of Jesse (1885) and Bronshten and Grishin (1976), have been described by Simmons (1977).

On the basis of the derived heights, the observations were divided into three groups. The first group, with height values within one standard deviation (1 SD) of the average for all 1680 reports, numbered 1053 (62.7% of the observations). These are regarded as being of high reliability as all had values for h , d and H that lay within the accepted ranges. The second group, with H values between 1 and 3 SD of the average, numbered 540 (32.1% of the total). These observations would appear to be of doubtful reliability because their H values (and sometimes their d values) lay outwith the accepted ranges. The remaining group contained 87 (5.2% of the total) observations. Their height values differed from the average by more than 3 SD which implies that they are 'outliers' of poor reliability. When the high reliability observations were related to their dates of occurrence, it became apparent that multiple reports on a single night were common which tends to confirm their authenticity. In contrast, many of the observations classified as being of doubtful or poor reliability were single, uncorroborated reports, some occurring at the extremes of, or even outwith, the noctilucent cloud season. These findings taken together suggest that the criteria adopted enable one to assess the reliability of the observational data with some degree of confidence. In this report we shall be mainly concerned with the high reliability reports except where comparisons with those of doubtful or poor reliability enable some significant conclusion to be drawn.

3. Survey of noctilucent cloud in the years 1966 to 1982

(a) *Apparent elevation of noctilucent cloud*

There is now a considerable body of observational evidence to the effect that noctilucent cloud is a phenomenon occurring during nautical twilight, with most of the illuminated cloud in the twilight segment of the sky. It therefore follows that the clouds are most frequently seen at low elevation along the northern horizon. This view is substantiated and measured quantitatively in Fig. 1 which shows the distribution of our high reliability observations with elevation (in 5° zones from the horizon to the zenith); 411 (39.0%), 797 (75.7%) and 914 (86.8%) of the observations lay within 10° , 20° and 30° of the horizon respectively. In only 14 (1.3%) of the reports (not shown in the histogram) were the clouds seen to cross the zenith into the southern sky. Indeed, as a rough approximation, the incidence of the clouds may be said to fall off exponentially from the horizon to the zenith. However, an exception to this generalization is seen in the $0^\circ - 5^\circ$ zone, which has a small number of observations, attributable to the obscuring effects of dust, haze and tropospheric cloud in the lower atmosphere.

When all the observations were analysed, it was found that the percentage of those of doubtful or poor reliability in each 5° zone increased with their apparent elevation. Although there was some scatter due in part to differences in the sample sizes, the 'best-fit line' showed a progressive and steady increase from 29% of doubtful or poor reliability results in the $0^\circ - 5^\circ$ zone to 68% in the $85^\circ - 90^\circ$ zone. The precise reasons for the doubtful reliability of individual observations remain indeterminate from a general analysis of this type. However, a small number are almost certainly due to recording and

observational errors whereas the majority would seem to be attributable to difficulty in determining the maximum elevation of the cloud perhaps, for example, by confusion with concomitant tropospheric (cirrostratus) cloud. In the observations of high elevation, the increase in the doubtful reliability results may be explained as a compounding of these errors with the well-known difficulty of estimating angular elevation as one approaches the zenith. These conclusions prompt us to suggest that, if further surveys of noctilucent cloud are to be undertaken, greater attention should be given to 'fixing' the upper border of the cloud in the direction of the sun and to the introduction of better methods (photographic and instrumental) for measuring elevation.

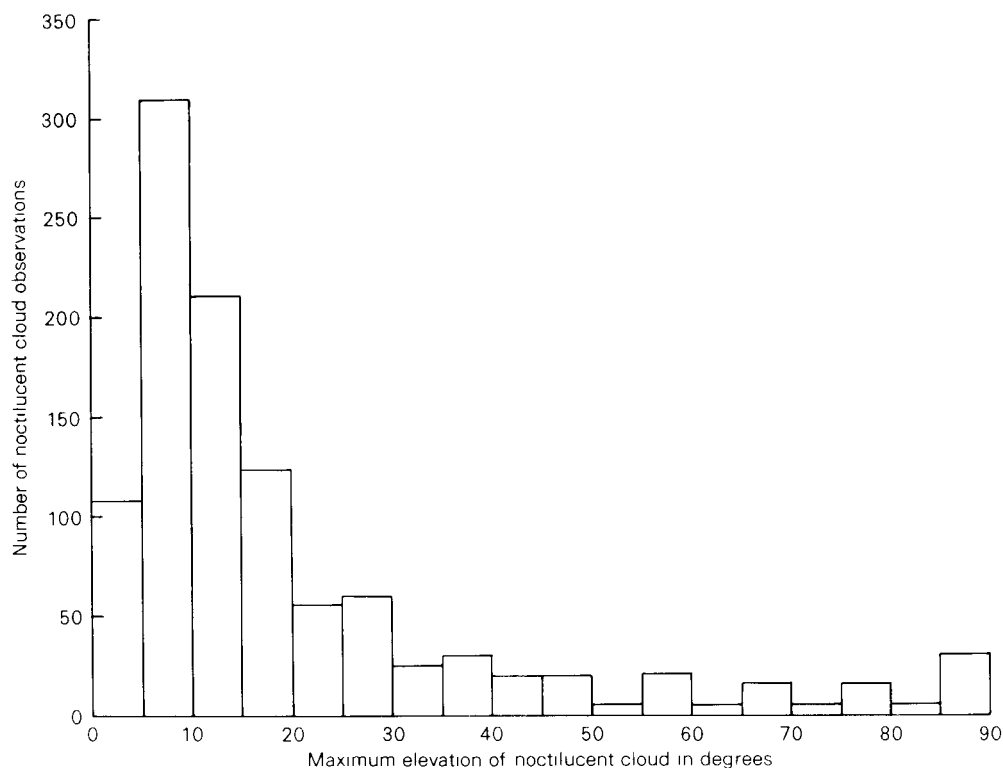


Figure 1. The incidence of noctilucent cloud at different elevations, in 5° zones between the northern horizon and the zenith. Fourteen reports of noctilucent cloud in the southern sky are not recorded in the histogram.

(b) Solar depression and noctilucent cloud

The solar depression can be determined accurately for any instant during a display given the observer's geographical coordinates and the date and time of the observation. Fig. 2 gives the incidence of noctilucent cloud at 0.2° intervals between 0° and 18° of solar depression for the 17-year period under review. The upper 'curve' shows the distribution of all observations including those of doubtful and poor reliability whereas the lower 'curve' shows the distribution of those of high reliability (i.e. with height values within 1 SD). The average solar depression from the lower, high reliability curve is 10.45° (corrected to the upper limb but not for atmospheric refraction) which is in good agreement with the

generally accepted view that noctilucent cloud is maximal in frequency and brilliancy when the sun is about 10° below the horizon. It will be noted that not one of the 68 observations made when the solar depression was less than 6.2° passes our liberal criteria of reliability. This finding is in agreement with that of Paton (1964) who records that none of the 70 displays personally observed by him became visible until the sun was at least 6.75° below the horizon. Similarly, only a few apparently genuine occurrences of noctilucent cloud have been made in the period under study when the solar depression was greater than 15° . Indeed, 96% of our high reliability observations were made when the solar depression lay in the range of $7^\circ - 14^\circ$. The generally accepted range of $6^\circ - 16^\circ$ would include all but two of our 1053 high reliability events.

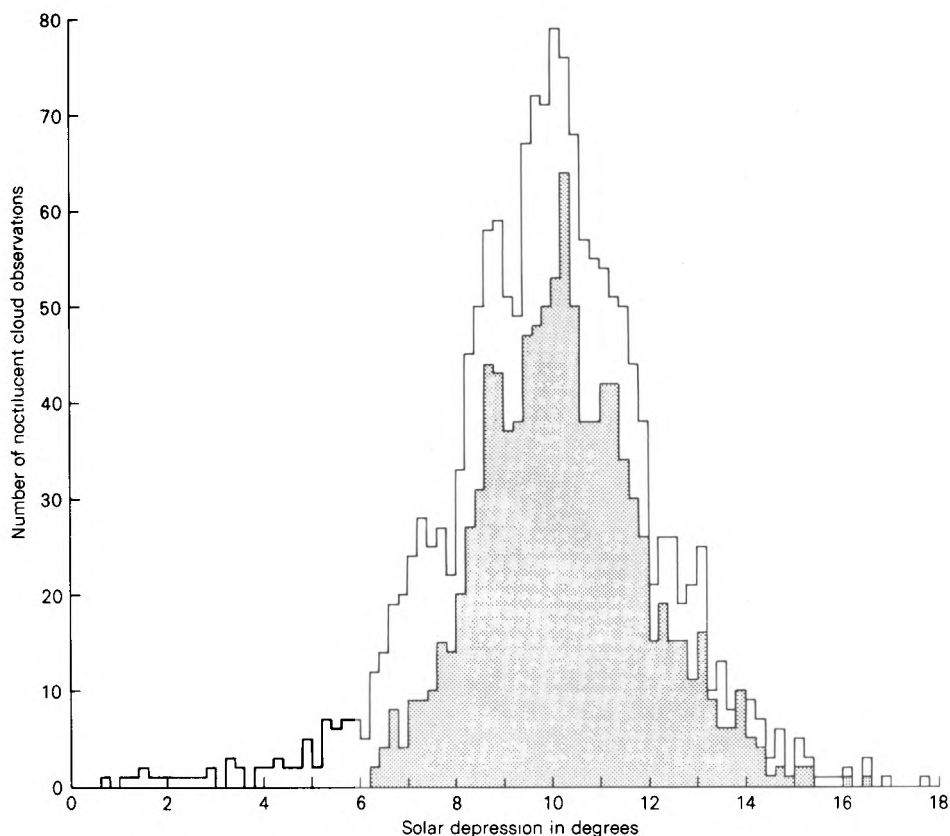


Figure 2. The incidence of noctilucent cloud observations at 0.2° intervals between 0° and 18° of solar depression. The lower shaded 'curve' gives the distribution of the reliable observations which had height values within 1 SD of the average. The upper 'curve' gives the distribution of all observations including those with height values in excess of 3 SD of the average.

(c) Height of noctilucent cloud

Noctilucent cloud occurs within a very narrow height range close to the temperature inversion layer at the mesopause. Most authorities quote this range as $82.4 \text{ km} (\pm 1 \text{ km})$ with extreme limits of 75 km and 93 km. The average height of the clouds over the past 17 years derived from all our observations was 83.76 km and from the high reliability results alone, 83.87 km. At first sight, these results may appear

to be highly satisfactory but, with $ISD = 15.04$ km, the range for the high reliability results was 68.83 — 98.91 km which is a much wider scatter than that indicated by the best modern practices. From these results one can only conclude that the good average heights obtained are due to the cancelling out of random errors in the large sample under study and that, as is generally agreed, good parallactic photography is still a necessary prerequisite for accurate height determination in any one display.

(d) *Distribution of noctilucent cloud observations in latitude*

In the 17-year period of the summary, only one report of noctilucent cloud was received from below latitude $50^{\circ}N$ and that proved to have a poor reliability rating by our criteria. Similarly, only ten reliable observations were received from latitudes higher than $60.5^{\circ}N$. Thus 99% of our reliable reports came from between latitudes $50^{\circ}N$ and $60.5^{\circ}N$. Even within these latitudes, Fig. 3 shows that there is a

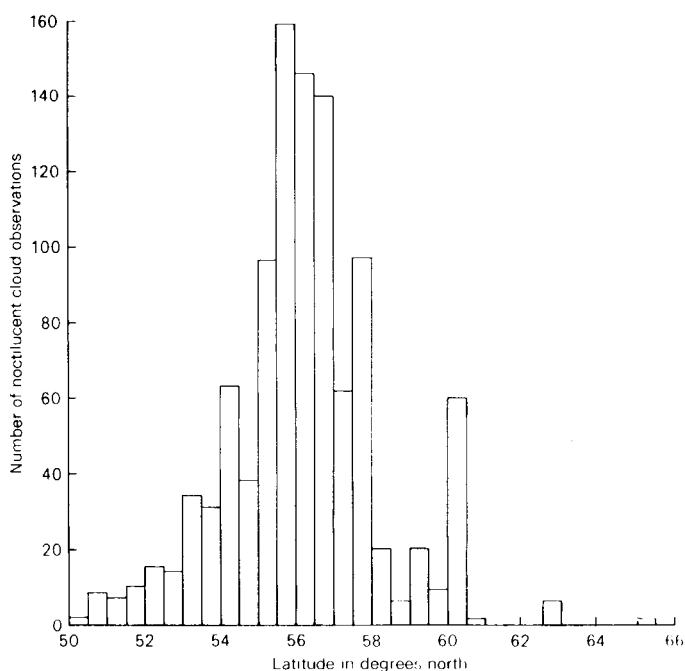


Figure 3. Histogram showing the distribution of noctilucent cloud observations with latitude.

decided peak in noctilucent cloud observations centred around $56^{\circ}N$ with 76.3% of the reports coming from the 4° zone between latitudes $54^{\circ}N$ and $58^{\circ}N$ and more than half (51.6%) from the 2° zone between latitudes $55^{\circ}N$ and $57^{\circ}N$. These findings can be readily explained in terms of the solar depression during the main noctilucent cloud season (12 May to 1 August). Between these dates at $56^{\circ}N$ and thereabouts, the sun lies within the critical depression limits of $6^{\circ} - 16^{\circ}$ for a large part of the summer night. At $61^{\circ}N$ the time spent within the critical limits begins to fall off sharply to zero at $66^{\circ}N$ approximately. However, noctilucent cloud may in principle be seen for short periods after the main season from latitudes higher than $66^{\circ}N$ when the solar declination is lower and the solar depression therefore greater.

Although the sharp decrease in observations from latitudes over 61°N is to be explained mainly in terms of solar depression, the population density and the consequent lack of observers in these regions is almost certainly an important contributory factor. A further population effect may also be present in Fig. 3. Fogel (1966) finds that the peak latitude for noctilucent cloud observations in the North American continent is 57.5°N . It may be that our value of 56°N is a genuine difference for the west European region over the period of study, but it more probably reflects a bias to the lower latitude (56°N) of the Central Lowlands of Scotland which have a high density population and a network of active observers reporting on a regular basis.

It is important to note that the site of observation does not necessarily define the geographical location of the clouds which may lie as much as 7° to the north of the observer when the clouds extend down to the northern horizon. However, the exact geographical location of the clouds may be determined by simple spherical trigonometry as outlined by Simmons (1977). When this was done for our high reliability observations at the extremes of latitude, it was found that all the clouds lay within the range of $51.8^{\circ}\text{N} - 72^{\circ}\text{N}$ which is appreciably narrower than the $45^{\circ} - 80^{\circ}$ band implied by Bronshten and Grishin (1976). However, as indicated above, noctilucent cloud can be observed from latitudes above 66°N , but no such sightings have been reported over western Europe in the period under review.

(e) *Seasonal incidence of noctilucent cloud and its variation with latitude*

The incidence of highly reliable noctilucent cloud observations by date of occurrence during the period under study, is shown at five-day intervals in Fig. 4. The vast majority of displays occurred

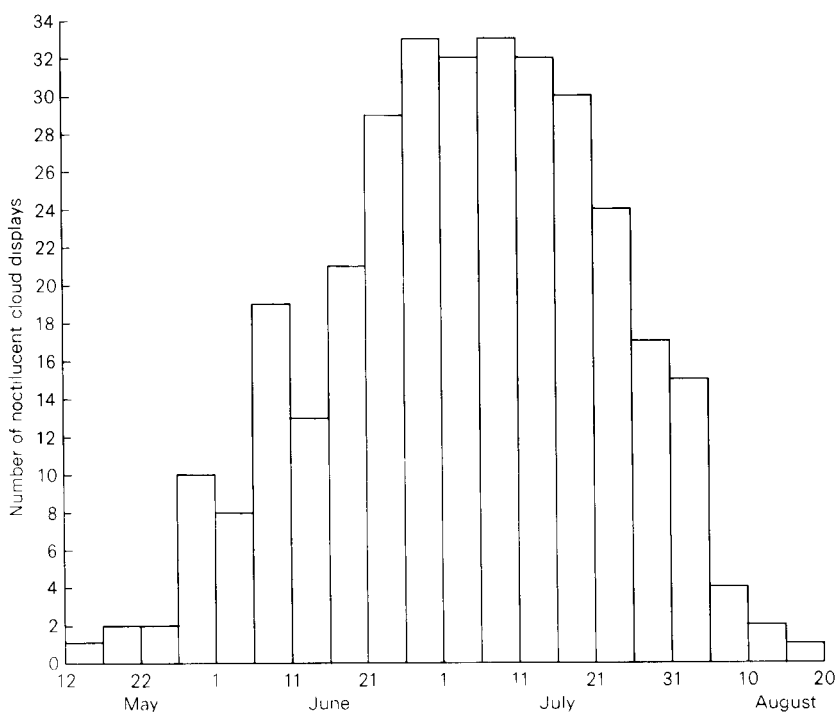


Figure 4. Histogram showing the seasonal incidence of noctilucent cloud displays.

between 27 May and 10 August with the median date at 4 July. The normal distribution of noctilucent cloud about this date and the two-week seasonal lag in the maximum from the summer solstice to 4 July are unremarkable, having been well documented in previous reviews. In contrast, Fig. 5 shows the seasonal incidence of the high reliability observations divided on the basis of latitude into the three zones $50^{\circ}\text{N} - 54^{\circ}\text{N}$, $54^{\circ}\text{N} - 58^{\circ}\text{N}$ and $58^{\circ}\text{N} - 62^{\circ}\text{N}$. The vast majority of observations were made from the $54^{\circ}\text{N} - 58^{\circ}\text{N}$ zone with a median date about 4 July. However, the majority of observations from the $50^{\circ}\text{N} - 54^{\circ}\text{N}$ zone were recorded before 1 July whereas the majority from the $58^{\circ}\text{N} - 62^{\circ}\text{N}$ zone were observed after that date. These conclusions, which are again in agreement with past findings, have given rise to the view that the clouds 'move' northwards during the season. However, this northward movement is readily explained by the fact that the region which most frequently satisfies the critical conditions for illumination of the clouds ($d = 6^{\circ} - 16^{\circ}$) moves north as the solar declination falls after the summer solstice.

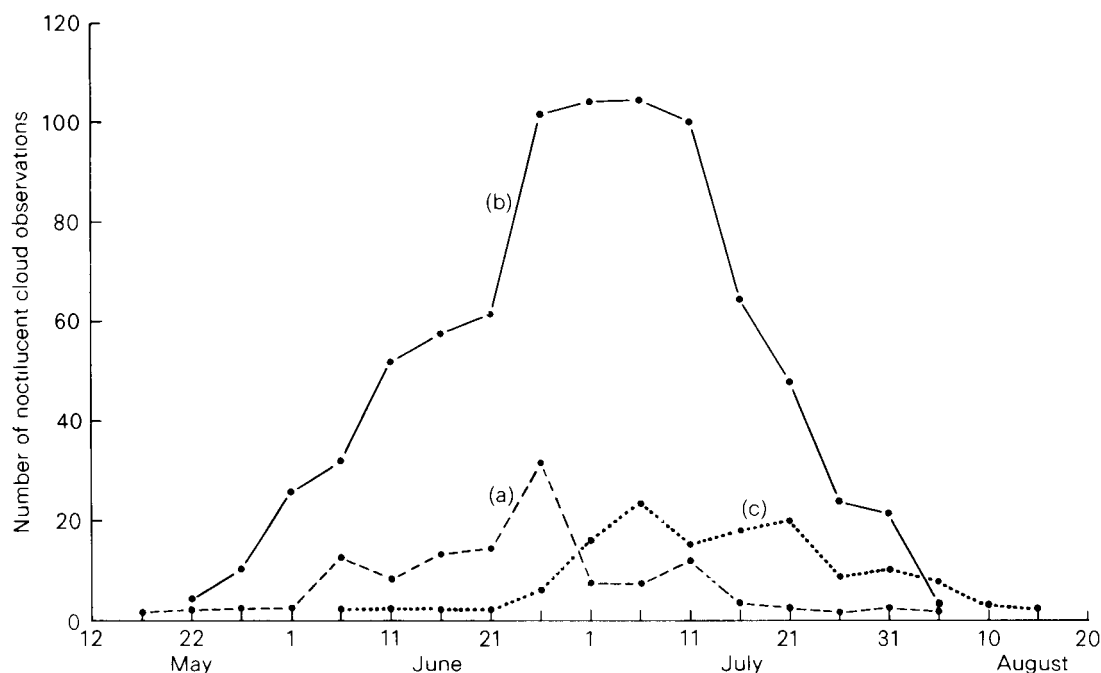


Figure 5. The seasonal distribution of noctilucent cloud observations at different latitudes. Curve (a) 50°N to 54°N , (b) 54°N to 58°N , (c) 58°N to 62°N .

(f) Year-to-year variation in the incidence of noctilucent cloud

The annual incidence of noctilucent cloud in the years 1966 to 1982 is shown in Fig. 6. The upper curve (a) gives the total number of nights for which reports of noctilucent cloud were received accompanied by sufficient information to test the reliability of the observations. The intermediate curve (b) gives the number of nights with noctilucent cloud observations that satisfied the criteria of reliability. The lower curve (c) gives the number of nights with major noctilucent cloud displays (nights with at least six reliable reports from at least three different observers). Curve (c) was drawn to exclude the possibility that a large number of random minor events might mask a periodicity in the less frequent

major displays. All three curves show a steady fall in the incidence of noctilucent cloud from a maximum in 1967 to a pronounced minimum in 1970. A similar but less pronounced minimum is evident in the summer of 1980 following a progressive fall from the maximum year 1977. A number of interesting points arise from Fig. 6. Firstly, the proportion of observations rejected as unproven seems to remain fairly constant from year to year. Secondly, the periodicity of noctilucent cloud shown by the high reliability results is also discernible in the major display curve (c). Thirdly, the minima of 1970 and 1980 follow closely on the solar activity maxima of 1969.7 and 1979.9 respectively.

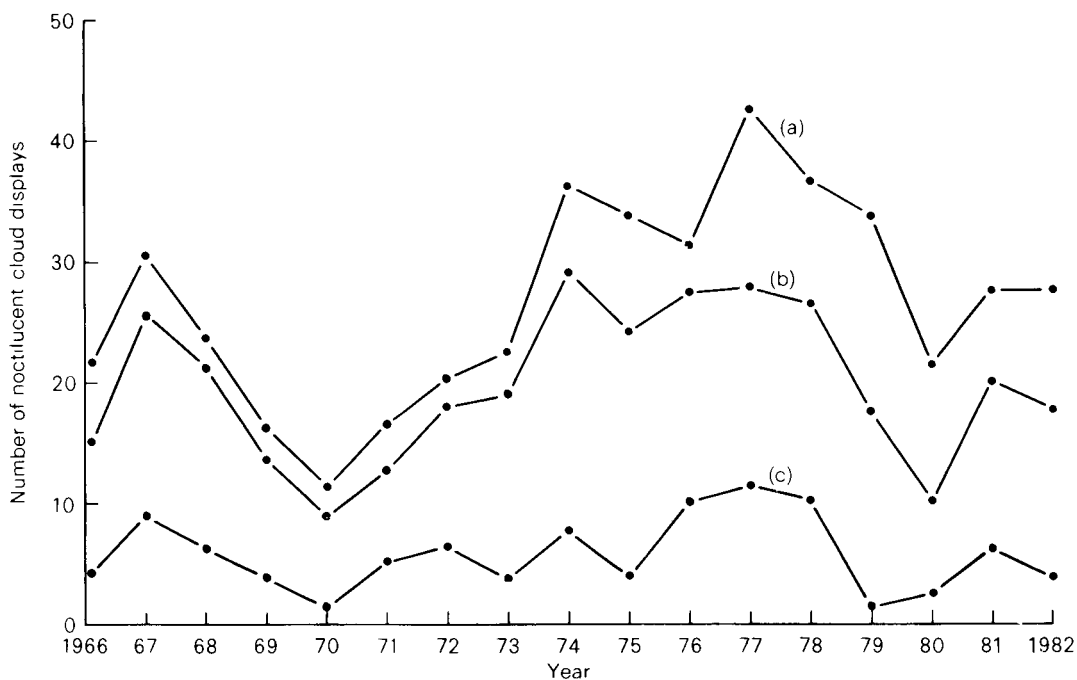


Figure 6. The year-to-year incidence of noctilucent cloud displays 1966 to 1982. Curve (a) total number of nights for which reports of noctilucent cloud were received accompanied by sufficient information to test the reliability of the observations, (b) total number of nights with observations that satisfied the criteria of reliability, (c) total number of nights with major displays (nights with at least six reliable reports from at least three different observers).

Although these results do not provide direct evidence of any causal effect between solar activity and the incidence of noctilucent cloud, the suggested inverse relationship of the two phenomena can be explained in terms of the nature of these clouds. According to the condensation hypothesis, they consist of hydrated protons of the general structure $H^+ (H_2O)_n$ which aggregate and precipitate when the temperature at the mesopause falls to about 160 K. At solar maximum when the mesopause temperature is relatively high, it is less likely to fall to this critical level but, at solar minimum when the mesopause temperature is generally lower, it is more likely to do so. However, it should be stressed that although the observed results are consistent with our present concepts of noctilucent cloud, the existence of an inverse relationship between solar activity and noctilucent cloud still requires confirmation from direct or more detailed circumstantial evidence.

4. Discussion and conclusions

Systematic observation of noctilucent cloud was initiated in this country in 1949 by Paton who built up a network of observers based on the Balfour Stewart Auroral Laboratory in Edinburgh. Paton's (1964) review of this program was followed by an extension of the network and by the introduction in 1966 of a more detailed format for recording observations. Without these two developments, this statistical study would not have been possible. In general terms, the main features and characteristics of noctilucent cloud noted over the period of Paton's early work have continued to be observed throughout the years of the present study. However, our more analytical approach using high reliability observations has enabled us to define the circumstances surrounding the appearance of noctilucent cloud rather more precisely.

Although it has been recognized that noctilucent cloud can, on rare occasions, extend overhead and into the southern sky, it is more typically observed at low elevation along the northern horizon. Paton (1964) found that 'it is only occasionally that the clouds are observed in central Scotland at elevations greater than 10° above the northern horizon'. However, in the period 1966 to 1982, 36.7% of our reliable observations had an apparent elevation greater than 10° (but less than 20°) and a further 11.1% had elevations between 20° and 30° . As a rule, only the brightest and most extensive of displays gave an upper border in excess of 45° .

The critical limits of solar depression at times of noctilucent cloud also require some revision, at least for the period of the present study. The generally accepted range of 6° – 16° is probably too broad as the majority (96.0%) of clouds were visible when the solar depression lay in the range 7° – 14° with the peak at 10.45° .

For height determination, our findings do no more than concur with the general consensus of opinion that 'one-sided' methods are virtually valueless for determining the height of any given display and that good parallactic photography is required for that purpose.

The distribution of noctilucent cloud in latitude also seems to have been more restricted than in earlier studies. During 1966 to 1982 all the clouds lay between 52°N and 72°N which is a much narrower range than the generally accepted 45°N to 80°N . The southern limit is probably close to the true value. However, the upper limit of 72°N may well be too low by reason of a 'population effect'.

The seasonal incidence of noctilucent cloud over the period of study followed the usual pattern of activity in that the vast majority of events occurred between 27 May and 10 August with the median date of 4 July showing a lag of two weeks after midsummer's day. Observations from lower latitudes tend to occur earlier in the season and those from higher latitudes later in the season.

Finally, our study of year-to-year variation in the incidence of noctilucent cloud shows two distinct minima in the years 1970 and 1980. A previous minimum was noted by Paton (1967) extending over the years 1957 and 1958. In contrast, two maxima for noctilucent cloud have been noted in the period covered by the present study from 1964 to 1967 and from 1974 to 1978. While these results support an inverse relationship between annual sunspot number and frequency of noctilucent cloud occurrence, they yet fall short of confirming it. It should be borne in mind that over the period of the survey there have been changes in the geographical area covered by observers and in the extent to which automatic photography throughout the night has been used to identify cloud occurrences, also year-to-year variations in the extent of interference caused by tropospheric clouds. Such systematic and casual influences may well have obscured a clearer relationship between solar activity and noctilucent cloud formation.

Acknowledgement

We are grateful to Dr A.P. Conway, Department of Natural Philosophy, University of Glasgow, for computer processing some of the results.

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Paton, J.	1967	<i>Meteorol Mag.</i>	96 ,	187–190.
	1968	<i>Ibid.</i>	97 ,	174–176.
	1969	<i>Ibid.</i>	98 ,	219–222.
	1970	<i>Ibid.</i>	99 ,	184–186.
	1971	<i>Ibid.</i>	100 ,	179–182.
	1972	<i>Ibid.</i>	101 ,	182–185.
	1973	<i>Ibid.</i>	102 ,	171–174.
McIntosh, D.H. and Hallissey, M.	1974	<i>Ibid.</i>	103 ,	157–160.
	1975	<i>Ibid.</i>	104 ,	180–184.
	1976	<i>Ibid.</i>	105 ,	187–191.
	1977	<i>Ibid.</i>	106 ,	181–184.
	1978	<i>Ibid.</i>	107 ,	182–187.
	1979	<i>Ibid.</i>	108 ,	185–189.
	1980	<i>Ibid.</i>	109 ,	182–184.
	1981	<i>Ibid.</i>	110 ,	109–112.
	1982	<i>Ibid.</i>	111 ,	122–125.
	1983	<i>Ibid.</i>	112 ,	245–249.

Notes and news

Extracts from an ancient file

The following extracts from an old file retained at Shoeburyness of correspondence between the Senior Meteorological Officer, a Branch at Headquarters (M.O.5.), and the Superintendent of Experiments at Shoeburyness tell their own story.

M. O. 5.

I attach herewith a report on the accident to the Kite Balloon this morning, in confirmation of telephone message.

I should be glad if this station could be supplied with two or three pairs of rubber gloves for use in attaching streamers to the cable and while working the winch. I think this will be a safeguard.

Meteorological Office,

New Ranges,

Shoeburyness.

28/3/1922.

M. O. 5.

I regret to inform you that the Kite Balloon at this station was struck by lightning this morning at 0959 G.M.T. The balloon itself was entirely destroyed together with 5000' of cable. The Dobson and Richard Meteorographs were recovered beyond hope of repair.

At the time, the balloon was stationary with 5000 feet of cable paid out. The weather was overcast with passing showers: it was raining at the time of the accident. The wind was very moderate, the tensionmeter recording about 5 cwt. Myself and one of the balloon squad were in the winch house and the remainder of the squad were in the balloon shed. The balloon itself was hidden, being above the low drifting cloud. Suddenly the cable appeared to become a mass of flame and almost simultaneously there was a loud explosion. I saw the cable in the winch house suddenly drop slack and, on running to the loading off gear, I saw that there was no cable beyond the tensionmeter. It was clear that a violent discharge of electricity had passed down the cable and destroyed the balloon.

On investigation, the remains of the Dobson Meteorograph were found in a field about $\frac{1}{2}$ mile away but no trace of the balloon was discovered nor were any fragments of it seen to fall. Later on, a villager gave the information that the main guys and Richard Meteorograph were in a field about a mile distant from Landwick from whence they were duly recovered. Some burning fragments of the balloon were smouldering near by. The hemp core of the burnt cable was lying across country — the metal part of the cable was entirely burnt away leaving the hemp core unscathed. A curious exception to this was found in the short length of cable lying between the attachments of the Dobson Meteorograph frame. This short piece of cable was intact, the discharge having apparently passed through the frame in preference to the cable.

Fortunately no one was injured. Had the accident occurred at 4000' instead of 5000', a tragedy might have taken place as at this point, we attach a streamer to the cable.

M. O. 5.

Confirming my telephone conversation of this morning (28 Nov. 1924), I beg to state that during a heavy gale last night, the skeleton of the balloon hangar was blown down and destroyed.

The wind had been increasing steadily and from 0200 this morning to the time of writing this report, it was well above gale force. I have been unable to ascertain at what time the collapse took place but I should imagine that it was between 0400 and 0500. The mean wind speed throughout this hour was 77 f/s. with a maximum gust of 98 f/s. at 0440. There appears to have been about a dozen gusts of 90 f/s. or over.

The shed collapsed by tilting over and folding up from front to back. It must have been a very violent gust which finally brought about its fall. The iron pickets holding the front iron guys were wrenched out of the ground as well as some of the wooden pickets. The steel hook of one of the iron strainers attached to the wire guys was smashed in half. The wood work is very much smashed and is now of little use — indeed some of it appears to be quite rotten.

Fortunately, the canvas cover had been entirely removed and the roof sheets were lying on the floor of the shed. As far as I can at present ascertain, no M.O. stores have been damaged but the four derelict Scammel winches are beneath the wreckage and a 40 ft. ladder belonging to the S. of E. has been broken.

Before clearing anything, I am endeavouring to secure some photographs of the wreckage. Then I will raise sufficient of the wood to rescue the canvas from the floor of the shed. It will be necessary, however, to clear the remains from the four winches as Messrs. Spencer may call for these any day now. These winches are under the thickest part of the heap and while we are freeing them, it would appear best to clear the whole of the pile. If you concur in this, will you please telephone me in the morning so that I can get all hands at work on it.

It is of interest to mention other local damage due to this gale. Two large elms on the New Ranges have been blown down and there is a good deal of smaller damage to fences and slated roofs.

Superintendent of Experiments (Shoeburyness)

I have been informed that it is the intention of the Air Ministry to abandon the Kite Balloon work at this station.

In order that the necessary data with regard to upper air temperatures should be available for use at this station for Range and Accuracy and other trials, two aeroplanes with the accompanying personnel have been attached to Eastchurch Aerodrome and flights will be made from that station as a matter of routine. The data thus obtained will be available for use here in working up meteorological reports.

This will probably be more satisfactory from your point of view as it will ensure that results are obtained on a much greater percentage of occasions and that there will be no enforced periods of inactivity on account of repairs to the balloon or hangar.

Meteorological Office,

New Ranges,

Shoeburyness.

8/12/24.

Honour

In the New Years Honours List for 1983 it was announced that Mr C.W.G. Gazzard, Professional and Technology Officer IV, Meteorological Office, Bracknell, had been awarded a British Empire Medal.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For Meteorological Magazine'.

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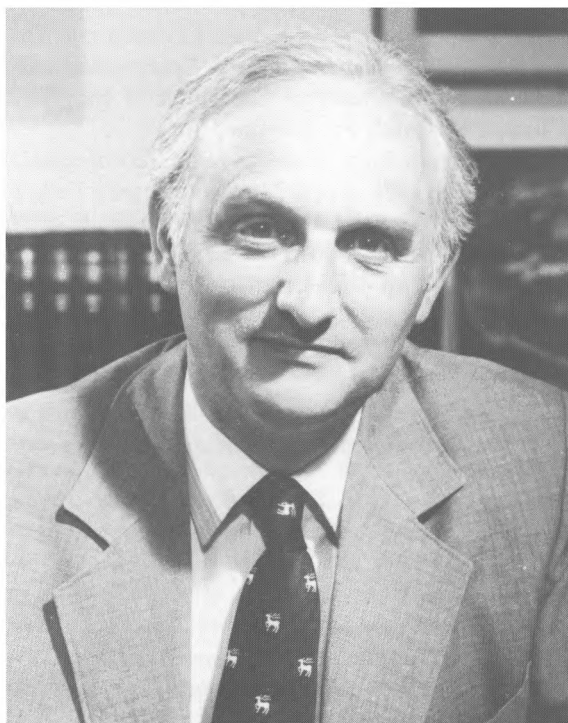
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Photograph by courtesy of Rutherford Appleton Laboratory

Director-General of the Meteorological Office

Dr J. T. Houghton, CBE, FRS, has been appointed to succeed Sir John Mason as Director-General of the Meteorological Office from 1 October 1983; he has been Deputy Director of the Rutherford Appleton Laboratory at Chilton since 1979, and Professor of Atmospheric Physics in the University of Oxford since 1976.

Dr Houghton was educated at Rhyl Grammar School and Jesus College, Oxford, where he graduated in Physics in 1951. After three years post-graduate work he became a Research Fellow at RAE Farnborough in 1954 but returned to Oxford in 1958 as Lecturer in Atmospheric Physics, being appointed Reader in 1962. While at Oxford he achieved a high international reputation for his investigations of the structure and composition of the stratosphere and mesosphere; in particular he has invented, designed, and operated ingenious radiometers and spectrometers to measure temperatures and the concentrations of trace chemicals in the high atmosphere from satellites. He has built up a strong research group at the University which, in collaboration with the Rutherford Appleton Laboratory, has been outstandingly successful in applying modern space technology to build a series of very advanced instruments to be flown on American meteorological satellites; the group is currently engaged in the design of new instruments to be flown both on American satellites and on the European Earth Resources Satellite (ERS1) due to be launched in 1988. His appointment will strengthen the ties between Oxford University and the Office in the field of satellite meteorology.

Internationally, Dr Houghton's expertise and judgement has been much in demand by the European Space Agency and the US National Aeronautics and Space Administration, and also in the meteorological world through his appointment as Chairman of the WMO/ICSU Joint Scientific Committee for the World Climate Research Programme.

Dr Houghton was awarded the Buchan Prize of the Royal Meteorological Society in 1966 and served as President of the Society from 1976 to 1978. In 1972 he was elected a Fellow of the Royal Society, and in 1979 was awarded the Charles Chree Medal and Prize of the Institute of Physics. He is the author of numerous scientific papers, a well-known textbook, *The physics of atmospheres*, and has collaborated with Professor S. D. Smith of Heriot-Watt University in writing another, *Infra-red physics*.

Dr Houghton is already well known to many of the staff of the Meteorological Office, and his membership of the Meteorological Committee, together with his experience as Chairman of the now discontinued Meteorological Research Committee, will have made him familiar with many of the problems facing the Office at the present time. He brings with him a distinguished record of achievement in scientific research and technical administration, and we wish him every success in his new post.

A study of the Gumbel and Weibull methods of extreme-value analysis using air temperature data from six Ocean Weather Stations

By Anne E. Graham

(Meteorological Office, Bracknell)

Summary

Extreme air temperatures for six locations at sea were estimated using both the Gumbel and Weibull methods of extreme-value analysis. No systematic relationships were found between the extremes derived using the Gumbel method and those derived using the Weibull method.

It is shown that reduction in the interdependence of the data used in the Weibull method has little effect upon the differences between extremes estimated using the two methods.

1. Introduction

The estimation of extreme values is important for design and planning purposes to ensure that a structure is able to withstand the likely extreme conditions which it could experience during its expected lifetime. For this purpose an extreme value is quoted as the value likely to be exceeded, on average, once in some number of years (often 50 or 100). The use of the expression 'on average' is very important though often misunderstood. The extreme is merely that value which is estimated to have a probability of occurrence equivalent to its being exceeded once in a given period. In reality it could be exceeded once, several times, or not at all during any period of that length. The period is known as the 'return period'.

In order to estimate extreme values it is necessary to fit a convenient distribution to the data and extrapolate the function to the desired return period. This technique depends upon the ability of the chosen function to describe the population of values with particular reference to the extremes located in the 'tail' of the distribution.

The two distributions most frequently used by the Climatological Services Branch of the Meteorological Office are the Gumbel (Gumbel 1958) and Weibull (Weibull 1951) distributions. The Gumbel (or Fisher-Tippett Type I) extreme-value distribution is usually fitted to annual maxima (or minima). The extreme-value analysis of annual maxima has been discussed by Tabony (1983), with particular reference to the need for sufficiently long periods of data.

To identify annual maxima, regular observations are required for a specific location. The only sources of regular observations over long periods at sea come from the Ocean Weather Stations (OWS) but there are few of these and extremes are often required in other areas where regular observations are not available. Data from ships of the Voluntary Observing Fleet (VOF) are available for most of the world's oceans. The VOF consists of ordinary merchant ships whose deck officers voluntarily make observations of meteorological and sea conditions during voyages so that these data are randomly distributed in space and time and maxima cannot be identified.

The method of extreme-value analysis used for the VOF data is that using the Weibull distribution (Appendix) in which the complete spectrum of all the observed data is fitted so that a complete set of regular observations is not necessary. The extremes are estimated according to the number of observations likely in the given return period.

The derivation of extremes using methods based on annual maxima (when available) are to be preferred since the data are likely to be more independent than in any other form. Also, Tabony (1983) has shown how the lower annual maxima, probably more typical of the main body of data than the rarer events, can affect the extrapolation of the extreme-value distribution; this problem is presumably accentuated in the case of extrapolation using the Weibull method.

Extremes estimated for short return periods by the Weibull method are generally higher than those estimated using Gumbel, and lower for longer return periods. The purpose of this project was to investigate the difference in the extreme values estimated by using each technique and, in particular, it was hoped to be able to identify any systematic differences and to 'calibrate' the extremes derived using the Weibull technique with those derived using the Gumbel technique.

The highly correlated nature of the data used in the Weibull analysis is a matter of some concern and a secondary aim was to investigate the effects of a reduction in the degree of correlation. This correlation is referred to as persistence in the following descriptions since it is often due to the persistence of a particular meteorological situation.

2. Data

In order to compare the extremes estimated by both methods it was necessary to use a data source from which the annual maxima could be extracted. A long period of regular data was used, although this is not the kind of data normally used in the Weibull analysis.

Six OWS were used: 'A', 'C', 'D', 'I', 'J' and 'M', each covering the same 23-year period, 1950–1972, the longest period available where all six OWS could be compared. It was decided to use values of air temperature observed at three-hourly intervals. Successive values of air temperature are highly dependent, therefore, if the Weibull technique should prove sensitive to persistence then any significant reduction in the dependence in the data should be reflected in the extremes produced by the distribution.

Since the comparison of the two methods was to be based on the assumption that Gumbel gave the 'better' result, some idea of the confidence that could be placed in these estimates was needed. This was not attempted quantitatively as in other studies, for example Challenor (1979) which in most cases used the accuracy of fitting the data to the distributions, but qualitatively with reference to the effect of the sample of maxima on the extremes estimated.

(a) *Sensitivity of the Gumbel technique*

The annual maxima for each station are shown in Fig. 1 grouped in 0.5 °C intervals in the form of a histogram. In order to investigate the sensitivity of the Gumbel method to different periods of data, two stations were chosen, OWS 'A' and OWS 'M', and Gumbel analyses were carried out on maxima for three different periods, 14, 23 and 26 years for 'A' and 14, 23 and 31 years for 'M' where 26 and 31 years are the maximum number of years in the data sets. Fig. 2 shows histograms of annual maxima for these periods.

The differences in the distributions of maxima are difficult to quantify but the 14-year period for OWS 'M' appears to be rather different from the 23-year and 31-year periods, while for OWS 'A' there is no such marked difference.

Figs 3 and 4 show the extremes predicted by Gumbel for OWS 'A' and OWS 'M' respectively. The extremes are plotted against log return period for ease of representation.

For OWS 'A' the actual values estimated for each period of data differ, but the relationship between return periods for each set of maxima is similar.

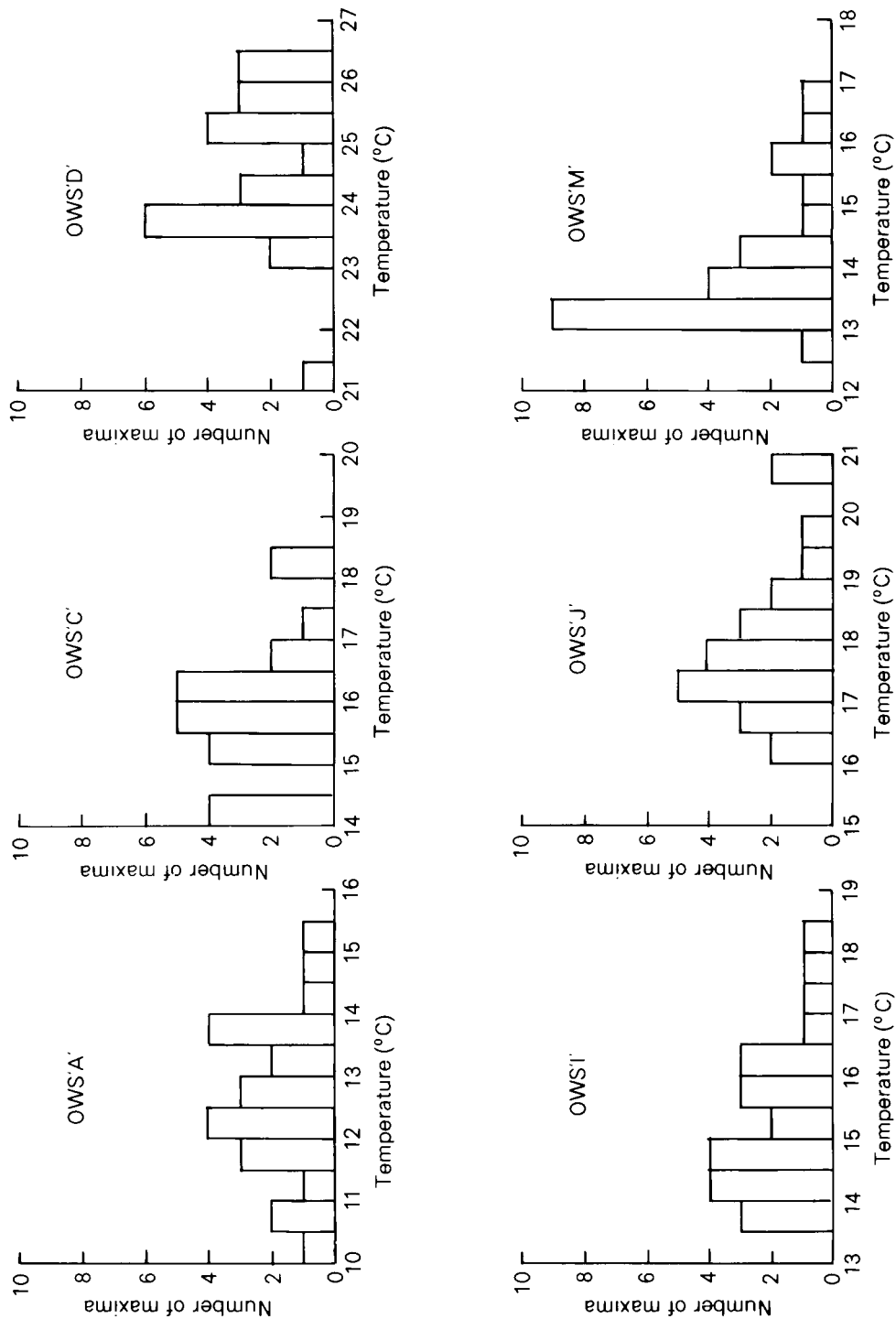


Figure 1. Annual maximum temperatures grouped in 0.5 °C intervals for selected Ocean Weather Stations for the 23-year period 1950–1972.

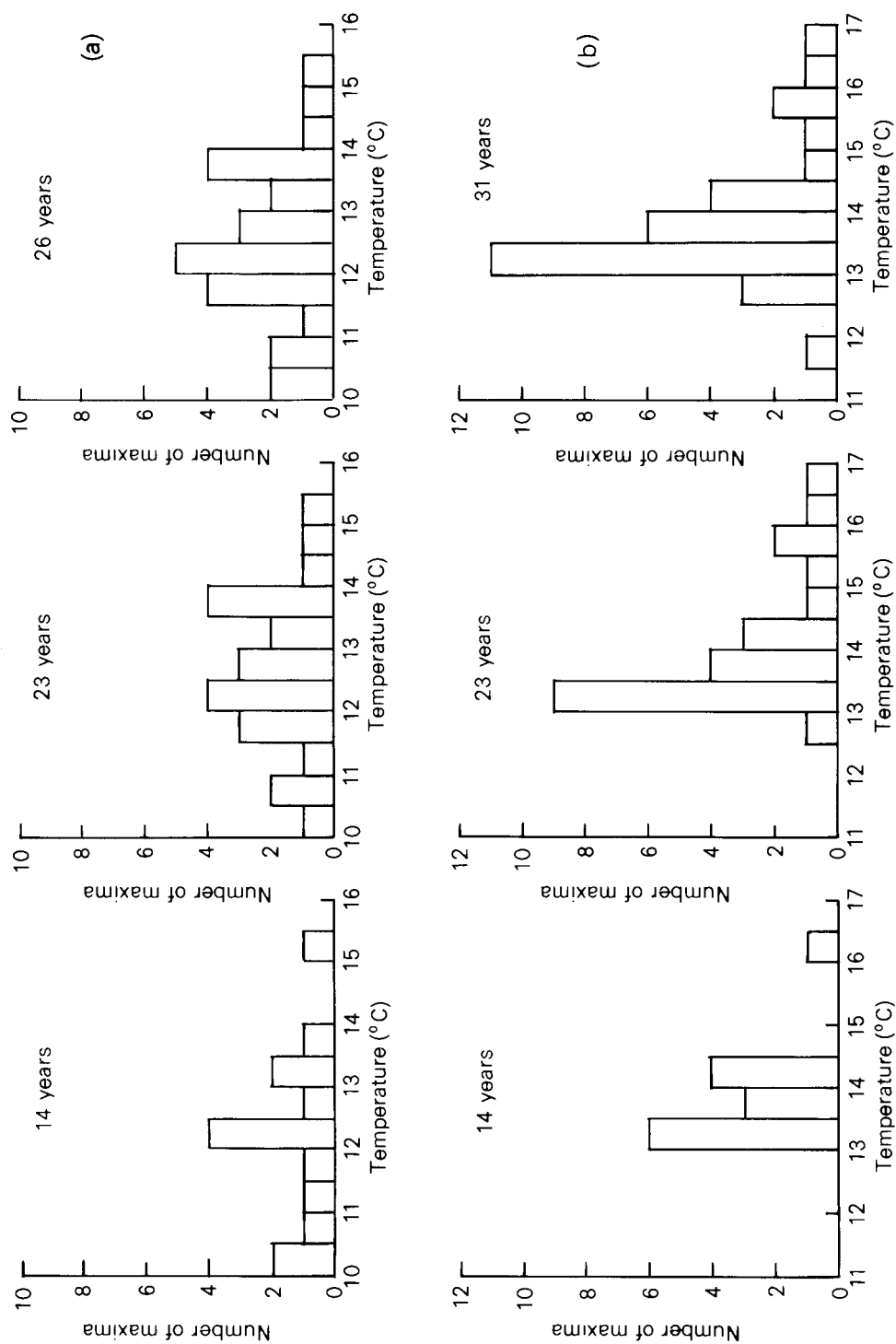


Figure 2. Annual maximum temperatures grouped in 0.5 °C intervals for selected periods for (a) OWS 'A' and (b) OWS 'M'.

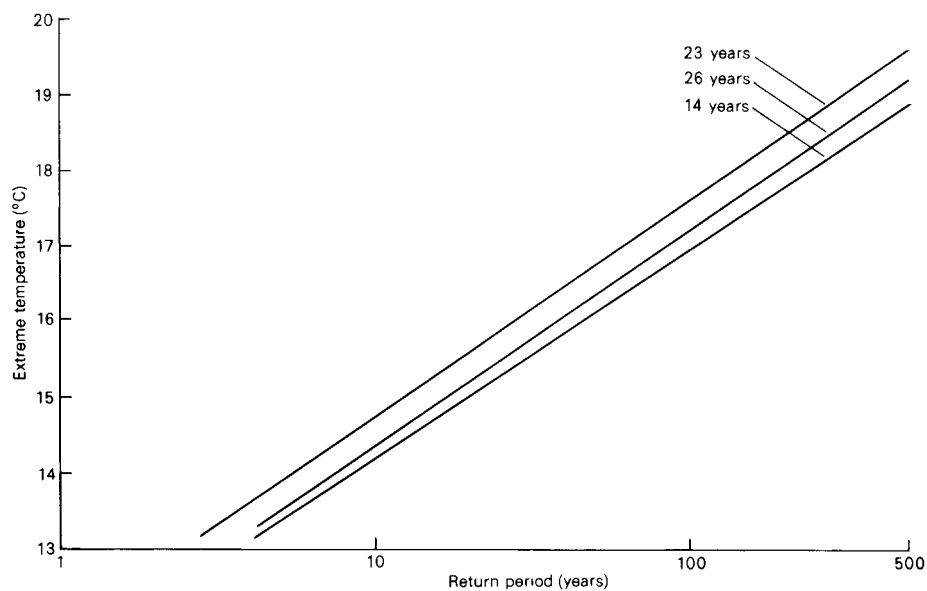


Figure 3. Extreme maximum temperature predicted by Gumbel analyses for OWS 'A' using 14, 23 and 26 years of data.

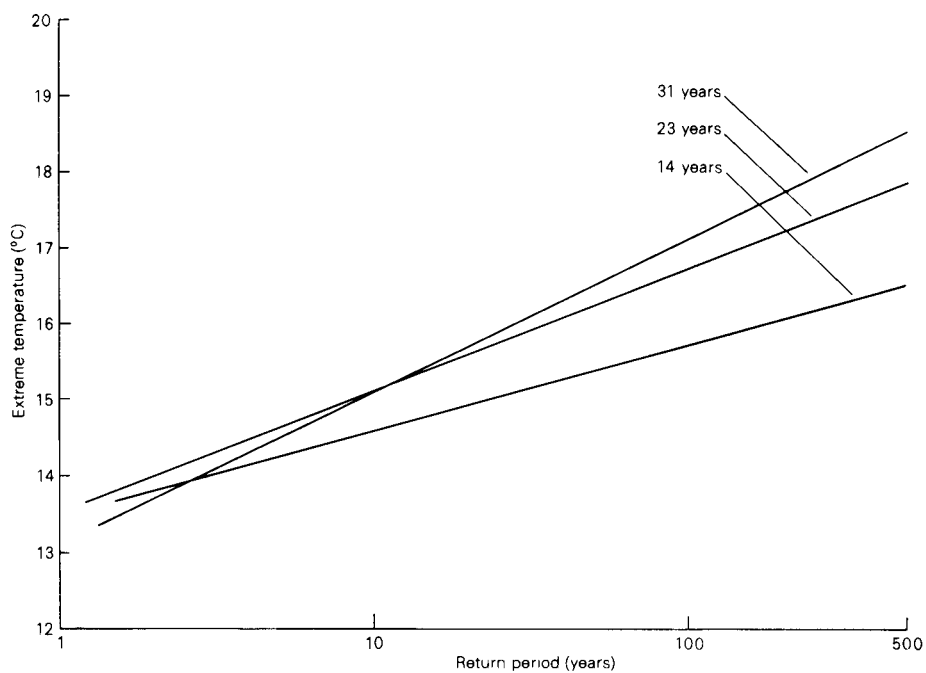


Figure 4. Extreme maximum temperature predicted by Gumbel analyses for OWS 'M' using 14, 23 and 31 years of data.

For OWS 'M', however, the extremes estimated from the 14 years of maxima are quite different from the other two.

Results derived using the Gumbel distribution are obviously sensitive to the sample of data and, therefore, unless a very long period of data is available, they should be treated with caution and the distribution of annual maxima must be examined carefully as this may give some indication of the reliability of the sample.

As shown in Fig. 1 the distributions of maxima for the 23 years covered by all the OWS seem reasonable for each station, except for the low value for OWS 'D' (21 °C). However, this made very little difference to the result when removed and so was included in the analysis. This allowed the same 23 years to be used for all six stations.

Frequency distributions of temperature for each station are shown in Fig. 5 with the temperatures grouped in 1 °C intervals. This grouping produced some irregular distributions which could be smoothed by using 2 °C intervals. However, this was found to make little difference to the results of the Weibull analysis (Fig. 6) and therefore the 1 °C intervals were retained.

3. Extreme values

Fig. 7 shows the extremes estimated by both methods for each station plotted against the log of the return period. This presentation does not actually produce a straight line, but rather a very shallow curve; however, it is a useful representation of the results.

When the Weibull extremes were compared with the Gumbel extremes they were seen to be overestimated for short return periods and underestimated for longer return periods. The terms 'long' and 'short' are used fairly loosely in this connection and vary markedly from station to station depending upon the point at which the curves shown in Fig. 7 actually intersect.

The differences between extremes for various return periods were compared with such statistical properties of the whole distribution as the mean, standard deviation, number of frequency groups in the Weibull fit, and also with the geographical position of the stations. These same factors were also compared with the return period for which both techniques gave the same extremes. None of these direct comparisons indicated any systematic connection. Attempts were also made to derive empirical relationships between two or more of these parameters. None were found that applied to all six stations. Of those that seemed to provide a good fit to the parameters, the resulting 'corrected' extremes were usually poor because small discrepancies in the fit produced large errors in the final result. It was concluded that no systematic relationship between the extremes existed for these data and, therefore, no way in which a 'Gumbel' extreme can be derived from a 'Weibull' extreme.

4. Persistence

The interdependence of observations of meteorological variables is often referred to as 'high' correlation. The real problem is not the correlation between observations but the repetition of records of a single event. This repetition of records of an event is caused by the persistence of a situation over more than one observation period.

If the effect of persistence upon the results is to be investigated it is necessary to remove it and compare the results before and after the modification of the data set. Firstly, it is necessary to define an 'event' in some way and produce a distribution of more 'independent' observations. Unfortunately, there is no easily identifiable phenomenon for temperature that allows the isolation of events and gives a large enough number of observations to be used in a Weibull analysis. Consequently, the method used

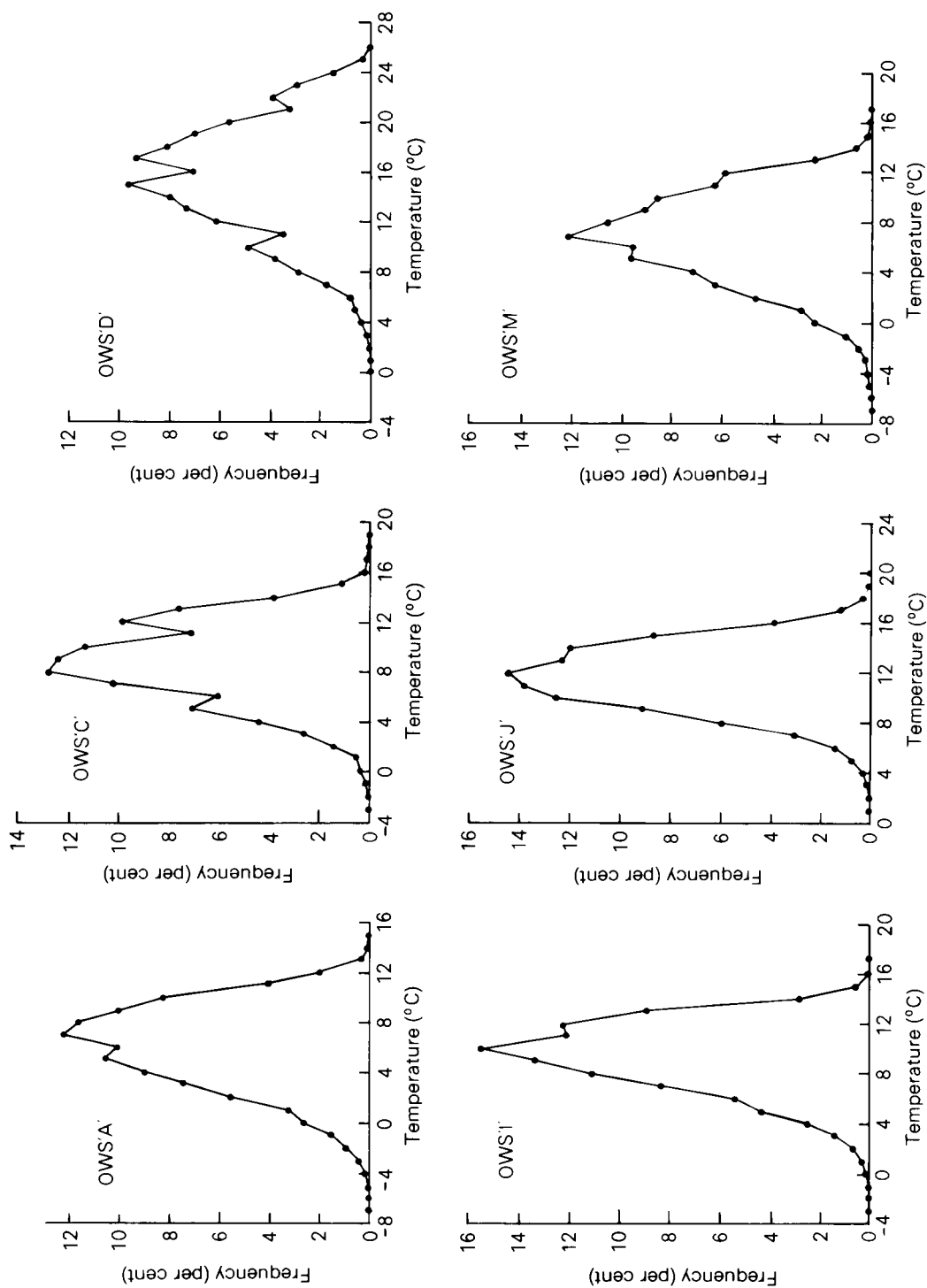


Figure 5. Frequency distribution of air temperature from readings at three-hourly intervals for selected Ocean Weather Stations for the 23-year period 1950-1972.

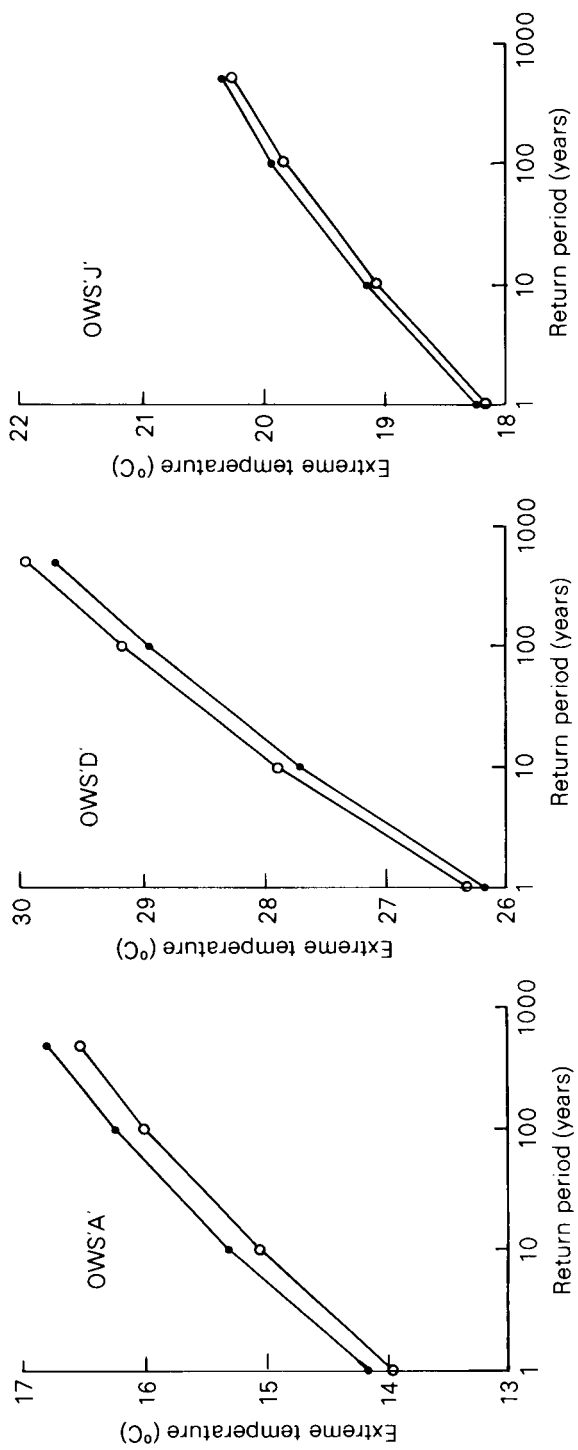


Figure 6. Frequency groups for three-hourly temperature readings for selected Ocean Weather Stations using a Weibull analysis on temperatures grouped at 1 °C intervals ●—● and 2 °C intervals ○—○

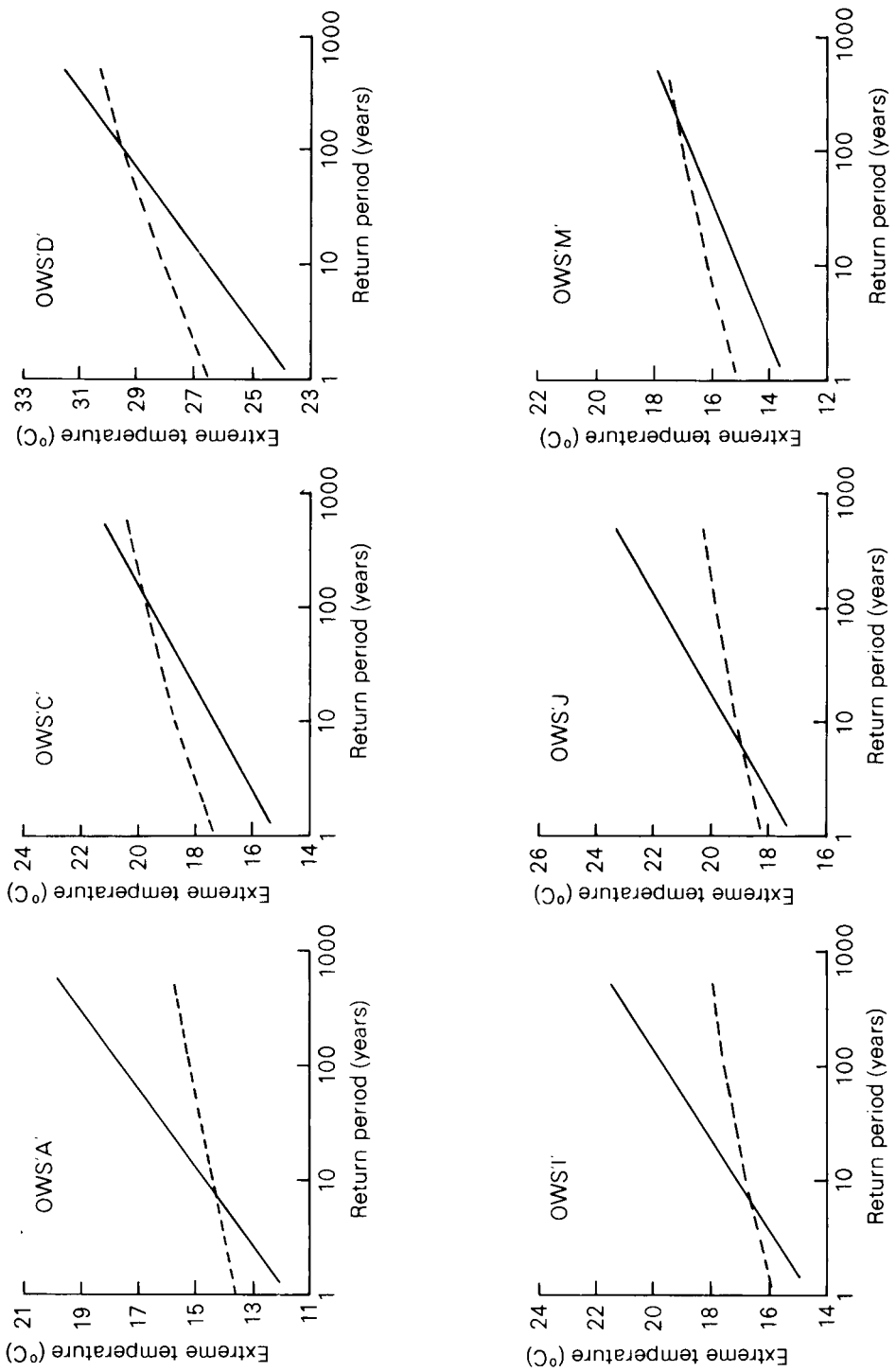


Figure 7. Extreme maximum temperatures for selected Ocean Weather Stations derived using Gumbel and Weibull techniques. (Gumbel — Weibull ----).

to define an average event size (in terms of degrees centigrade) and length (hours) was as follows. The difference ΔT between 3-hourly observations was calculated for each OWS. Twice the standard deviation of the resulting distribution was then used to give the size (in degrees centigrade) of a single event such that the minimum difference between successive independent observations was ΔT . The value of ΔT was also used to determine the number of events that would be expected to occur on average each year so that the return periods could be identified. To do this a distribution of 'spells' was constructed, each spell consisting of observations within one standard deviation of ΔT of one another. The median value of this distribution of spells was used to give the best estimate of the length of time for which an independent observation was representative.

Each whole distribution of temperatures was modified using this method, in each case reducing the observation count to about 30% of the original total consistent with the choice of twice the standard deviation as the event size. The time for which independent observations were representative varied for different OWS, being four hours for 'A', 'I' and 'J', three hours for 'M' and six hours for 'C' and 'D'. For each OWS except 'C' and 'D' it was possible to use hourly observations to determine the representative time. For 'C' and 'D', however, only three-hourly observations were available so it is possible that the representative time for these OWS is three or four hours as for the others. The representative time does not affect the fitting of the data, it is involved only in the definition of the return period.

5. Results and discussion

The extremes estimated by Weibull analysis of the modified distributions are shown in Fig. 8 and compared with the original Weibull and Gumbel extremes.

The removal of observations in order to reduce the effect of persistence within the data makes very little difference to the Weibull extremes despite the large reduction in the number of observations. Fig. 9 shows the percentage frequency distribution for each station before and after the reduction in the effect of persistence.

Another modification of the distribution was attempted by identifying observations of separate events. On a plot of temperature against time the 'gradient' at a point (or observation) can be calculated by finding the gradient between the previous observation and the one after it. Where successive gradients changed sign a turning point had been found and the corresponding temperature was considered to be an observation of an independent event.

The resulting distributions were much the same as the unmodified ones, although again the number of observations was considerably reduced. The estimated extremes were slightly different, but the change did not account for the difference between the Weibull and Gumbel extremes.

All meteorological variables are persistent to some extent and temperature is particularly so. There is a correlation not only from observation to observation but also from day to day due to the diurnal variation (rather less marked for temperatures over the sea than on land) and also seasonal variations.

It is not possible to make the data sequence totally independent in a statistical sense, but a positive attempt can be made to make it less dependent by removing values similar in magnitude to those preceding them. This was achieved by imposing an empirical threshold value and discarding any observation within one threshold of the value immediately before it. It was also necessary to adjust the time used in the Weibull analysis for which an observation may be said to be representative.

The remaining events are still dependent, but repeated records of an event should have been removed. The reduction of the number of observations to one third of the original total by this method implies a great change in the distribution, but the Weibull analysis is not significantly altered. This is explained by

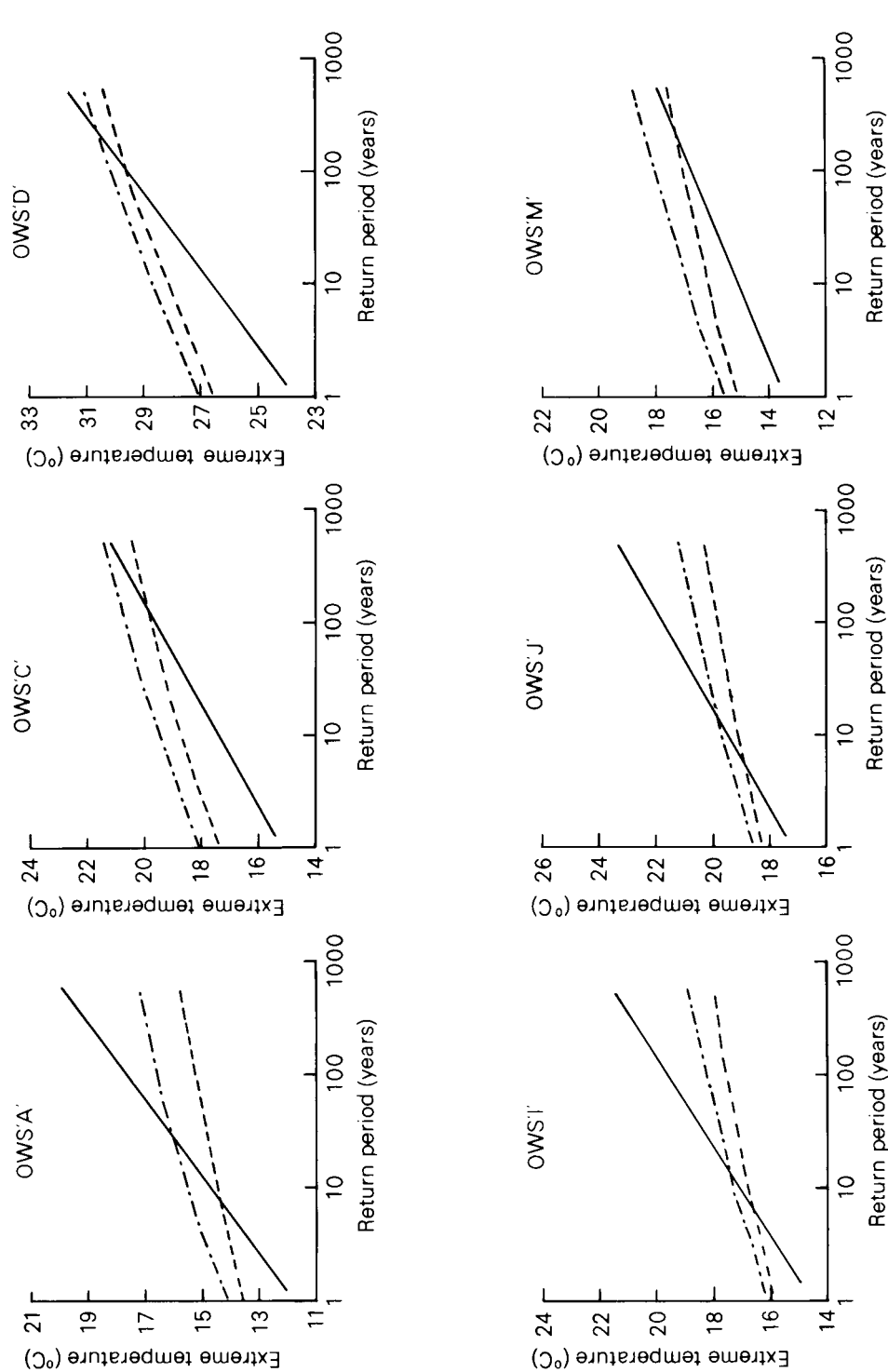


Figure 8. Extreme maximum temperatures for selected Ocean Weather Stations derived using a Weibull analysis on a modified temperature distribution compared with the original Gumbel — and Weibull - - - analyses.

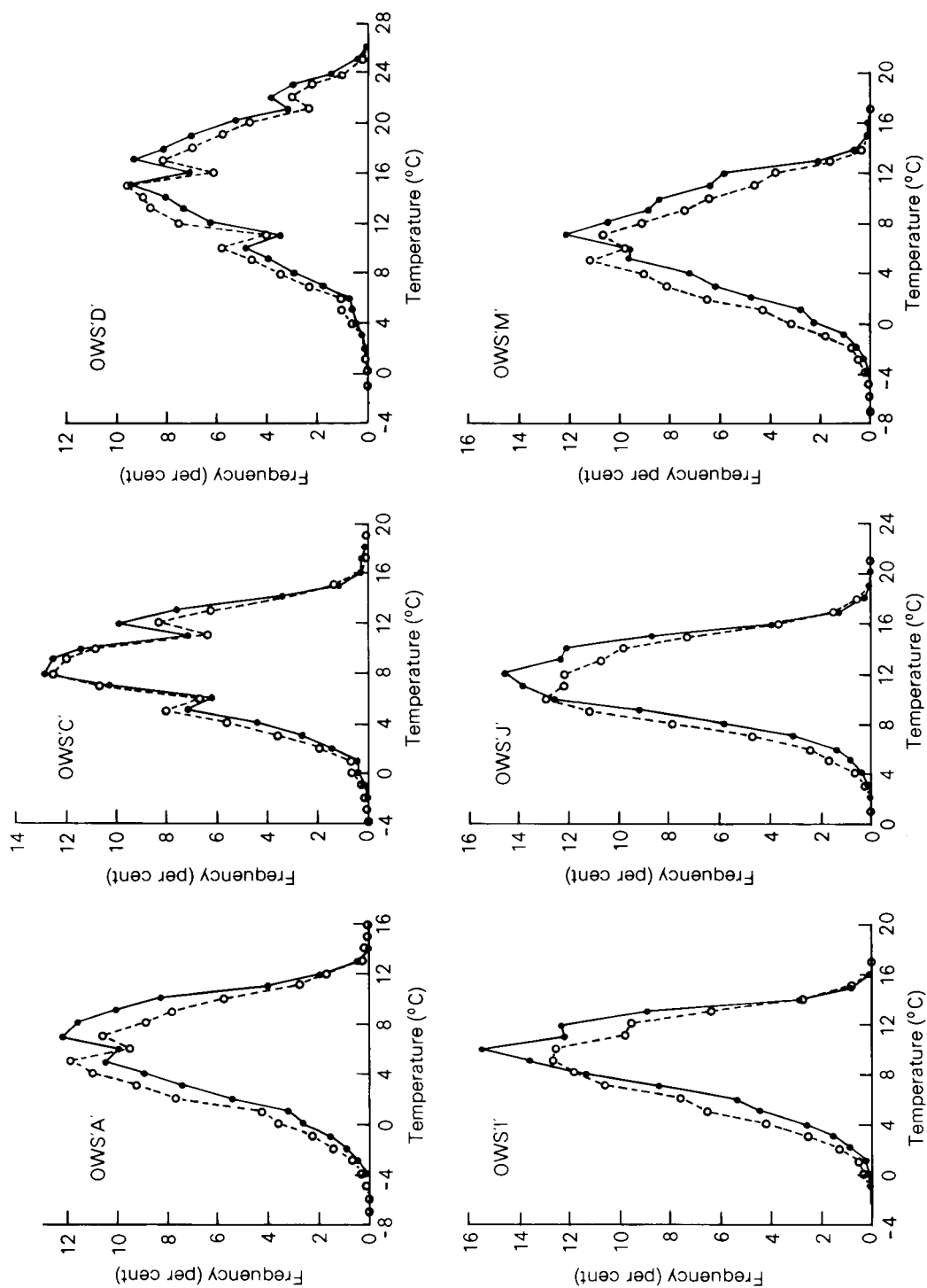


Figure 9. Air temperature distributions for selected Ocean Weather Stations for the 23-year period 1950-1972. Unmodified \bullet — \bullet , modified to reduce the effect of persistence \circ — \circ .

the fact that though the number of observations has changed, the range and shape of the distribution is still similar to its original form. This is to be expected since only repeated records of an event have been removed, not the actual event.

6. Conclusion

It has been confirmed that extremes estimated using the Weibull technique are overestimated for short return periods and underestimated for longer return periods when compared with those estimated by the Gumbel technique. The definition of 'short' and 'long' return period is different for each location and there appears to be no consistent systematic relationship between extremes derived from the two methods.

It has also been shown that the effect of persistence upon the estimated extreme is insignificant compared with the difference between extremes derived from the Weibull and Gumbel techniques.

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- | | | |
|------------------|------|---|
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Appendix — The three-parameter Weibull distribution

Distribution function:

$$F(x) = 1 - \exp \left\{ - \left(\frac{x - x_0}{B} \right)^A \right\} \quad \dots \quad (A.1)$$

This distribution function is fitted to the cumulative frequency distribution of the whole spectrum of 'available' data.

Expression (A.1) is rearranged to give

$$\ln \ln \left(\frac{1}{1 - F(x)} \right) = A \ln (x - x_0) - A \ln B \quad \dots \quad (A.2)$$

which is in the form of a straight line, $y = mX + c$.

$$F(x) = \frac{\text{number of observations below limit } x}{\text{total number of observations}}$$

so

$$\{1 - F(x)\} = \frac{\text{number of observations above } x}{\text{total number of observations}}$$

then

$$y \equiv \ln \ln \left(\frac{\text{total number of observations}}{\text{number of observations above } x} \right) \quad \dots \quad (A.3)$$

A straight line is fitted using various values of x_0 until the best line is found. A , B and x_0 are the three parameters of the best fit.

The resulting Weibull distribution is then assumed to have the same three parameters, however many observations are made, so that it can be used to estimate extremes for any return period.

In estimating the extreme value, y is redefined to be used in the expression

$$(\text{extreme}) = \exp\left(\frac{y + A \ln B}{A}\right) + x_0 \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (\text{A.4})$$

which is a rearrangement of expression (A.2).

The extreme value required is that value likely to be exceeded at least once in the given return period. The 'number above x ' in expression (A.3) is therefore 1. The total number of observations in a given return period depends on the 'representative time' of the observations used in the Weibull fit.

When using the Weibull method, the distribution of available data is assumed to be representative of the whole population. Obviously the more observations there are the more likely the distribution is to be representative of the whole population. Therefore, observations made at hourly intervals would be likely to produce a better sample than observations made at three-hourly intervals over the same period. However, provided that the observations are all made in the same way the representative time will be the same for both distributions, and over a long enough period the percentage frequency distributions would be identical.

Very often the representative time chosen is the interval between observations. This means that with two distributions of, say, air temperatures, one with observations made at hourly intervals and one at three-hourly intervals, but both taken over the same period which was long enough to produce identical percentage frequency distributions, the extremes estimated would be different. This is because in one year there would be 8760 observations made at hourly intervals and only 2920 at three-hourly intervals.

The true representative time is not the interval between observations but the time for which each observation is representative of the conditions.

For air temperatures over the sea the representative time was three hours with the event length as chosen. For OWS 'I', 'J' and 'M' over the period 1962–75 (14 years) two distributions of air temperatures were constructed, one of hourly and one of three-hourly observations. Table A.I shows the resulting percentage frequency distributions for OWS 'I'. The two distributions are almost identical. Table A.II shows the results of the Weibull fit and Table A.III the extremes estimated for the 10- and 50-year return periods using observation interval and the three-hour representative time. The extremes are very similar when using the three-hour representative time for OWS 'I' as are 'J' and 'M' (not shown). Using the observation interval of one hour for the distribution of hourly observations gave higher estimates. The difference is not great in this case, but if the true representative time was shorter than the observation interval the extremes would be underestimated and this is much more serious.

This is probably so for wind speeds. Wind speed is very variable and is generally measured over some fixed time interval, say one hour, and the resulting value is the average wind speed over that time, i.e. hourly mean wind speed. In this case the representative time would be one hour and there would be 24 possible observations per day, whatever the observation interval. For the 10-minute means using the same argument there would be six possible 10-minute wind speeds every hour, and for gusts, assuming 3 seconds, 1200 every hour. Obviously the argument cannot be extended without limit. One 10-minute wind speed and the next will be correlated, as will one 3-second gust and the next. The representative time will be somewhere between the averaging time and one hour, depending upon the scale of the meteorological phenomenon concerned. So the best solution is to do some analysis to determine the actual representativeness of the observations in a manner similar to that done for the air temperatures.

Table A.I. *Percentage frequencies of air temperatures from OWS 'T' for hourly and three-hourly observations*

Temperature (°C)	Hourly observations	Three-hourly observations
-2	0.01	0.01
-1	0.04	0.05
0	0.08	0.08
1	0.23	0.23
2	0.71	0.72
3	1.48	1.52
4	2.60	2.62
5	4.28	4.17
6	5.99	6.02
7	9.00	8.97
8	11.48	11.61
9	14.54	14.50
10	16.09	16.08
11	12.65	12.62
12	11.49	11.52
13	6.89	6.82
14	1.94	1.97
15	0.41	0.39
16	0.09	0.09
17	0.02	0.02
Total number of observations	113 011	37 734

Table A.II. *Results of Weibull fit to temperature distributions from OWS 'T' for hourly and three-hourly observations*

	Hourly observations	Three-hourly observations
Gradient (A)	6.29	6.40
Intercept ($A \ln B$)	-17.06	-17.45
Third parameter (x_0)	-5.30 °C	-5.55 °C

For explanation of A , $A \ln B$ and x_0 see expression A.2.

Table A.III. *Temperature extremes (°C) estimated from hourly and three-hourly temperature distributions from OWS 'T'*

Distribution	Representative time	Once in 10-year extreme	Once in 50-year extreme
3-hourly	3 hours	16.43	16.93
Hourly	1 hour	16.85	17.33
Hourly	3 hours	16.52	17.03

For wind speeds work is to be done using DALE (digital anemograph logging equipment) data to try to establish a general relationship between averaging time and representative time. It is clear that averaging time alone is not the answer although in the absence of anything else it may be best to use it.

When averaging time or observation interval must be used it is important to remember that the extremes estimated are based on a sample of a particular kind of measurement made at the specified reporting interval.

The Ben Nevis Meteorological Observatory 1883–1904

Part 1. Historical background, methods of observation and published data

By Marjory G. Roy

(Meteorological Office, Edinburgh)

Summary

This article contains: a brief history of the Ben Nevis Observatory and the corresponding low-level observation sites at Fort William close to the foot of the mountain; a description of the observational routine and the resulting data, both published and unpublished.

1. Introduction

October 17 1983 marks the centenary of the opening of a high-level meteorological observatory on the summit of Ben Nevis, 1344 m (4407 ft), the highest mountain in the British Isles. The hourly weather observations which were made there over a period of nearly 21 years were published in detail in the *Transactions of the Royal Society of Edinburgh* and comprehensively analysed at the time, notably by Alexander Buchan (the Secretary of the Scottish Meteorological Society) and by members of the Observatory staff. However, to a large extent the observations appear to have been overlooked by those carrying out research in more recent times into conditions in the lower layers of the atmosphere. In the light of the great advances in meteorological knowledge that have occurred in the intervening years there is considerable scope for the reuse and reinterpretation of these (generally) extremely high-quality data. It is hoped that some, at least, of these data will be put into computer compatible form*.

2. Historical background

In an article published on the occasion of the 50th anniversary of the closing of Ben Nevis Observatory, Paton (1954) gives a graphic and comprehensive description of the planning, building and running of the Observatory. Further details can be found in Buchan (1890) and Kilgour (1905).

Briefly, the Observatory was proposed, established and run principally by the Scottish Meteorological Society, which was founded in 1855 and was incorporated with the Royal Meteorological Society in January 1921. The Scottish Meteorological Society had, from its inception, set up and maintained, in Scotland, a network of climatological stations manned by voluntary observers. The network continues today as part of the UK voluntary cooperating climatological network. The Edinburgh Climatological Office, formerly headquarters of the Scottish Meteorological Society, became part of the Meteorological Office in 1921 and still administers the Scottish climatological stations.

The enterprise of setting up the Observatory was proposed in 1877 by the Scottish Meteorological Society on the basis that the location of Ben Nevis close to the western seaboard of Scotland, and also frequently close to the storm tracks of Atlantic depressions, would make the observations of particular

*In June 1983 a Manpower Services Commission Community Project started work on putting the Ben Nevis and Fort William observations into computer compatible form. The data will be available on magnetic tape through the Scottish Centre of the Royal Meteorological Society.

interest. Early in 1883 a public appeal was launched and a sum of £4 000 was subscribed within a few months with Queen Victoria heading the subscription list. During the summer of 1883 the bridle path to the summit and the Observatory building were constructed, the Observatory being formally opened on 17 October 1883 by Mrs Cameron Campbell, the owner of the estate of Callart which included the western half of Ben Nevis. The Observatory was managed by a committee consisting of the Council of the Scottish Meteorological Society and representatives nominated by the Royal Societies of London and Edinburgh.

Regular hourly observations commenced on 28 November 1883, the three observers taking 4-hourly watches by day and 8-hourly watches by night. However, during the first winter the build up of snow became so great that an access tunnel 30 ft long and with a rise of level of 12 ft had to be dug. During bad weather it was impossible to keep this tunnel open and observations were interrupted. In order to overcome this problem a 30 ft-high tower was added in the summer of 1884 to provide an exit door in winter, and the observatory building was enlarged.

It was considered essential to provide a nearby low-level comparison station at Fort William 4 miles away and the schoolmaster at the public school there was responsible for making observations five times per day. During July 1890 a low-level observatory, see Fig. 1, equipped with autographic instruments, was opened in Fort William. Comparisons were made between the observations at the school and at the low-level observatory.



Figure 1. Fort William Observatory

From the start it had been hoped that government funds would be made available to support the running of Ben Nevis Observatory, but the Meteorological Council was only willing to make a grant of £100 per annum for the receipt by the Meteorological Office of occasional telegraphic reports and of copies of the hourly observations. (For the low-level observatory, which conformed more closely to their expectations of how an observatory should be run and equipped, the Meteorological Council provided autographic instruments and a grant of £250 per annum.) As can be imagined, the cost to a learned society of running such an enterprise with negligible financial support from government sources was very great, even though the Superintendent received only a small nominal salary and his two assistants small emoluments. It was only thanks to a number of generous, mainly Scottish, benefactors that the Observatory was able to continue to function until 1904, when it was closed after the noon reading had been made on the first of October.

3. Weather observations at Ben Nevis Observatory

As a result of observations made by observers who climbed the mountain daily from Fort William during the summers of 1881, 1882 and 1883 it was clear to the Council of the Scottish Meteorological Society that it would be impossible to maintain an observatory of the standard pattern of the time with photographically recording instruments. Even in summer the rate of build-up of rime was frequently so great that instrument shelters became clogged, preventing proper exposure of the thermometers. Anemometers were incapable of operation except when the temperature was above freezing point.

Consequently it was decided that observations would have to be made manually. Duplicate screens and rain-gauges were provided so that one could be brought inside to be thawed out and de-iced while the other was used for the observations. During a considerable part of the year the anemometer could not operate and, consequently, estimates of wind speed were made by the observers using a variation of the Beaufort scale, hereinafter referred to as the 'Ben Nevis scale', more appropriate to the high winds observed on the mountain (Table I). The observers could, with practice, achieve a high degree of consistency in their wind speed estimates, and they calibrated these both against the instrumental records in the summer and against each other's estimates.

Table I. *Comparison of Ben Nevis and Beaufort wind scales*

Force	Mean wind speed (knots)		Mean wind speed (miles per hour)	
	Ben Nevis	Beaufort	Ben Nevis	Beaufort
0	<5	0	<6	0
1	5	2	6	2
2	10	5	12	5
3	18	9	21	10
4	26	13	30	15
5	34	19	39	21
6	43	24	49	28
7	52	30	60	35
8	63	37	72	42
9	(73)	44	(84)	50
10	(84)	52	(97)	59
11	(97)	60	(112)	68
12	(113)		(130)	

Bracketed values are estimates — no comparison with an instrumental record was available.

Once the tower to the Observatory had been built during the summer of 1884, interruptions to the hourly routine generally only occurred during periods of very high winds when it was unsafe for the observers to leave the shelter of the building. However, from August 1890 thermometers were mounted in a screen attached to the tower, with stems projecting through holes in the wall so that they could be read in safety.

Details of the methods employed in making the meteorological observations, and the problems encountered, are given below.

3.1 Atmospheric pressure

Hourly observations of pressure were made at Ben Nevis Observatory with two Fortin barometers that had been calibrated at Kew. Readings were corrected for instrumental error and to 32 °F (0 °C), but published values were not corrected to mean sea level thus enabling research workers to examine in detail the relationships between the hourly values of pressure at Ben Nevis Observatory (1344 m, 4407 ft above mean sea level) and those at the same time at Fort William Observatory (barometer height 13 m, 42 ft above mean sea level) 4 miles away. At the latter site pressure observations were obtained from a photographic barograph and the readings were corrected to 0 °C and reduced to mean sea level using tables based on Laplace's formula i.e. the hydrostatic equation. Prior to the opening of Fort William Observatory pressure readings were made five times a day (08, 09, 14, 18 and 21 GMT) at the school at Fort William (barometer height 10 m, 33 ft above mean sea level) using a Board of Trade pattern barometer. These were also corrected to 0 °C and reduced to mean sea level. The unit of pressure employed was the 'inch of mercury' (inHg) where 1 inHg = 33.863 mb; all pressures quoted in the present paper have been converted to millibars for the convenience of the modern reader.

At Ben Nevis Observatory and Fort William School, Richard aneroid barographs were used as a check on the barometer readings.

A 'table of corrections for height' to reduce the barometric observations at Ben Nevis Observatory to mean sea level was prepared by Buchan using the synchronous observations at Ben Nevis and Fort William. This table assumed that the temperature of the air in between was the arithmetic mean of the temperatures at the Observatory and Fort William. However, when departures from normal were investigated it became clear that when high winds prevailed at the summit the pressure observed inside the Observatory was reduced owing to the airflow over the building. Consequently an amended table of mean corrections was computed (Buchan 1890) using only those occasions on which the wind at the Observatory was less than 30 mph (26 knots). This correction table is published as Table VIII of the Introduction to Volume 34 of the *Transactions of the Royal Society of Edinburgh*. (Studies of the difference in calculated mean-sea-level pressure for Ben Nevis and Fort William under conditions that exclude occasions of strong winds at the summit are referred to later.)

The effects of both wind speed and wind direction on the mean-sea-level pressure differences (calculated using the mean correction table) between Ben Nevis and Fort William were studied in detail by Buchan (1902). (At the relatively sheltered site at Fort William winds exceeding 30 or even 20 mph were rare occurrences.) When all wind directions were combined the mean depressions shown in Table II were obtained. At wind speeds in excess of 57 mph (52 knots) the barometric depression exceeded 1.7 mb and reached almost 6 mb with the highest wind speed recorded.

However, it was evident to Buchan that the pressure diminution observed differed considerably according to the wind direction. Table III has been converted to present-day standard meteorological units of millibars from Buchan's analysis of 10 months' data for the high- and low-level observations, supplemented by use of some of the pairs of data between the high-level observatory and the observations made five times a day at the school in Fort William. Buchan noted that for certain wind

Table II. *Depression of barometer at Ben Nevis Observatory for different wind speeds (all wind directions combined) adapted from Buchan (1902)*

Wind speed on Ben Nevis scale	0	1	2	3	4	5	6	7	8	9	10	11	12
Equivalent mean wind speed in knots	<5	5	10	18	26	34	43	52	63	73	84	97	113
Barometric depression in millibars	<0.1	0.1	0.2	0.3	0.5	0.9	1.2	1.7	2.4	3.5	4.3	5.1	5.8

directions speeds in excess of 30 mph had not been observed on Ben Nevis during the period January 1885 to May 1891 (see Table III), and that speeds in excess of 72 mph were confined to winds between east-south-east and south-east. The observatory was situated on the edge of a 550 m (1800 ft) cliff, immediately to the north of the building. Visual observations confirmed that the speed of clouds moving from the north, at only a small height above the mountain, were considerably greater than the wind speeds observed manually and instrumentally at the observatory. Table III shows that for wind speeds of less than force 4 the diminution of pressure was small for wind directions from south-east through south and west to north-west, but that it was very much greater for winds blowing from the other half of the compass. Buchan's conclusion was that 'the depression of the barometer ... clearly indicates the formation of a restricted space of low pressure outside and around the building of the Observatory'.

Thus care must be taken with the interpretation of the barometric pressure, including hourly pressure changes, during periods of strong, or even moderate, winds (from certain directions), particularly since the barometer 'pumps' violently at these times. The barometer readings were taken at the point which the mercury was seen to rise to, and hold steady at, briefly.

3.2 Stevenson screen observations — dry- and wet-bulb temperatures

During the summer months the dry- and wet-bulb thermometers at the Ben Nevis Observatory were placed in an ordinary Stevenson screen with their bulbs 4 ft (1.2 m) above the surface of the ground, which consisted of broken rocks without any vegetation. However, during the winter the thermometers were placed in a slightly smaller screen of similar pattern attached to a ladder-like stand so that the screen could be raised or lowered as the depth of snow varied (see Fig. 2), and thus the thermometers kept between three and five feet above the surface. When the louvres of a screen got choked with snow or rime it was removed bodily to the observatory to be thawed out and replaced by a duplicate with fresh thermometers. Self-registering thermometers were not used for maximum and minimum temperatures. During very stormy weather when it would have been dangerous to go outside, the temperature was read, from August 1890 onwards, from a screen attached to the wall of the Observatory tower. The thermometers could then be read without going outside and it was found that with wind speeds of force 9 or more (Ben Nevis scale) there was little difference between the tower and Stevenson screen observations.

Care was taken to ensure that if the temperature was below 0°C the 'wet bulb' was coated with ice, i.e. was a true 'ice bulb'. Since the usual condition on Ben Nevis was one of a saturated atmosphere, the dry bulb quickly became coated with water in summer and water or ice during most of the rest of the year. As a result the 'dry bulb' frequently read lower than the wet bulb (not only in conditions when the ice bulb temperature *could* be slightly higher than the dry bulb) since it responded more quickly to temperature changes than the latter. All published values of dry- and wet-bulb temperatures were 'as read', without correction for such problems.

Table III. Mean depression of barometer (in millibars) at Ben Nevis Observatory for different wind directions and wind speeds (Ben Nevis scale) adapted from Buchan (1902)

Force	Wind direction											
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
0	0.3	0.4	0.5	0.4	0.4	0.3	0.2	0.1	0.0	0.1	0.1	0.2
1	0.3	0.4	0.4	0.5	0.2	0.0	-0.1	-0.1	-0.1	-0.0	-0.0	0.0
2	0.7	0.8	0.9	0.8	0.5	0.3	0.1	0.0	0.0	0.0	0.0	0.0
3	0.9	1.2	1.3	1.0	0.7	0.4	0.3	0.1	0.1	0.1	0.2	0.2
4	1.1	1.5	1.6	1.5	1.1	0.8	0.5	0.3	0.2	0.1	0.2	0.2
5	1.8	1.8	1.8	-	-	0.9	0.8	0.6	0.4	0.3	0.3	0.4
6	2.2	-	-	-	-	1.2	1.2	0.9	0.7	0.6	0.6	-
7	2.8	-	-	-	-	1.9	1.8	1.5	1.5	-	-	-
8	-	-	-	-	-	2.7	2.4	2.0	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	-

*Combined directions ESE and SE

Although the usual state of the atmosphere was one of saturation, there occurred also spells of weather when very low humidities were observed, sometimes for a considerable number of hours and sometimes alternating rapidly with high humidities. These very low humidities were associated with anticyclonic conditions. The hygrometric tables in use in the United Kingdom at the time were those of Glaisher, but since these did not extend to the observed conditions of dry- and wet-bulb temperatures, it was necessary to extrapolate the tables from his factors or make use of the formulae published by Apjohn, August or Regnault. The daily sheets of hourly data that were completed at the time (and are held in the Archives of the Meteorological Office, Edinburgh) contain values of relative humidity and dew-point which were derived from an extension of Glaisher's tables. However, a series of experiments carried out on Ben Nevis by Dickson in 1885 and Herbertson (with the assistance of the observers) in 1892 and 1893 showed that Glaisher's tables gave values of dew-point that were too low for temperatures below about 35 °F (1.7 °C) and too high for temperatures above 1.7 °C, though the latter differences were less marked. It is very fortunate that the published observations were of dry- and wet-bulb temperatures and not of dew-point. (Herbertson (1905) also discussed the problems of measuring temperatures in a Stevenson screen under calm, cloudless conditions and compared the readings with those of aspirated psychrometers.)

At the school in Fort William, readings were taken five times a day (08, 09, 14, 18 and 21 GMT) from dry- and wet-bulb thermometers in a Stevenson screen, and self-registering thermometers were read and reset daily at 18 GMT for the maximum thermometer and 09 GMT for the minimum thermometer. These readings covered the period from December 1883 to 31 December 1891.

The Fort William Observatory (located about 150 yards from the school) came into operation on 1 August 1890 and the hourly temperatures were obtained from traces of photographic dry- and wet-bulb thermometers placed in a large louvred screen on the north wall of the observatory. The louvred screen also contained dry- and wet-bulb thermometers read by eye at 09, 10, 12, 14, 16, 21 and 22 GMT, and



Figure 2. Ben Nevis Observatory in winter.

maximum and minimum thermometers read and reset at 22 GMT. (These data were *not* published in the *Transactions of the Royal Society of Edinburgh*.) In addition similar readings of temperature were made in a Stevenson screen located on a grass plot to the south of the observatory in a position freely exposed to sun and wind; these have been published.

Omond (1894) carried out a comparison of the differences in maximum and minimum temperature between the schoolhouse Stevenson screen and observatory Stevenson screen for each month of the year in 1891, and between the schoolhouse Stevenson screen and the photo-thermograph (dry bulb, wet bulb and maximum and minimum temperatures extracted from the trace) from August 1890 to December 1891. (Tables IV and V).

Table IV. Difference (°F) between Fort William School and Fort William Observatory Stevenson screen temperatures for 1891. Positive values indicate schoolhouse temperatures higher than those at the observatory.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Maximum	-0.5	-0.1	+0.1	+0.7	+1.2	+2.2	+1.4	+1.1	+0.8	-0.8	-0.4	-0.4	+0.4
Minimum	+0.5	-0.1	+0.4	-0.8	-0.2	-1.0	-0.8	-0.6	0.0	-0.4	-0.1	-0.9	-0.3
$\frac{\text{Maximum} + \text{Minimum}}{2}$	0.0	-0.1	+0.2	0.0	+0.5	+0.6	+0.3	+0.2	+0.4	-0.6	-0.2	-0.6	+0.1

Table V. Difference (°F) between Fort William School Stevenson screen temperatures and Fort William Observatory photo-thermograph temperatures. Positive values indicate schoolhouse temperatures higher than those at the observatory. (Aug. 1890 – Dec. 1891).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Maximum	+0.2	+0.7	+1.4	+1.8	+1.6	+2.9	+1.5	+1.8	+1.8	+1.3	+0.5	+0.2	+1.3
Minimum	-1.0	-1.1	-0.9	-1.6	-1.6	-1.9	-1.5	-1.3	-1.0	-1.4	-1.3	-1.5	-1.3
$\frac{\text{Maximum} + \text{Minimum}}{2}$	-0.4	-0.2	+0.2	+0.1	0.0	+0.5	0.0	+0.2	+0.4	0.0	-0.4	-0.6	0.0

3.3 Wind

A modified Robinson hemispherical cup anemometer was mounted 5 ft (1.5 m) above the roof of the tower, 18 ft (5.5 m) above the roof of the main part of the observatory and about 32 ft (9.8 m) above ground level. It had four cups. The records were obtained as the mean wind speed in miles per hour from a counter, the number of revolutions being read hourly. However, the anemometer could only be used when the temperature was above freezing point, so the instrumental records of wind speed were confined to the summer months, mainly June to September.

Throughout the year wind direction and force were estimated each hour by the observer standing on the flat roof of the observatory, using the Ben Nevis scale (Table I). Equivalent wind speeds for force 9 and above are rough approximations only.

At the school in Fort William the direction and force of the wind were estimated at 09 and 21 GMT daily, during the period 1883 to December 1890. Wind speed and direction were also estimated at the observation hours at Fort William Observatory, but were not published. They are, however, available in the observers' notebooks (held at the Meteorological Office, Edinburgh).

In the publications (*Transactions of the Royal Society of Edinburgh*) a range of wind speed was given for each observation and this provides a useful guide to the 'gustiness' of the wind.

3.4 *Cloud*

The species, and amount of cloud on the scale 0 to 10, were noted for each hour. A fog symbol was used to indicate that the summit was covered by fog or mist, i.e. the sky was obscured. At Fort William, cloud observations were made at the standard reporting hours at both the school and the observatory.

3.5 *Rain*

Five-inch rain-gauges with their rims one foot above the ground were used on Ben Nevis, with one gauge being brought inside each hour for measurement, being replaced outside by a similar one. It must be accepted that with the frequent occurrence of strong winds, particularly during periods of precipitation, the Ben Nevis gauges were very overexposed and the catch consequently less than that which would have been received at ground level. Consequently, the absolute values of rainfall are suspect, and the data can only be regarded as indicating periods of slight, moderate or heavy precipitation. During snowfall with strong winds it is likely that much of the potential catch was blown past the gauge.

The Superintendent of the Observatory, R. T. Omond, recognized the limitations in the use of the rain-gauges in such an exposed situation (Omond 1889) and deduced the wind flow over the gauges from observations of ice-crystal deposition from drifting fog.

A 5-inch gauge was also used at the school at Fort William and read at 09 GMT, but at the Fort William Observatory hourly rainfall was obtained from a Beckley self-recording rain-gauge, with rim 20 inches (51 cm) above ground and diameter 11.3 inches. During periods when the precipitation was of snow daily totals only were given.

3.6 *Sunshine*

Sunshine was recorded with Campbell–Stokes sunshine recorders at both the Ben Nevis and Fort William Observatories. At the latter the hills surrounding Fort William considerably reduced the possible sunshine at all seasons of the year when compared with the open horizon on Ben Nevis.

Published values for the hourly sunshine values referred to Greenwich Mean Time up to 31 December 1890 at Ben Nevis Observatory, but thereafter were in Local Mean Time. At Fort William Observatory they were in Local Mean Time throughout. The amounts entered under each hour were the totals recorded in the 60 minutes ending at the hour.

3.7 *Other observations*

Visibility was recorded using a scale from 0 to 4, with a value 0 when the summit of Ben Nevis alone could be seen, ranging up to 4 when Barra Head, Paps of Jura, Moray Firth, etc. could be seen. However, problems arose since the densest haze layer often lay below the level of the Observatory, though it could rise up and envelope it during the middle part of the day. The term 'mist' was used for a very wet fog and 'fog' for a comparatively dry fog.

The observers noted the occurrences of different types of 'weather'. Among these were the various forms of precipitation, including freezing rain which they called 'silver thaw'. This was of fairly common occurrence with 198 cases being reported in the six years 1885–1890 (Mossman 1893). The mean depth of snow was recorded daily whenever it lay at the summit of the Ben.

The occurrence of thunderstorms was noted; as also was that of 'St Elmo's Fire', normally only seen in the winter months and during the night owing to the feebleness of the light emitted. It was, however, occasionally heard in the daytime.

Various optical phenomena such as haloes, glories, zodiacal light, aurorae, etc. were described in detail in the observatory log-book and measurements made of their appearance.

The Observatory was used as a location for a number of special experiments. For example, a series of measurements of dust particles in the atmosphere were made using an Aitken dust counter (Aitken 1902). Both Dickson and Herbertson carried out important researches on hygrometry at low temperatures and low humidities. These were referred to earlier.

4. Published data

Volumes 34, 42, 43 and 44 parts I and II of the *Transactions of the Royal Society of Edinburgh* contain the greater part of the observed data from the Ben Nevis and Fort William Observatories and from the school at Fort William. The form of publication is one of separate tables of the hourly values of each individual element, apart from air temperature where dry bulb and wet bulb are presented side by side. For the three sites the published data comprise the following:

Ben Nevis Observatory 28 November 1883 to September 1904

Hourly values of:

Pressure at station height (1344 m) and 0 °C in inches of mercury;

Dry-bulb and wet-bulb temperature in degrees Fahrenheit;

Direction and force of the wind (wind direction is given in terms of the 16 principal points of the compass and wind as a range of forces on the Ben Nevis scale);

Mean hourly wind speeds for the periods in the summer when the anemometer was in operation;

Rainfall in inches;

Sunshine in minutes from February 1884 to December 1887, and in fractions of an hour from January 1888 to September 1904; and

Amount of cloud in tenths (or occurrence of mist or fog).

The log-book comments are also printed.

Fort William Observatory August 1890 to September 1904

Hourly values of:

Pressure reduced to mean sea level and 0 °C in inches of mercury, obtained from photo-barograph traces;

Dry-bulb and wet-bulb temperatures in degrees Fahrenheit read from the photographic thermometer records;

Rainfall in inches; and

Sunshine in fractions of an hour.

Tables are also given for:

Stevenson screen values of dry-bulb and wet-bulb temperatures read at 09, 10, 12, 14, 16, 21 and 22 GMT;

Amount of cloud at 09, 10, 14, 21 and 22 GMT; and

Maximum and minimum temperatures for the 24 hours ending at midnight for those derived from the thermograph trace and 22 GMT for those read in the Stevenson screen.

Fort William School December 1883 to December 1890

The tables contain for the observation hours of 08, 09, 14, 18 and 21 GMT:

Pressure reduced to mean sea level and 0 °C in inches of mercury; and

Dry-bulb and wet-bulb temperatures in degree Fahrenheit in a Stevenson screen.

Also published are:

Maximum and minimum temperatures in degrees Fahrenheit read at 18 GMT for maximum and 09 GMT for minimum;

Direction and force of the wind at 09 and 21 GMT;

Cloud amount in tenths at 09, 14 and 21 GMT; and

Rainfall total for the day in inches, read at 09 GMT.

5. Unpublished data

The archives of Meteorological Office, Edinburgh contain a considerable amount of unpublished data from the Ben Nevis and Fort William observations. In particular the daily observation sheets for the Ben Nevis Observatory, copies of which were sent to the offices of the Scottish Meteorological Society and the Meteorological Office in London, contain additional entries for visibility, type of precipitation, type of cloud, and special phenomena (such as thunderstorms, squalls, etc.). These sheets set out the observations in a form very similar to the hourly returns which have been provided by Meteorological Office and auxiliary synoptic stations in recent years.

The original observation notebooks for the Fort William Observatory are also available and these contain estimates of wind speed and direction for the hours when manual observations were made.

6. Summary tables

Summary tables for the period of operation of the Ben Nevis and Fort William Observatories are contained in volume 43 of the *Transactions of the Royal Society of Edinburgh*. Part of these summaries is given in Table VI.

Table VI. *Summaries of observations at Ben Nevis and Fort William Observatories*

(a) Mean temperature 1884–1903 at Ben Nevis in degrees Fahrenheit

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
24.0	23.8	24.0	27.6	33.0	39.7	41.1	40.4	38.0	31.4	28.9	25.2	31.4

(b) Mean temperature 1891–1903 at Fort William in degrees Fahrenheit

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
38.7	38.8	40.4	45.1	49.7	55.4	57.1	56.5	53.2	46.6	44.0	40.1	47.1

(c) Mean hours of sunshine as % of possible 1884–1903 at Ben Nevis

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
10	16	15	19	23	22	16	13	16	13	11	9	16

(d) Mean time summit clear of fog or mist as % of possible 1884–1903 at Ben Nevis

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
22	27	28	39	45	46	36	30	30	27	22	21	31

(e) Wind direction as % of total observations 1884–1903 at Ben Nevis for complete year

N	NE	E	SE	S	SW	W	NW	CALM
20	8	7	13	13	13	12	8	6

(f) Mean wind speed (Ben Nevis scale) 1884–1903 at Ben Nevis

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
2.89	2.68	2.50	2.26	1.95	1.75	1.64	1.72	2.10	2.46	2.68	2.73	2.28

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- | | | |
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Note.

The dates given for the references from the *Journal of the Scottish Meteorological Society* may be in error since the Journals did not specifically include a publication date. Dates used are those found in the bound volumes held at the National Meteorological Library, Bracknell.

Award

We note with pleasure that the International Meteorological Organization Prize for 1983 has been awarded by the Executive Council of the World Meteorological Organization (WMO) jointly to Professor Juan Jacinto Burgos, Professor Emeritus at the University of Buenos Aires, Argentina and to Mr Mohamed Fathi Taha, Counsellor in Meteorology to the Ministry of Civil Aviation, Egypt.

Professor Burgos started his career as an agricultural engineer in 1936, later holding high academic posts in agronomy at the Universities of La Plata and Buenos Aires. He was Head of the Agricultural Meteorology Division of the Argentine National Meteorological Service and has published numerous papers on agrometeorology. He was first President of the WMO Commission for Agricultural Meteorology, a position he held from 1951 to 1958, and was President of the Argentine National Committee for the Global Atmospheric Research Programme in 1976.

Mr Taha started his career as an aeronautical meteorologist in 1934, subsequently becoming Head of the Egyptian Meteorological Department in 1953, and Chairman of the Egyptian Meteorological Authority (which replaced it) from 1971 to 1976. He has served on many national and international committees concerned with the development of meteorology and other geophysical sciences, and served as President of WMO for two consecutive terms from 1971 to 1978.

Notes and news

The Steeple Challenge Trophy

The Meteorological Office stand at the Bath and West Show (Shepton Mallet, 1–4 June 1983) was awarded the Steeple Challenge Trophy for the best stand in the show with a frontage of 30 feet or less.

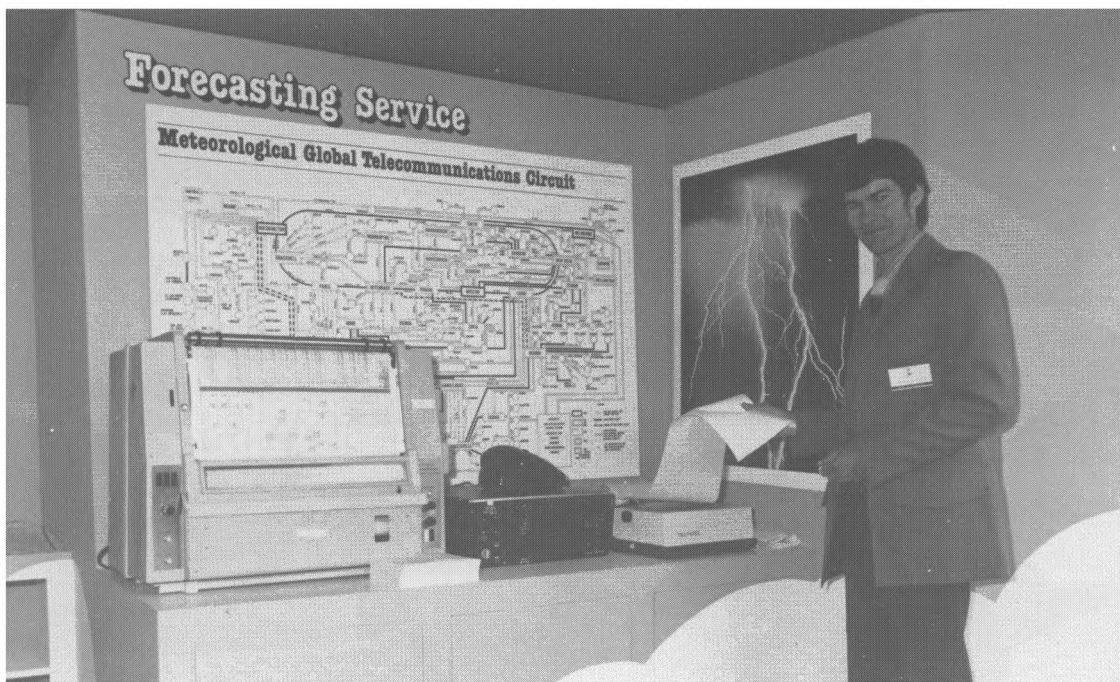
The trophy was presented to Mr Ted Young, the stand manager, by the Lord-Lieutenant of Somerset, Lt.-Col. G. W. F. Luttrell, MC.



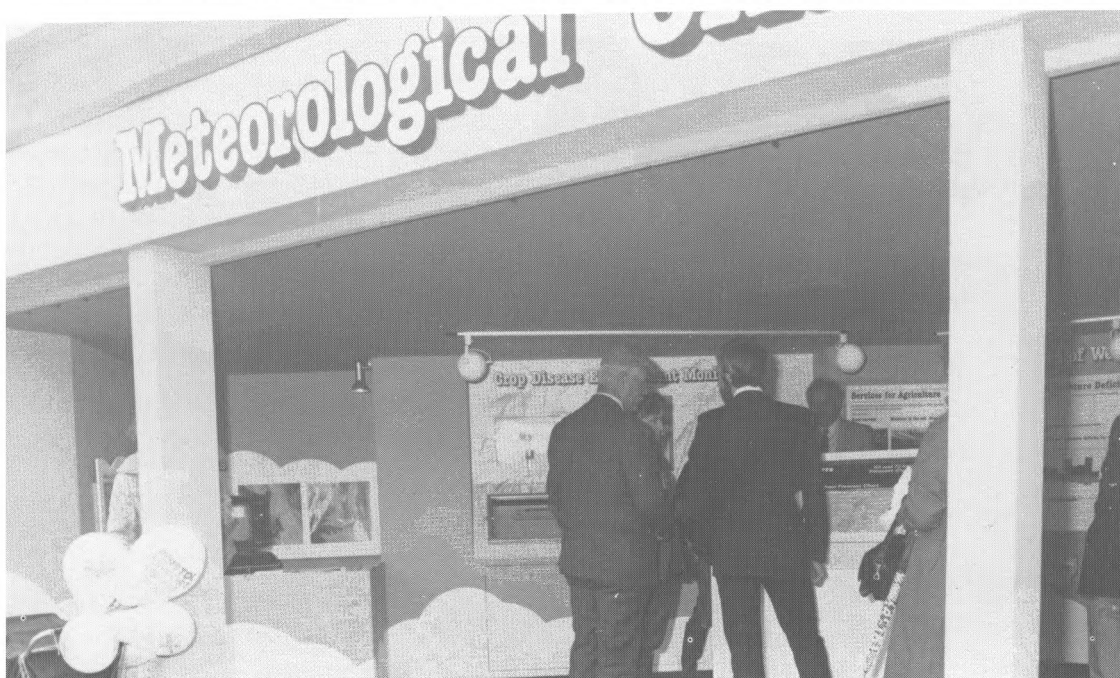
Mr Ted Young, on the right, receives the Steeple Challenge Trophy on behalf of the Meteorological Office from the Lord-Lieutenant of Somerset, Lt.-Col. G. W. F. Luttrell, MC.



The Meteorological Office stand at the Bath and West Show, Shepton Mallet, 1-4 June 1983.



Mr R. Downton, Bristol Weather Centre, on duty at the Bath and West Show, Shepton Mallet, 1-4 June 1983.



Some visitors to the Meteorological Office stand at the Bath and West Show, Shepton Mallet, 1-4 June 1983.

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NOTICES

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The use of rainfall data from radar for hydrometeorological services

By S. G. Palmer, C. A. Nicholass, M. J. Lee and M. J. Bader

(Meteorological Office, Bracknell)

Summary

Rainfall amounts measured from rain-gauges currently form the basis for answering many hydrometeorological enquiries involving rainfall and evaporation over the United Kingdom. However, rainfall information is now also available from a network of radars. Methods of combining the data from the two sources for producing more representative rainfall distributions on daily and sub-daily time scales are described and examples showing the benefits of incorporating the radar data are given.

1. Introduction

The Meteorological Office's Hydrometeorological Branch provides information on rainfall and evaporation to many users. Two very common questions are: 'How much rain has fallen over a particular area on a certain day or over a period of days, months or years?' and 'How often is a given amount of rainfall reached or exceeded for a specified period?' The first type of question is asked, for a variety of purposes, by people from many organizations, including water authorities, builders, insurance companies and farmers. The second type of question is chiefly asked by design engineers from, for example, civil engineering firms and local councils. For instance, if a new drainage system must not overflow, on average, more often than once in 10 years, the engineer will base his design on the rainfall amount that is reached or exceeded, on average, once in 10 years at the location of interest.

All these enquiries are answered using rainfall observations in the National Rainfall Archive (Shearman 1980) held at the Meteorological Office in Bracknell. The observations come from rain-gauges (i) read daily at 0900 GMT (daily rainfall totals) and (ii) which record rainfall during periods of less than a day (e.g. hourly totals).

There are currently about 3400 locations in England and Wales where the rainfall totals are read daily, which is sufficient to enable the daily rainfall distribution to be determined adequately over most regions. However, there are four aspects of daily rainfall observations to be considered:

(a) The network density varies from region to region; in some upland and rural areas where the gauge network is sparser, more detailed rainfall information is required.

(b) There is a financial requirement to reduce the number of rain-gauge stations measuring daily rainfall, so ways must be found to provide an acceptable standard of information from fewer stations.

(c) Most observers record their month's observations on cards which are sent to the Meteorological Office by collecting centres. Processing the observations requires manual intervention involving transcription to computer media, quality control, etc., and data processing would become more efficient if more automation could be incorporated.

(d) The rainfall observation cards reach the Office at the end of each month so that the rainfall distribution from all gauges for any particular day only becomes available during and sometimes after the following month; there would be a market for observations that were made available much sooner than this.

In contrast to the large number of locations where observations of daily rainfall totals are made, there are only about 150 locations in England and Wales where rainfall information from recording gauges is available at the Meteorological Office for determining rainfall totals for periods of less than a day. Sub-daily totals are particularly useful for providing information (e.g. connected with urban drainage) on local storms which can deposit very heavy rainfall for periods of up to a few hours over areas of 1000 km² or less. In general the short-period recording gauge network is so sparse that such storms could easily slip between gauges without being detected, particularly if they are slow moving.

A further problem with observations from all rain-gauges is that, although the measurements can be made very precisely, they only provide values of rainfall at a point. Such measurements may not be representative of the surrounding area, particularly if the rain is showery in character. Improved determinations of rainfall over areas are needed.

Alternatively, rainfall can be measured using radar (see Browning 1978). For several years now the Research and Development section of the Hydrometeorological Branch have been investigating the use of radar data to provide information on rainfall:

- (i) within the gaps in the daily, and especially the sub-daily, network,
- (ii) on time scales of a day or less,
- (iii) over areas rather than at points,
- (iv) soon after the event of interest (within one day), and
- (v) automatically, to reduce the need for manual data processing.

Rainfall data from a network of radars form the basis of work being carried out by the Meteorological Office Radar Research Laboratory, Malvern in their Short Period Weather Forecasting Project and in near-real-time flood control (see Browning 1979) but there the emphasis is on having rainfall information available within a few minutes.

2. Measurement of rainfall using radar

The use of radar for measuring rainfall has been widely documented (see Battan 1973). Briefly, the radar emits pulses of microwave radiation in a near-horizontal beam which rotates in azimuth. When a pulse intercepts precipitation the signal is scattered and a small proportion returns to the receiver. This back-scattered power is a function of the precipitation rate through the sampling volume, but the relationship varies with the type of rain (see Wilson and Brandes 1979). In practice, assumptions are made about the droplet size distribution and a single relationship between the back-scattered power and

rainfall rate is used. One of the reasons for making rainfall observations by radar is to provide frequent observations and therefore only a limited time is available for the observation of rainfall at any specific location. This determines the signal-to-error ratio of the return radar signal and hence of the inferred rainfall rate. As a consequence the return signals from areas of $5 \text{ km} \times 5 \text{ km}$ (or $2 \text{ km} \times 2 \text{ km}$ from locations closer to the radars) are combined, leading to rainfall rate estimates averaged over the areas with acceptably small errors. This averaging over areas also reduces the otherwise vast amount of data to be handled. So, radar provides estimates of areal rainfall observed above the ground with useful accuracy while the gauges give generally more accurate measurement of point rainfalls at the surface. Also, the radar, whose beam scans continuously in time and space, can provide information automatically for large areas in real time, thus fulfilling the requirements (i) to (v) listed at the end of Section 1.

The aim of a research and development project, currently being carried out in the Meteorological Office, is to combine the precision of measurement from the rain-gauges with the areal and temporal variations observed from the radar to provide a better picture of the rainfall in time and space than either system gives alone.

3. Radar data processing methods

3.1 Production of hourly rainfall totals

The UK Weather Radar Network currently comprises four sites (Fig. 1): Hameldon Hill and experimental sites at Clee Hill, Upavon and Camborne. Others are planned, notably one to cover London and south-east England. The radar observations are used to produce rainfall measurements over squares of $5 \text{ km} \times 5 \text{ km}$ every 5 minutes. These measurements are integrated by the Meteorological Office Radar Research Laboratory at Malvern to give hourly totals and are then sent on magnetic tape to Meteorological Office Headquarters at Bracknell.

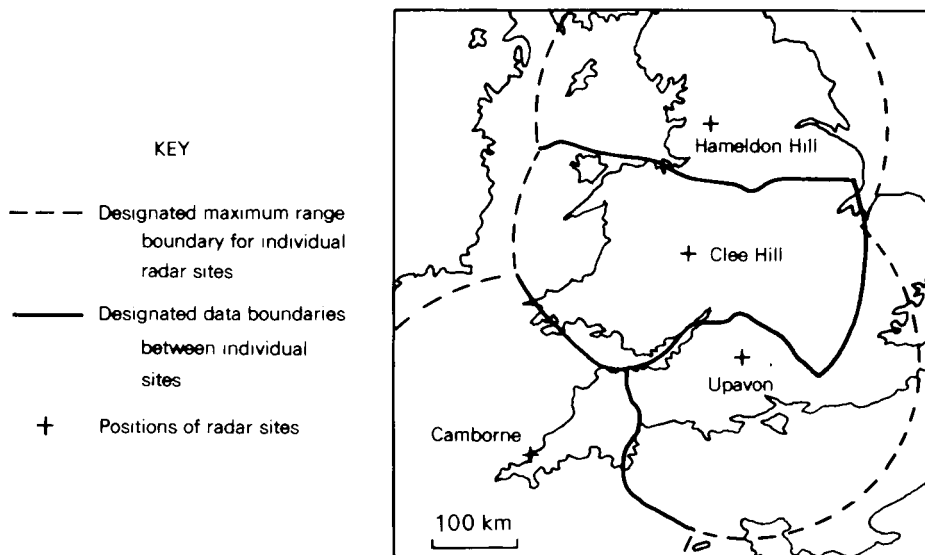


Figure 1. Locations of the four radar sets in the UK Weather Radar Network, together with data boundaries used when all four sets are working. At present, the whole of England and Wales is covered, except for parts of East Anglia and Kent.

3.1.1 *Quality control.* Quality control procedures are applied to eliminate some of the defects of the radar data. They are as follows:

(i) *Occultation.* The radar beam is partly blocked by permanent obstructions such as hills or masts, resulting in spokes of reduced power reception centred on the radar. These spokes are always blanked out.

(ii) *Permanent echo.* Certain locations give abnormally strong return signals and these are always blanked out. (This operation is in addition to the clutter cancellation previously applied by the electronics attached to the radar at each site.)

(iii) *Anomalous propagation (ANAPROP).* Under certain atmospheric conditions the radar beam may be refracted more than usual and may strike the ground, giving high return signals. These often occur over preferred areas. A method of detecting ANAPROP, relying on the difference in signal between those preferred areas and adjacent unaffected areas, is under development. For the time being, those areas subject to severe ANAPROP are being blanked out.

3.1.2 *Compositing of the hourly data.* The data from the individual sites are composited to form a data set of radar-derived totals for the region covered by all the radars. The boundaries between the coverage of each radar are chosen according to the radar sets that were operating during each hour. Fig. 1 shows the boundaries when all four radars are operating. At present all England and Wales is covered, except for parts of East Anglia and Kent. These areas should be covered by the forthcoming London radar.

The composite data are stored in the 'Hourly Radar Archive Dataset' in blocks corresponding to $100 \text{ km} \times 100 \text{ km}$ National Grid squares; each block contains values for four hundred $5 \text{ km} \times 5 \text{ km}$ squares. The data sets are constructed using a package of computer routines designed for direct-access storage and retrieval of meteorological data (Shearman 1980), which means that data from any area covered by radar may be retrieved quickly and output in map form.

3.2 *Production of daily rainfall totals*

Once the hourly radar archive has been constructed, the next step is to sum the hourly totals into rainfall-day totals (0900–0900 GMT) to correspond with the nominal time of reading the rain-gauges. The problem with the summation is that, with the present experimental radar network, few days have 24 hours of data from all four sites, but typically one or more sites will have a few missing hours. If these hours are wet a daily total cannot be calculated. However, if, using information from the existing data set of hourly rainfall from gauges which is held in the Hydrometeorological Branch, it is likely that these hours were dry, a daily total is computed (though it is flagged in the data set). The problem should become less severe as more radar sets are added to the network, giving a greater degree of redundancy. For example, the forthcoming London radar will allow for triple redundancy over most of England south of Nottingham. The radar-derived daily totals are stored in a direct-access archive, in a similar way to the hourly totals.

4. *Combination of radar and rain-gauge data*

4.1 *Method*

The radar rainfall observations are now ready to be combined with the gauge-derived observations in order to compute the most representative distribution of rainfall at the ground, within the region covered by the radars.

It is often observed that over extensive areas the radar consistently overestimates or underestimates surface rainfall; for instance at large ranges from a radar the beam can be above the bulk of the

precipitating cloud, so the radar registers a relatively small rainfall. The radar rainfalls need to be adjusted by a spatially varying calibration factor to bring them into agreement with the general level of rainfall as measured by gauges, while at the same time allowing them to contribute to the definition of the rainfall distribution between gauges.

The two kinds of observations for a specific day are combined in the following way:

(i) A calibration factor $c = g/r$ is computed for each $5 \text{ km} \times 5 \text{ km}$ square that contains at least one gauge, where r is the radar rainfall and g is the gauge-derived areal rainfall over the same square, computed using the methods of Shearman and Salter (1975).

(ii) Interpolation is carried out between these calibration factors to form a continuous calibration field, using a local fitting least-squares technique. The most reliable calibration factors are in the vicinity of gauges.

(iii) The calibration field and the radar rainfall field are multiplied together to form the combined radar and gauge-derived rainfall field, but only where the calibration factor is within reasonable limits. Naturally this method constrains the combined rainfalls to be weighted strongly towards the gauge-derived rainfalls in the neighbourhood of gauges.

(iv) Areas not covered by the calibrated radar data (owing, for instance, to occultation, permanent echo or ANAPROP) are filled with interpolated rain-gauge data in order to complete the combined rainfall field.

Further details are given by Nicholass *et al.* (1981).

4.2 Removal of bright band

The 'bright band' is a region of strong echo that is produced when the radar beam intersects the melting layer (Battan 1973) and is caused by the large reflectivity of wet snowflakes. The bright band appears on a map of radar-derived rainfall as an annulus located about the position of the radar: the lower the melting layer, the closer is the bright band to the radar position. The boundaries of the bright band are not sharp because of the depth of the melting layer and the vertical depth of the radar beam.

Calibration using data from gauges with a spacing smaller than the horizontal extent of the annulus can remove the undesirable effect of the bright band. With a sparser gauge network the bright band would have to be identified by other means and removed at least partially before combining the radar and gauge observations.

5. Examples of combining rainfall observations from radar and rain-gauges

5.1 Daily rainfall

To illustrate the combination of observations of daily rainfall by radar and gauges results are shown for two days, 11 October 1981 and 2 June 1982. The first day was one of fairly uniform rainfall while the rainfall on the second day was localized and heavier.

5.1.1 *Rainfall on 11 October 1981.* Fig. 2(a) shows the distribution of rainfall during the period 0900 GMT on 11 October to 0900 GMT on 12 October 1981, over North Wales and north-west England using observations from the full gauge network (mean gauge spacing about 6 km). Rainfall amounts were between 10 mm and 15 mm over the Pennines, the Snowdon area and Liverpool, between 5 mm and 10 mm over a large area to the west of the Pennines and over west Wales and between 0 mm and 5 mm over east Wales, the Midlands and south-east of Preston.

The radar-derived distribution, Fig. 2(b), shows clearly the tendency for radar to overestimate rainfall close to the radar over the Pennines and Liverpool, and to underestimate rainfall at large ranges, over the north Midlands and west Wales. The radar rainfall distribution nevertheless shows many of the

features of the detailed distribution given by the full gauge network. Fig. 2(b) also shows an area of occultation extending north-west from the radar at Hameldon Hill and areas of permanent echo.

The rainfall distribution as observed by a reduced gauge network consisting of one-tenth of the original number of gauges (mean spacing 19 km) is shown in Fig. 2(c). As would be expected in these widespread rainfall conditions the main features of the rainfall field are preserved but smoothed and some significant detail is lost. For instance, the curved elongated area of 10–15 mm rainfall over the Pennines reduces from three separated areas to one smaller area, the 0–5 mm rainfall area extending south-east from Blackpool degenerates into small isolated areas, an area of 10–15 mm rain between Liverpool and Manchester disappears altogether and the 0–5 mm rainfall area no longer extends to the coast of North Wales.

All these rainfall features are restored to a great extent by the addition of the radar data to these sparse gauge network observations (Fig. 2(d)). Even though the rainfall distribution in areas of occultation, permanent echo and rainfall less than 1 mm are derived from gauges only, the retrieval of detail of rain over and to the west of the Pennines is particularly encouraging. This example demonstrates both the purpose of calibration by gauges, to adjust the general level of the calibrated radar rainfalls to surface values, and the contribution of radar observations in inserting detail between gauge observations. These results suggest that in widespread daily rain the radar observations can compensate greatly for a loss of observations from a large proportion of the total number of rain-gauges. Obviously the contribution that radar data can make to observations from a full gauge network is less. (The combined rainfall distribution from radar and the full gauge network is not shown for this day as it is almost identical to that from the gauges above.)

5.1.2 Rainfall on 2 June 1982. Fig. 3(a) shows the distribution of rainfall for the period 0900 GMT on 2 June to 0900 GMT on 3 June 1982, over north-eastern England. The gauges indicated isolated areas of rain between 10 mm and 20 mm north-east of Hexham, near Newcastle, west of York and south of Leeds, and a larger area with a peak rainfall between 30 mm and 40 mm to the west of Darlington, all superimposed on an extensive area of rainfall of less than 10 mm.

The radar observations, Fig. 3(b), also registered those areas of rainfall but indicated larger extents and greater amounts, especially for the rain to the north-west of Hexham. Radar observations through the day showed that these localized heavy rainfalls occurred during the period 1600 to 2100 GMT on 2 June, moving northwards.

Fig. 3(c) shows the radar observations combined with the observations from the full gauge network, the positions of the gauges in the vicinity of the heavy rainfall also being shown. It is to be noted that the radar improves the detail and reveals the extended coverage of the heavier rainfall into areas which are lacking surface observations. Radar observations indicate that there are central areas of rainfall greater than 60 mm (peak value 61.8 mm) south-west of York and greater than 50 mm (peak value 56.6 mm) west of Darlington, larger than those observed by gauges alone, but also that gauges have been effective in reducing the large radar rainfalls observed near Hexham and Newcastle to more plausible values. All peak values occur within 10 km of adjacent calibrating gauges, so errors in the combined rainfalls caused by error in the interpolation of calibration factors are thought to be small.

This example demonstrates that radar can add information to observations from even the full daily gauge network in localized heavy rainfall conditions, in contrast with its performance in uniform rainfall. It is possible that some very localized rainfalls would not be observed at all with the one-tenth gauge network but could be detected by radar with its uniform 5 km (or 2 km) resolution.

5.2 Sub-daily rainfall

Short-period rainfalls are very important, for instance in the design of storm-water drainage systems which is determined by the frequency and coverage of high-intensity rainfall lasting for up to a few

hours. Storms responsible for such rainfall often have dimensions of only a few kilometres or tens of kilometres and could easily slip through the sparse network of recording gauges from which sub-daily rainfall is available. For instance, the detailed time-variation of the localized heavy rain on 2 June 1982 simply was not observed by the available recording gauges which are shown plotted in Fig. 3(a).

Hourly radar and gauge rainfalls cannot be effectively combined directly by the method described in Section 4.1 because of the large distances between the gauges leading to large errors in the calibration factors. Instead a procedure is used in which the daily rainfall in each $5 \text{ km} \times 5 \text{ km}$ square from the combined rainfall field (radar plus full-gauge network) is multiplied by the ratio of the radar-measured hourly and daily totals for the same square. This procedure ensures that the sum of the hourly totals over the day is equal to the daily total. Also the combined hourly field is not constrained to be in close agreement with the observations from nearby independent recording gauges.

An example of the use of this procedure to prepare maps of hourly rainfall from radar observations is given for an outbreak of heavy rain over southern England on 20 September 1980. Figs 4(a) to (d) are maps of the rainfall for each hour between 1800 and 2200 GMT on which the positions of short-period recording rain-gauges are also shown. The heavy rain began around Worthing between 1800 and 1900 GMT (Fig. 4(a)), extended north-westwards during the next 3 hours (Figs 4(b) to (d)) but a maximum in the isohyetal pattern persisted over Worthing throughout the 4-hour period. The wettest clock hour was between 2000 and 2100 GMT when more than 40 mm fell over a 50 km^2 area a few kilometres to the north-east of Worthing.

A recording rain-gauge was situated at Worthing very close to the area of interest. In Fig. 5 the hourly rain-gauge totals from this gauge are compared with those incorporating radar data in the $5 \text{ km} \times 5 \text{ km}$ square covering Worthing. Clearly, precise agreement would not be expected because the gauge measures point rainfall and radar measures areal rainfall. However, Fig. 5 shows that:

(a) the maximum values are recorded between 2000 and 2100 GMT by both methods and are similar in magnitude, and

(b) during the 4-hour period 1800–2200 GMT the totals are in good agreement; the gauge measured 68 mm while the other method gave 77 mm.

This measure of agreement shows that the radar-derived totals in Figs 4(a) to (d) are realistic and enables confidence to be placed in using the radar data for obtaining storm profiles over areas where the recording gauge network is very sparse. For those areas close to recording gauges a method is being devised for incorporating the recording gauge data into the final answer: the closer the area of interest to a gauge, the more influence the gauge reading will have.

Provided the information from the radar can be calibrated accurately, it can also be used to enhance existing knowledge of the characteristics of storms and to revise rainfall depth-area-frequency statistics for short durations. A discussion of how radar data have been used to determine the detailed characteristics of a storm over Manchester in 1981 and how the derived areal rainfall totals compare with advice given in the *Flood Studies Report* (NERC 1975) is given by Bader *et al.* (1983).

6. Operational use of radar and sparse gauge network observations

The foregoing examples show that radar data should be able to fulfil a useful role when supplementing gauge observations, particularly from sparse networks. One interesting operational application is in *The Meteorological Office Rainfall and Evaporation Calculation System MORECS* (Thompson *et al.* 1981) in which estimates of average evaporation and soil moisture in $40 \text{ km} \times 40 \text{ km}$ squares are made weekly and sent to a variety of subscribers for near-real-time use. In order to produce the estimates each week using the latest information, the weekly rainfall totals (comprised of seven daily totals added together) are needed promptly, and certainly before observers send in their data to the

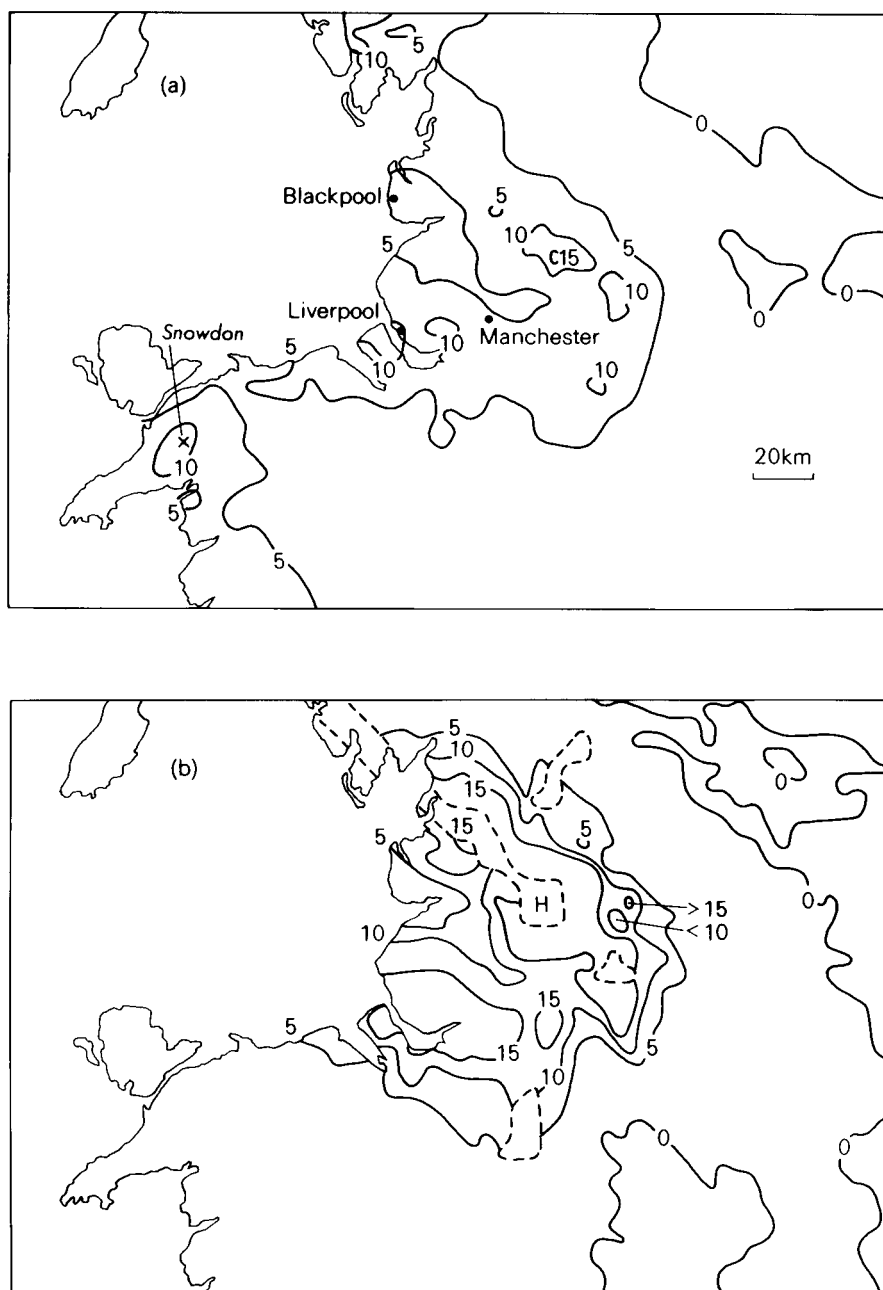
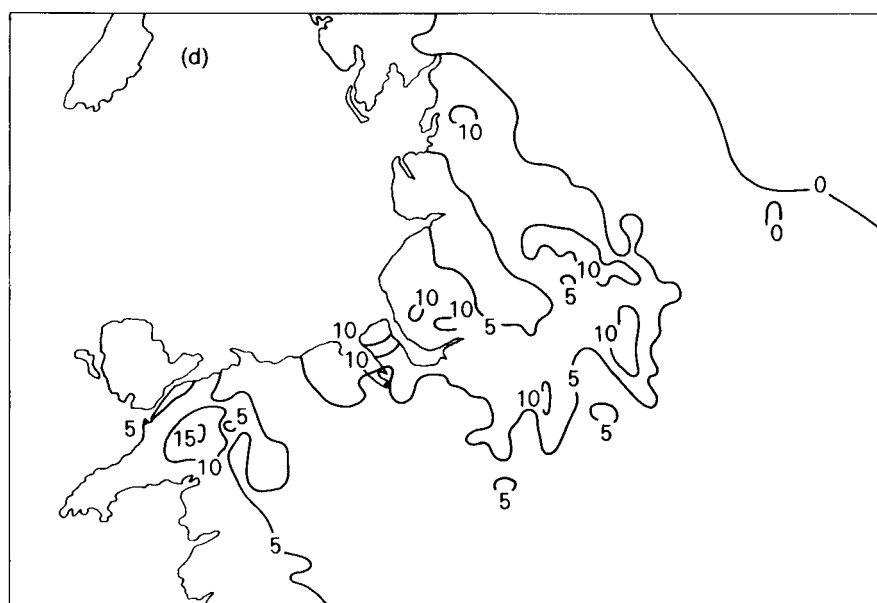


Figure 2. Rainfall distribution (mm) for the period 0900 GMT on 11 October to 0900 GMT on 12 October 1981 using (a) the full daily gauge network, (b) radar only (dashed lines denote regions subject to occultation or permanent echo, H denotes position of radar at Hameldon Hill), (c) one-tenth of the gauges of the permanent network, chosen randomly, and (d) the combination of (b) and (c). Isohyets are at 5 mm intervals.



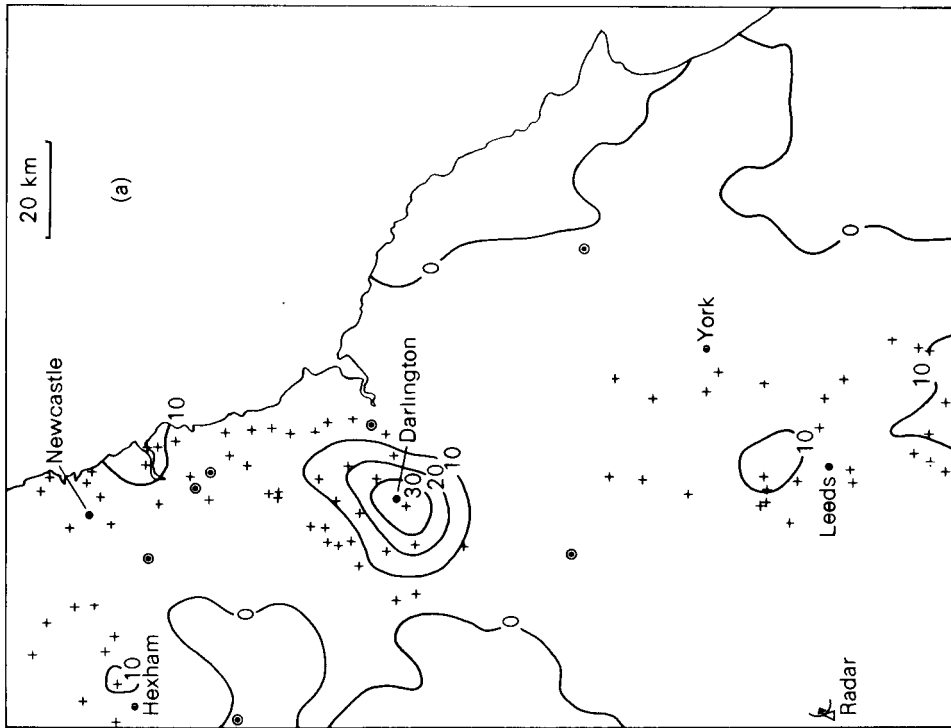
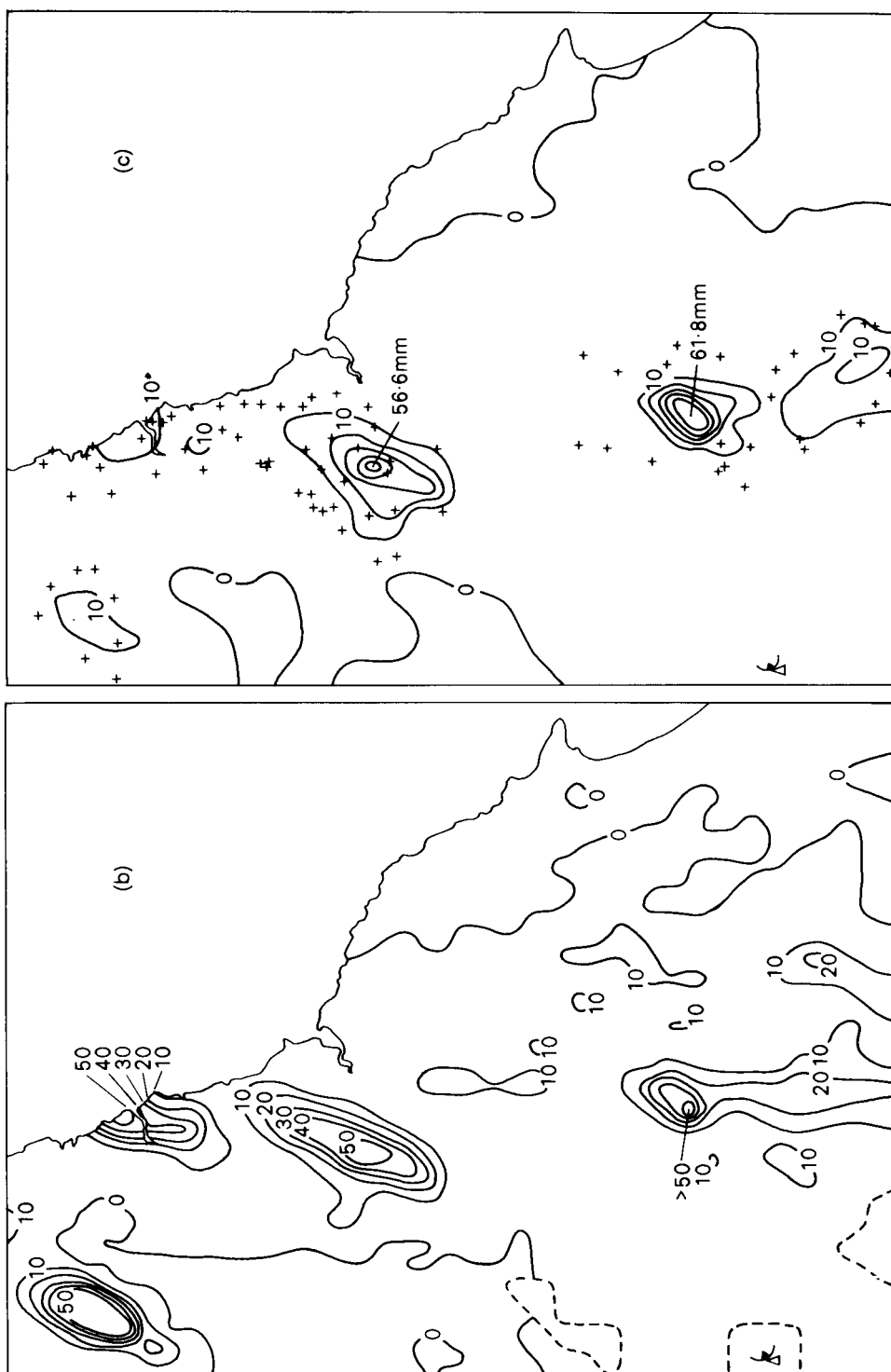


Figure 3. Rainfall distribution (mm) for the period 0900 GMT on 2 June to 0900 GMT on 3 June 1982 using (a) the full daily gauge network, (b) radar only, and (c) the combination of (a) and (b). The positions of daily gauges in the vicinity of the heavy rain are shown as crosses and the short-period rain recorders are shown as ringed dots. Isohyets are at 10 mm intervals.



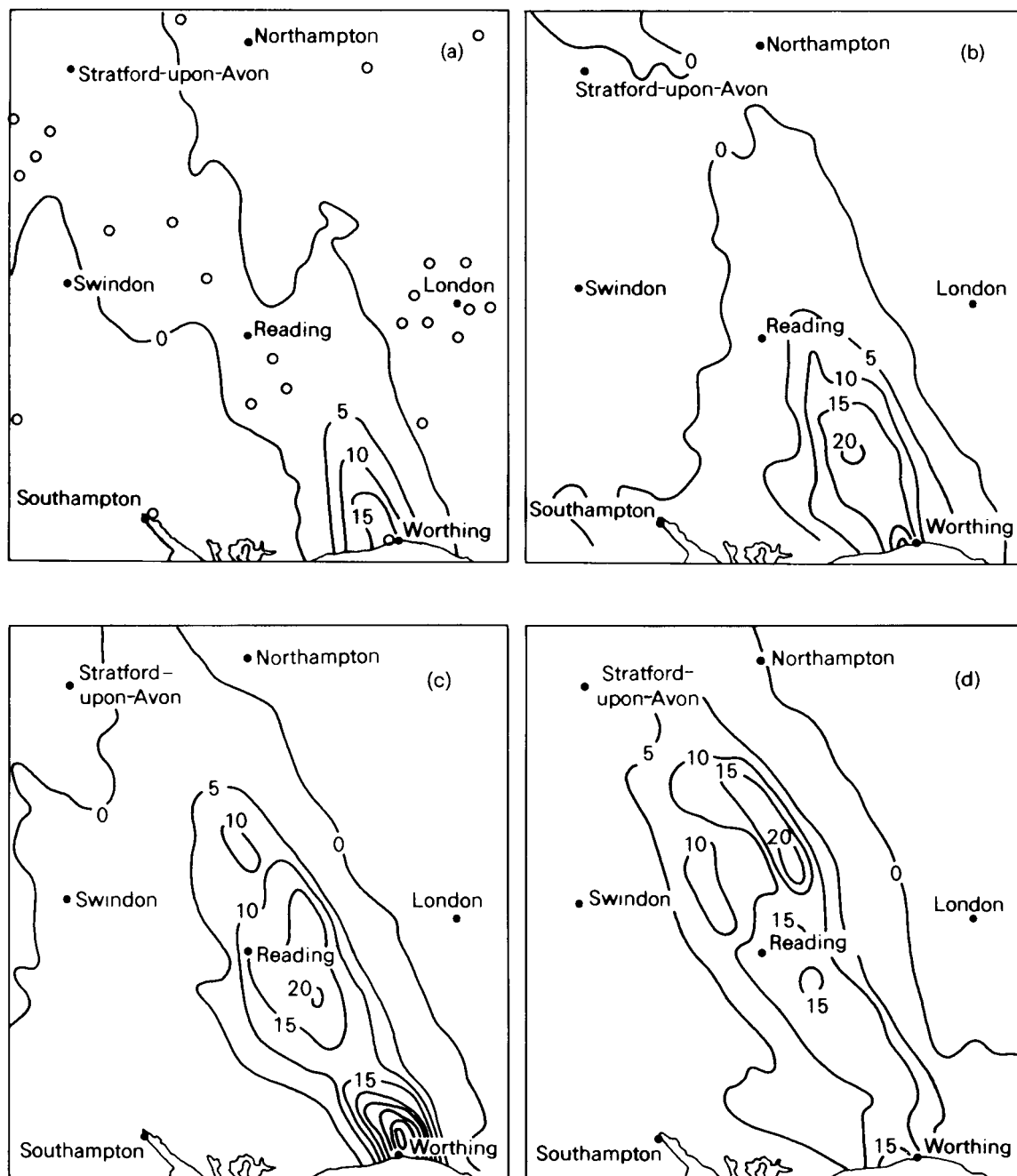


Figure 4. Rainfall distributions on 20 September 1980 for the periods (a) 1800–1900 GMT, (b) 1900–2000 GMT, (c) 2000–2100 GMT, and (d) 2100–2200 GMT. The positions of short-period rain recorders are shown by circles. Isohyets are at 5 mm intervals.

collecting centres. The only daily rain-gauge data available in near-real time are those from about 150 weather observing stations in the Meteorological Office's synoptic network (mean gauge spacing 40 km, but very irregularly distributed). The previous results (Section 5.1) indicate that in both uniform and localized heavy rainfall radar data could usefully supplement daily rainfalls from the sparse synoptic network to improve the MORECS rainfalls, aided by the capability of radar data to be processed automatically and transmitted rapidly. The same up-to-date daily rainfall information can be used for forecasting the risk of imminent crop and animal diseases and for the automatic dissemination of daily rainfall amounts on teletext systems (e.g. Prestel or CEEFAX). It should be emphasized, however, that the combination using such a sparse network of gauge data will have to incorporate a scheme to identify and correct for the bright band.

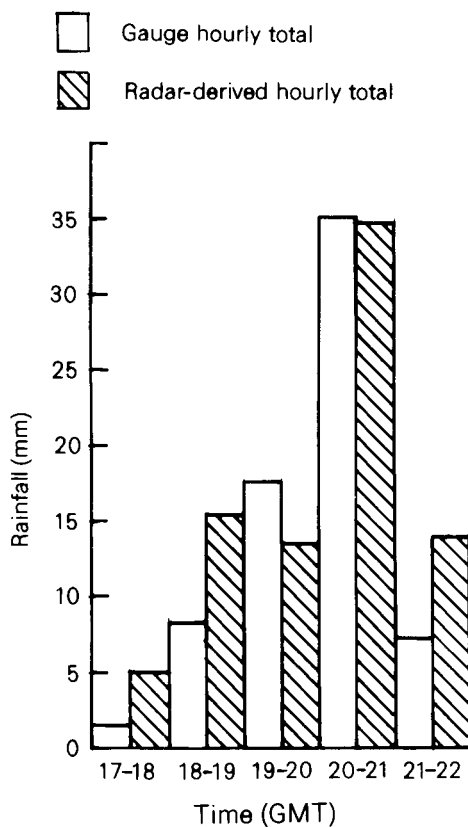


Figure 5. Comparison of hourly rainfall totals at Worthing on 20 September 1980, as measured by the recording rain-gauge and by radar.

7. Conclusion

Recent research and development work in the Hydrometeorological Branch of the Meteorological Office on supplementing rainfall data from rain-gauges by those from radar has been discussed. A description has been given of how the radar data are processed, archived and finally combined with the

gauge-derived data to form representative rainfall distributions on daily and sub-daily time scales over large areas of the United Kingdom.

Observations from rain-gauges provide accurate information on rainfall at a point but have limited representativeness for surrounding areas.

Furthermore, many of them are available well after an event, or from sparse networks, and require a large degree of manual processing. The incorporation of radar data will enable catchment areal rainfall totals and statistics to be determined directly, automatically (without the need for much manual processing) over large areas and on all time scales. It is expected that the addition of information from radar will enable the range of hydrometeorological services provided by the Meteorological Office to be enhanced.

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The estimation of point rainfall over the south-west peninsula by gauges and radar

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Summary

The capability of radar and gauges in determining hourly and daily rainfall at an ungauged point is investigated statistically using data from the Cornish peninsula in mainly frontal rain conditions. The analysis involves both the probability of inferring correctly the occurrence or non-occurrence of rain at the point in any hour or day and the accuracy of the estimate of amount.

Notation

g	gauge rainfall
g^*	estimated gauge rainfall
r	rainfall estimated from radar
R	root-mean-square value of $\lg(g^*/g)$
d	distance of separation
n	sample size
$se(R)$	estimated standard error of R
$P(S)_G$	probability that test and calibration gauges register the same (rain or no rain) for the same hour or day
$P(S)_U$	probability that co-located gauge and radar observations register the same
Subscripts for g :	
c	calibration value
t	test site value
Subscripts for R :	
G	gauge only
U	uncalibrated radar
C	calibrated radar

1. Introduction

For many years now rainfall has been measured by surface gauges. At present there are about 6500 gauges measuring daily totals and 200 gauges measuring hourly totals in the United Kingdom whose observations are incorporated in the National Rainfall Archive held by the Meteorological Office at Bracknell. These data are used for many diverse purposes, for instance, rainfall climate studies, horticultural applications, design studies for drainage systems, calculations of soil moisture deficits, forecasting research and resource planning.

More recently radar observations of rainfall have become available but these observations have different features from gauge data.

Gauges measure rainfall at a point on the ground and by avoiding overshelter by trees or buildings

(and their wake effects) and overexposure in windy sites reasonable standardization of measurements can be achieved. Standard daily gauges collect the rainwater which is measured manually each day but hourly gauges use the float and siphon or tipping-bucket principle combined with a recording device. Considerable organization and manual effort is required in collecting and processing gauge observations.

Measurement of rainfall by radar involves projecting a nearly horizontal beam of centimetre-wavelength radio waves which is scattered by raindrops. The strength of the returned radio waves depends upon the size of the raindrops but the signal is contaminated by noise due to random motions of the drops. To improve the signal-to-noise ratio the returned signals from volumes swept by the radar beam (usually standing on $5\text{ km} \times 5\text{ km}$ squares) are integrated so that the resulting rainfall rate estimate is for an area and not a point. In practice radar observations are subject to several errors. These are:

(i) Drop-size distribution errors. For simplicity a single conversion from returned signal strength to rainfall rate is used appropriate to the typical drop-size distribution for widespread frontal rain. For the smaller drops of drizzle or the large drops of convective rain the conversion is incorrect.

(ii) Obstruction of the radar beam by hills or buildings which obscure the region beyond and cause spurious bright reflections.

(iii) Enhanced reflections from wet ice particles if the beam intersects the melting layer.

(iv) Anomalous propagation from long distances in abnormal atmospheric conditions.

(v) Incomplete filling of the radar beam or square at the ground surface by rain.

(vi) The correspondence between co-located gauge and radar observations can be affected by rain observed by radar above the surface being swept away by wind and not reaching the gauge beneath, and by low-level growth or evaporation beneath the radar beam.

Thus there are many reasons why co-located gauge and radar observations of rainfall can differ. However, the advantages of radar observations, in that a single radar can observe rain over a circle of about 100 km radius every five minutes with the data being available centrally and promptly for automatic processing and dissemination, are a compelling reason for studying ways of combining gauge and radar observations to exploit their respective features. Browning (1978) and Collier (1980) give more complete descriptions of the characteristics and processing of radar rainfalls.

Since the radar observes areal rainfall it would be appropriate to make comparisons with areal rainfalls estimated from gauges as the agreement would be expected to be better. Gauges capable of measuring hourly rainfalls are usually separated by many kilometres which removes any possibility of estimating areal rainfalls over $5\text{ km} \times 5\text{ km}$ squares. The alternative adopted here is to assume that the radar observation is an estimate of the point rainfall at all points within the square. In slowly varying spatial variations of rainfall the areal rainfall would be a good approximation to a point close to the centre of the square but the displacement of a gauge from the centre adds a further contribution of error to the comparisons. For daily rainfalls many more gauges are available and it is feasible in many areas to estimate $5\text{ km} \times 5\text{ km}$ areal rainfalls for comparison with radar. Since one of the objects of this work is to compare, for both hourly and daily rainfalls, different methods of estimating rainfalls, point-gauge rainfalls are used throughout.

The work described here demonstrates, in terms of probability rather than pictorially, the accuracy with which point rainfall can be estimated. There are so few hourly gauges that hourly rainfall fields with a 5 km resolution corresponding to those depicted by radar observations cannot be drawn, so 'pictorial' comparisons cannot be made. Rainfalls at fixed points but random times are investigated instead to show how gauge and radar observations compare, for both hourly and daily rainfalls.

The practical problems of drawing maps of point rainfall from gauge or radar observations (or combinations of both) are not dealt with here.

This work was undertaken as the first step in a project to improve the information available to the Meteorological Office's customers concerning the occurrence and amount of rainfall at specified ungauged points. The aim is to give a probability of occurrence of rain, an estimate of the amount and a probability that the amount lies between specified limits, based on nearby gauge or radar observations.

2. Method of analysis

2.1 Estimation of rainfall amount

Consider an estimate of the hourly or daily gauge rainfall g^* at a point where the true (observed) rainfall is g . The relative error of the estimate represented by the ratio g^*/g is used here so that, if required, the ratios for different sizes of rainfalls can be combined sensibly. For any reasonable method of estimating g^* the mean value of a sample of g^*/g values would be expected to be close to 1.0 but with individual values in the range 0 to $\gg 1.0$ so that their distribution will be skew. To reduce the skewness $\lg(g^*/g)$ is used rather than g^*/g .

The average measure of a sample of $\lg(g^*/g)$ values is represented by their root-mean-square (rms), R . Table I gives the mean ratio g^*/g (or g/g^* , since $\lg(g/g^*) = -\lg(g^*/g)$) as a function of R .

Table I. Equivalence of R and g^*/g .

R	g^*/g (or g/g^*)
0.0	1.0
0.1	1.3
0.2	1.6
0.3	2.0
0.4	2.5
0.5	3.2
0.6	4.0
0.7	5.0
0.8	6.3
0.9	7.7
1.0	10.0

Estimated standard errors of R are given in brackets or as error bars in the figures and these have been calculated from the expression $se(R) = R \{ [1 - (\bar{x}/R)^4] / 2n \}^{1/2}$, where \bar{x} and n are the sample mean and size ($x = \lg(g^*/g)$). There is a 68% probability that the true value of R lies between $R \pm se(R)$, a 96% probability that it lies between $R \pm 2se(R)$ etc., with corresponding limits for g^*/g .

In this work estimates of point rainfall are made in three ways which can best be explained with reference to Fig. 1. Two gauges A and B within co-located radar rainfall squares are separated by a distance d km. One of the gauges is regarded as a source of calibration values or rainfall estimates (subscript c) and the other as the test site (subscript t) where comparisons are to be made. Denoting gauge rainfall by g and radar rainfall by r we can estimate g^* by:

- (i) using $g_t^* = g_c$ so that $\lg(g^*/g) = \lg(g_c/g_t)$ - Gauge only
- (ii) using $g_t^* = r_t$ so that $\lg(g^*/g) = \lg(r_t/g_t)$ - Uncalibrated radar
- (iii) using $g_t^* = r_t \cdot (g_c/r_c)$ so that $\lg(g^*/g) = \lg\{r_t/g_t \cdot (g_c/r_c)\}$ - Calibrated radar.

Values of g_t , g_c , r_t and r_c are for the same hour or day, i.e. the calibrations and comparisons are simultaneous. Values of r/g and g/r are often referred to as assessment and calibration factors respectively. By taking different pairs of sites the variation of R_G and R_C with d can be established and for a particular pair of sites, by interchanging them as calibration and test sites an indication can be obtained of the scatter of R_G and R_C for a particular distance of separation d .

R_G , R_U and R_C are measures of the accuracy of the three methods of estimating gauge rainfall and can be assumed to be appropriate to estimation at ungauged locations.

It is stressed that the method of simply transferring an observation from one place to another to simulate estimation at a distance would not be used in practice where more elaborate methods involving interpolation procedures would be appropriate. However, it does allow a simple comparison to be made of the relative performance of the three estimation methods.

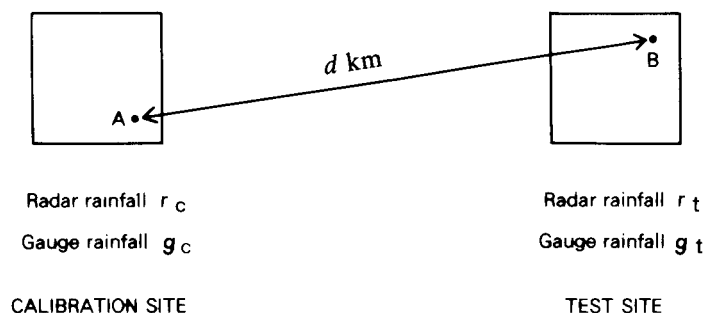


Figure 1. Calibration and test sites for estimating gauge rainfall from radar rainfall, showing calibration (A) and test (B) gauges with their associated 5 km \times 5 km radar rainfall squares.

2.2 Inference of occurrence of rain or no rain

Also in this paper are given some estimates of the success rate of inferring the occurrence or not of rain at the test site (on a yes/no basis) from observations of the occurrence of rain at the calibration gauge and from the co-located radar observation. Specifically $P(S)_G$ is the probability that the test and calibration gauges register the same (either rain or no rain) for the same hour or day and $P(S)_U$ is the probability that the co-located gauge and radar observation register the same.

3. The data

The data used in this investigation are hourly and daily (09 to 09 GMT) point rainfalls measured by gauges at five sites in the Cornish peninsula, Goonhilly, Cudrose, Drift, St Mawgan and the Scilly Isles, and simultaneous co-located radar rainfalls measured by the Camborne radar. The radar observations are of areally averaged rainfall within 5 km \times 5 km squares containing the gauges. Table II gives details of the sites and the intersite distances. Fig. 2 shows the location of the sites and the Camborne radar.

The rainfall observations cover the period 23 September 1979 to 19 March 1980 during which most of the rain was widespread and fairly uniform. For those parts of the analysis involving amounts of rain, only hours with $g_i \geq 2.0$ mm or days with $g_i \gg 4.0$ mm were used and these were distributed evenly throughout the period. For the analysis of probability of occurrence of rain, hourly rainfall observations for 1000 hours from 23 September to 4 November 1979 were used, but for daily rainfall data from the whole period of 179 days were used. The Scilly Isles gauge was not used in the hourly rainfall analysis.

Table II(a). Site details.

Site	Distance of gauge from centre of radar square (km)	Distance from Camborne radar (km)
Culdrose	0.8	15
Drift	1.8	22
Goonhilly	1.1	22
St Mawgan	1.7	34
Scilly Isles	1.2	77

Table II(b). Inter-site distances.

Sites	Distance between gauges (km)
Culdrose — Goonhilly	7
Culdrose — Drift	25
Goonhilly — Drift	30
Culdrose — St Mawgan	40
Goonhilly — St Mawgan	43
Drift — Scilly Isles	55
Drift — St Mawgan	57
Culdrose — Scilly Isles	77
Goonhilly — Scilly Isles	83
St Mawgan — Scilly Isles	110

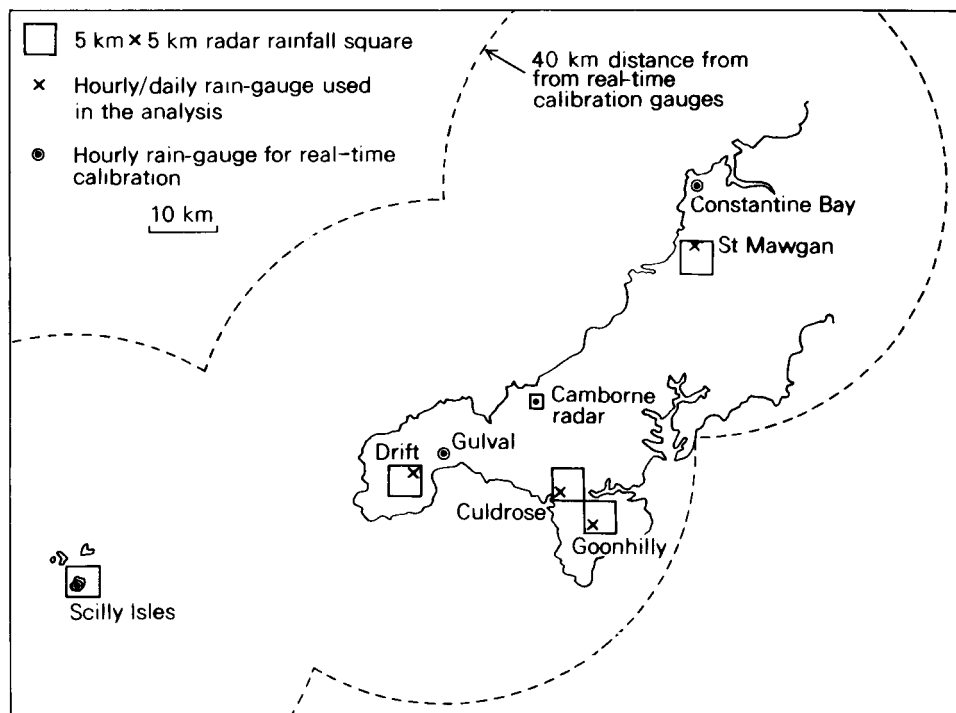


Figure 2. Location of rain-gauges and associated radar rainfall squares.

The gauge rainfalls were observed with tilting-siphon recorders with a resolution of 0.1 mm; the resolution of the radar observations is 0.031 mm. No quality control of the data was carried out apart from eliminating observations for some hours during which the gauges or radar were obviously malfunctioning. In the case of radar these appeared as identical rainfalls for all locations for several successive hours. About 100 hours spread over 7 days in 4300 hours of data were lost in this way. No attempt has been made to determine whether any of the propagation effects described in Section 1 were present — it was assumed that the radar observations were authentic and were of typical quality. They were supplied by the Meteorological Office Radar Research Laboratory, Malvern. The five locations used are the closest ones to Camborne from which hourly observations are available during the specified period.

4. Results and discussion

4.1 Probabilities of successfully inferring the occurrence or not of rainfall

Values of $P(S)_G$ for both hourly and daily rainfalls are plotted against d in Figs 3(a) and (b). Trend lines have been drawn and extended to an assumed value of near 1.0 at $d=0$ km. Values of $P(S)_U$ for each site are given in Table III.

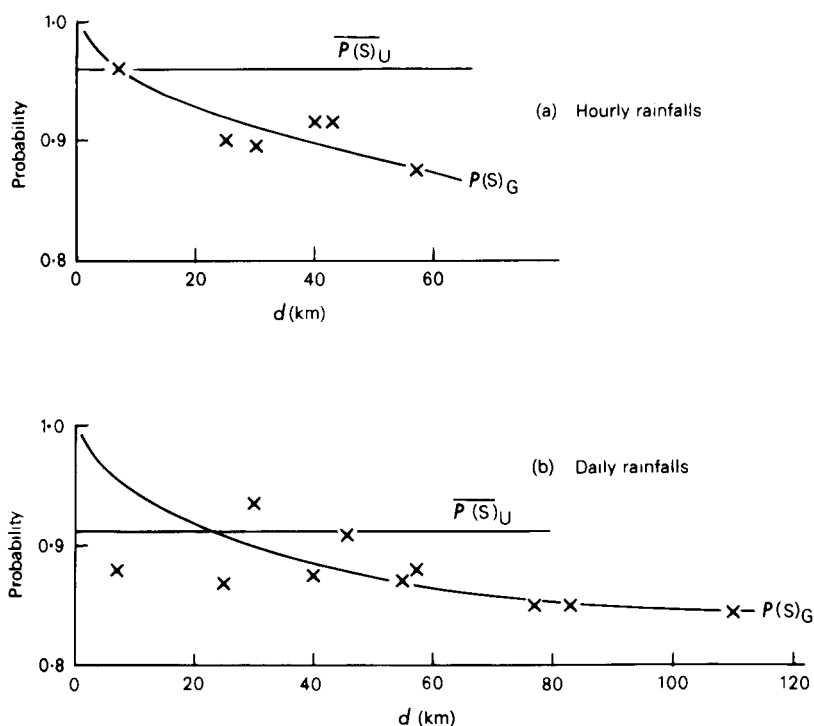


Figure 3. $P(S)_G$ as a function of distance d where $P(S)_G$ is the probability of correctly inferring rainfall occurrence at a point from observations at a nearby gauge. Also shown is the mean probability $\overline{P(S)}_U$ of co-located radar and gauge observations registering the same occurrence.

Table III. *Values of $P(S)_U$ for individual sites*

Site	Hourly rainfalls	Daily rainfalls
Culdrose	0.97	0.94
Goonhilly	0.96	0.93
Drift	0.94	0.92
St Mawgan	0.96	0.92
Scilly Isles	—	0.85
Mean	0.96	0.91

From Figs 3(a) and (b) it can be seen that the probability $P(S)_G$ of inferring correctly the occurrence or not of rainfall at a point from observations by a nearby gauge is generally high, ≥ 0.87 within a distance of 60 km for both hourly and daily rainfalls, and falls only slightly for daily rainfalls to 0.85 at 110 km. The probability $P(S)_U$ of co-located radar and gauge observations registering the same (from Table III) is also high for both hourly and daily values. The individual site values are in good agreement for hourly rainfalls. For daily rainfalls the probability decreases steadily with distance from the radar. In Figs 3(a) and (b) the mean values of $P(S)_U$ have been superimposed upon the trend lines of $P(S)_G$ with d . For hourly rainfalls the distance from the calibration site at which $\bar{P}(S)_U \approx P(S)_G = 0.96$ is well determined at 7 km; for daily rainfalls the distance is less well determined because of scatter but $P(S)_U \approx P(S)_G = 0.91$ at about 25 km. If greater probabilities of correct inference at ungauged points than these are required then they can only be obtained from nearby gauges at distances less than 7 km and 25 km for hourly and daily rainfalls, implying networks of gauges at regular spacings of about 10 (i.e. $\approx 7 \times \sqrt{2}$) and 35 km respectively. However, the improvement in probability to be obtained by using gauges over using radar is small even with these networks of gauges. The high values of $P(S)_U$ indicate that radar well defines areas of rain and no rain for both hourly and daily rainfalls.

It is stressed that these results are appropriate to widespread rain conditions. The small advantage of using closely spaced gauges will be further decreased in localized heavy rainfall situations where the continuous spatial coverage of radar becomes increasingly beneficial.

4.2 Errors of estimates of point rainfall

4.2.1 Variation of R_G , R_U and R_C with rainfall amount. A relative error in the estimate of a small rainfall is likely to be less important than the same error in a larger rainfall. For instance, an error of $R = 0.3$ (equivalent to a factor of 2.0 or 0.5 in g^*/g) in a rainfall of $g = 2 \text{ mm h}^{-1}$ would be less important than for $g = 20 \text{ mm h}^{-1}$ if that rainfall was being estimated in near real time as part of an operational flood control scheme. The general variation of R_G , R_U and R_C with g_i is therefore of interest. There are insufficient data for the variation of errors of R_G and R_C with g_i for a fixed d to be studied so that general mean errors only are given for distances up to 60 km from a calibration site for hourly rainfalls and up to 100 km for daily rainfalls. For R_U the values are means for all sites combined, i.e. for distances up to 80 km from the radar. The errors are calculated for bands of g_i values beginning at 2.0 to 2.9 mm for hourly rainfalls and beginning at 4.0 to 5.9 mm for daily rainfalls. R_G , R_C and R_U are plotted in Figs 4(a) and (b) as a function of g_i and the points are joined by lines as a visual aid.

Fig. 4(a) shows that for gauge-only estimates of hourly rainfalls R_G increases rapidly from near 0.50 for amounts close to 4.0 mm to 1.0 for amounts greater than or equal to 8.0 mm. For uncalibrated radar observations R_U is more uniform over this rainfall range, varying between 0.34 and 0.50; R_C , for calibrated radar observations, is also uniform, varying between 0.30 and 0.46. Generally then, radar observations estimate rainfall amounts at ungauged points with a greater uniformity of error (which is

also smaller) than gauge estimates which have large errors, particularly for heavy rainfalls. It is to be expected, therefore, that peaks in the spatial distribution of hourly rainfall are liable to be more flattened when estimated by nearby gauges than when observed by radar.

Fig. 4(b) shows that for daily rainfalls the errors of all three estimation methods tend to decrease slowly with increasing rainfall amount at least up to 30 mm, and that for rainfalls greater than this amount calibrated radar observations are the most accurate.

Generally the R values for daily rainfalls are relatively smaller than for hourly rainfalls. It is suggested that this result is consistent with daily rainfall having a smoother spatial distribution than hourly rainfall, at least when the rainfall is widespread.

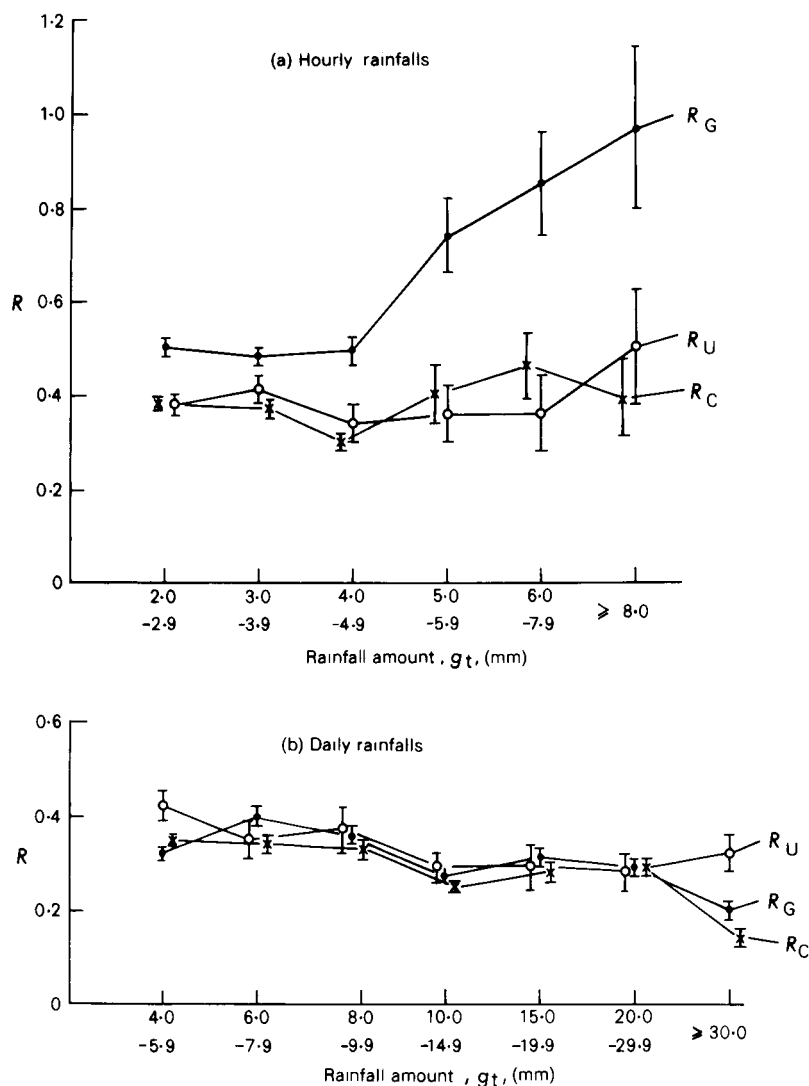


Figure 4. Variation of rms values R_G , R_U and R_C with rainfall amount; standard errors are shown.

4.2.2 *Errors of uncalibrated radar observations.* Values of R_U together with their standard errors are given in Table IV for the individual sites in order of distance from Camborne along with the overall mean values for all sites combined.

Ideally it is desirable that uncalibrated radar observations should be of uniform accuracy over the area of radar coverage. The values of R_U in Table IV show that in practice they vary from site to site. The variations do not appear to be related simply to the distance of the site from the Camborne radar or to distance from the gauge to the centre of the radar square (as given in Table II), so these values are assumed to be generally representative of the spatial variability of errors of uncalibrated radar observations. The general mean R_U for daily and hourly rainfalls are almost equal.

Table IV. Values of R_U with their standard errors for individual sites.

Site	Hourly rainfalls (for all $g_t \geq 3.0$ mm)		Daily rainfalls (for all $g_t \geq 4.0$ mm)	
	n	R_U	n	R_U
Culdrose	32	0.40 (0.04)	43	0.34 (0.04)
Goonhilly	33	0.36 (0.04)	56	0.40 (0.04)
Drift	50	0.46 (0.04)	55	0.40 (0.04)
St Mawgan	26	0.30 (0.04)	45	0.30 (0.03)
Scilly Isles	—	—	43	0.31 (0.03)
Mean	141	0.38 (0.02)	242	0.36 (0.02)

4.2.3 *Variation of R_C and R_G with distance d .* Because of the spatial variability of hourly or daily rainfall amount and type it is to be expected that R_C and R_G vary with d . Fig. 5 shows the values of R_C and R_G plotted as a function of d for hourly rainfalls; Fig. 6 shows the same for daily rainfalls. There are two values for each d because for a pair of sites each site can act as either the calibration or the test site and the difference between the values gives an indication of the uncertainty in the trend lines. These lines have been extended back to near-zero values for $d = 0$ km on the assumption that the ratio g_c/g_t for two gauges tends to unity as d tends to zero and generally in this case the gauges will be within the same radar square so that $r_t = r_c$ and hence $(r_t/g_t).(g_c/r_c)$ also tends to unity in the same way.

From Figs 5 and 6 we see that R_C and R_G increase with d in a systematic fashion from near zero to values which exceed the mean values of R_U from Table IV. From these results the following conclusions can be made.

To achieve a modest accuracy in estimated hourly or daily rainfalls at an ungauged point of $R = 0.40$ ($\triangle g^*/g = 2.5$) uncalibrated radar rainfalls can be used directly. A greater accuracy of $R = 0.30$ ($\triangle g^*/g = 2.0$) requires the use of calibration gauges at a distance of less than 12 km for hourly rainfalls (50 km for daily rainfalls) irrespective of whether the estimate is made with or without the use of radar observations. For an even greater accuracy of $R = 0.20$ ($\triangle g^*/g = 1.6$) these distances decrease rapidly to 4 km and 7 km for hourly and daily rainfalls respectively. It appears therefore that the use of dense networks of gauges is inevitable if rainfall estimates of high accuracy are required.

It is of interest to determine approximately the distances from a calibration gauge within which

- the errors of gauge-only estimates are less than those of uncalibrated radar observations (i.e. $R_G < R_U$) which can reveal the spatial equivalence of gauge and radar observations,

- the errors of calibrated radar observations are less than those of uncalibrated radar observations ($R_C < R_U$) which define an area of benefit of calibration, and

- the errors of calibrated radar observations are less than for gauge-only estimates ($R_C < R_G$) which indicates the capability of calibrated radar observations to improve on gauge-only estimates.

The results are shown most clearly by plotting the ratio of the corresponding individual values of R_G , R_C and R_U against d ; in the case of (a) and (b) above we are effectively comparing the error at each site resulting from the use of calibrated radar or gauge-only estimates with the error which would be observed from using uncalibrated radar estimates. The variations of R_G/R_U , R_C/R_U and R_G/R_C with d for hourly rainfalls are shown in Fig. 7; corresponding results for daily rainfalls are shown in Fig. 8.

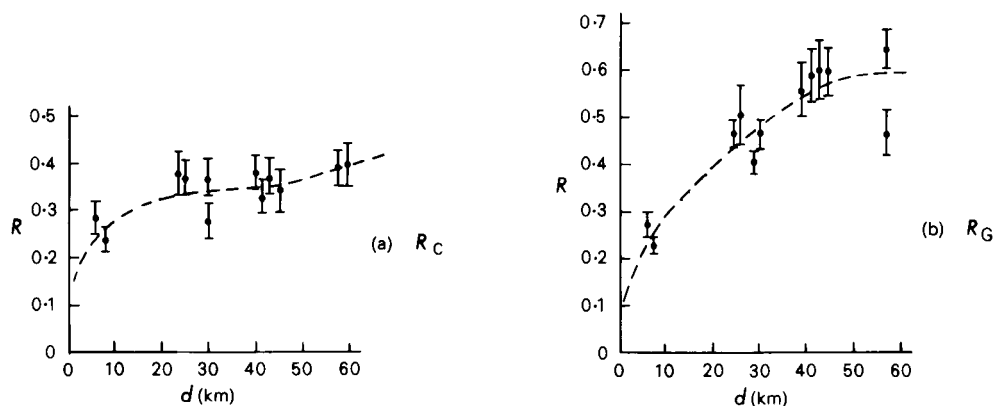


Figure 5. Variation of R_C and R_G with d for hourly rainfalls.

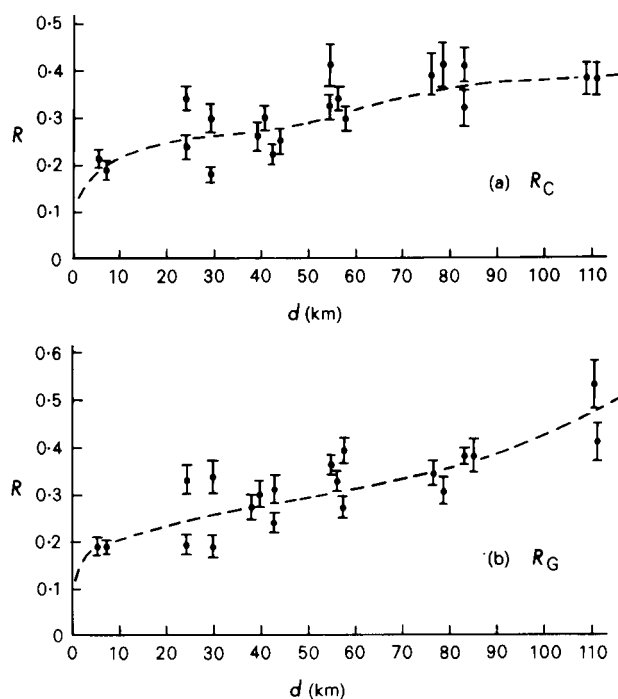


Figure 6. Variation of R_C and R_G with d for daily rainfalls.

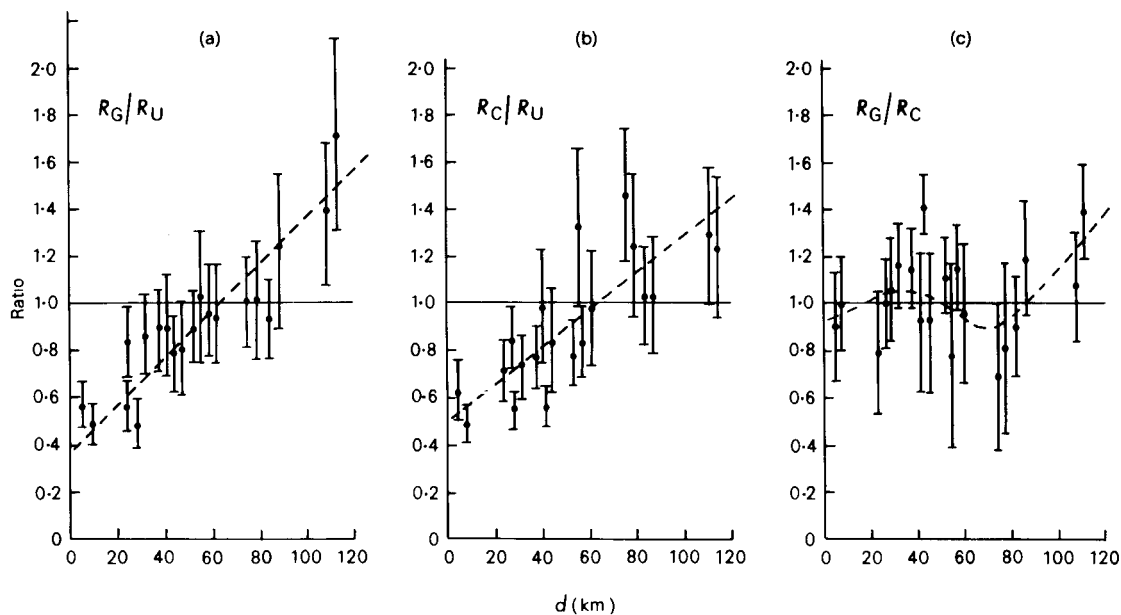


Figure 7. Variation of ratios of R_G , R_U and R_C with d for hourly rainfalls.

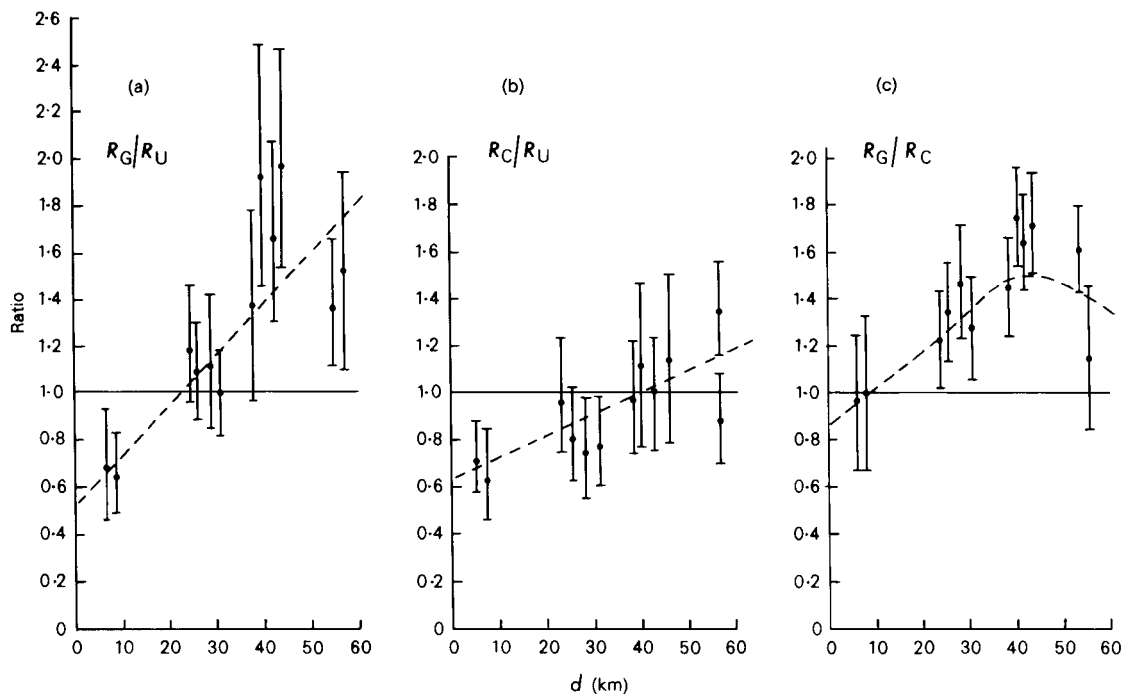


Figure 8. Variation of ratios of R_G , R_U and R_C with d for daily rainfalls.

For both hourly and daily rainfalls, in spite of the large standard errors, there are clear trends for R_G/R_U and R_C/R_U to increase with distance d , from values of about 0.5 to 0.7 for $d=7$ km to over 1.0. Trend lines, fitted by eye, give the distances within which R_G/R_U and $R_C/R_U < 1.0$ in Table V.

For hourly rainfalls R_G/R_C appears to be slightly less than 1.0 for $d < 7$ km but at greater distances is clearly greater than 1.0. In comparison, for daily rainfalls there is no obvious trend of variation of R_G/R_C with d , certainly for $d < 100$ km. The distances at which $R_G/R_C = 1.0$ are also given in Table V.

Table V. Critical distances for R_G , R_C and R_U .

	Approximate distances (km) from a calibration site within which		
	$R_G < R_U$	$R_C < R_U$	$R_G < R_C$
Hourly rainfalls	25	40	7
Daily rainfalls	60	65	>100?

For hourly rainfalls, calibrated radar observations are more accurate than uncalibrated ones within 40 km from a calibration site, so that for all locations to benefit from the calibration of radar observations regularly spaced calibration sites should be no more than $55 (\approx 40 \times \sqrt{2})$ km apart. The corresponding gauge spacing for daily rainfalls is 90 km. Gauge-only estimates are more accurate than uncalibrated ones within 25 km and 60 km from a calibration site, which indicates that for estimates of rainfall at all locations from gauges only to be at least as accurate as those from uncalibrated radar, the spacing of gauges should be no more than 35 km and 85 km for hourly and daily rainfalls respectively. Similarly reasoning for hourly rainfalls indicates that if gauges are more than about 10 km apart then at all locations calibrated radar observations are more accurate than gauge-only estimates; alternatively, for gauge spacings of less than 10 km the addition of radar observations does not improve the accuracy of estimates obtainable from gauges only but for spacings greater than 10 km it does. For daily rainfalls the corresponding spacing is uncertain but could be as large as 140 km.

The Camborne radar rainfall observations are reputed to be less accurate than those from other modern radars such as the radar installed at Hameldon Hill in the Pennines. More accurate radar observations would presumably result in a decrease in the distance at which $R_C = R_G$. Lee (private communication) has demonstrated that for Hameldon Hill radar observations of daily rainfall totals in widespread uniform rain the gauge spacing for $R_C = R_G$ is closer to 15 km compared with the approximate (and uncertain) spacing of 140 km for Camborne observations. It is not suggested that all this large reduction in gauge spacing is attributable to the superiority of Hameldon Hill radar data: part of the reduction is believed to be caused by the greater complexity of Pennine topography, and hence rainfall distributions, making it easier for the addition of radar observations to improve on rainfall estimates from gauges alone. More accurate radar observations would also result in a decrease in the distance at which $R_G = R_U$ by an uncertain amount but the effect on the distance at which $R_C = R_U$ is likely to be small because both R_C and R_U would be reduced.

It must be stressed that the analysis here is simplified in the interests of clarity. Normally a gauge-only estimate of rainfall at an ungauged site would not be made from a single distant gauge but from a surrounding group of gauges. The same principle applies to calibrated radar estimates – the calibration factor g/r would be estimated from several surrounding gauges not simply one gauge – so it is argued that the essential feature of Figs 7(c) and 8(c) would not be materially changed by a more sophisticated analysis

An alternative method of combining gauge and radar observations involving the analysis of the time variation of 15-minute calibration factors from a few widely spaced gauges to identify types of rain and their areas of applicability has been investigated using Hameldon Hill radar observations (Collier *et al.* 1983). It appears to be able to reduce R to about 0.23 over large areas in both frontal and convective rain.

5. Real-time calibration of radar rainfalls

It has been proposed to use three interrogable gauges at Constantine Bay, Gulval and Scilly Isles (see Fig. 2) for operational use in near-real-time calibration of hourly rainfalls by the Camborne radar. The benefit of these calibration stations in increasing the accuracy of rainfalls observed by radar extends to about 40 km from each site so that together they influence most of the area of the Cornish peninsula. The use of these gauges also increases the probability that at least one of them can provide a calibration factor.

6. Conclusions

From the results described, the following conclusions can be made for hourly and daily rainfalls in mainly widespread rainfall conditions and within a distance of about 80 km from the Camborne radar. They are based on a probability analysis rather than pictorial analysis of radar and ground-gauge observations using the simplest method of estimating rainfalls and calibration factors at a distance. The conclusions would not necessarily be the same if interpolation methods for estimating rainfalls and calibration factors were to be used, as they would be in practice.

(a) Radar observations can define areas of rain with considerable certainty. Comparable success of inferring rain from gauges only would require gauges spaced less than 10 km apart.

(b) Gauge estimates of hourly rainfall at nearby ungauged points have errors which increase rapidly with rainfall amounts greater than 4 mm; for daily rainfall the errors decrease with amounts up to 30 mm. In contrast, hourly and daily rainfall amounts are observed by radar (uncalibrated or calibrated by gauges) with an error which is less dependent on rainfall amount.

(c) For high-accuracy estimates of rainfall at ungauged points, dense networks of gauges are needed irrespective of whether radar observations are used or not.

(d) For hourly rainfalls observed by radar, calibration is effective up to a distance of 40 km (65 km for daily rainfalls) from the calibrating gauge.

(e) Camborne radar observations can add useful information to gauge-only estimates of hourly rainfalls at ungauged points for gauge spacings of greater than 10 km. For daily rainfalls the corresponding gauge spacing is uncertain but appears to be about 140 km.

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| Collier, C. G. | 1980 | Data processing in the Meteorological Office Short-period Weather Forecasting Pilot Project. <i>Meteorol Mag</i> , 109 , 161–177. |
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Notes and news

Papers requested for AAAS meeting

The 65th Annual Meeting of the American Association for the Advancement of Science (Pacific Division) will be held from 10 to 15 June 1984 at San Francisco State University, San Francisco.

The American Meteorological Society and Section W (Atmospheric and Hydrospheric Sciences) of the Pacific Division of the AAAS will, for the seventh year in sequence, co-sponsor paper sessions and other programs. It is expected that the following will be among the topics to be investigated: air-ocean interaction (including El Niño); coastal meteorology, climatology and oceanography; energy; environmental pollution; and urban climatology and meteorology.

Abstracts of papers should be typed on $8\frac{1}{2} \times 11$ inch white bond paper. Title and text of abstract should be camera ready without paragraphs and should fit inside a 5-inch square box, with a 1-inch margin to the left of the box. Special symbols and signs that must be hand lettered should be rendered in reproducible black ink. Author's name, affiliation and address should appear at the bottom of the page. Abstracts will be published in a booklet for distribution to registrants. Each presentation will be allotted 20 minutes, including discussion.

Abstracts should be sent by 31 March 1984 to the Program Chairman: Dr John Lier, Department of Geography, California State University, Hayward, CA 94542 (telephone: 415-881-3193). The Program Chairman should be informed by the abstract deadline of any need for 35 mm, lantern slide, opaque, or overhead projectors, or for special equipment.

Further details will appear in a later issue of the *Meteorological Magazine* and can also be obtained from Dr Alan E. Leviton, Executive Director, AAAS (Pacific Division), California Academy of Sciences, Golden Gate Park, San Francisco, CA 94118 (telephone: 415-752-1554). Non-members of the AAAS are encouraged to attend.

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NOTICES

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Predictability in science and society

By Sir John Mason, CB, FRS

(Formerly Director-General, Meteorological Office)

(The Presidential Address to the British Association for the Advancement of Science, Brighton 1983)

The theme of this address is based on the premise that the validity and power of any theory, scientific, economic or social, rests on its ability to make predictions that can be tested by observation or experiment. Such is the power and success of scientific prediction that scientists are almost bound to experience frustration and disappointment when they turn their attention to social and economic problems. The predictability of any system depends largely on its stability and its susceptibility to random disturbances (noise) and on the strength of the underlying theory. In classical astronomy the system is very stable, the noise level is low and the theory is well established, so the predictions are very accurate. In meteorology the atmosphere is inherently unstable to small disturbances, the noise level is higher, and the theory, though firmly based in physics and dynamics, is less complete, so the predictions are less accurate. In economic and social systems the noise level is higher still and there is no adequate underlying theory, so the predictions are very uncertain; moreover man himself is an integral part of these systems and is often a destabilizing influence. This being the case, one may ask whether human judgements are being helped or are in danger of being overwhelmed by modern techniques of data storage, retrieval and processing on ever more powerful and sophisticated computers. The technology advances relentlessly but does it lead to better decisions?

The future of the world, nations and individuals, is being determined to an increasing extent by the predictions or forecasts of enormously complex mathematical models run on giant computers. As scientists we would probably agree that major policy decisions should be based as far as possible on rational analyses of the facts and objective predictions rather than on intuitive and subjective judgements. However, there is a danger that the sheer size and complexity of the numerical models now employed in such diverse fields as war-gaming and the arms race, weather forecasting and economics, with their hundreds of equations and backed by millions of calculations per second, may come to dominate the judgements of governments and corporations without sufficient understanding of the structure, behaviour and limitations of the models and of the degree of uncertainty attached to their predictions.

The nature of prediction

In exploring the nature of the prediction process, we may recall that man has an innate requirement to predict the future course of events, including the consequences of his own actions, as part of his survival mechanism. In performing ordinary tasks, like riding a bicycle or driving a car, he makes a rapid sequence of observations, predictions and reactions, his sensors, brain, nerves and muscles forming the components of an automatic predictor-and-control system which can, however, be overruled by conscious decisions through the exercise of free will. Of course these capabilities are limited by the range of the human sensors and by the capacity and speed of the human computer. Outside this innate, unconscious experience, one has to rely on the recall and extrapolation of past experience or construct for oneself predictive models which may range from purely mental concepts to complex mathematical models programmed for a computer.

The more complex the situation the less likely are past experience and intuition to lead to useful long-term predictions. Whilst an amateur observer may successfully forecast the weather over the next few hours by watching the sky and calling on his past experience, he will be quite unable to predict what will happen a few days ahead. This will be determined by developments far beyond the range of his senses that are not amenable to simple extrapolation and involve data processing and calculation far beyond human powers.

In economics, too, prediction by simple extrapolation of past experience — the technique of the chartists — is an unreliable, ill-founded procedure because the past record almost never contains regular cycles or fluctuations of repeated amplitude and frequency. Of course if it did, and the causes were understood, forecasting would be simple — like forecasting sunset and sunrise. In fact historical records, both of the weather and the economy, are so irregular with so much random variation (noise) that they have little predictive power. No extrapolation of past trends, nor any theory or model based on past experience, could have given warning of the dramatic rise in oil prices in 1973 or, for that matter, of the hot summer of 1976 — the hottest in 250 years.

Weather forecasting

In weather forecasting it had already become apparent, twenty years ago, that the time-honoured empirical methods, based largely on extrapolation of very recent developments and the experience of individual human forecasters, were unlikely to improve significantly or produce reliable forecasts for more than about 24 hours ahead. Fortunately, with the arrival of powerful digital computers, it became possible to replace these highly subjective, empirical methods by objective techniques that treat weather forecasting as a problem in mathematical physics.

This involves the building of very large and complex mathematical models of the atmosphere based on the physical and dynamical laws that govern the birth, growth, decay and movement of the main weather systems. They incorporate the principles of conservation of momentum, mass, energy and water in all its phases, the Newtonian equations of motion applied to an air mass, the laws of thermodynamics and radiation, and the equation of state of a gas. Parameters which are specified in advance include the size, rotation, geography and topography of the Earth, the incoming solar radiation and its diurnal and seasonal variations, the radiative and heat conductive properties of the land surface according to the nature of the soil, vegetation and snow or ice cover, and also the surface temperature of the oceans.

The physical state of the atmosphere itself is updated every 12 hours from observations made simultaneously over the whole globe both at the surface from land stations, ships and buoys and in the upper air from satellites, balloons and aircraft. The model atmosphere is divided into 15 layers between the ground and 25 km (about 80 000 ft) and each level is divided into a network of points about 150 km apart — one-third of a million points in all. Each of these points is assigned new values of temperature,

pressure, wind and humidity every 12 hours and the governing differential equations are integrated in 12-minute time steps at each point to provide forecast values for up to six days ahead twice daily. A forecast for 24 hours ahead involves about one hundred thousand million (10^{11}) calculations but with a computer making 400 million calculations per second, these are performed in less than four minutes. The whole operation results in the automatic production of hundreds of different forecast charts of pressure, temperature, wind, humidity, vertical motion and rainfall that form the basis of the weather forecasts issued to the general public and to almost every weather-sensitive industry.

In particular the Meteorological Office provides more than two million forecasts a year for civil and military aviation and will soon provide flight-planning forecasts for all the world's airlines covering the whole of the globe.

This new approach to weather forecasting has extended the range of reliable deterministic forecasts from only one day to 4–5 days ahead and significantly increased their accuracy and detail, the new Meteorological Office model now producing 3-day forecasts that are as accurate as 2-day forecasts were five years ago and 2-day forecasts as accurate as 24-hour forecasts were then. Although the model remains stable for much longer periods the detailed predictions tend to deteriorate rather sharply beyond the fourth or fifth day. Reliable forecasts for a week or more ahead, which would be of great economic value, will require improved models with better representation of the physical processes, improved computational methods and even more powerful computers but, above all, a much better supply of global observations. There are, however, *inherent* limitations to the predictability of atmospheric behaviour which we shall now discuss.

Atmospheric predictability

We now raise the crucial question of whether there is for each scale of motion a time limit beyond which it is not possible to make a deterministic forecast. This question is of great importance for practical weather forecasting because the answer may set ultimate limits to what is achievable and to what is worth aiming at. If we had a physically faithful model of the real atmosphere, were able to specify exactly the initial conditions for all scales of motion, and made no computational errors in integrating the non-linear differential equations, could we expect to predict the atmospheric evolution from an initial state with infinite precision infinitely far ahead? Or, would small random perturbations (noise) develop in the real atmosphere and amplify to a point at which the numerical simulation and the real atmosphere would progressively diverge and ultimately become uncorrelated?

There is evidence that the atmosphere is inherently unstable to small perturbations so that two states, with only slight differences initially, and each evolving according to the same physical laws, may progressively diverge and eventually develop into quite different states. Experiments with complex global weather models indicate that the root-mean-square differences between two initially very similar fields of pressure, temperature or wind double about every 3–5 days so that weather systems on the scale of large depressions, which are well represented in such models, may be predictable up to 2–3 weeks ahead. Beyond this, it is doubtful whether further improvements in the models, the initial conditions (observations), or in computing power would increase predictability for these scales. This is so because even if the larger-scale systems were observed perfectly and represented perfectly in the models their behaviour would eventually be affected by the action of much smaller disturbances such as thunderstorms and tornadoes which cannot be adequately observed or represented and yet may double in amplitude within a few minutes. These may, within a day or two, induce uncertainties in the larger scales comparable to the initial errors resulting from inadequate observations.

This does not mean that models are necessarily incapable of making any useful predictions beyond 2–3 weeks. Although deterministic forecasts of individual mobile weather systems may not be generally

feasible beyond this time range, we sometimes observe relatively stable systems embedded in the general turbulent flow which retain their character and predictability for considerably longer periods, an example being the blocking anticyclone that produced the prolonged hot summer in western Europe in 1976. A supreme example is the Great Red Spot on Jupiter, an enormous anticyclonic vortex, larger than the Earth, which has retained its essential character for more than 300 years!

And, even if models cannot predict the evolution of individual depressions several weeks in advance, they may be able to predict the general tracks of such depressions and thereby the general character of the weather over the next month or two even if they fail to capture the day-by-day variations.

Numerical modelling of the economy

From our experience of the behaviour and predictability of complex, non-linear physical systems like the atmosphere, can we infer anything of value about even more complex and variable economic and social systems? To what extent can we apply the techniques of mathematical modelling on powerful computers to simulate, understand, predict and control such systems?

The boldest steps in this direction have been taken by economists, sometimes working with scientists, mathematicians or control engineers, who have built large, complex models in which the working of the economy is described by a system of hundreds of equations in the case of the Treasury and London Business School versions. But apart from their size and complexity, these economic models have little in common with weather forecasting models. They both deal with highly complex, interactive, non-linear and strongly constrained systems but the differences are both fundamental and instructive.

Whereas weather and climate models are firmly based on the fundamental laws of physics such as Newton's Laws of Motion and the laws of thermodynamics, there are no such fundamental laws in economics but only empirical relationships which may hold for quite long periods in a particular economy but are not sufficiently stable or universal to qualify as laws.

These empirical economic relationships are established by fitting equations to past data, usually from inadequate records going back less than 25 years. It is salutary to recall that this method of using past statistical data to predict future developments has proved unsuccessful in producing reliable weather forecasts for even a few days ahead. Weather forecasting is now treated as an initial value problem using entirely new data every 12 hours.

Since there are no universally accepted economic laws the models are very much creatures of their builders who may introduce relationships that express personal or political judgements. This is one reason why different economic models often give quite different predictions. If they are to be acceptable and not just ignored by the policy-maker, they must be tuned to some extent to his requirements and are not therefore objective in the same sense as the weather forecast.

The weather forecast has no effect on the weather but the economic forecast may well affect the economy!

All forecasts, if they are to be credible, must be capable of verification. Weather forecasts are checked every day against the actual weather so mistakes are quickly recognized and experience and understanding can be built up much more rapidly than in economics where it may take many months to verify a prediction.

Economic prediction is more difficult than weather forecasting for the following reasons:

It is often required to predict the residuals between two large quantities, each of which may be subject to considerable errors: e.g. the balance of payments is the difference between imports and exports and may amount to less than 1% of the gross national product.

The media and markets tend to exaggerate the importance of small movements in the economic indicators and this has a destabilizing effect. Economic calculations and forecasts are made in terms of

monetary units which do not have a fixed value. Dealing with currency fluctuations has been likened to running the electricity supply industry with a variable electronic charge!

The economy, unlike the weather, is subject to the quirks of human behaviour. These unquantifiable and unforeseeable disturbances, amplified by speculation, loss of confidence and even panic are liable to induce instability and make the management of an economic crisis much harder.

The stability and predictability of an economic model (and a weather model) will be limited by the cumulative action of a gamut of random fluctuations in the real economy which cannot be properly represented in the model so that the predictions will progressively diverge from reality. Such models are also inherently unlikely to predict an unprecedented situation although one can hope to control the model and the economy in such a way that they will be less vulnerable to sudden shocks.

On the other hand, our thinking should not be entirely dominated by short-term fluctuations but should recognize that, on larger time-scales, economies, like the atmosphere, are remarkably resilient. Given even moderately competent management, total collapse of the system is unlikely because the overall constraints such as the total resources of material and manpower are largely unaffected by temporary fluctuations and the restoring forces eventually assert themselves and bring the system to a new equilibrium. Economic crises, like bad weather, do not last for ever. But, of course, electorates and governments are not prepared to wait for the system to adjust and adapt of its own accord. *Laissez-faire* attitudes are unfashionable and governments, under continual pressure to do something, tend to over-react and to get their timing wrong. So, given our imperfect understanding of how economic systems work, and given the inability of models to produce unique or even consistent solutions, what is the decision-maker to do? What guidance can models offer him in his attempts to manage and control the economy?

Guidance for policy-makers

It does not seem reasonable to expect models to provide accurate predictions either of short-term fluctuations or of very long-term developments far removed from recent experience on which the models are built. Instead we should use them to indicate underlying trends in the medium term, to help educate policy-makers in the workings of the economic system, its external and internal constraints, on what may be feasible and what is unattainable. For example, models can be used to investigate the sensitivity and response time of the economy to various fiscal and monetary controls and to help to decide between alternative ways of achieving a particular set of policy options involving inflation, unemployment, economic growth, balance of payments etc. Alternative strategies may be tested and optimization procedures applied to select one policy from a number of internally consistent options that do not violate the overall constraints of the real world. Models usually make deterministic forecasts but one could test the sensitivity of their outputs and predictions to various uncertainties introduced by deficiencies in the input data or in the model itself.

In their present state of development, economic models should perhaps be used more for experimentation designed to improve understanding of how the economy works, its sensitivity to various uncertainties and the assessment of various controls rather than give too much weight to the forecasts themselves.

One can learn, for example, that in applying a control signal to the economy, it is very important to ensure that it is the correct magnitude and phase otherwise it may destabilize the system. This only serves to confirm what we know from bitter experience that if governments, intent on fine-tuning of the economy, attempt to correct short-period anomalies in a system which takes several months to respond, they will almost certainly get their timing wrong and make matters worse. In attempting to correct for an

imbalance in the system, the control signal should be a function of the imbalance averaged over a period comparable to the response time of the system and therefore action should be delayed until this can be assessed.

However, this poses a problem for governments under pressure from articulate electorates and the media for 'instant fixes' which may destabilize the economy and make rational longer-term decisions even more difficult. It is, for example, very difficult to make sensible long-term investment decisions during a period of high inflation and with high and rapidly fluctuating interest rates. A deeper understanding of the dynamical behaviour of economic systems might also help convince governments that it is virtually impossible to react sensibly to short-term fluctuations in a sluggish system and that they should concentrate on longer-term objectives designed to produce a more stable economic and social climate in which transient events will have less impact. This cannot be done effectively without international co-operation to achieve greater stability of exchange rates, interest rates and commodity prices, thereby reducing the scope for speculation and damping down the turbulence which so often obscures the fundamental developments. Above all, governments should avoid introducing sudden major changes. Economic systems are usually sufficiently robust to adjust to gradual changes but not to cope with large shocks that may induce instability and have quite unforeseen consequences.

These propositions may seem obvious, even self-evident, but it is remarkable how often they are ignored by governments who appear to believe that they can circumvent the laws and constraints of the system and gain at least a temporary advantage.

Conclusions

Despite the reservations made earlier, I am convinced that numerical models offer the best means and the greatest promise of improving our understanding of how economic systems work; for simulating past economic situations; for studying the sensitivity of the economy to various perturbations and controls and for predicting the likely outcome of present policies. I also believe that the study of such difficult but crucial problems calls for close collaboration between some of the best minds in both the physical and the social sciences. The physical scientist, by application of his powerful tools of mathematical modelling, computing, systems analysis and control theory, has an important contribution to make provided that he is willing to tackle real problems and not engage in purely technical or academic exercises. However, he is unlikely to be successful unless he has the insight, understanding and humility to realize that social systems are much more complex, less well-defined and constrained and therefore more difficult to simulate than the physical systems which he operates so successfully in the laboratory and factory. By the same token it will not be enough for the social scientist to adopt uncritically the tools of the physical scientist or, worse still, to imitate his symbolism and jargon without understanding what lies behind it. Working together and learning from each other, they stand a better chance of exposing the essential nature and behaviour of economic systems and of educating policy-makers on the dangers of simplistic solutions by setting limits to what may or may not be feasible.

At the same time many important social problems are not amenable to rational scientific analysis and mathematical modelling if only because human motivation and behaviour cannot be formulated in quantitative terms. In these cases little will be gained by discussing the issues in pseudo-scientific terms, obscuring them in a blanket of sociological or systems-analysis jargon, or by forcing them into the straightjacket of an over-simplistic model that has little to do with the real world.

The outputs and predictions of mathematical models are only as good as the theory and thought on which they are based and the facts that are fed into them. Like most powerful tools they are dangerous if used unintelligently and for the wrong job.

The NAVAID dropsonde

By P. Ryder, A. F. Lewis and D. A. Bennetts

(Meteorological Office, Bracknell)

Summary

A NAVAID dropsonde system has recently been developed by the Cloud Physics Branch of the Meteorological Office. The sondes, which measure temperature, humidity, pressure and winds, are designed for ejection from the Meteorological Research Flight C130 aircraft. This paper discusses their performance and illustrates their scientific potential with the results obtained during a pilot study of a weak warm front.

1. Introduction

Following successful attempts to study the fine structure and dynamics of certain weather systems (Hardman *et al.* 1972; Browning *et al.* 1973), the Meteorological Office decided to develop an aircraft dropsonde capable of measuring ambient temperature, humidity, pressure and wind. The sondes were to be used to obtain a sequence of atmospheric soundings on a scale of 20–50 km in a chosen weather system, anywhere within a large operational area over the North Atlantic. The use of sondes was to replace the technique used in the earlier studies which required that suitable systems passed over a specially manned and instrumented, land-based observing site. The design requirements were set by the scientific objectives of the proposed studies, while at the same time achieving an independence of special ground-based facilities.

The design, development and production of a suitable sonde has been achieved in parallel with that of the necessary instrumentation and a safe, effective sonde ejector for the Meteorological Research Flight C130 aircraft. This paper, which reports the development of the sonde, is divided into two parts. The first describes the general characteristics of the sonde and the accuracy with which atmospheric observations can be made, and the second presents the results of an evaluation trial on 29 March 1979.

2. The dropsonde

A sketch of the sonde is shown in Fig. 1. It is in the form of a cylinder of length 84 cm and diameter 12.5 cm. The total weight is 3.5 kg. The body of the sonde is divided in its mid-section by a polypropylene insulator so that the two halves of the sonde casing act as the elements of a UHF dipole. Release from the aircraft initiates a time delay circuit which, 1 second after ejection, turns on the UHF transmitter and fires an explosive bolt to release the parasheet. A spring loaded drogue is used to pull out the main parasheet before falling away to leave the sonde suspended beneath an aerodynamically clean canopy. The average terminal velocity of the sonde from 30 000 ft to the surface is approximately 12 m s^{-1} . The transducers for measuring temperature and humidity are located at the downward facing end of the sonde within a small, well ventilated duct. Data from these sensors are passed to the aircraft via the sonde's UHF transmitter.

The guide surface parasheet, which supports the sonde during its descent, was chosen as a result of comparative tests to establish wind following characteristics. Unlike some conventional parachutes this type possesses positive stability and is therefore not prone to 'fly' relative to the air. Given that the sonde responds to and moves with the local horizontal component of the air motion, the problem of deriving the horizontal velocity is one of measuring the rate of change of its position. Classically such position finding has been achieved by radar, or optical tracking. Unfortunately these techniques require a very stable reference platform and are essentially short-range (<100 km) methods. These characteristics are not compatible with the desire to carry out self-contained aircraft experiments over the North Atlantic.

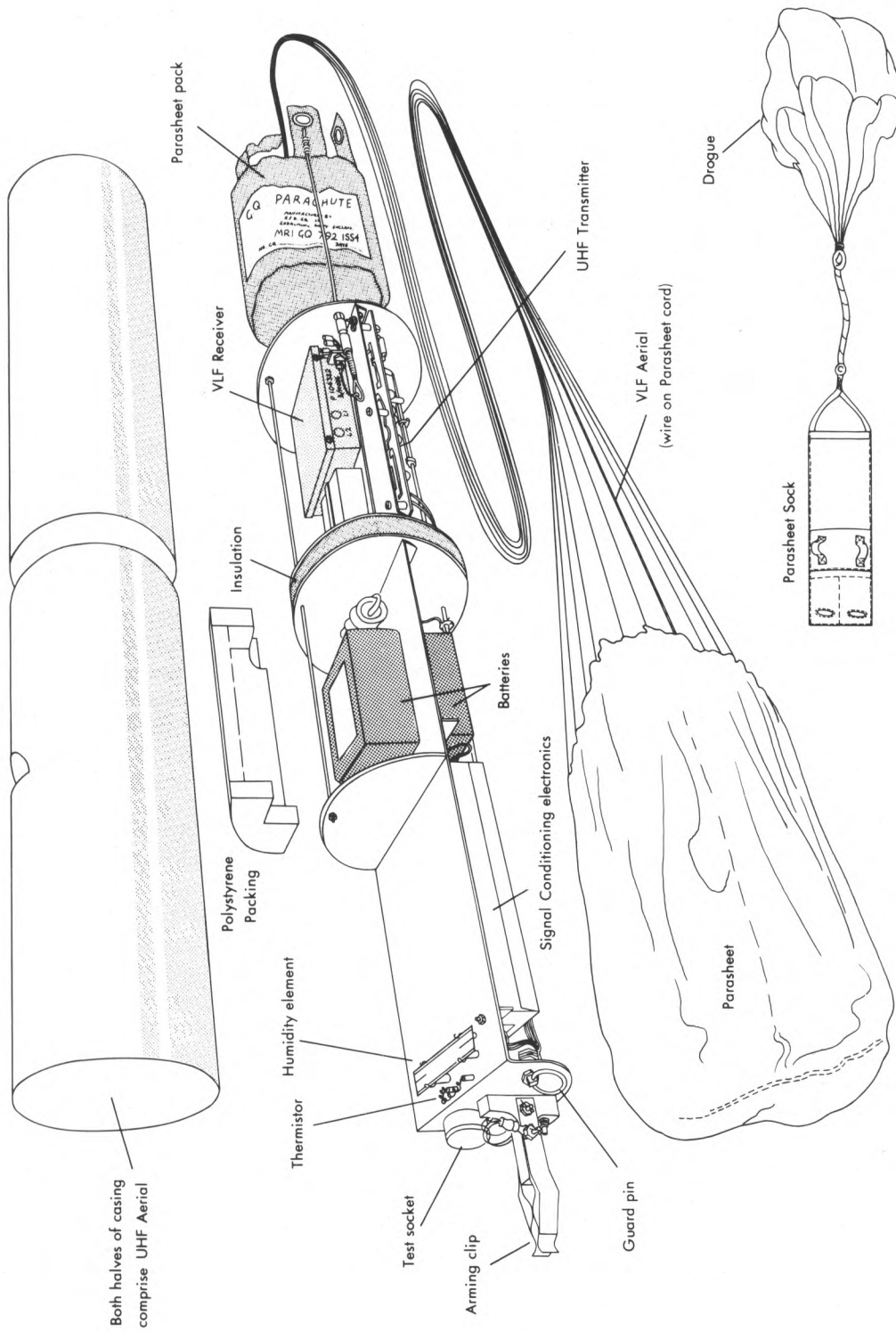


Figure 1. The NAVAID dropsonde.

As a result sonde tracking through the retransmission of the long-range navigation aid, 'Loran C', was chosen after a careful ground-based assessment of its potential accuracy (Ryder *et al.* 1972). The Loran C signal is received by the sonde through a low-frequency aerial located within one of the rigging lines of the parasheet, frequency-multiplexed with data from the meteorological sensors, and retransmitted to the aircraft via the UHF link.

(a) *Wind-finding characteristics*

Loran C consists of a set of powerful transmitters which emit pulses of 100 kHz signal on a common and closely controlled time-base. The difference in time of arrival of signals from two separate but coherent transmitters defines a 'line of position'. Two such time differences obtained from at least three transmitters create intersecting lines of position and hence effectively define a unique plan position. The advantage of this technique for sonde positioning arises from the fact that position can be inferred provided only that time differences are preserved without distortion. In particular, any common signal path such as when the sonde retransmits received Loran signals to the moving aircraft, preserves time differences.

Loran C is operated by the US Coastguard in co-operation with host nations and has been set up to provide an accurate navigation aid in various parts of the world. The accuracy with which it can be used to define the local wind vector is a function of the relative position of the transmitters and sonde, and upon received signal strength and stability. The predicted wind finding accuracy for the North Atlantic is shown in Fig. 2, taken from Ryder *et al.* (1972). These data are based upon ground based measurements of received signal stability and the known transmitter locations. However, the predictions have been confirmed in trials at Aberporth and Benbecula test ranges when sondes have been tracked by both radar and Loran C (Ryder 1979).

The ability of the sonde to measure the magnitude and direction of the wind during the descent is an important requirement. Such information from a sequence of sondes is necessary to infer regions of vertical motion, and hence those areas likely to produce cloud and precipitation. The expected scale and magnitude of such motion fields demands measurements of horizontal winds, averaged vertically over 600 m or so, to $\pm 0.4 \text{ m s}^{-1}$ or better. The 0.4 m s^{-1} contour is clearly marked in Fig. 2.

Three sondes were dropped at Aberporth on 18 July 1978 to test the ability of the data acquisition system to accept data from more than one sonde at a time. Near Aberporth the intersecting lines of position (LOPs) created by transmissions from Loran C transmitters at Ejde, Sandur and Sylt form parallelograms as sketched in Fig. 3. The component of motion perpendicular to a given set of LOPs can be inferred from the rate of change of the time difference which defines those lines. Thus the Ejde-Sylt time difference can be used to calculate the wind speed perpendicular to 032° . Similarly the Ejde-Sandur time difference provides an estimate of the component perpendicular to 342° . These components are compared for sonde A001 with their equivalent radar estimates in Figs 4(a) and (b). When viewed in this way the great importance of LOP geometry is isolated and emphasized. Each component is derived from the rate of change of time difference assessed over 60 seconds centred on the time of the estimate. This is calculated by fitting a straight line by the least squares method to the 60 one-second time differences obtained from each source. The error bars, which represent standard error estimates of the time difference gradient, are a measure of the 'goodness of fit' of the straight line to the measured one-second time differences.

Conversion from rate of change of time difference to rate of change of distance (i.e. wind component) is achieved by use of the LOP scale factors. As might be expected from Fig. 3, the small scale factor for the Ejde-Sylt time difference allows a good estimate of the wind component perpendicular to 32° (parallel to 122°); Fig. 4(a) confirms this.

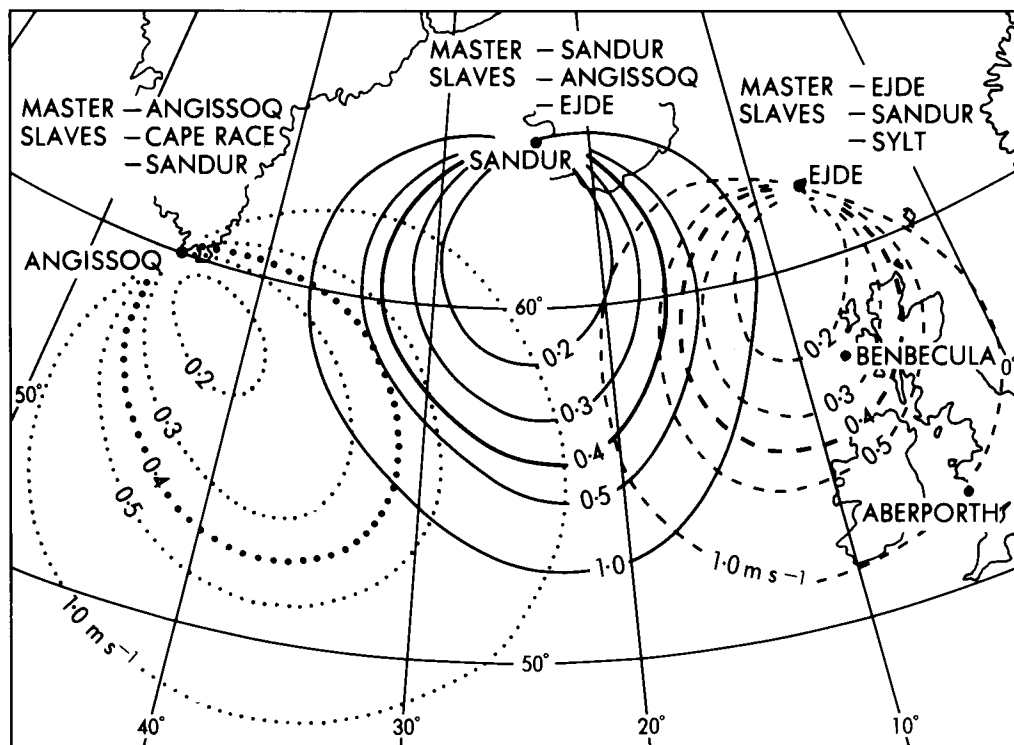


Figure 2. Predicted root-mean-square 1-minute wind errors for daytime using the indicated Loran C transmitters. Data are smoothed by a 15-second running mean.

Note that the root-mean-square (RMS) difference between radar and Loran C estimates of the wind component is 0.3 m s^{-1} , which is in good agreement with the error predicted from goodness of fit (0.2 to 0.3 m s^{-1}). The large scale factor in the Aberporth area, which applies to the Ejde-Sandur time difference, produces much larger differences between radar and Loran C estimates for that wind component (i.e. parallel to 072°), but again the RMS differences are comparable to the goodness of fit estimates (i.e. 1.2 m s^{-1} compared with 0.6 to 1.0 m s^{-1}). Of course this latter error dominates the estimation of the *total* wind vector error, which is close to that predicted in Fig. 2 for the Aberporth area. The results have further significance, however, because they demonstrate that where the geometry and scale factors are favourable, as in the North Atlantic, low total wind errors may be achieved. (The scale factors are important in determining the accuracy of each wind component and the geometry is important for determining the accuracy of the total wind.)

In an analysis of the algorithm which is used to trace the time of the individual Loran C signal zero crossing from which time differences are derived, Ryder (1976) has pointed out that the response of the algorithm can be oscillatory if the algorithm is not correctly matched to the signal-to-noise ratio (SNR). Accordingly the SNR for each transmission is also shown in Fig. 4. There is an obvious correlation between low SNRs at about 1505 GMT and the increased component errors at that time. The oscillatory nature of the departure of the 'Loran' wind from the 'radar' wind is also evident. Unfortunately, there are at present insufficient data to determine the modifications to the algorithm necessary for a better matching in low SNR conditions.

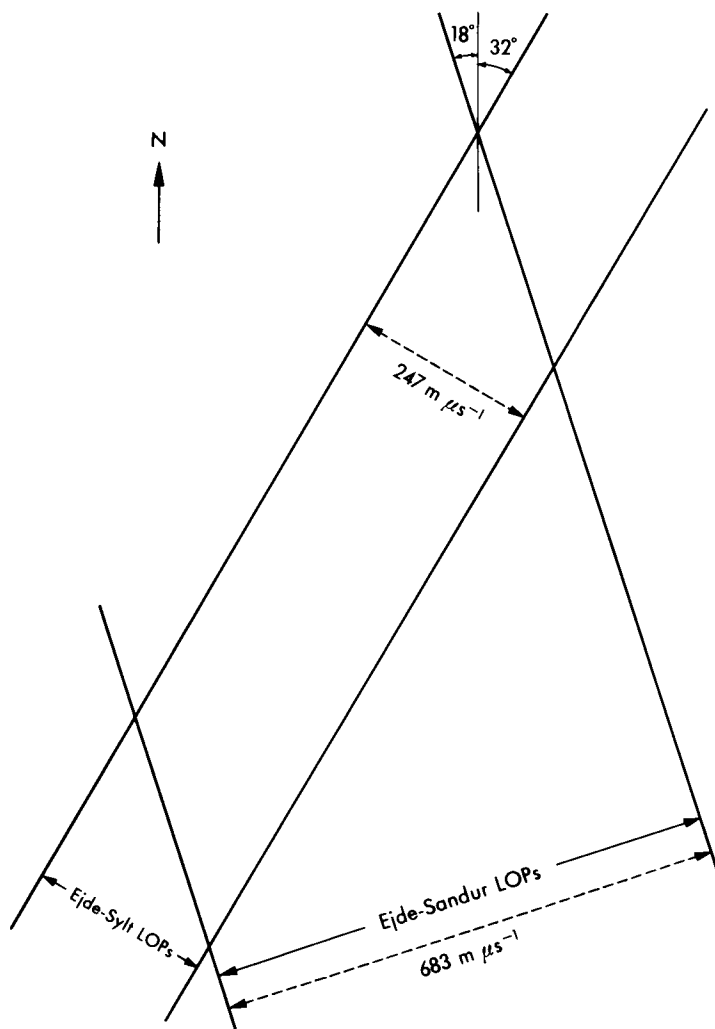


Figure 3. Line of position (LOP) geometry in the vicinity of Aberporth created by transmissions from Loran C transmitters at Ejde, Sandur and Sylt.

(b) *Air temperature and humidity*

A thermistor, with a time-constant of about 1 second at the achieved ventilation rate, is used to sense the air temperature. The sonde can experience a thermal shock of the order of 70 °C when it is ejected at 30 000 ft. Since measurements are required as soon as possible after ejection, when the body of the sonde may be far from thermal equilibrium with its surroundings, great care has been taken to ensure that, in addition to being protected from the heating effects of solar radiation, the sensor experiences ambient atmospheric conditions. For example, it has proved necessary to coil the thermistor leads to reduce the effects of heat conduction along them. The difficulty of providing a comparable measurement in the field does not allow a complete statement of the accuracy to be expected under operational conditions, but absolute errors appear to be generally less than 0.5 °C. Unfortunately this only permits the vertical

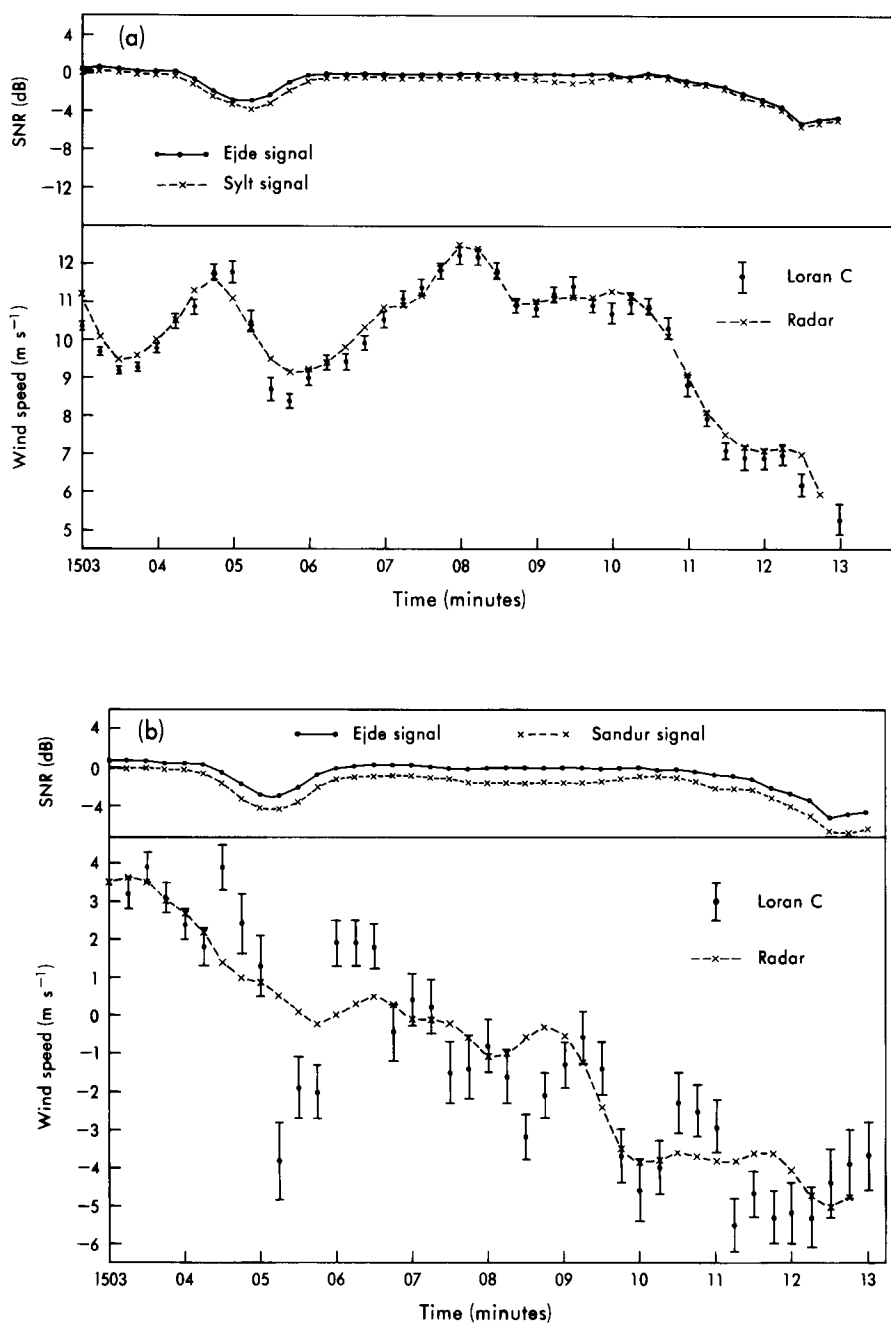


Figure 4. Wind components measured by Loran C and radar tracking at Aberporth on 18 July 1978 (a) parallel to 122° and (b) parallel to 072°.

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wind shear to be evaluated from the thermal wind equation to an accuracy of about $5 \times 10^{-3} \text{ s}^{-1}$, which is insufficient for many meteorological purposes.

The humidity element is a carbon hygistor of the type used in the VIZ radiosonde (VIZ Manufacturing Co., Philadelphia, PA, USA). The device was chosen after careful evaluation in the laboratory and in field trials (see Gibbs *et al.* 1975). Again exposure is most important; speed of response is a function of ventilation rate, humidity and temperature. Trials suggest that accuracy in the range 30% to 95% relative humidity is better than $\pm 5\%$.

Fig. 5 shows a comparison between the temperature and humidity profiles measured by sonde A021 at Benbecula at 1400 GMT and the midday Stornoway radiosonde ascent on 28 February 1979. On this occasion the aircraft was flying above the tropopause, but despite the temperature difference of some 70°C between the aircraft cabin and the external environment it is clear that the sonde's temperature transducer rapidly responded to the environmental conditions. Lower in the atmosphere many small-scale features can be detected in the humidity profile. On close inspection many of these are seen to be linked to small changes in temperature lapse rate. Transit through at least one layer of cloud in the vicinity of 840 to 900 mb demonstrates the ability of the humidity element to dry out below cloud, although in other tests it has been found that after a long passage through wet, icing cloud, drying out may be delayed by up to 30 mb. When this occurs a significant wet-bulb effect can be seen in the temperature profile. On future sondes it is hoped to incorporate a fast response cloud detector.

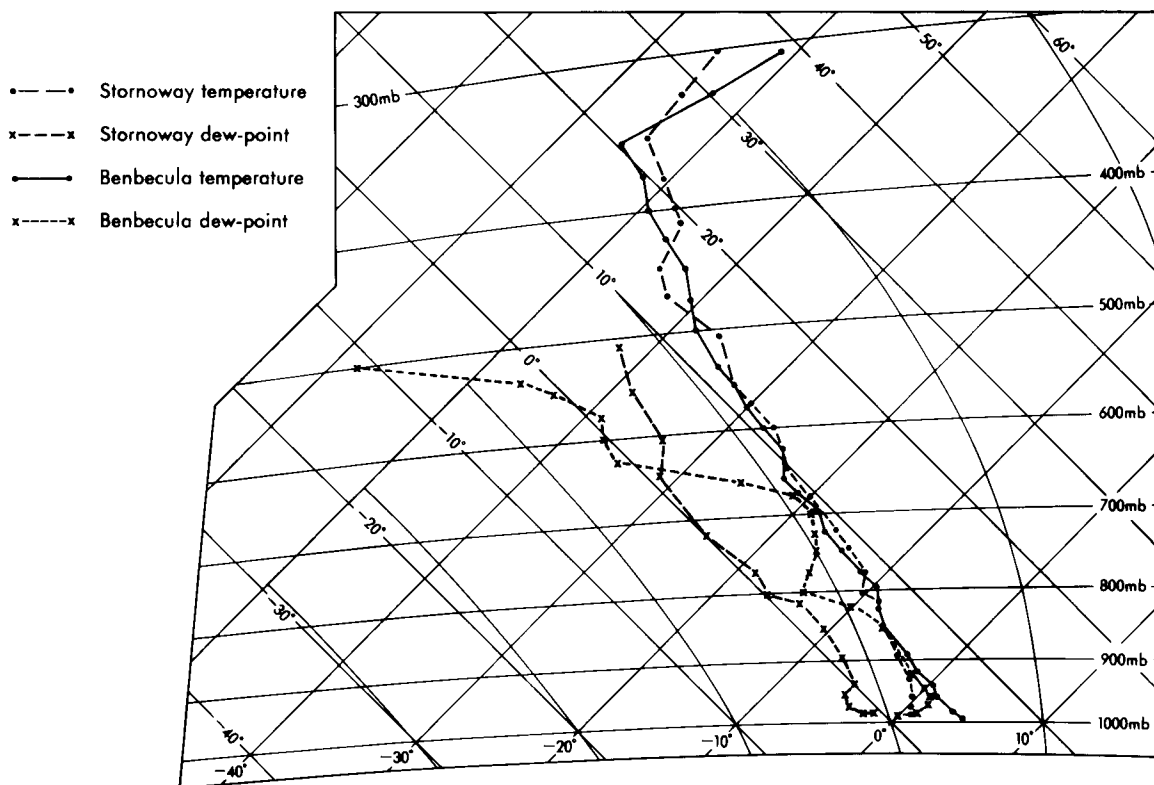


Figure 5. A comparison between the temperature and humidity measured by dropsonde A021 at Benbecula at 1400 GMT and the midday radiosonde sounding from Stornoway on 28 February 1979. No humidity data were received from the radiosonde above 500 mb.

(c) *Pressure*

The pressure transducer (Ryder and Lewis 1979) is a proprietary integrated circuit device (National Semiconductor LX 1602A). A vacuum reference cell is created by etching a silicon chip. This is sealed by a diaphragm on which are diffused four piezo-resistors. These form a strain gauge bridge on the diaphragm which, together with signal conditioning electronics and temperature sensing elements, generate high level voltages which are functions of pressure and diaphragm temperature. Trials have shown that the transfer characteristics of the devices, including their temperature coefficients, are stable except for an offset error which varies slowly with time. The sensors are not sensitive to shocks of the type experienced at ejection.

The accuracy of the pressure element was investigated by comparing its output with the sonde height derived from simultaneous ground based radar observations. The radar height data were converted to a pressure altitude by use of the hydrostatic equations, the necessary constants being provided by an estimate of the surface pressure and the sonde measurements of temperature. The result of one such comparison is summarized in Table I. Most of the differences are less than 2 mb, well within the expected accuracy of the pressure transducer, and their systematic nature reflects the tolerances permitted in the initial calibration. (The sonde was dropped close to the radar and errors in radar height are negligible.) Similar results have been obtained from several other comparisons, except for one which was unusual in that a constant difference of about 6 mb was observed. The reason for this is unknown. It was always expected that the absolute measurement of pressure would be difficult and it is for this reason that each sonde undergoes a single pressure calibration before ejection. Fortunately experience suggests that a further check may be possible. The loss of signal indicates entry of the sonde into the sea with a resolution of ± 0.2 s, allowing estimation of the surface pressure to ± 0.2 mb. Provided that the surface pressure can be inferred from some other source, gross errors at least can be avoided.

(d) *The aircraft instrumentation*

Equipment on the aircraft is required for three purposes: firstly, to test and perform simple calibration checks on the sondes before use; secondly, to store sondes and to eject them safely when required; and thirdly, to receive, process and store data from the sondes. Hardware and software for this last purpose were purchased from Beukers Labs Inc., Philadelphia, PA, USA.

The testing of sondes is carried out on a purpose-built rig through the sonde test socket (Fig. 1). All data are displayed during a test and are also stored on magnetic tape for subsequent analysis. The rig is used in the laboratory for the calibration of all the sensors and their signal conditioning electronics, over a range of temperature and pressure, before their incorporation into the sondes, and on the aircraft to allow a single-point calibration at cabin pressure shortly before use. If this calibration has drifted too far from the laboratory calibration the sonde is rejected.

The dropsonde ejector is a hydraulically operated, spring-loaded device in the rear loading ramp of the C130 aircraft. Sondes are ejected with their long axes parallel to the aircraft wings. A seal is provided to allow use when the cabin is pressurized. A nearby storage rack allows up to 80 sondes to be carried on a sortie. The ejector has been tested extensively and the facility incorporates several monitoring features including a rearward-facing television camera to verify satisfactory ejection.

The aircraft is fitted with a downward-facing broad-band UHF receiving antenna, which feeds a suitable preamplifier with the meteorological and Loran data. Each sonde transmits at one of five separate, crystal controlled frequencies in the 400 MHz band. By using receivers each tuned to one of these frequencies, data from up to five sondes can be processed simultaneously. This is a very valuable capability when frequent soundings are required; to study features on the scale 20 to 30 km for example. The audio frequency signals from each of these five sources are separately detected, decommutated, digitized and provided as input to a 32K memory computer.

Table I. Comparison of output from dropsonde pressure element with pressures derived from ground-based radar observations. Sonde No. A003, launched at 13.54:21 GMT on 28 April 1978.

Time (s)	Sonde Pressure (mb)	Radar Pressure (mb)	Difference (mb)	Time (s)	Sonde Pressure (mb)	Radar Pressure (mb)	Difference (mb)
488.4	1006.7	1008.8	-2.1	238.6	712.4	712.0	0.4
458.6	971.1	973.9	-2.8	228.6	701.4	700.7	0.7
448.6	958.9	961.3	-2.4	218.6	690.4	689.7	0.7
438.6	946.6	949.1	-2.5	208.6	679.4	678.4	1.0
428.6	934.2	936.7	-2.5	198.6	668.7	667.6	1.1
418.6	922.0	924.8	-2.8	188.6	657.7	656.5	1.2
408.6	909.8	912.0	-2.2	178.6	647.0	645.5	1.5
398.6	897.6	900.1	-2.5	168.6	636.0	634.6	1.4
388.6	885.6	887.1	-1.5	158.6	625.2	623.6	1.6
378.6	873.5	875.1	-1.6	148.6	614.6	612.7	1.9
368.6	861.7	863.2	-1.5	138.6	604.0	602.2	1.8
358.6	849.9	851.2	-1.3	128.6	593.4	591.3	2.1
348.6	838.1	839.8	-1.7	118.6	583.0	580.9	2.1
338.6	826.3	827.8	-1.5	108.6	572.5	570.4	2.1
328.6	814.7	815.7	-1.0	98.6	562.2	559.9	2.3
318.6	803.2	804.1	-0.9	88.6	552.0	549.5	2.5
308.6	791.7	792.3	-0.6	78.6	541.7	539.1	2.6
298.6	780.0	780.8	-0.8	68.6	531.6	528.8	2.8
288.6	768.7	769.1	-0.4	58.6	521.4	518.6	2.8
278.6	757.3	757.6	-0.3	48.6	511.4	508.5	2.9
268.6	745.9	746.0	-0.1	38.6	501.5	498.5	3.0
258.6	734.7	734.5	0.2	28.6	492.0	488.0	4.0
248.6	723.5	723.2	0.3	18.6	482.0	477.9	4.1

The aircraft receives Loran C transmissions directly as a so-called 'local' signal as well as from the five 'remote' sonde sources. In each case the signals are amplified and shaped to provide an in-phase square wave. The time of arrival (TOA) of one zero crossing in each of the eight repetitive Loran C pulses is measured against a stable internal clock. Each such group of zero crossings is effectively tracked by a second-order error detection algorithm in the computer to provide a continually updated assessment of the TOA. The characteristics and optimization of this technique have been discussed by Ryder (1976). Time differences are formed by straightforward subtraction of the relevant TOAs. The 'local' source provides a suitable first estimate of the times of arrival of the 'remote' source immediately after sonde ejection. This ensures that stable tracking and hence useful information is available as soon as possible after a sonde is released. Acquisition of the optimum zero crossing of the 'local' signal is obtained at leisure under a combination of automatic and manual control before the sonde dropping sequence is entered. Individual time of arrival estimates are formed from each of the tracked signals from each of the sondes once per second, and are stored with the digitized audio frequency data on magnetic tape for subsequent analysis. Various analogue signals are produced by a digital-to-analogue converter for real-time display on chart recorders. The data are subsequently processed in the laboratory to give profiles of wind components. It is hoped that in due course a real-time analysis facility will be available to allow the temperature and humidity to be displayed in the aircraft. The 'local' source also provides a valuable means of tracking the aircraft. A post-flight record of the C130 ground position is produced as a matter of routine by this method.

The C130 aircraft is also fully equipped with other instruments for meteorological research. Of particular interest to the study to be described later is the Ekco E290 3 cm weather radar. The antenna, which has a beam width of 3°, is programmed to scan the 180° sector ahead of the aircraft at one of a

number of angles of tilt to the horizontal. This facility combined with the forward motion of the aircraft allows a three-dimensional view of the precipitation echo to be constructed. The radar has range compensation and an experimentally determined threshold equivalent to a rainfall rate of about 0.25 to 0.5 mm h^{-1} out to ranges of 40 km . The radar display is photographed at regular intervals to allow detection of areas of rainfall exceeding this threshold.

3. A pilot study of an Atlantic front

The surface analysis for 1200 GMT on 29 March 1979 is shown in Fig. 6. Although rather a weak feature with little thermal contrast and producing only light rain and drizzle, the occlusion/warm front S was chosen as the subject of a pilot study. The objectives were primarily to test some operational procedures for locating and studying such fronts, but a number of results were obtained which augur well for future investigations.

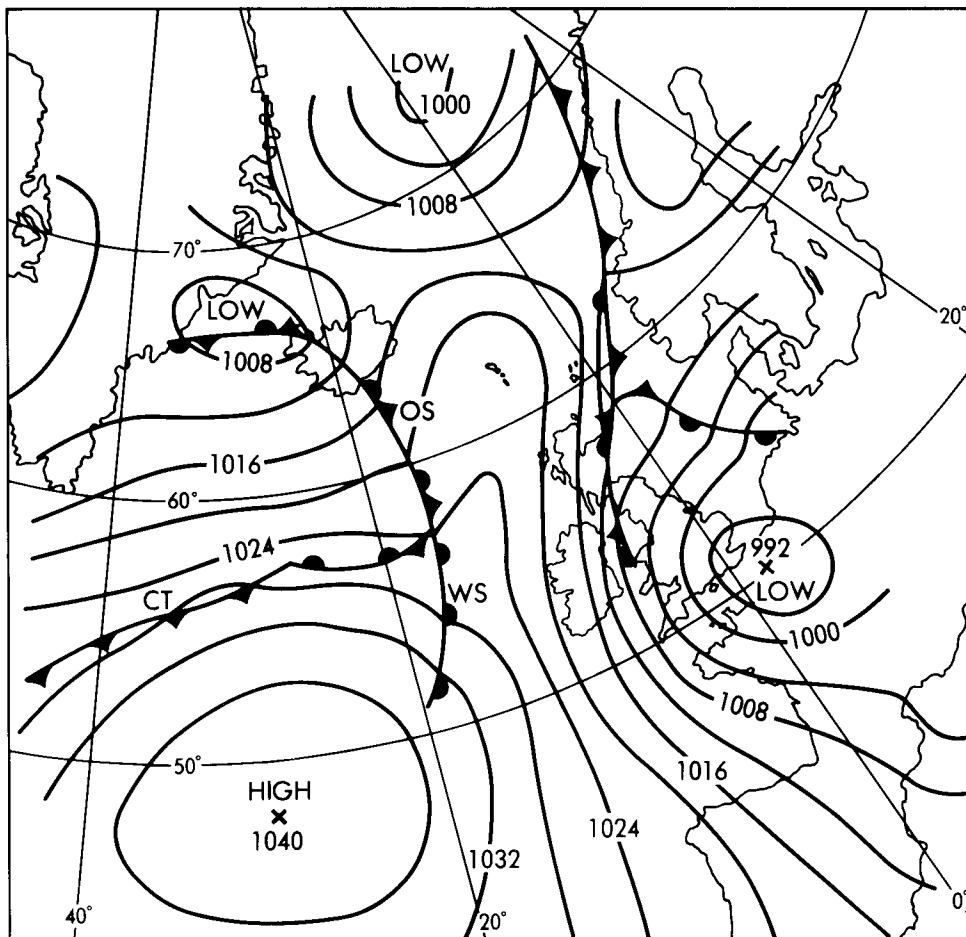


Figure 6. Surface analysis for 1200 GMT on 29 March 1979.

Measurements were made between 1100 and 1300 GMT by sondes dropped along an east-west line centred at 57°50'N, 17°W. Nine sondes were released in two groups from an altitude of 7.3 km in the vicinity of the front. Although wind data were obtained from only five of these and one parachute failed to deploy correctly so that temperature and humidity data from that sonde are suspect, a number of east-west cross-sections of interest have been derived.

Data are presented in a $(p, x-st)$ frame of reference where p is pressure, s is the component of the system velocity vector in the x direction — west to east in this case — and t is time. Normally a sequence of sondes would be dropped both to test the validity of the system velocity concept (which assumes a non-developing system being advected at some constant velocity s) and where appropriate to define the vector. This was not done on 29 March. However, the synoptic-scale observations suggest that the front was moving eastwards at between 10 and 15 m s⁻¹ and the 700 mb westerly wind measured by all the sondes was close to 12.5 m s⁻¹. Accordingly a value of 12.5 m s⁻¹ from 270° has been assumed to be the system velocity; because the time between sonde ejections is short the resulting fields are not very sensitive to the choice of system velocity. The origin of the x -coordinate is arbitrarily set to the west of the observations.

Fig. 7 shows the variation of relative humidity in this frame of reference. The major feature is the layer of saturated air in the lower half of the figure with a long sloping tongue of dry air overlying it. Above the dry zone is another layer of moist air. The location of the radar echo above the threshold (i.e. the location of precipitation) is superimposed on the diagram. The same echo structure was observed throughout the area 20 km to the north and south of the section shown, but the extent to which the echoes represent bands of precipitation beyond that range is unknown.

The field of wet-bulb potential temperature calculated from the sonde data, Fig. 8, exhibits the expected strong gradient in what is assumed to be the frontal zone extending from the surface at 150 km, to 850 mb at 300 km, and weaker gradients elsewhere. Of special interest are the hatched regions denoting air which is potentially unstable. Three of the zones (centred at 25 km, 950 mb; 250 km, 950 mb; 250 km, 700 mb) are both saturated with respect to water and have a lapse rate at, or greater than, the moist adiabatic. Precipitation echoes were observed in the vicinity of all three regions, possibly indicative of the release of the instability. The band of potentially unstable air above the frontal surface (extending from 150 km, 775 mb to 300 km, 550 mb) correlates well with the dry tongue of air identified in Fig. 7. It is conceivable that the implied instability there may have been realized subsequently, following saturation of the air by moistening or lifting. Overall, the precipitation zones exhibit an interesting mesoscale structure, if not periodicity, which is readily resolved by the pattern of sondes. In this context, it is particularly unfortunate that further data were not obtained between 50 and 150 km; the observations at 75 km were made from the sonde with a failed parasheet.

Fig. 9 shows the u -component of velocity relative to the system (positive values indicate motion from west to east). Although perhaps distorted by the choice of system velocity, air above the front is, as expected, moving to the east and overrunning that beneath the front. The v -component (not shown) is consistent with the thermal wind equation and exhibited an upper-level jet parallel to the front. Because the divergence is unknown owing to the lack of data parallel to the surface front, it is not possible to derive the vertical motion rigorously from the equation of continuity. However, within a frontal zone it is reasonable to expect that locally $|\partial u/\partial x| \gg |\partial v/\partial y|$ (the y -axis is parallel to the front) and that changes in vertical motion occur where $|\partial u/\partial x|$ is a maximum. In particular ascent is likely where $\partial u/\partial x$ is large and negative, implying convergence, and descent is probable where $\partial u/\partial x$ is large and positive. The field of $\partial u/\partial x$ shown in Fig. 10 is compatible with ascent near 250 km, 600 mb just below the moistest part of the dry zone (Fig. 7), and descent at the same level at 175 and 275 km, which correlate well with the two humidity minima. Ascent is also predicted at 150 km, 700 mb and 250 km, 975 mb, coinciding well with the regions of potential instability (Fig. 8) and precipitation (Fig. 7). The region of implied descent at 220 km, 925 mb is closely related to the break in the radar echo (Fig. 7).

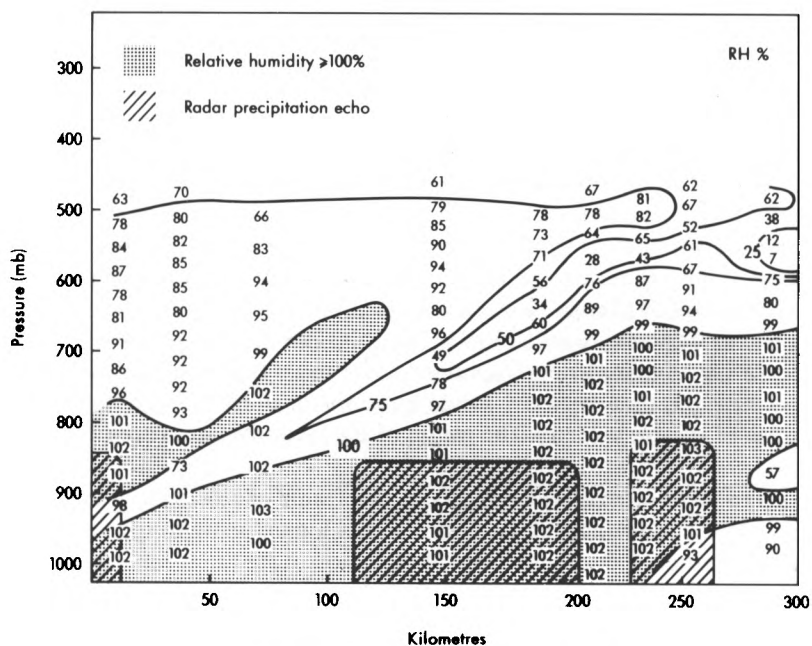


Figure 7. East-west cross-section centred on $57^{\circ}50'N$, $17^{\circ}00'W$ of relative humidity with respect to water between 1100 and 1300 GMT on 29 March 1979. The location of radar precipitation echo is superimposed.

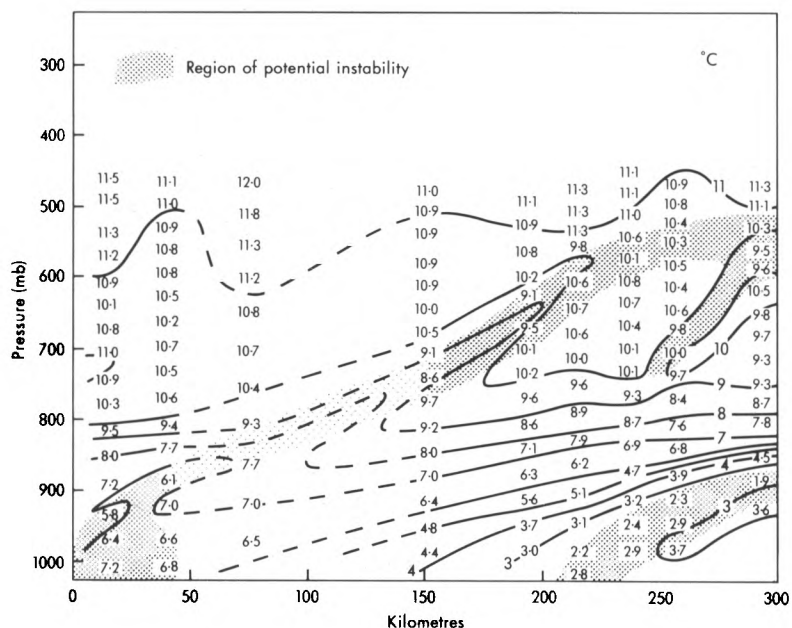


Figure 8. East-west cross-section of wet-bulb potential temperature.

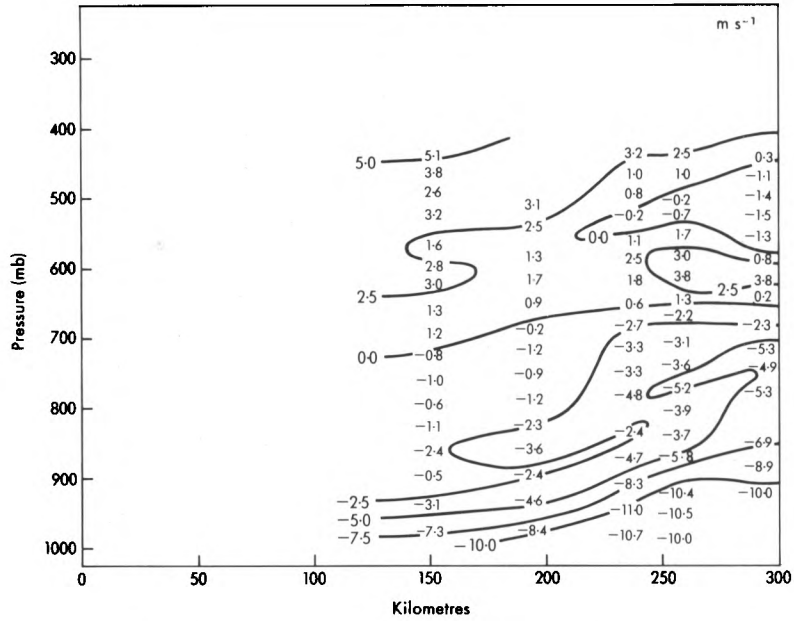


Figure 9. East-west cross-section of the westerly component of wind relative to the system, assumed to be moving from 270° , 12.5 m s^{-1} . Positive values imply motion from west to east.

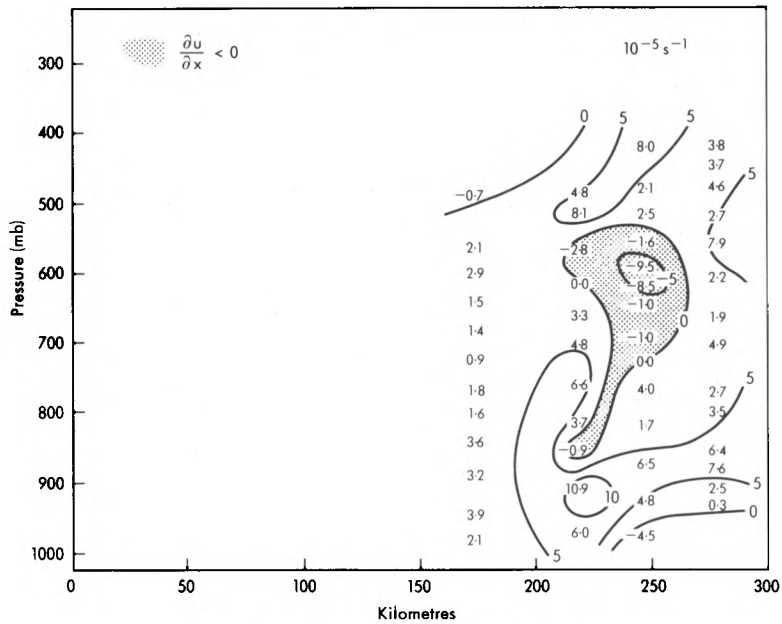


Figure 10. East-west cross-section of $\partial u / \partial x$.

4. Conclusion

This first use of a new facility has highlighted its potential for the study of the mesoscale structure and dynamics of the atmosphere. In particular, the ability to define thermal and moisture fields together with the coexisting air motions has been shown to provide a self-consistent and mutually supportive data set.

Although the data are limited in extent in the example described above, a number of interesting features have been identified and a coherent description of the airflow, cloud and precipitation has emerged.

More recently the dropsonde facility has been used to investigate the banded structure of convective rainfall behind a cold front (Bennetts and Ryder 1984).

Acknowledgements

The development of this facility represents the combined efforts of numerous members of the Meteorological Office Cloud Physics Branch and the Meteorological Research Flight. Their contribution is gratefully acknowledged.

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Notes and news

Sir John Mason appointed Scientific Director of acid rain project

Immediately after his retirement as Director-General on 30 September, Sir John Mason took up a new appointment as Scientific Director of a major new research project on acid rain to be conducted over several years by the Royal Society in association with the Norwegian Academy of Science and Letters and the Royal Swedish Academy of Sciences. The project is being funded by the Central Electricity Generating Board and the National Coal Board to make a completely independent investigation of the acidification of surface waters in Norway and Sweden and of the extent to which this is responsible for the reduction of fish populations in some Scandinavian lakes. This investigation will be conducted in parallel with researches already being undertaken by the Central Electricity Research Laboratories and the Meteorological Office to determine to what extent the acidification of precipitation falling in Norway and Sweden may be attributed to the emission of sulphur and nitrogen oxides from UK power stations and to what extent this might be reduced by the partial or total removal of sulphur dioxide from the effluents.

Sir John's main tasks will be to review the current status of recent research in this complex field, to identify important gaps in knowledge and understanding, to formulate key questions and to commission research on at least a five-year time scale in the United Kingdom, Norway and Sweden as appropriate. Sir John's base for this task, which he expects to occupy half his time, will be at Imperial College where he is an Honorary Fellow and former Professor of Cloud Physics.

He will also retain his interest in numerical weather prediction and climate studies by joining the Joint WMO/ICSU Scientific Committee which plans and co-ordinates the World Climate Research Programme and by becoming Scientific Director of the WMO World Conference on the First Global Weather Experiment to be held in Geneva in 1985. These assignments will keep him in close touch with the Meteorological Office.

Sir John has also been appointed by the Secretary of State for Education and Science to the Advisory Board for the Research Councils which funds and determines the broad programs of all the Research Councils covering more than half the scientific research conducted in the universities.

He will continue with his duties as Treasurer and Senior Vice-President of the Royal Society and as Pro-Chancellor of the University of Surrey.

50 years ago

The following letter was published in the *Meteorological Magazine*, December 1933, 68, 258–259.

Where is the Rainbow?

The elementary theory of the rainbow explains how the phenomenon is produced by reflection and refraction of the sun's rays falling on raindrops, and that the bright coloured arch that we see is actually a multitude of drops which are momentarily in the right position to transmit the refracted and reflected light into the eyes of the observer. This is all quite simple and straightforward, but if we pursue the matter a little further we arrive at a curious and paradoxical result.

Suppose we attempt to locate the position of the rainbow in space by using one of the ordinary methods depending on parallax. We might, for example, use a range-finder, or take the bearings of a point on the bow, *e.g.*, the apex, from two points at the ends of a measured base line. If that be done, the distance so determined is not the distance of the raindrops but "infinity," for the simple reason that it is impossible to observe the same rainbow from two different positions. When the observer moves from

one position to the other, the rainbow moves too. The bearings measured from the two ends of the base line will be identical. It does not matter whether the bow is formed by a shower a mile away or by the spray from a garden hose-pipe a few yards away, the result must always be the same.

Now our own normal optical equipment consists of a pair of eyes which enable us to judge distances and to see things in their proper spatial relationship by observing simultaneously from two view points, about two and a-half inches apart. Speaking for myself, I feel positive that when I look at a rainbow formed by the spray of a garden hose, I judge it to be close at hand among the falling drops. The theory given in the preceding paragraph indicates, however, that I should judge it to be far behind the drops, at an infinite distance (or to be more accurate, at the distance of the sun). Possibly the explanation is that parallax due to binocular vision is only one of the factors entering into our judgement of distance, other factors being brightness, contrast and apparent relative position. In the case of the rainbow the eyes see a bright translucent object associated with the water drops, and interfering with the visibility of objects beyond the spray. The illusory evidence arising from binocular vision is rejected and the brain judges the bow to be where it really is — among the water drops.

Has anyone ever taken a stereoscopic photograph of the rainbow formed in spray a few yards from the camera? It would be very interesting to see what it looks like in the stereoscope.

E. G. BILHAM

******Mr Bilham's letter elicited no response. The point he makes does not seem to be dealt with specifically in subsequently written treatises on atmospheric optics such as Minnaert's *Light and colour in the open air*, Tricker's *Introduction to meteorological optics*, or Boyer's *The rainbow*. We have certainly seen, from the seventh floor of the Meteorological Office Headquarters building, a rainbow one end of which clearly arose from the garden of a house adjacent to the main car park.

Oceanology International Conference and Exhibition

Oceanology International 84, sponsored by the Society for Underwater Technology, will take place at the Hotel Metropole, Brighton, from 6 to 9 March 1984.

Forty-nine papers will be given under four main session headings: navigation and position fixing; geophysics, geology and geotechnics; environmental data; and hydrography and seabed surveys. The environmental data sessions will have papers grouped under the headings of user emphasis, ocean climate, measuring systems, wind and remote sensing. There will be poster presentations on a further dozen topics.

Further information may be obtained from the organizers, Spearhead Exhibitions Ltd, Rowe House, 55/59 Fife Road, Kingston upon Thames, Surrey KT1 1TA. Telephone: 01-549 5831. Telex: 928042.

Correction

'Global solar radiation measurements on 6 August 1981. A day of midday darkness' by R. J. Armstrong, *Meteorol Mag*, 112, 1983, 200–209.

The graph showing the hourly irradiation for East Malling in Fig. 2 on page 203 (broken line) should have its ordinate values multiplied by 2.5. The corresponding daily total in Table II of 2679 W h m⁻² is correct.

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NOTICES

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