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The effects of pollutants on global climate*

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Summary

Man has the potential to change the earth's climate by altering the composition of the atmosphere. This paper discusses the physical processes through which certain gases influence climate, summarizes those constituents which are most likely to make a significant contribution to the climate change over the next few decades, and illustrates how numerical models are being used to estimate details of such changes in climate.

1. Introduction

Over the last decade there has been a growing interest in man's impact on climate (Massachusetts Institute of Technology 1971; National Academy of Sciences 1979a, 1982; Bach *et al.* 1979). This increase in awareness has been fostered, at least in part, by the improved monitoring of trace gases in the atmosphere (for example, Keeling *et al.* 1982) and by our increased understanding of the influence of these gases on climate through the use of numerical models of climate (for example, Mason 1976). The first climate impact research program to make extensive use of mathematical models of climate was stimulated by the possibility that supersonic aircraft could alter the concentration of stratospheric ozone. The US Government set up their climate assessment program (Grobecker *et al.* 1974), and were quickly followed by the French (COVOS 1976) and the United Kingdom (Meteorological Office 1975). More recent studies have been concerned with the effects of chlorofluorocarbons on the stratosphere (National Academy of Sciences 1976, 1979b) and carbon dioxide (CO_2) on the troposphere (see for example, Clark 1982). In 1978 the World Meteorological Organization set up its World Climate Research Programme to co-ordinate research at an international level.

Recently there has been much concern that a global warming due to increases in CO_2 and other radiatively active gases could produce changes in global patterns of temperature, precipitation and winds. This has led to speculation that agriculture may be adversely affected and, in particular, that the

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main regions of grain production will become more arid. There have also been suggestions that the predicted rises in polar temperatures are sufficient to cause rapid disintegration of the vast grounded west Antarctic ice sheet. This would raise sea level by about 5 metres and flood many of the world's major cities. While some of these conjectures are probably exaggerated, there is much evidence that changes following an increase in CO_2 and other trace gases will be significant.

This paper is concerned with the effects of pollutants on global climate. Most of the paper is devoted to modelling the effects of increased CO_2. Other trace gases are discussed, and many aspects of CO_2 research are relevant to other radiatively active gases. The next section contains a brief description of the physical processes by which pollutants may alter climate. In the third section, I discuss the atmospheric constituents which are thought likely to affect climate, and give a crude estimate of their potential to change global mean surface temperature. In the following section, the validity of the simple climate models used to obtain these estimates of temperature change is assessed. Results from three-dimensional models of climate are presented in the penultimate section. This is followed by some concluding remarks and a short summary.

2. The physical processes by which pollutants affect climate

The earth–atmosphere system is heated by short-wave radiation (wavelengths up to about 4×10^{-6} m) from the sun and cooled by long-wave radiation to space. The intensity of radiation emitted from a body increases with temperature. The temperature of the earth and atmosphere is such that, in the long term, the outgoing long-wave radiation at the top of the atmosphere just balances the net incoming radiation from the sun. In the absence of the atmosphere, the earth's surface temperature would be about 255 K, some 30 K lower than at present (assuming the earth continued to reflect about 30% of the incident solar radiation). The presence of the atmosphere raises the surface temperature owing to a combination of two effects. First, clouds and certain atmospheric gases (for example, water vapour, carbon dioxide and ozone, but not oxygen or nitrogen) absorb and emit long-wave radiation. Thus, much of the terrestrial radiation reaching space originates from the atmosphere rather than the earth's surface. Second, the temperature of the lower atmosphere (troposphere) decreases with height at a mean rate of 6 K km^{-1}. Hence, radiation from the atmosphere is emitted at a lower temperature than that of the surface. An observer in space would receive long-wave energy consistent with an emitting temperature of 255 K, corresponding to a level about 5 km above the ground, but the surface is some 30 K warmer. This anomalous increase in surface temperature is often referred to as the greenhouse effect. Water vapour is responsible for the largest contribution to this warming.

If the concentration of an atmospheric constituent which absorbs long-wave radiation is increased, this 'greenhouse' effect will be enhanced. The magnitude depends not only on the size of the increase, but also on the extent to which the constituent absorbs radiation, which is a function of its molecular structure, and whether or not other atmospheric gases are already absorbing radiation at the same wavelength. Water vapour and carbon dioxide already absorb long-wave radiation at most wavelengths from 4 to 8×10^{-6} m and above 13×10^{-6} m. At the intermediate wavelengths, sometimes known as the atmospheric window, the atmosphere absorbs little radiation in the absence of cloud, and energy escapes directly from the surface to space. Gases which absorb over this spectral interval will be more effective in contributing to the greenhouse effect.

Many atmospheric pollutants have the potential to alter global climate by enhancing the earth's greenhouse effect, as is discussed in the following section. Some pollutants may also affect climate indirectly through chemical reactions which alter the concentration of radiatively active gases. Most of these reactions are associated with the presence of ozone in the upper atmosphere. Ozone is formed following the absorption of solar radiation by molecular oxygen in the middle stratosphere and is removed in the lower stratosphere by photodissociation, which produces excited oxygen atoms, and by further reactions with these excited oxygen atoms. Ozone is also destroyed in catalytic chain reactions involving certain chemical fragments (free radicals) including OH, H, NO and Cl. These radicals can be injected directly into the atmosphere (for example, NO from oxides of nitrogen produced in the exhausts of stratospheric aircraft) or formed by various reactions involving water vapour (H_2O), nitrous oxide (N_2O), methane (CH_4) and halocarbons (CF_2, Cl_2, $CFCl_3$, CH_3CCl_3) which originate from the surface. The rates of some of the above reactions are temperature dependent, so a chemically inactive gas such as CO_2 can also alter ozone distributions through radiatively induced changes in atmospheric temperature. Many of the above processes are summarized in Fig. 1.

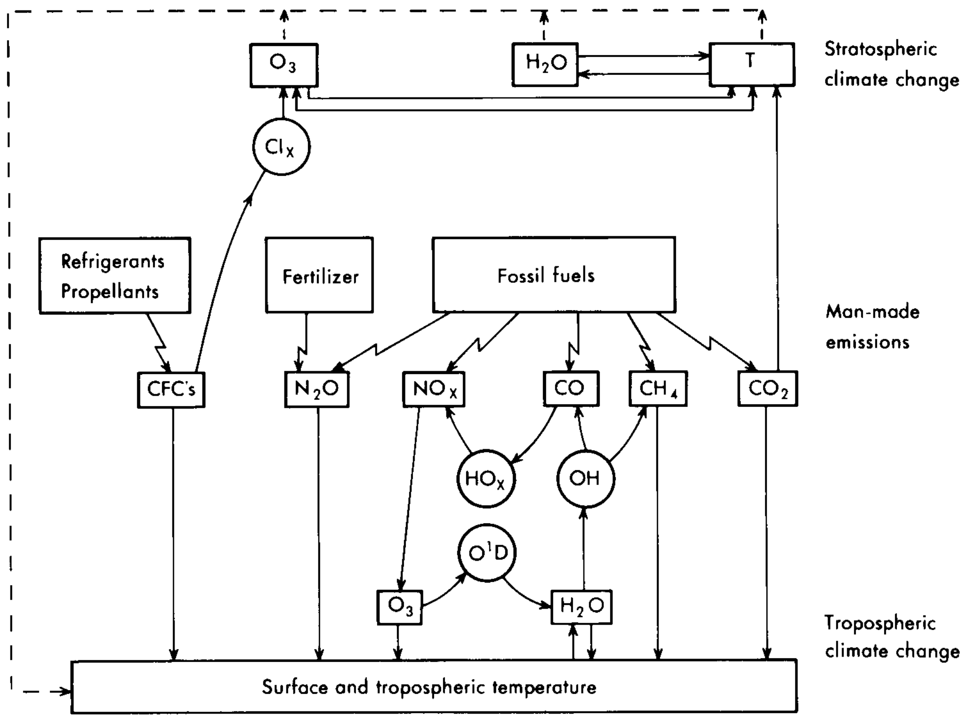


Figure 1. Climate–chemical interactions due to trace gases (adapted from Ramanathan 1980).

3. A brief survey of atmospheric pollutants

Carbon dioxide (CO_2)

The concentration of atmospheric carbon dioxide has increased from about 315×10^3 to 340×10^3 ppb (parts per American billion, or 10^9, by volume) since 1958. This increase is attributed to the burning of carboniferous fuel (coal, gas, oil) which releases carbon dioxide into the atmosphere directly. In fact, only about half the CO_2 released in the burning of fossil fuel appears to have remained in the atmosphere; the remainder is believed to have been absorbed by the ocean.

Attempts to forecast the changes in concentration of atmospheric CO_2 over the next 100 years or so have been made by first estimating the world's energy requirements over the next century, and then postulating what fraction will be produced by burning fossil fuels; the resulting concentration of atmospheric CO_2 has usually been estimated by assuming that a fixed fraction remains airborne.

However, as living organisms both absorb and release CO_2 this may be too simple an approach and, alternatively, one can attempt to predict the uptake of CO_2 by the oceans and the biosphere in detail. As there is much uncertainty in both the projected use of fossil fuels and the partition of the resulting CO_2 between the atmosphere and the rest of the carbon cycle, it is not surprising that there is a wide range of concentrations predicted for future atmospheric CO_2. A typical forecast is that CO_2 will reach 600×10^3 ppb in the next 70 or 80 years, or about a doubling of the estimated pre-industrial level.

CO_2 absorbs long-wave radiation at wavelengths near 15×10^{-6} m. Although CO_2 is by far the most abundant of atmospheric pollutants, the effect of a doubling is relatively small since with the present concentrations of CO_2 and water vapour most of the radiation near this wavelength is already absorbed by the atmosphere. Simple one-dimensional models suggest a doubling of CO_2 concentrations will produce an increase of 2 K in global mean surface temperatures (Table I). Results from more complex but still incomplete three-dimensional models predict changes of just over 2 K, although one study predicted a rise of 3.5 K (National Academy of Sciences 1982). On this basis the expected warming over the last century would have been about 0.3 K, but this would have occurred within much larger variations due to other natural causes. As yet a CO_2 signal cannot be identified with confidence.

Table I. *Estimates of global mean change in surface temperature due to increasing the concentration of various trace gases, ignoring atmospheric chemistry (World Meteorological Organization 1982).*

Gas	Mixing ratio (ppb) Reference	Perturbed	Surface temperature change (K)
*CO_2	330×10^3	660×10^3	2.0
*N_2O	300	600	0.3–0.6
CH_4	1500	3000	0.3
*$CFCl_3$	0	1	0.15
*CF_2Cl_2	0	1	0.13
SO_2	2	4	0.02
O_3 (troposphere)	F(ø, z)	2F(ø, z)	0.9
O_3 (stratosphere)		25% decrease	0.5
H_2O (stratosphere)	3×10^3	6×10^3	0.6

* Clear evidence of increased tropospheric abundance of these gases. Water vapour feedback included implicitly.
F(ø, z) denotes the distribution of ozone with latitude and height.

Nitrous oxide (N_2O)

Measurements by Weiss (1981) indicate that the tropospheric concentration of N_2O may have increased by 4% since 1963. Weiss suggests that most, if not all, of the increase is due to the burning of fossil fuels, though some may be due to fertilizer nitrification. More extreme estimates suggest that the N_2O concentration could double by the end of the next century. Nitrous oxide absorbs radiation over several wavebands including one centred on 7.8×10^{-6} m near the edge of the atmospheric window, so although its present abundance is only about 300 ppb, a thousand times less than that of CO_2, one-dimensional models predict a 0.3 to 0.6 K rise in temperature with a doubling of N_2O concentration, compared with the 2 K expected on doubling the concentration of CO_2.

Chlorofluoromethanes (Freon 12 and Freon 11; CF_2Cl_2 and $CFCl_3$)

Although present concentrations of Freons are small (about 0.1 ppb) they are of interest because of their long lifetime in the atmosphere and their part in the catalytic destruction of ozone. They also have strong absorption bands in the atmospheric window. The observed increases of about 10% a year agree well with figures from industrial production, the only source. It has been speculated that concentrations will increase by a factor of 20 over the next century, causing a temperature rise of 0.5 to 0.6 K (World Meteorological Organization 1982).

Methane (CH_4)

Methane is a naturally occurring gas which absorbs infra-red radiation near the atmospheric window. Its present concentration is about 1.7 ppb and there is some evidence that it has been increasing in recent years, though it is not understood why. Model results suggest a doubling of methane concentration would increase global surface temperature by about 0.3 K.

Ozone (O_3)

Ozone absorbs incoming ultraviolet radiation, preventing radiation at wavelengths which are harmful to biological processes from reaching the surface. For example, there is some evidence that excessive exposure to ultraviolet radiation can cause skin cancer.

The concentration of ozone varies with height, latitude and season. However, the effectiveness of ozone as a shield against ultraviolet radiation is a function only of the amount of ozone between the top of the atmosphere and the earth's surface, referred to as the column density.

Early investigations on ozone concentrations were concerned with the possible reduction of stratospheric ozone by pollutants from stratospheric aircraft and, more recently, from Freons released from aerosol cans. Freons can lead to the catalytic destruction of ozone (that is, they can bring about the destruction of an ozone molecule without being changed themselves; one molecule of pollutant can take part in the destruction of many ozone molecules). The estimates of the change in column density with a given increase in Freon concentration have varied considerably over the last decade as our knowledge of the relevant stratospheric chemistry has increased. Latest estimates (World Meteorological Organization 1982) suggest that the ozone column density is not likely to be reduced by more than a few per cent. Nevertheless, the results from numerical models indicate that ozone concentrations would decrease in the upper stratosphere but increase in the lower stratosphere. As ozone also absorbs long-wave radiation strongly in the atmospheric window, this change in the vertical distribution would lead to a slight increase in surface temperature. Ten per cent of atmospheric ozone occurs in the troposphere. A doubling of tropospheric ozone would increase the earth's global mean surface temperature by about 0.9 K. It should be noted that the chemistry of ozone is dependent on temperature, so that an increase in CO_2 which would cool the stratosphere would also increase the concentration of ozone (for example, Groves *et al.* 1978).

Water vapour

Water vapour is not normally regarded as a pollutant. It is included since it absorbs long-wave radiation at most wavelengths. The amount of water vapour which the atmosphere can hold increases rapidly with temperature. Any change which warms the lower atmosphere is likely to increase the concentration of water vapour, producing a further atmospheric warming. This is often referred to as the 'water vapour feedback'. Changes in water vapour concentrations can also alter the levels of tropospheric ozone by perturbing the chemical equilibrium.

Particulate matter

Small particles suspended in the atmosphere (aerosols) may perturb the fluxes of both solar and long-wave radiation in the atmosphere. Dittberner (1978) estimated that about a third of the aerosols released in the atmosphere originate from man's activities, including the burning of fossil fuels and agriculture.

As the typical lifetime of a tropospheric aerosol is only a few days, the concentration of 'anthropogenic' aerosols falls off sharply away from regions of industrial and agricultural activity. It is difficult to obtain evidence of a long-term trend in aerosol concentrations because of the large temporal and spatial variabilities. The effect of aerosols on climate depends on the size and shape of the particles, their radiative properties and vertical distribution. An aerosol layer both reflects and absorbs solar radiation. The aerosol layer becomes warmer but the surface receives less radiation and cools. Kellogg (1977) has suggested that an increase in aerosol over a highly reflective surface such as the Arctic will produce a local warming, whereas over a dark surface it will lead to cooling. In short, the effect of man-made aerosols on global climate is uncertain and likely to be small. There is evidence that volcanic aerosols which reach the stratosphere where they persist for several months may influence global mean surface temperatures (for example, Hansen *et al.* 1978).

Summary

The above list is far from complete but it includes constituents which are more likely to affect the earth's climate. A more complete account is given by the World Meteorological Organization (1982). The main point is that the size of the effect depends not only on the concentration of the pollutant but also on the wavelength at which it absorbs radiation, the strength of the absorption and its lifetime in the atmosphere.

4. Simple models of climate

Most of the predicted changes in global mean surface temperature described in the previous section were obtained using simple climate models consisting of a single atmospheric column with globally averaged conditions. In this section the physical processes represented in such models are described and the limitations of the model results are emphasized.

The earth's surface is heated by solar radiation and cooled by the emission of long-wave radiation, and the loss of heat to the atmosphere through conduction, or evaporation of moisture (Fig. 2.). The atmosphere is cooled by long-wave radiation and heated by conduction from the surface, and by latent heat released during the condensation of water vapour evaporated from the surface. Heat and moisture are transported from the surface and distributed throughout the troposphere by vertical atmospheric motions (convection), producing a global mean reduction of temperature with height (lapse rate) of about 6 K km^{-1}.

A radiative convective model mimics these processes at a set of levels in the atmospheric column, known as grid points. The radiative heating or cooling is calculated by solving the standard equations of radiative transfer at each level in the atmosphere. The redistribution of heat and moisture from the surface is accomplished by not allowing the reduction of temperature with height to exceed some observed value (for example, the global mean) or by attempts to represent the vertical redistribution of heat more explicitly. (More sophisticated models may incorporate the effects of ozone chemistry.) The change in surface temperature due to an increase in the concentration of a given gas may be found by running the model to equilibrium with the present-day and perturbed vertical distributions of absorbing gases.

These models are relatively cheap to construct and use and can provide valuable insight into the physical processes through which pollutants may affect climate. For example, if the concentration of CO_2 in a typical atmospheric profile is doubled, there is an instantaneous increase of 1 to 2 W m^{-2} in the downward flux of radiation at the surface (Ramanathan 1981). This is small compared with the ambient fluxes which are of the order of 100 W m^{-2} (Fig. 2). If the atmospheric profile is allowed to respond radiatively (ignoring the expected increase in the transfer of heat from the surface) the troposphere

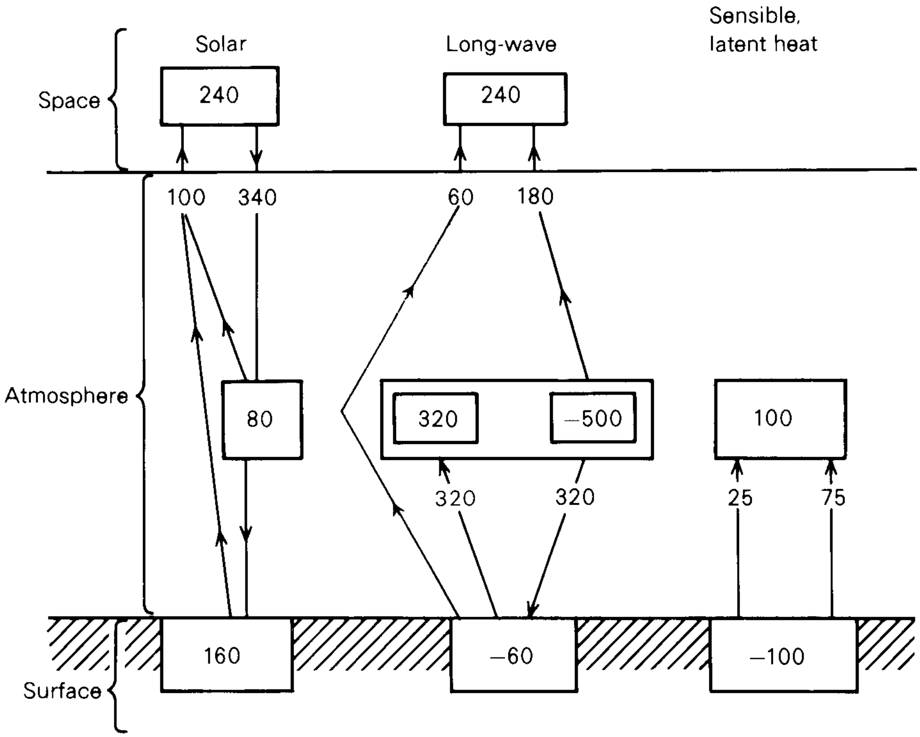


Figure 2. Simplified heat balance of the earth and atmosphere. The figures are derived from satellite observations and general circulation model results, and should be regarded as only approximate. Units are W m^{-2}.

warms and the downward flux of long-wave radiation increases by 3 W m^{-2}. If the changes at the surface are allowed to feed back to the atmosphere, there is a further increase in surface heating of about 12 W m^{-2}, largely through the water vapour feedback discussed earlier. The associated changes in surface temperature are given in Table II. This shows that doubling CO_2 produces a small perturbation in the atmospheric heat balance, which is amplified by several positive feedbacks.

Table II. *Effect of doubling CO_2, with and without feedbacks, in a radiative convective model (Ramanathan 1981).*

	No feedback	Radiative warming of troposphere	Surface, water vapour feedbacks
Effect on troposphere	3 W m^{-2} warming	Increased temperature	Increased temperature, humidity
Surface flux increase (W m^{-2})	1.2	3.5	15.5
Surface temperature change (K)	0.17	0.5	2.2

In the example above it was assumed that the relative humidity of the atmosphere remained unchanged. Results from another single-column model (Rowntree and Walker 1978) demonstrate the sensitivity of results to this and other assumptions. If the water vapour content (absolute humidity) of the atmosphere is held constant, doubling CO_2 produces an increase of 1.29 K, whereas making the water vapour concentration increase with temperature by fixing relative humidity produces almost twice the effect. Neither assumption is correct, though the second assumption is generally felt to be more realistic. Other choices will affect the magnitude of the response. For example, the response due to doubling CO_2 is smaller when cloud is included in the model than when it is omitted (Table III). In low latitudes much of the increased heating received at the surface due to increasing CO_2 is transferred to the atmosphere by the evaporation of water vapour and released as latent heat. When this process is taken into account the temperature rise at the surface is smaller, and the rise in the atmosphere is larger than that found using the global mean lapse rate.

Table III. *Sensitivity of radiative convective model results to imposed assumptions (Rowntree and Walker 1978)*

Assumption	Temperature change on doubling CO_2 (K)
Fixed absolute humidity	1.29
Fixed relative humidity	
(a) No cloud	2.46
(b) Average cloud	2.20
(c) Average cloud, allowance for latent heat	1.40

Many of the factors governing climate, such as orography, ocean temperatures, winds, sea ice and land–sea contrast cannot be represented in a single-column model, nor can such a model predict the changes at a given location at a given season. At best, it can give a crude estimate of the likely change in global mean surface temperature. Three-dimensional models of climate have the potential to provide more detailed estimates of climate change which are required by agriculture and other industries.

5. Three-dimensional models

In a three-dimensional atmospheric general circulation model the values of temperature, humidity and wind are stored at points around the globe on a horizontal grid at several levels in the atmosphere. In the Meteorological Office 5-layer model these grid points are about 330 km apart, and the state of the atmosphere at a given instant is represented by 10^5 numbers (Corby *et al.* 1977). These values are updated time-step by time-step by solving the equations of motion and thermodynamics at each point, subject to the mass, heat and moisture of the system being conserved. The grid-point values are updated every 10 minutes, and it requires 15 minutes of central processing time on an IBM 360/195 to advance the model by one day.

There are many atmospheric processes which occur on scales much smaller than that of the horizontal and vertical grid (for example, convective precipitation) and so cannot be modelled exactly. Their effect is represented in simplified forms (parametrizations) which are based on observations of the real atmosphere, on laboratory experiments or on results from more detailed numerical models.

In principle, a general circulation model can be used to forecast the day-to-day development of individual disturbances from a given initial atmospheric state. As with numerical models which have been specifically designed for such work, the accuracy of the forecast deteriorates with time until, after two or three weeks, the forecast fields contain little or no forecasting skill. For climate prediction, however, the models are run over much longer periods (months or even years) and the long-term mean behaviour of the simulations is studied. The climate of the model may be assessed by comparing the simulation obtained from a model with present-day sea surface temperatures, sea ice extents, CO_2 concentrations and so on, with climatological data. For example, the surface pressure pattern meaned over the final three northern summers of a four-year integration with the Meteorological Office 5-layer model (Fig. 3(a)) includes all the main features of the observed circulation (Fig. 3(b)), including the anticyclones centred over the winter continents and the summer oceans, the region of low pressure in the tropics which extends into the monsoon low over Asia, and the zone of low pressure over the southern ocean off Antarctica.

Estimates of the change in climate are found by comparing a simulation made with the standard model (the control integration) with a parallel simulation (the anomaly integration) in which only the relevant parameter (for example, the CO_2 concentration) has been changed. However, the model atmosphere, like the real atmosphere, shows an inherent year-to-year variability, so statistical tests must be carried out to show that the differences between the control and anomaly integrations are due to the changes in the model (in our example, the increase in CO_2) and are unlikely to have arisen by chance.

A full climate model should incorporate all the elements which contribute to climate, including the oceans and the continental ice sheets. Coupled ocean–atmosphere models are in their infancy and, as yet, the detailed interactions between the atmosphere and ocean and the major ice sheets have not been included in climate models. Hence, I will describe a few results from a model in which the continental ice sheets were held constant, sea ice extents were unchanged but a 2K increase in sea surface temperature was prescribed and CO_2 amounts were doubled (Mitchell 1983). The ocean temperature rise was chosen largely on the basis of single-column results.

The changes in surface temperature during winter (December to February) and summer (June to August) due to increasing CO_2 concentrations and sea surface temperatures, shown in Fig. 4, vary considerably with season and location. There are particularly large changes near 55°N in winter, which are due in part to the increased absorption of solar radiation by the land surface in the region where the model's snow line has retreated. The large rises over Scandinavia and north-western Russia, where there is little winter insolation, are due to increased westerly flow which has led to an increase in the frequency of occasions with winds off the warm ocean, and a decrease in the frequency of winds blowing from the centre of the cold Asian continent. In summer the largest rises (4–5 K) are found in the centre of the Eurasian continent. There is a noticeable minimum over western Europe, possibly due to the prevailing westerly flow (Fig. 3(a)) which carries air from an ocean which has been warmed by only 2 K. The variations in the seasonal changes are even more marked in precipitation (Fig. 5). In general, precipitation decreases over large areas of the subtropics, but generally increases in the inner tropics, along the eastern coasts of the summer continents, and over much of middle and high latitudes, particularly in the winter hemisphere. The broad zones of increased and reduced precipitation are further north during June to August, so that some regions are drier in the winter and wetter in the summer, and vice versa.

The assumption of a uniform increase in sea surface temperature is probably unrealistic, so a further integration has been performed in which the rise in sea temperatures increases with latitude, changes in high latitudes being over twice those at the equator (Mitchell and Lupton 1983). The changes in soil moisture (surface wetness) in this and the previous experiment are shown in Figs 6(a) and (b) respectively. Both experiments predict a drier land surface over most of North America and Eurasia between 30° and 60°N and a wetter surface over Mexico, south-east Asia and south-west Africa. Note that the predicted changes are inconsistent over the Sahara and the east of North America. These results

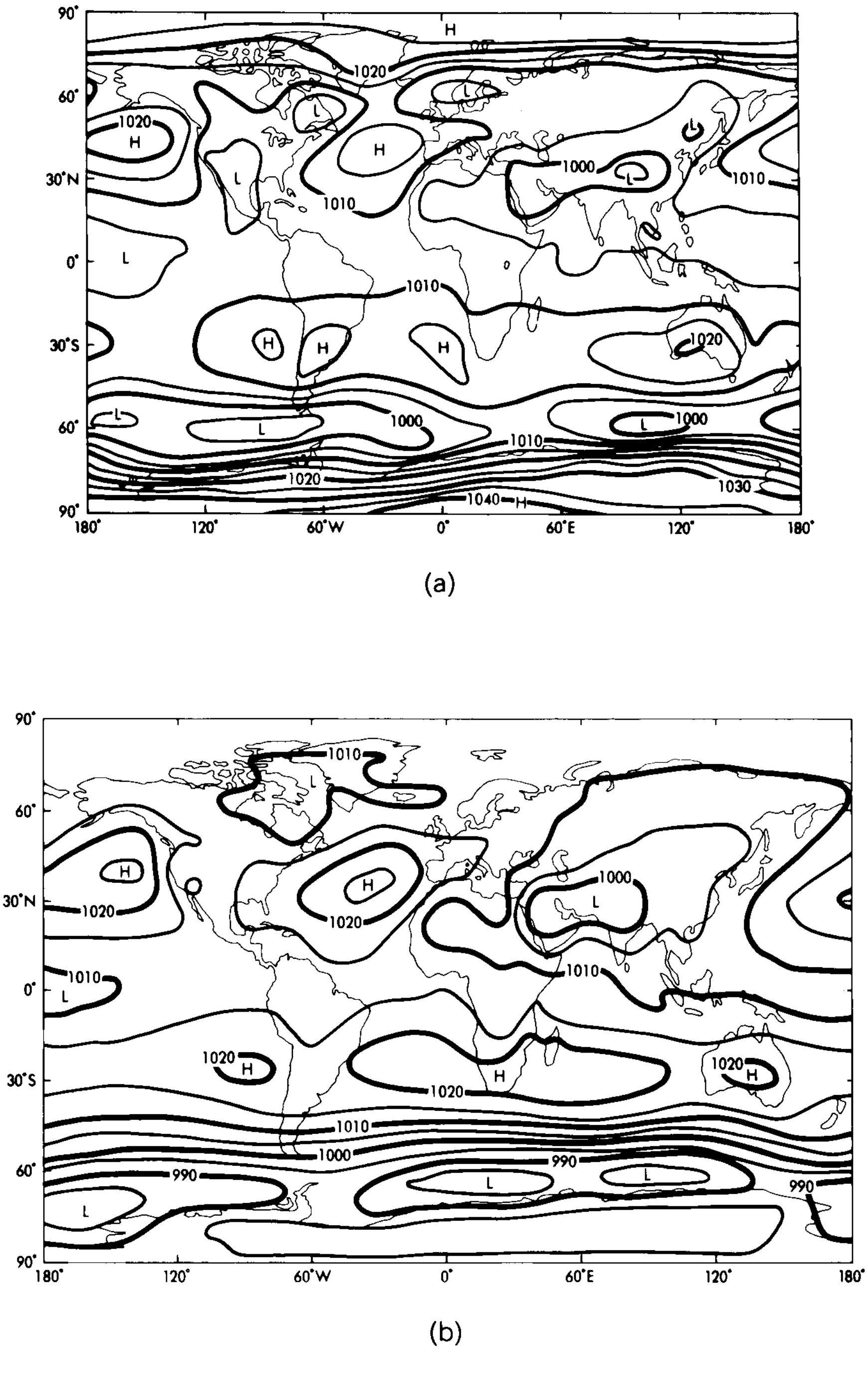


Figure 3. Pressure at mean sea level (isobars at 5 mb intervals).
(a) From Meteorological Office 5-level model, June, July and August.
(b) Observed, July (from Schutz and Gates 1972).

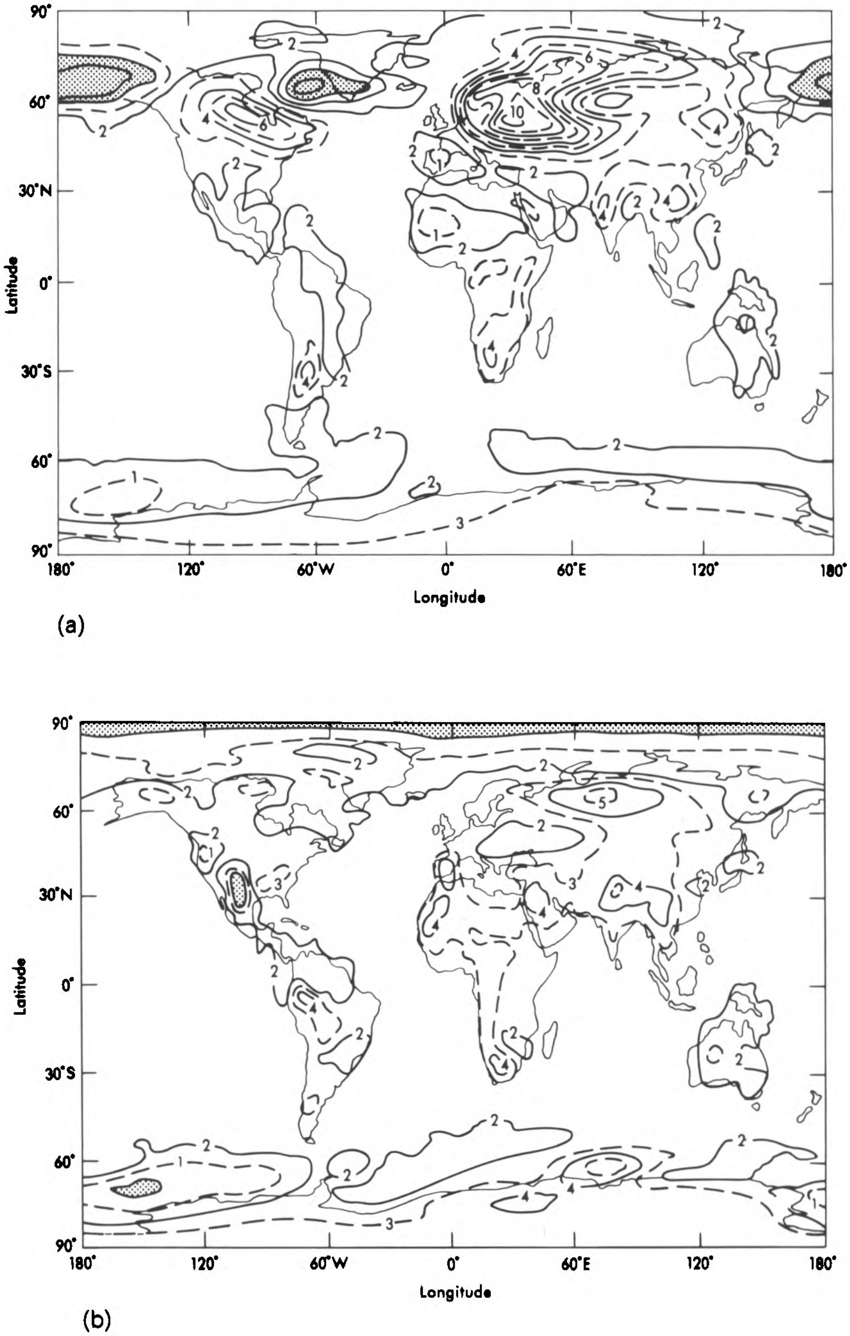


Figure 4. Changes in model surface temperatures due to doubling CO_2 and increasing sea temperatures by 2 K. Isopleths are drawn at 1 K intervals with odd-numbered isopleths indicated by dashed lines; areas of decrease are stippled.
(a) Winter (December, January and February).
(b) Summer (June, July and August).

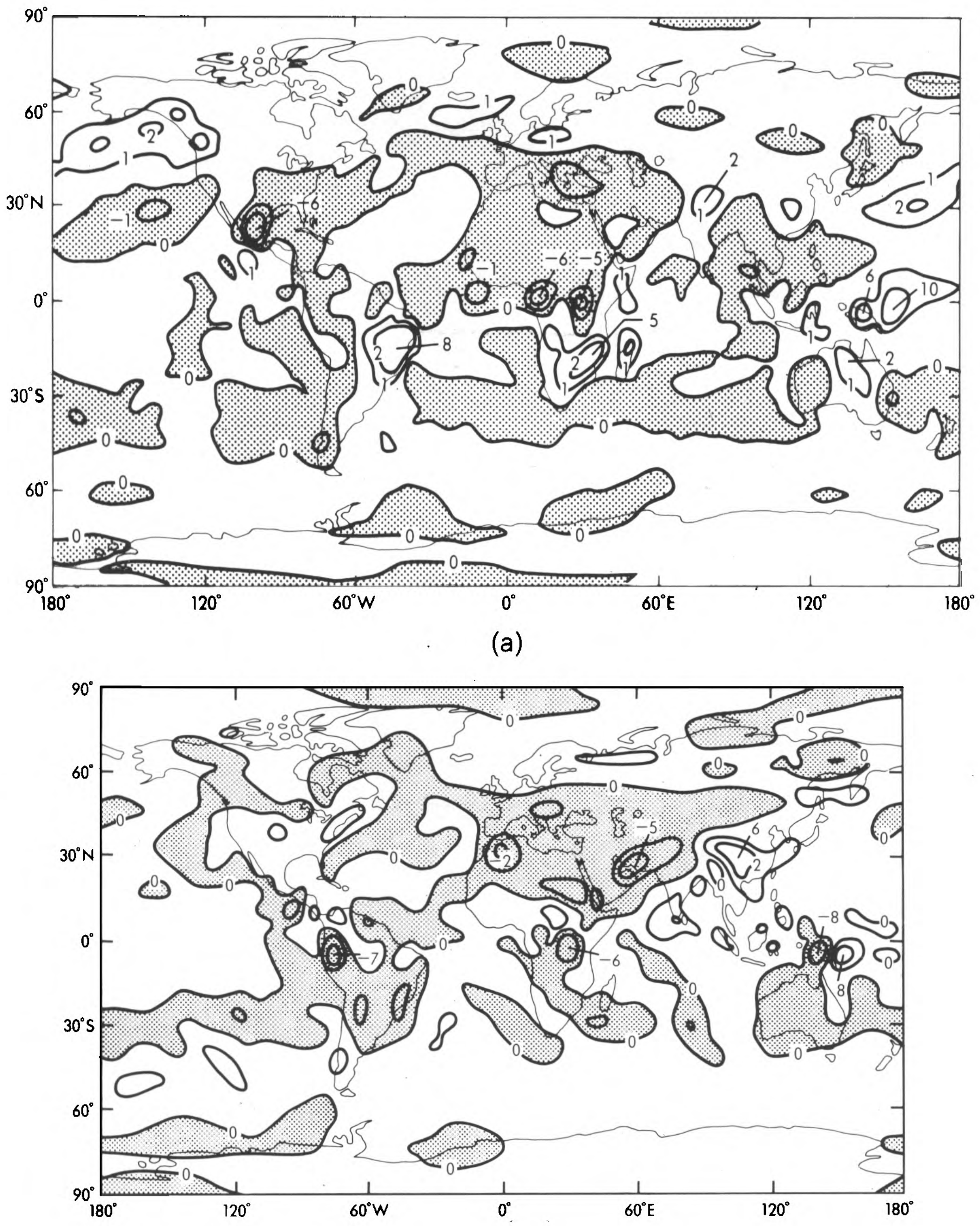
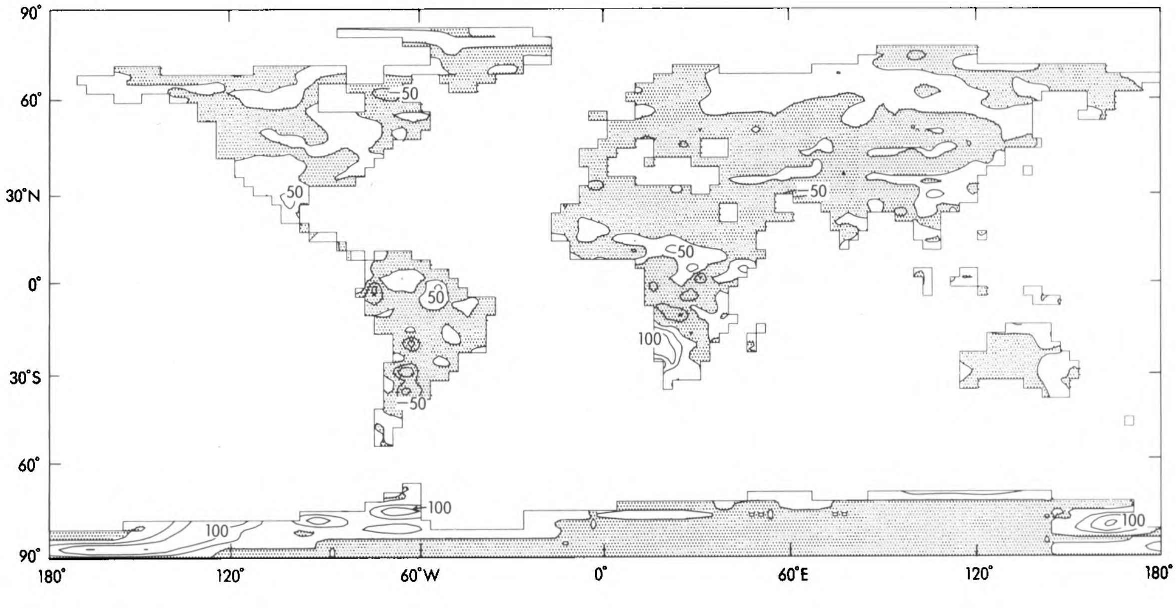
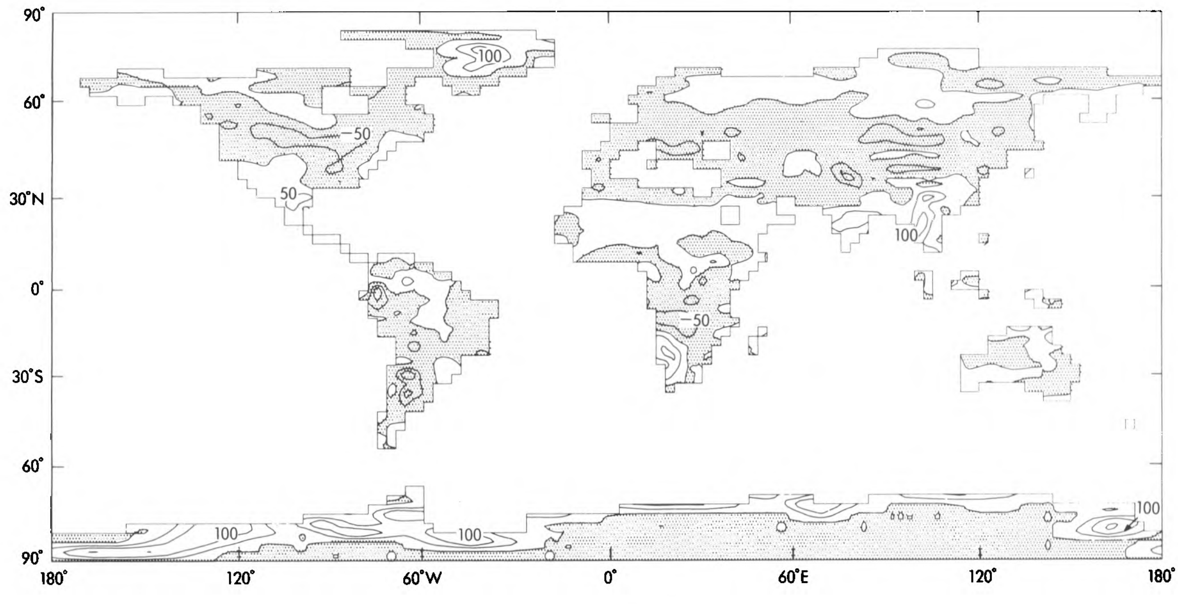


Figure 5. Changes in model precipitation due to doubling CO_2 and increasing sea temperatures by 2 K. Isopleths are drawn at 1 mm/day intervals; areas of decrease are stippled.
(a) Winter (December, January and February).
(b) Summer (June, July and August).



(a)



(b)

Figure 6. Changes in model soil moisture in summer (June, July and August). Isopleths are every 50 mm; areas of decrease are stippled.

(a) Due to doubling CO_2 and a uniform 2 K increase in sea temperatures.

(b) Due to quadrupling CO_2 and rises in sea temperature which increase with latitude. (Changes should be halved for comparison with Fig. 6(a)).

give some guide to the reliability of predicted changes in regional climate obtained to date. The only other published accounts of detailed seasonal changes in a climate model (Manabe and Stouffer 1980, Manabe *et al.* 1981) described the effects of quadrupling CO_2 in an atmospheric model coupled to a simple model of the upper ocean. Despite the difference in the models used, the changes in the hydrological cycle are generally similar to those described here.

6. Concluding remarks and summary

I have described in some detail the physical processes through which pollutants influence climate and how those processes are represented in numerical models of climate. Although the initial change in radiative heating due to increased pollutants is in most cases known with reasonable accuracy, the subsequent response of the atmosphere and other elements influencing climate is less well understood.

There are several ways in which our understanding of man's impact on climate is being advanced. The contribution from chemically active gases is continually being updated as measurements of concentrations and reaction rates are revised. The parametrization of physical processes in climate models is being improved through both observational studies and numerical experiments. The most recent climate models represent the ocean explicitly. The increase in computing power made available by the advent of vector computers will enable models with adequate horizontal resolution to be integrated over decades rather than years. Nevertheless, the problem of understanding climate and climate change will occupy atmospheric scientists for many years to come.

Measurements made over the last decade or so have shown that the concentration of certain trace gases is increasing. In most cases the increase can be attributed to man's activities. The increase in the concentration of those gases which are radiatively active is expected to raise the global mean surface temperature. The magnitude of the contribution of an individual constituent to this rise depends not only on the size of the increase in concentration but also on the gas's capacity to absorb long-wave radiation and the wavelengths at which it does so. The increase in chemically active constituents will alter the vertical distribution of ozone, though present estimates indicate that the total amount of ozone will not be greatly affected.

Many of the statements which have been made concerning the effects of pollutants on climate have been based on evidence from single-column models of the atmosphere. The results depend to a great extent on the assumptions made in the model and do not take into account many of the elements which govern climate. Even where three-dimensional climate models have been used to study the consequences of increased CO_2, considerable simplifications, particularly in the treatment of oceans and cloud, have been made. However, these studies do indicate that the changes accompanying a global warming would vary considerably with time of year and geographical location, and that changes in the hydrological cycle are likely to be as important as the changes in temperature.

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I am grateful to Dr A. Tuck for drawing my attention to the most recent estimates of concentrations of trace gases and their potential effects, and to members of the Dynamical Climatology Branch, past and present, who have contributed to the development and running of the atmospheric general circulation model featured in this paper.

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Changes in the seasonal variation of temperature over the United Kingdom between 1861 and 1980

By S. G. Smith

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Summary

Harmonic analysis of daily mean maximum and daily mean minimum temperatures has been performed for (i) five UK stations using data for 1901–30 and 1941–70 separately and (ii) for Oxford using data for ten overlapping 30-year periods between 1861 and 1980. Differences are observed between the different periods in the amplitudes of the first (annual) harmonic and the amplitude and phase of the second harmonic. These differences are interpreted in terms of changes in the seasonal variation of temperature.

1. Introduction

Some time ago the climatological research group in the Climatological Services Branch of the Meteorological Office were asked to give advice relating to the variation of temperature through the winter months. In the course of answering this enquiry it was found that 30-year means of daily temperatures failed to remove irregular day-to-day variations in the temperatures. The means also produced apparent warm or cold spells of several day's duration which were, in general, purely a function of the particular period chosen. These features are illustrated in Fig. 1, which is a plot of mean daily maximum temperatures at Oxford for 1 January to 17 February over the periods 1901–30 and 1941–70.

Harmonic analysis of the data was therefore undertaken to smooth out the 'noise' and this was considered to produce a more satisfactory description of the seasonal variation than the raw 30-year means. This form of analysis has been carried out by, amongst others, Craddock (1956a) who investigated the amplitude and phase of the first and second annual harmonics of monthly mean temperatures at 160 stations in the British Isles, using data for 1921–50. In a related paper (1956b) he fitted two-term annual harmonics to non-overlapping five-day means of daily temperatures at 42 stations in central and northern Europe. In both papers his primary interest was to determine the spatial patterns in the parameters, in particular relating variations in the phase of the second harmonic to changes in the seasonal variation of temperature.

In this paper harmonic analysis was performed on daily maximum and daily minimum temperatures from five United Kingdom stations using data for 1901-30 and 1941-70. The procedure was then repeated on Oxford data only for ten overlapping 30-year means between 1861 and 1980, the results of which are assumed to be applicable to the other four stations and indicate differences that can occur in the seasonal variation over different 30-year periods.

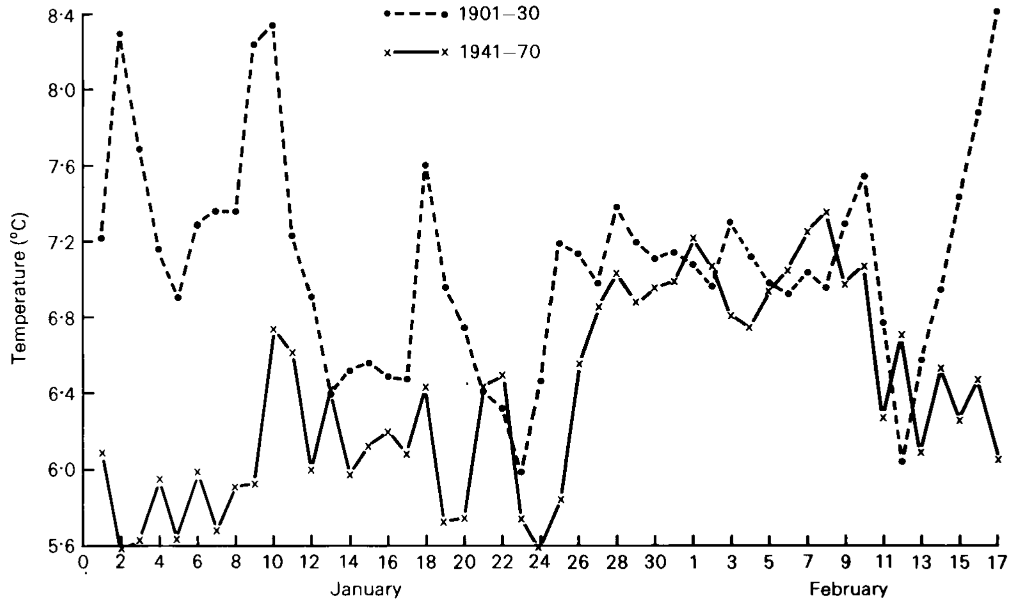

Figure 1. Mean daily maximum temperatures at Oxford for 1 January to 17 February, over the periods 1901-30 and 1941-70.

2. Data

Five widely scattered stations having almost unbroken daily maximum and minimum temperature records between 1900 and 1970 were selected for the first part of the analysis. These five are Plymouth, Oxford, Armagh, Durham and Gordon Castle, and their locations are shown in each of Figs 2-5. Minimum temperatures for Gordon Castle for October 1956 are missing and are therefore excluded. Temperatures are available for Oxford since 1853 and data for 1861 onwards have been used for the second part of the analysis.

With regard to the homogeneity of the observations, Smith (1978) found evidence for changes in the mean of the Plymouth maxima and minima series which may be due to the change of site between the Hoe and Mount Batten in 1930. There is also a possibility that the series for the other stations are not entirely homogeneous owing to minor changes of site or changes in observing hour, or both. However, since the main purpose of this study is to investigate changes in the variation of temperature within a year, these potential inconsistencies should not seriously affect the analysis.

3. Method of analysis

Future references to 'maxima' and 'minima' will denote the highest and lowest daily values. 'Peak value' will refer to the highest temperature attained by a harmonic in the regression model described below.

For each 30-year period and for each station, maxima and minima were averaged separately for each day of the year; 29 February was omitted, so each series comprised 365 terms. Each term y_t was assumed to follow an expression of the form

$$y_t = \bar{y} + \sum_{i=1}^{N} (a_i \cos ict + b_i \sin ict),$$

where $\bar{y}$ is the mean, a_i and b_i are the components of the ith annual harmonic (up to i=N), $c=2\pi/365$ and t is measured in days from midnight on 31 December.

It was found that the first two harmonics accounted for over 95% of the variance of both the maxima and minima series and higher-order harmonics were therefore neglected.

The components of the first two harmonics were estimated using a least-squares regression program available in the BMDP statistical package (Dixon and Brown 1979). The amplitudes A_i and the phases ϕ_i were calculated from the components, where

$$A_i = (a_i^2 + b_i^2)^{1/2}$$

and $$\phi_i = \arctan (b_i/a_i).$$

The date of the peak value of the first harmonic and the date of the summer peak value of the second harmonic were determined from ϕ.

4. Results

Results are presented in two sub-sections. Section 4.1 relates to analyses for the five stations over the periods 1901–30 and 1941–70. Section 4.2 considers Oxford data only for the longer period 1861–1980.

4.1 *Five stations, 1901–30 and 1941–70*

Table I presents means and variances of the y_t values together with amplitudes and phases of the first and second harmonics. For both maxima and minima the 1941–70 means are about 0.3 °C higher than the 1901–30 means, the exception being the Plymouth maxima (which may be due to the effects of site change). The general increase occurs despite the fact that January and February temperatures are lower in the 1941–70 period. The variances are also higher in the later period, which is mainly a reflection of the fact that there is a greater annual range of daily temperatures for 1941–70.

The standard errors of the amplitude and phase of the first harmonic have been derived from the standard errors of the components supplied by the BMDP regression program. That of the amplitude was found to be approximately 0.04 °C and that of the date of peak value 0.4 days, with the latter inversely proportional to the amplitude. The variance of the amplitude is given by $A^2/2$ where A is the amplitude. In the table this variance is expressed as a proportion of the variance of the series.

It is seen that the amplitude for maxima is 20–30% greater than for minima and the date of peak value occurs 8–11 days earlier. The result for the amplitudes is a measure of the greater annual range of maxima; that for the dates of peak value probably arises from the fact that:

(i) maxima are highly related to the amount of solar radiation received at the earth's surface and the maximum and minimum elevation of the sun occurs in June and December respectively, and

(ii) minima are governed more by the atmospheric dew-point which in turn is related, amongst other factors, to the earth and sea temperatures which reach their maximum and minimum after the solstices.

The proportion of variance of the daily means accounted for by the first harmonic increases slightly between 1901–30 and 1941–70 for maxima (except at Gordon Castle) and more substantially for minima. The peak value date for both variables remains fairly constant, the only appreciable change occurring for Plymouth minima.

Table I. *Summary data for each station and period.*

Station and period		Mean (°C)	Variance (°C)^2	First harmonic: Amplitude: Value (°C)	First harmonic: Amplitude: Variance as % of total	First harmonic: Phase: Date of peak value (day/month)	Second harmonic: Amplitude: Value (°C)	Second harmonic: Amplitude: Variance as % of total	Second harmonic: Phase: Date of summer peak value (day/month)
(a) Maxima									
Oxford	1901–30	13.68	28.14	7.42	97.8	19/7	0.55	0.54	13/8
	1941–70	13.89	31.14	7.82	98.2	20/7	0.43	0.30	8/9
Plymouth	1901–30	13.76	16.81	5.73	97.6	27/7	0.47	0.66	11/8
	1941–70	13.48	17.00	5.78	98.2	28/7	0.24	0.17	2/9
Armagh	1901–30	12.60	18.97	6.09	97.7	20/7	0.54	0.77	8/8
	1941–70	13.04	20.69	6.38	98.4	19/7	0.36	0.31	8/9
Durham	1901–30	11.85	23.43	6.76	97.5	22/7	0.63	0.85	8/8
	1941–70	12.38	26.22	7.17	98.1	22/7	0.43	0.35	4/9
Gordon	1901–30	11.87	19.79	6.20	97.1	22/7	0.55	0.76	9/8
Castle	1941–70	12.07	21.41	6.43	96.5	22/7	0.41	0.39	6/9
(b) Minima									
Oxford	1901–30	5.96	14.73	5.27	94.3	28/7	0.94	3.00	29/7
	1941–70	6.28	17.44	5.82	97.2	28/7	0.50	0.72	7/8
Plymouth	1901–30	7.66	12.09	4.78	94.5	1/8	0.82	2.78	28/7
	1941–70	7.89	12.20	4.86	96.8	5/8	0.34	0.47	5/8
Armagh	1901–30	5.39	11.22	4.56	92.5	31/7	0.98	4.28	27/7
	1941–70	5.68	12.77	4.96	96.2	30/7	0.48	0.90	12/8
Durham	1901–30	4.50	13.67	5.07	94.0	31/7	0.97	3.44	1/8
	1941–70	4.83	15.13	5.43	97.4	31/7	0.42	0.58	11/8
Gordon	1901–30	4.45	11.42	4.64	94.3	29/7	0.89	3.47	27/7
Castle	1941–70	4.82	13.41	5.11	97.3	30/7	0.39	0.57	9/8

Figs 2–5 show, for the first harmonic in 1941–70, the variation across the country of the amplitude (Figs 2 and 3) and date of peak value (Figs 4 and 5) for maxima and minima. The spot values shown are those for the five stations given in Table I; the isopleths are based on the pattern of variation observed by Craddock (1956a) but it would be unwise to infer absolute values from Figs 2–5 alone.

For the second harmonics, the standard error of the amplitude is again about 0.4 °C but the date of peak value approximately 2 days, with its magnitude inversely proportional to the amplitude. The variance explained for maxima is less than 1% of the total and shows a decrease from 1901–30 to 1941–70. For minima the amount explained is about 3.5% in 1901–30 but drops to below 1% in 1941–70. The phase of the second harmonic has also altered considerably, particularly for maxima. The date of peak value for maxima occurs about one month later in the 1941–70 period and 11 days later for minima, compared to 1901–30. These findings are discussed in Section 5.

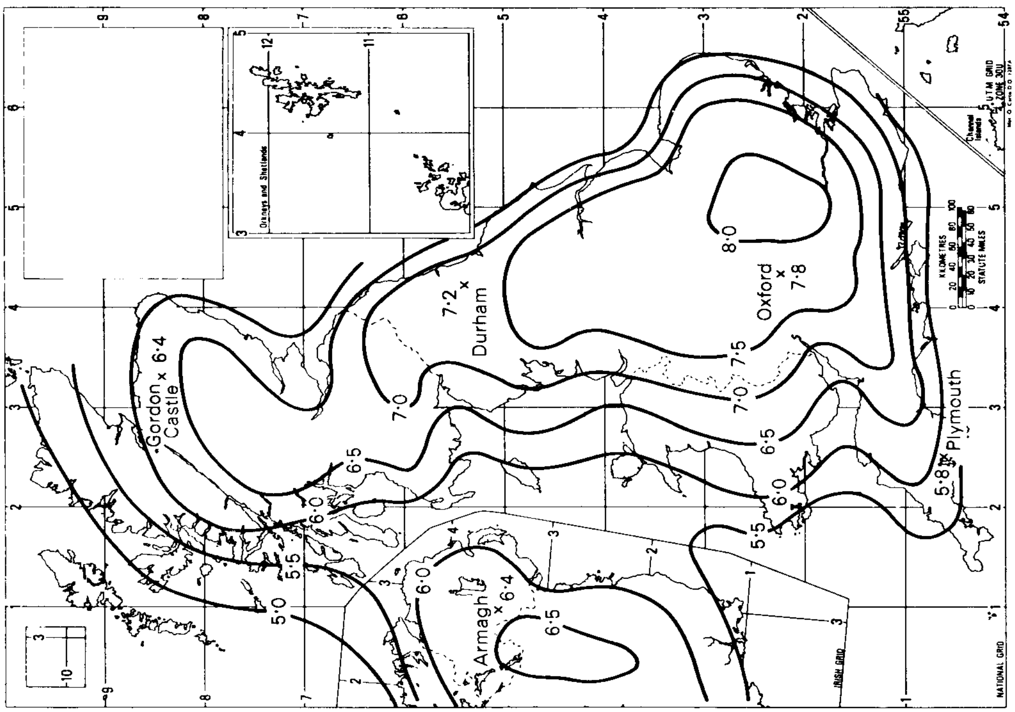

Figure 2. Maxima 1941–70. Amplitude of first harmonic (°C).

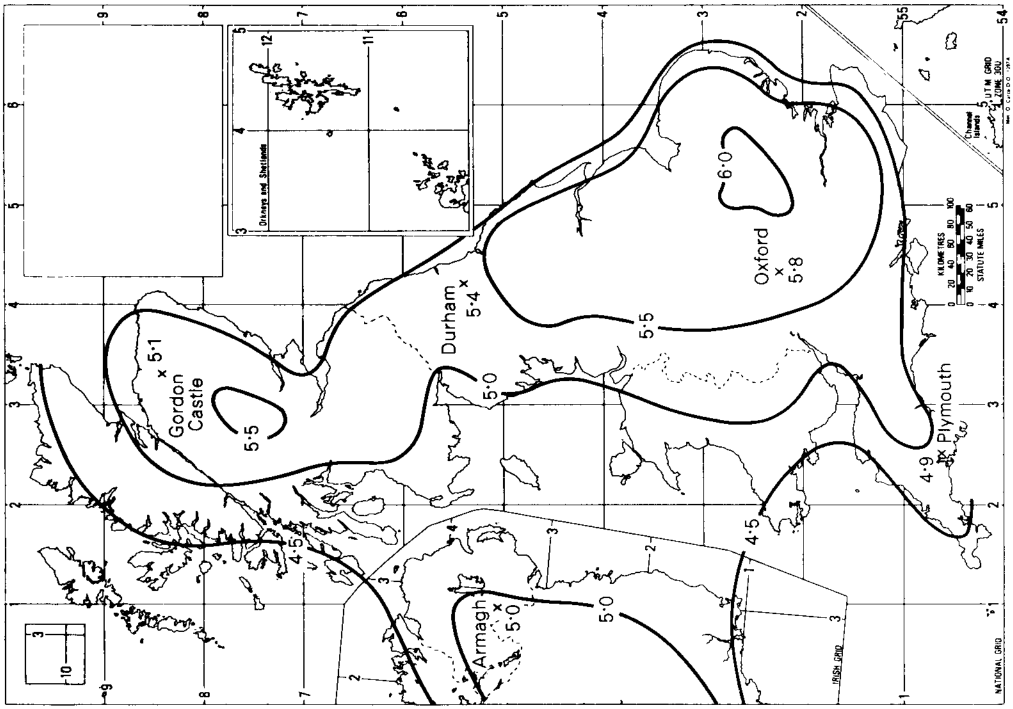

Figure 3. Minima 1941–70. Amplitude of first harmonic (°C).

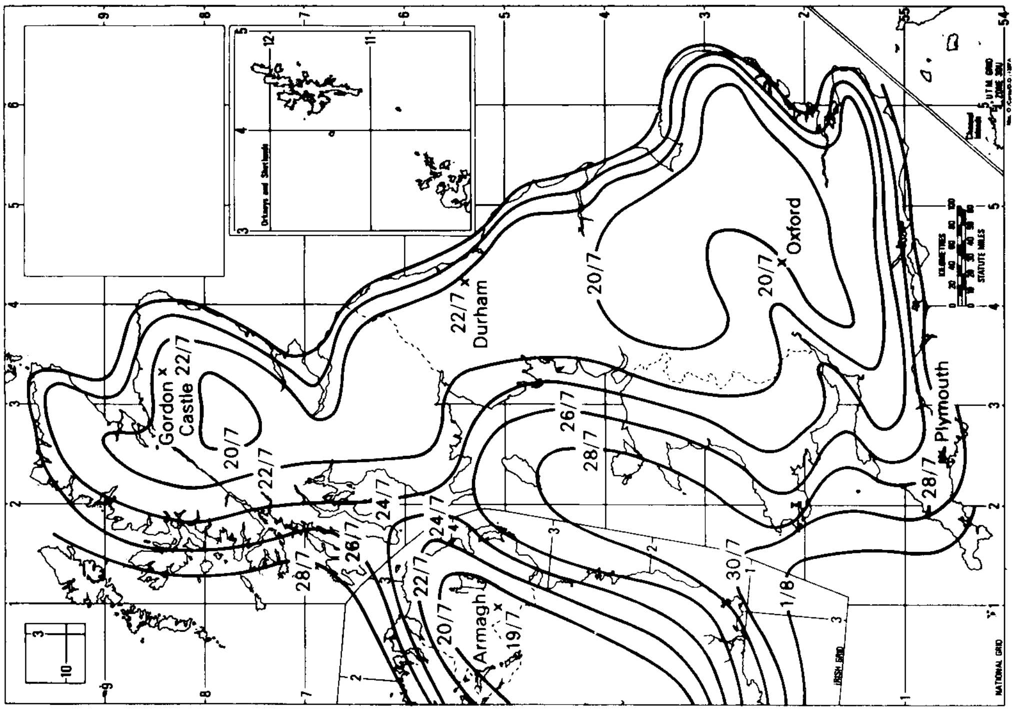

Figure 4. Maxima 1941–70. Date of peak value for first harmonic (day/month).

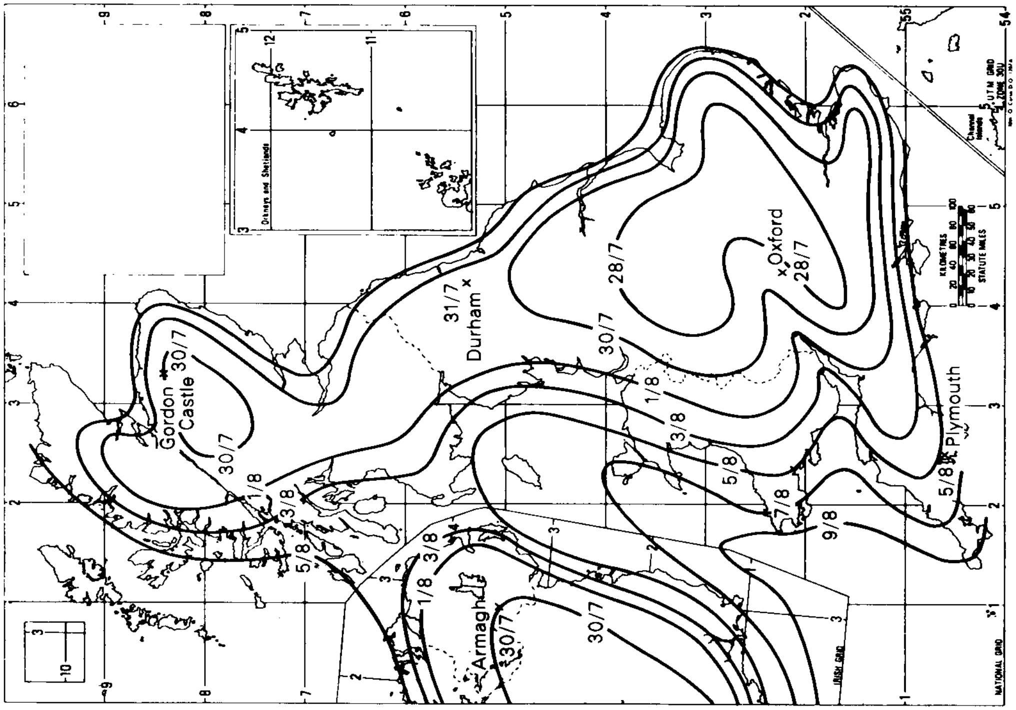

Figure 5. Minima 1941–70. Date of peak value for first harmonic (day/month).

4.2 *Oxford 1861–1980*

To relate changes in the magnitude and phase of the harmonics between 1901–30 and 1941–70 to other periods the analysis of 4.1 was repeated for the periods 1861–1890, 1871–1900, ... 1951–80 for Oxford data. The results of the previous sub-section showed little deviation from station to station in regard to the differences between 1901–30 and 1941–70. It is therefore assumed that results for Oxford presented below can be considered representative of the other four stations and indeed of the United Kingdom as a whole.

Various statistics are presented for the different periods in Table II. For maxima, the mean increases between 1881–1910 and 1921–50 followed by a decline. The variance reaches its maximum in 1941–70. For minima, the mean increases monotonically after 1881–1910 but for the variance the variation with time is more complex.

Table II. *Summary data for Oxford.*

			First harmonic			Second harmonic		
			Amplitude		Phase	Amplitude		Phase
Period	Mean (°C)	Variance (°C)^2	Value (°C)	Variance as% of total	Date of peak value (day/month)	Value (°C)	Variance as % of total	Date of summer peak value (day/month)
(a) Maxima								
1861–90	13.57	31.87	7.91	98.1	18/7	0.66	0.68	15/8
1871–1900	13.51	31.06	7.79	97.8	18/7	0.72	0.83	17/8
1881–1910	13.46	29.80	7.65	98.3	19/7	0.55	0.51	20/8
1891–1920	13.63	29.32	7.59	98.3	18/7	0.47	0.38	16/8
1901–30	13.68	28.14	7.42	97.8	19/7	0.55	0.54	13/8
1911–40	13.92	29.03	7.53	97.7	19/7	0.61	0.64	14/8
1921–50	14.12	30.32	7.70	97.8	19/7	0.68	0.76	16/8
1931–60	14.10	31.07	7.81	97.9	19/7	0.53	0.45	27/8
1941–70	13.89	31.14	7.82	98.2	20/7	0.43	0.30	8/9
1951–80	13.73	29.78	7.66	98.5	21/7	0.39	0.26	22/8
(b) Minima								
1861–90	5.83	15.65	5.45	94.7	27/7	0.82	2.15	3/8
1871–1900	5.78	16.25	5.56	95.2	28/7	0.93	2.66	30/7
1881–1910	5.77	15.88	5.52	96.1	29/7	0.79	1.97	26/7
1891–1920	5.91	15.23	5.40	95.7	28/7	0.85	2.37	26/7
1901–30	5.96	14.73	5.27	94.3	28/7	0.94	3.00	29/7
1911–40	6.04	15.37	5.41	95.1	27/7	0.91	2.69	28/7
1921–50	6.12	16.79	5.67	95.8	28/7	0.78	1.81	31/7
1931–60	6.21	17.51	5.82	96.8	28/7	0.61	1.06	29/7
1941–70	6.28	17.44	5.82	97.2	28/7	0.50	0.72	7/8
1951–80	6.29	16.71	5.70	97.1	29/7	0.54	0.87	2/8

Considering the first harmonic, the proportion of variance and the phase for maxima are relatively constant although some differences emerge for the most recent periods. For minima the phase is constant but the proportion of variance decreases until 1901–30 then increases.

In the results for the second harmonic the proportion of variance for maxima is highest in 1921–50 and has fallen since then. The date of peak value is earliest in 1901–30 and latest in 1941–70, the two periods considered in 4.1. For minima, these same two periods almost yield the two extremes for the proportion of variance and the date of peak value.

5. Interpretation of results

It has been shown that between 1861-90 and 1951-80 some large differences occurred in the proportion P_1 of the variance accounted for by the first harmonic and the corresponding quantity P_2 and date of peak value D_2 for the second harmonic. A period in which P_1 is relatively large and P_2 relatively small (for example 1941-70) has, on average, a seasonal variation in temperature more closely resembling a pure sine curve than a period for which the reverse is true, e.g. 1901-30. If D_2 is later in the year for one period than another (up to a maximum of 45 days later), as it is in 1941-70 relative to 1901-30, the winter trough is more pronounced and the summer peak extends later into the year, with a consequent decrease in length of the autumn season. These effects are displayed diagrammatically in Craddock (1956a).

It was decided to study the results in quantitative terms by comparing, for the periods 1901-30 and 1941-70, plots of daily values through the year generated from their respective means and first two harmonics only. These periods were chosen because in general they give the most extreme results, in opposite senses, for the phases and magnitudes of the harmonics. Plots for maxima and minima are given in Fig. 6; note that only values every fifth day are shown. It is observed that the features discussed above can be identified and that for maxima the greatest difference between the two curves is just under 1 °C (in the autumn). The same is true for minima but the differences are more pronounced with the greatest discrepancy between the two curves about 1 °C again occurring in the autumn. However, it is noted from Table I that the mean temperature difference (1941-70 minus 1901-30) is 0.2 °C for maxima and 0.3 °C for minima. If one therefore considers the differences in the seasonal variation with these mean differences removed, the maximum difference takes place in midwinter, equal to about 0.8 °C for maxima and 1.0 °C for minima.

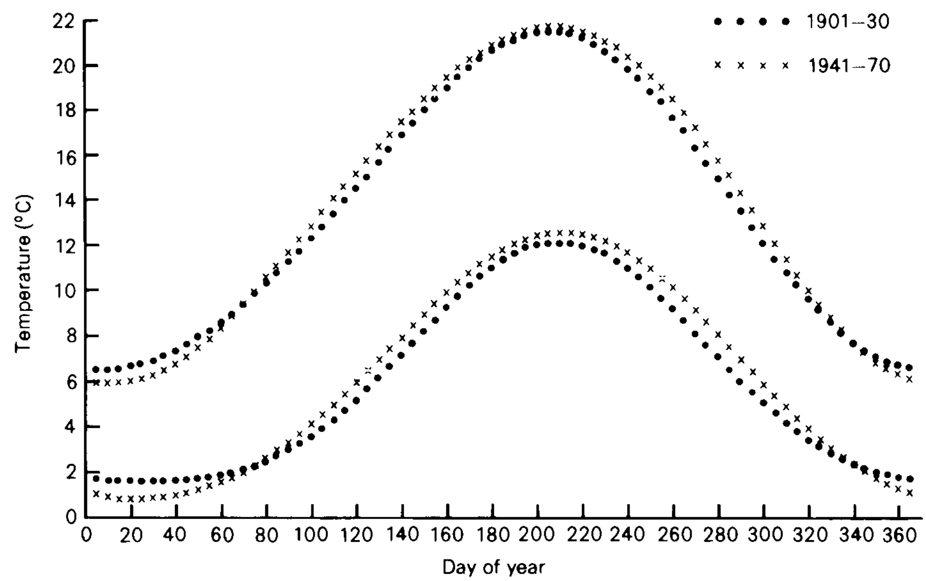

Figure 6. Generation of seasonal variation of maxima and minima from the means and first two annual harmonics for Oxford. (Points are plotted for every fifth day.)

6. Conclusion

Harmonic analysis of UK daily maximum and minimum temperatures averaged over different 30-year periods has shown some statistically significant differences in the amplitude of the first harmonic and the amplitude and phase of the second harmonic. When results are compared for the periods 1901–30 and 1941–70, the effect is observed to give a shorter but sharper winter for the later period, a summer which extends later into the year and a shorter autumn. In terms of temperatures, if differences in the annual mean are removed the greatest difference in the seasonal variation occurs in midwinter where 1941–70 averages are about 0.8–1.0 °C less than the 1901–30 values.

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The mystery of the missing bronze plaques

By R.P.W. Lewis

(Meteorological Office, Bracknell)

In 1911 the Director of the Meteorological Office (Dr Napier Shaw, as he then was) planned a series of bronze plaques for the entrance hall at the top of the main staircase in the new building at South Kensington, commemorating five distinguished meteorologists who had been intimately associated with official British meteorology. The three tablets were executed by the Bromsgrove Guild who also made the wooden plaques bearing the Meteorological Office emblem with interlaced MO letters, a rising sun and a weathercock (Lewis 1978)*. A short leading article in *Symons's Meteorological Magazine* for January 1912 stated:

> We reproduce in the frontispiece to this volume a photograph of the three tablets, which were executed by the Bromsgrove Guild, which is to be congratulated on the simple effectiveness of the work. The actual size of each is about 21 inches in length and 8 inches in height. We understand that casts in bronze of any of the medallions can be obtained from the Guild, for the price of £2.2s. each.
>
> First in date comes Admiral FitzRoy, who was the first Official Meteorologist in this country, and presided over the Meteorological Department of the Board of Trade from 1854 to 1865. No more enthusiastic pioneer in meteorology ever lived in this country, and no more fitting effigy than his could appear on the walls of the new Meteorological Office.
>
> The next plaque commemorates the Meteorological Committee of the Royal Society, which was responsible for the Meteorological Office from 1867 to 1877, and bears the heads of Lieutenant-General Edward Sabine, Chairman of the Committee, and of Dr. R. H. Scott, Director of the Office during this period. Dr. Scott is thus placed in the proud position of being honoured in his lifetime by a monument if not "more durable than brass," at least as enduring.

*Lewis. R.P.W.; The Meteorological Office badge. *Meteorol Mag*, **107**, 1978, 338–339.

The third records the Meteorological Council, with portraits of Professor Henry J.S. Smith, who was Chairman of the Council from 1877 to 1883 and of Sir Richard Strachey, perhaps the most successful of them all, who succeeded him and continued in office to the beginning of the new order in 1905.

(The frontispiece referred to is here reproduced as Fig. 1.)

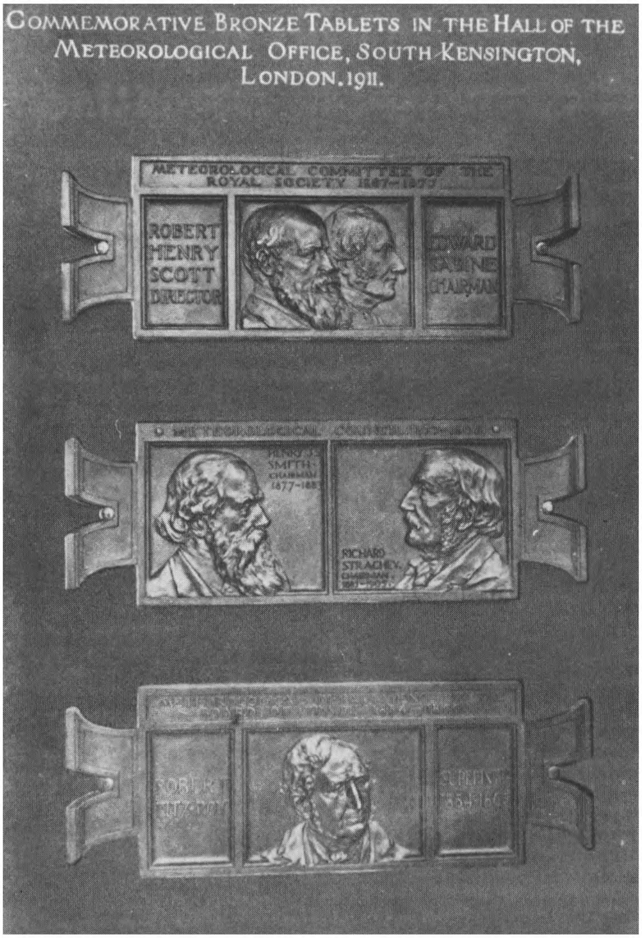


Figure 1

The plaques remained in place in the South Kensington building until the Second World War. After the war it seems that they were placed on display in the conference room in Victory House, Kingsway, the principal Meteorological Office Headquarters until the move to Bracknell in 1961. Since that time they have been lost, probably having disappeared during the move. An attempt was made a few years ago to trace their whereabouts but was unsuccessful, possibly because by that time everyone who had been actively concerned with implementing the move was dead. Perhaps they are still languishing in a packing case in a store-room on some remote airfield. We shall be glad to hear from anyone who can provide either a clue, or a replacement set originally purchased for six guineas by his grandfather.

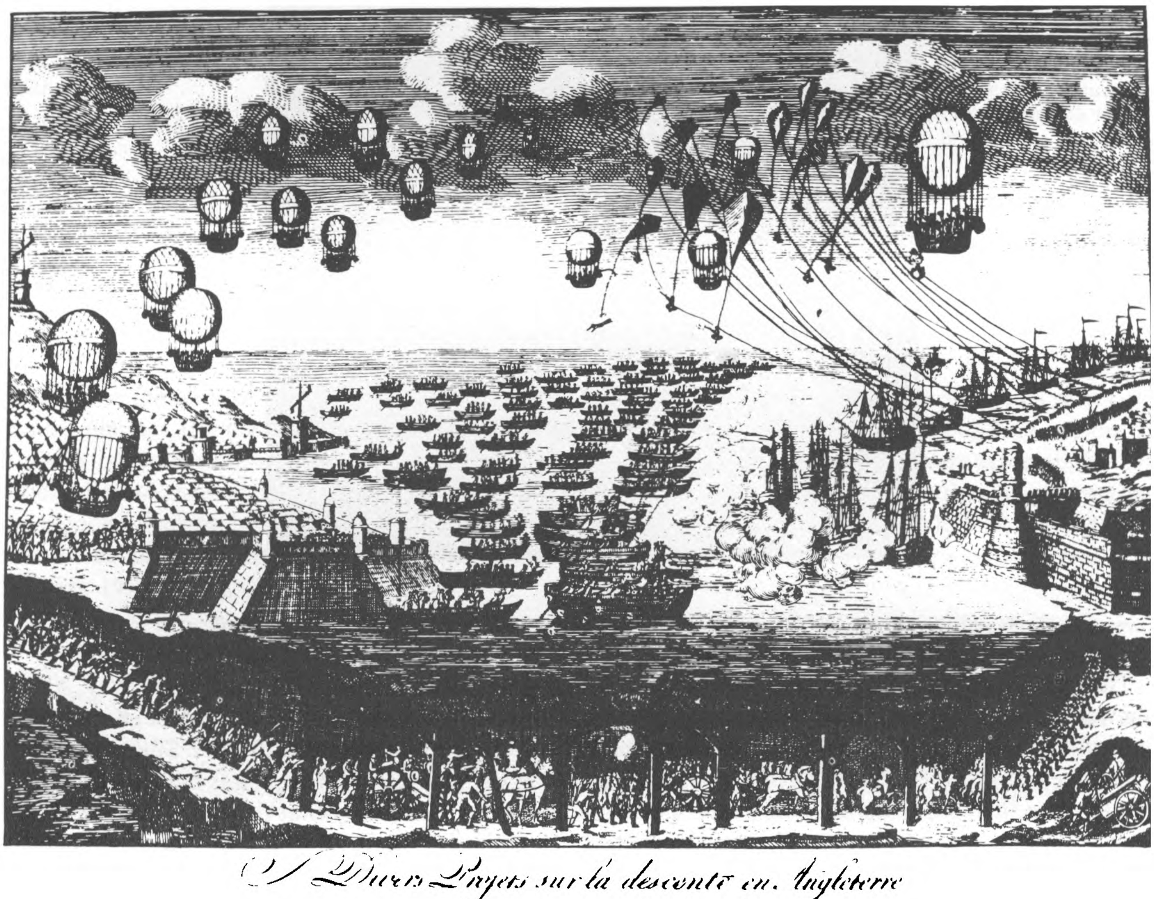
Notes and news

75 years ago

The following extract is taken from *Symons's Meteorological Magazine*, January 1909, **43**, 225–226.

THE MASTERY OF THE AIR.

The year 1908 will be memorable in history as that which saw the art of aërial navigation or aviation perfected so far as to pass from the advanced experimental to the rudimentary practical stage. It had long been recognised that movement through the air can be effected by two types of machine, one lighter than air, *i.e.*, of the nature of a balloon, in which the problem is one of propulsion and steering only; the other heavier than air, in which the motive power must not only drive the machine forward, but maintain its position against the force of gravity. The latter, or aëroplane type, is essentially a kite, which instead of being lifted by the rush of air acting against the resistance of the surface held by the string, is lifted by the rush of the surface driven by a motor against the resistance of the relatively stationary air. The



Divers Projets sur la descente en Angleterre success of this type depended mainly on the construction of a motor which was sufficiently powerful and sufficiently light, and the provision of such a motor is the direct result of the development of internal combustion engines for road locomotion.

In 1908 Count Zeppelin's great balloon airship achieved the unprecedented feat of performing a whole day's journey in the air — the unhappy wreck of the vessel in no way detracted from the epoch-making nature of the cruise. In 1908 also Mr. Wilbur Wright, in an aëroplane of the heavier than air type and of the simplest possible construction, achieved the more remarkable feat of flying 77 miles in 2 hours 20 minutes without touching the ground, and with perfect control of movement both horizontal and vertical. The rest is merely the development of proved possibilities, and no doubt can be felt that within the next few years aviation will be one of the most pressing of practical problems.

Already questions are being asked as to how the law can be adapted to regulate aërial traffic, and no doubt the military authorities of all countries have been busy devising new methods of attack and defence. One of our German friends, as a gentle satire on the dread of invasion (which some portions of the British press have almost persuaded the less enlightened members of the foreign public to believe is a brooding terror in this country) sent us by way of a Christmas card a copy of the curious French engraving, dated 1804, which we reproduce as a frontispiece to this volume. It depicts various plans supposed to have been worked out in Napoleon's camp at Boulogne when the invasion of England was nearer than it has been since, and it is curious to notice that the Channel tunnel — itself one of the bogies of the twentieth century — was there, and that the troop-balloon was to be hurled against our country only to be met by a corps of gallant riflemen, each suspended to the tail of a man-lifting kite.

Though there is no new thing under the sun in popular scares or scientific imagination, there will undoubtedly follow a vast impetus to meteorology, leading to the discovery of many new facts, as a result of the opening of the fields of the air to the activity of man, and for many years to come the advancement of our science and the perfecting of the art of aviation will progress by mutually benefiting each other.

A.C. Wiin-Nielsen awarded Wihuri International Prize

Professor A.C. Wiin-Nielsen, Secretary-General of the World Meteorological Organization, received the prestigious Wihuri International Prize in Helsinki on 9 October 1983. He is the first meteorologist to be awarded this honour.

The Wihuri Foundation for International Prizes was established in 1953 to promote and sustain the cultural and economic development of society by distributing international prizes. The Wihuri Sibelius Prize, named after its first recipient, is awarded for distinction in the field of music. The Wihuri International Prize is awarded to individuals, groups or organizations for contributions to a much broader concept of cultural and economic development. Since 1953, 17 Prizes have been awarded — 9 Wihuri Sibelius Prizes and 8 Wihuri International Prizes — the last one in 1979.

Professor Aksel C. Wiin-Nielsen, Secretary-General of the World Meteorological Organization from 1980 to 1983, was born in 1924 in Klakring, Denmark. After taking his degree in Mathematics, Physics, Chemistry and Astronomy at the University of Copenhagen, Denmark, he joined the Meteorological Institute of Denmark in 1952 as a Scientific Officer. From 1952 to 1955 he was engaged mainly in the Weather Service Department and at the same time was pursuing postgraduate studies in Meteorology under Professor R. Fjørtoft. In 1955 he joined the staff of the International Meteorological Institute in Stockholm, Sweden, where he served under Professor C.G. Rossby and participated in the early operational aspects of the introduction of numerical weather prediction in the Swedish Weather Services. He completed his degree in Meteorology at the University of Stockholm in 1957 and his doctoral degree in 1960.

From 1959 to 1961 he was a staff member of the Joint Numerical Weather Prediction Unit, Suitland, Maryland, USA, where he continued his research on numerical weather prediction and the general circulation of the atmosphere. He joined the staff of the National Center for Atmospheric Research where he served as an Assistant Director in the Laboratory of Atmospheric Science from 1961 to 1963 when he was appointed as Professor and Chairman of a newly established Department of Meteorology and Oceanography at the University of Michigan, Ann Arbor, Michigan, USA. He served the University of Michigan until 1974 except for the academic years 1969–70 and 1971–72 when he was a Visiting Professor at the Universities of Copenhagen, Denmark, and Bergen, Norway, respectively.

The European Centre for Medium Range Weather Forecasts was created in 1973 by 17 European countries. Professor Wiin-Nielsen was engaged as Head of the Planning Staff in 1974 and became the first Director of the Centre when it was formally established in November 1975. He served in this position until he was appointed Secretary-General of the World Meteorological Organization.

Professor Wiin-Nielsen has been President of the International Commission on Dynamic Meteorology, a Member of the Joint Organizing Committee for the Global Atmospheric Research Programme, a Member of the Scientific Advisory Committee to the Director-General of the European Space Agency and Chairman of the Earth-oriented Space Research Group, and a Member of the Scientific Advisory Committee for the Max Planck Institute for Meteorology. He is also a Fellow of the American Meteorological Society, a foreign Member of the Royal Meteorological Society and of the Finnish Academy of the Sciences and the Arts, and a Member of the Norwegian Geophysical Society. Professor Wiin-Nielsen is the author of numerous scientific papers on subjects in atmospheric dynamics, numerical weather prediction and the general circulation of the atmosphere. He has also written a textbook on dynamic meteorology.

The Wihuri International Prize for 1983 amounts to US $30 000.

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NOTICES

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Retirement of Mr F. H. Bushby

When Mr F. H. (Fred) Bushby retired as Director of Services on 9 January 1984, the Office bade farewell to one of its most able and colourful characters who had served it with great success and deep commitment for almost 40 years.

Fred Bushby was an outstanding student, graduating from Imperial College with First Class Honours in mathematics in 1944 and taking both the Sir John Lubbock Memorial Prize and the Governors' Prize in mathematics as the best student of his year. In normal times he would almost certainly have stayed on to do research but he joined the RAF Meteorological Branch in November 1944 and served at several stations at home and in south-east Asia whence he returned as a Flight Lieutenant for demobilization in early 1948. He then started his civilian career as a Scientific Officer in the Meteorological Office but it was his posting to the Forecasting Research Branch in Dunstable in 1950 that launched him on a remarkable career in numerical weather prediction spanning some 27 years with only one surprising break of 2½ years as Chief Meteorological Officer in Aden.

In 1950 a remarkably far-sighted decision was made to send Bushby back to Imperial College for a course on numerical methods, including relaxation techniques, given by Sir Richard Southwell. In 1952 he attended a course on computing methods at Cambridge where the first EDSAC computer was being installed. Then, under the leadership of J. S. Sawyer, he wrote numerical programs to compute fields and tendencies based on Sutcliffe's ideas of development using a copy of the EDSAC machine built for J. Lyons & Co. at Cadby Hall. Sawyer and Bushby then proceeded to develop a so-called 2½-dimensional numerical prediction model which produced its first forecast in 1954 using the Ferranti Mk I computer at Manchester University. This led to the construction of a 3-level geostrophic model which went ahead when the Office acquired its own Ferranti Mercury computer in 1959. However, since the performance of this machine, capable of only 3000 floating-point operations per second, was not much greater than a modern programmable pocket calculator, operational forecasts were not possible until the Office installed its second computer, an English Electric KDF9, in 1965. The first operational 48-hour forecast was issued on 2 November 1965 and marked a new era of forecasting in the Meteorological Office.

Meanwhile Fred Bushby had been recently promoted to Assistant Director in charge of the Forecasting Research Branch. I well remember this because, having been Director-General for only a few days, this was my first important decision, and when my advisors suggested that Fred was too young to be promoted ahead of many of his seniors, I gently reminded them that he was only five months younger than I but with a good deal more meteorological knowledge and experience! The Office soon recovered from the initial shock and Fred Bushby entered a very important and successful phase of his scientific career.

Since 1963, ably supported by Mavis Hinds and Margaret Timpson, he had been developing a very advanced 10-level primitive-equation model formulated well ahead of its time by John Sawyer. This was designed to predict the development of fronts and make the first quantitative forecasts of precipitation on a fine-mesh, 100 km, horizontal grid. For this Bushby was quick to exploit the greater computing power of the new Ferranti ATLAS computer at Harwell, which was capable of about one million instructions per second, and he soon established himself as one of the most gifted and resourceful users of advanced computers in the country. The fine-mesh model was later stretched to cover most of the northern hemisphere on a coarser grid and both were ready for operational testing when we acquired the very fast IBM 360/195 computer in 1971. Their impact on the quality of general forecasts for up to three days ahead and of rainfall forecasts for up to 36 hours ahead was marked and immediate and put the UK in the world forefront of numerical weather prediction. Both the scientific reputation and public image of the Office were thereby enhanced and a good deal of the credit must to to Fred Bushby whose foresight, initiative and single-minded dedication to achieving his clear-sighted objectives were an inspiration to his young colleagues and to the senior management alike.

In 1974 his achievements were marked by promotion to Deputy Director in charge of Dynamical Research. With this wider remit he was able to encourage the development of even more advanced models for numerical weather prediction, climate simulation and stratospheric studies, all on the global scale. In 1977 he was transferred to the post of Deputy Director Forecasting Services in preparation for his ultimate promotion to Director of Services in 1978.

During the last four years Fred Bushby has applied his wide experience, knowledge and enthusiasm to guiding the Services Directorate through a difficult period when ever-increasing demands for its services have had to be met by an ever-decreasing staff. A doer rather than a philosopher, his resilience, shrewd judgement and far-sightedness have been great assets and although he sometimes revelled in combative argument, especially with his erstwhile research colleagues, he would always, in the end, agree to what was best for the Office as a whole. Indeed the Office was the centre of Fred's life and I am grateful for his unfailing support and many personal kindnesses. He had a genuine interest and concern for the staff at all levels and, being widely known throughout the Office, he will be the subject of many stories — some apocryphal, mostly true — wherever meteorologists meet and reminisce.

In the computer world Fred Bushby was well known and greatly respected as one of the most experienced and knowledgeable users of giant machines. In international meteorology his advice was much appreciated especially in the WMO/ICSU Working Group on Numerical Experimentation and on the Scientific Advisory Group of the European Centre for Medium Range Weather Forecasts.

Outside meteorology, Fred's main passion is bridge; in 1981 he reached the high-point but, we hope, not the apogee of his career when, with Colin Flood, he reached the last 16 in the National Championships.

I am sure that all his colleagues will wish to join with me in wishing Fred and Joan many years of happiness and time to enjoy their common, but not identical, enthusiasms for cricket and other club activities.

B. J. Mason

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Applications of automated weather radar and Meteosat displays in an aviation forecast office

By B. J. Booth

(Meteorological Office, Royal Air Force Lyneham)

Summary

During June 1982 a digital framestore and colour TV monitor were installed in the meteorological office at Royal Air Force Lyneham. The equipment stores and displays preprocessed digital Meteosat or weather radar data, which can be replayed in sequence by the recipient. Using case studies this paper describes some of the situations in which automated displays can provide, and have provided, valuable analytical and briefing material for the aviation forecaster.

Introduction

During the last decade the Meteorological Radar Research Laboratory (Met O RRL) Malvern, has expended a considerable amount of effort in developing an automated weather radar network (Browning 1980). Although it was appreciated at its inception that data from such a network would be of great value to the forecaster (Taylor and Browning 1974), until recently the main beneficiaries have been such bodies as water authorities. This in part arises from the network's natural development, which has required much of the research effect to be directed toward (a) the quantification of both radar and satellite data in terms of precipitation intensity, and (b) the presentation of these quantities in an easily assimilated format, as shown, for instance, on the cover of the April 1980 issue of *Weather* or by Hill (1982).

Detailed descriptions of the network have appeared elsewhere, for example Browning and Collier (1982), so for the purposes of this paper it is sufficient simply to state that data from both Meteosat and a network of radars is processed into digital format at the Met O RRL, then automatically transmitted in near real time along standard telephone lines to the user's display equipment, which consists of a digital framestore and colour TV monitor (Ball *et al.* 1979). At the present stage of development only one type of data (Meteosat or network rainfall radar) can be received at any one time, but the data type sent to Lyneham can be changed manually by Met O RRL at the request of the recipient.

As previously remarked, non-aviation operators have been the major beneficiaries of the automated weather radar network, but since June 1982 the data have been relayed to the Meteorological Office at Royal Air Force Lyneham, the main transport base of the Royal Air Force, for evaluation in an operational aviation environment. This location is ideally suited for the task since Lyneham's resident Hercules squadrons fly over 10 million air miles in an average year, in a wide variety of roles, ranging from 2 to 4 hour low-level (250 ft above ground level) flights which often involve the dropping of troops or freight by parachute, to 8 to 14 hour non-stop trooping/freight flights direct to such diverse destinations as Bahrain, Canada or Ascension Island. Some Hercules have an air-to-air refuelling capability and as a consequence a considerable amount of time is spent practising the necessary skills. In addition both civil and foreign aircraft are frequent visitors to the base.

Besides meeting the various meteorological requirements of aircraft operating from Lyneham, the meteorological office is also responsible for the supply of meteorological information to another seven military airfields/establishments and three civilian airfields (operating light aircraft, gliders or hot-air balloons) within a 40 km radius (Fig. 1). Consequently, although up to 60% of briefings take place face to face, a substantial number are given over the telephone.

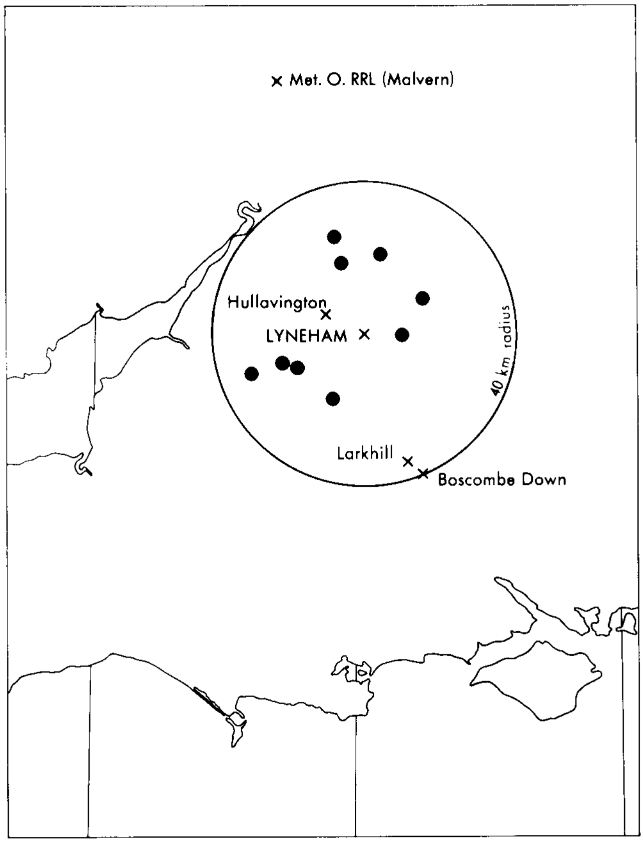

Figure 1. Sites of airfields and other establishments dependent on Lyneham meteorological office for meteorological services. Named sites (×) are referred to in the text.

Since only one forecaster is on duty at any one time at Lyneham, such a diverse forecasting requirement demands a constant adjustment of thought processes from local to international meteorological problems which in turn requires frequent reference to the latest synoptic chart or telecommunications data. The former presents data which are at best 80 minutes old ($H+80$) when placed in front of the forecaster and is rarely updated until $H+140$ minutes ($H=$ data time). At Lyneham this means that in exceptional circumstances a fast-moving system, identified at the edge of a chart, data time H, may reach the airfield before the subsequent chart ($H+60$ minutes) is received some two hours after H.

On the other hand, whilst the meteorological telecommunications network disseminates coded weather messages rapidly, the presentation is not conducive to forming a mental picture of the situation. These are problems common to all aviation forecast offices and clearly an automated display system which can present near-real-time information on precipitation or cloud distribution, can only improve a forecaster's ability to react both rapidly and confidently to those awkward questions which always seem to be asked at briefings.

With this in mind the Lyneham display unit is prominently positioned in the forecast office and, because of the bright colours of the display, the forecaster is constantly aware of the current precipitation or cloud distribution, since one or the other is always on view.

Radar network rainfall data

The rainfall data, covering most of England and Wales (Fig. 2), are received at 15-minute intervals, usually within 10 minutes of data acquisition, and are displayed in an array of 5 km square grid squares (pixels). Every alternate picture (at $H + 15$ minutes and $H + 45$ minutes) is placed in the digital frame-store — a maximum of four pictures covering a period of 1½ hours. These can be replayed in sequence at various speeds by the local operator.

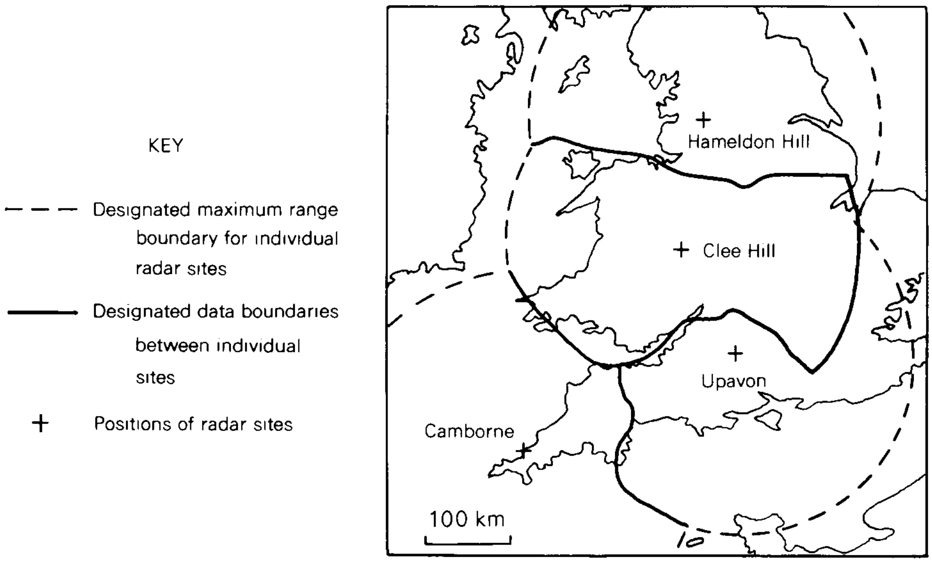

Figure 2. Maximum radar coverage displayed on the TV colour monitor and locations of the four radars in current operational use.

The colour of each pixel indicates the mean rainfall intensity within that pixel at data acquisition. Eight intensity levels can be displayed and these together with the colour scheme adopted at Lyneham are shown in Table I.

Table I. *Rainfall intensity levels and colour scheme adopted at Lyneham.*

Intensity level	Rainfall intensity ($mm\ h^{-1}$)	Colour
0	<⅛	Black
1	⅛ to <1	White
2	1 to <4	Yellow
3	4 to <8	Green
4	8 to <16	Cyan
5	16 to <32	Blue
6	32 to <126	Violet
7	⩾126	Red

For reference purposes a background coastline map is provided electronically, together with a pair of movable 'crosswires'.

As it is an operational airfield there is little call at Lyneham for quantitative assessments of rainfall, so the data have necessarily been utilized in other ways.

Cloud and visibility

While rain itself is not normally a hazard to low-flying aircraft, the associated conditions of poor visibility and/or low cloud are. Although the display unit cannot present specific data on these variables, by assuming that observed relationships (from routine synoptic observations) between precipitation and cloud and/or visibility apply to most of the precipitation area, at least the extent of the hazardous conditions may be inferred. This can be particularly useful when preparing forecasts for low-level flights over data-sparse areas (such as central Wales) especially when frontal movement has been slow and erratic.

Icing and turbulence

Hazards to aircraft flying at higher levels are generally of a different nature — icing and turbulence being the main causes for concern, especially when associated with convective cloud. Although on-board weather radar enables aircraft to circumnavigate such areas, prior knowledge of their existence and location is useful to crews.

Once again the system does not provide specific information, but occasionally, as on 12 November 1982, areas of intense precipitation within a frontal rainbelt can indicate embedded convective activity and hence associated icing and turbulence.

In this instance a very active eastward moving cold front crossed Wales, then England, at 45 to 50 km h^{-1}. At Lyneham the frontal passage between 0500 GMT and 0600 GMT (Fig. 3) was accompanied by a burst of very heavy rain, a wind veer from 190° to 230° and a 3.5 °C fall in temperature.

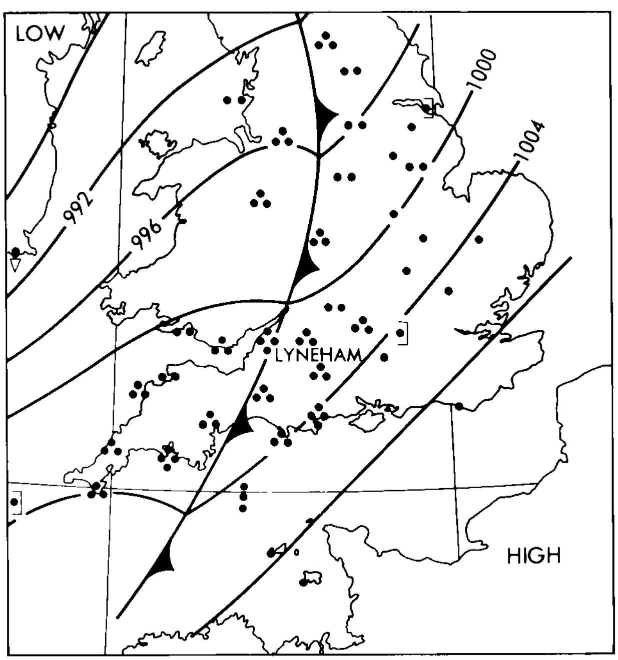

Figure 3. Synoptic chart for 0500 GMT on 12 November 1982, approximately one hour before the cold front reached Lyneham. Although the rain area is clearly extensive, there is no indication that a squall-line has developed or of the extent of the rain over Wales. This chart would have been handed to the forecaster, unanalysed, at approximately 0610 GMT.

As can be seen from the 0400 GMT precipitation distribution picture, Plate I, the rain area associated with the cold front at this time was extensive and, although embedded convective precipitation was evident over Wales, the distribution must be considered irregular. During the following hour, however, these convective elements became organized along the line of the surface front as a line squall developed, Plate II, and this feature, with rainfall intensities exceeding 32 mm h^{-1}, was followed to the periphery of the radar coverage.

Remembering that at 0610 GMT (the reception time of the 0600 GMT precipitation distribution picture) the forecaster would still have been briefing from the 0400 GMT synoptic surface chart (data time 0350 GMT), this is an excellent example of the system (even with only 50% of normal radar coverage) providing not only an early indication of developments but also the means to follow them in real time.

Thunderstorms

The loading and refuelling of aircraft at Lyneham, together with the flying of balloons for parachute training at nearby RAF Hullavington, are particularly sensitive operations in thundery weather. Consequently, there is a requirement to provide, and continuously review, forecasts of lightning risk.

While forecasters' confidence in their predictions has greatly improved in this context, due to their ability to track thunderstorms with the automated display system, the speed of *in situ* development and decay of convective precipitation has emphasized the care needed in interpreting the displays in thundery situations.

For example, a line of thunderstorms developed very quickly just south of Boscombe Down between 0715 GMT and 0730 GMT on 14 July 1982, and its northward movement was subsequently monitored in near real time on the precipitation display. Although conventional surface observations gave no indication of renewed thundery activity to the south of the trough line, it was clear from the 0830 GMT precipitation distribution picture (not reproduced) that a small detached convective cell was developing to the south-east of Lyneham in a previously precipitation-free area.

Normally this period of the morning is a very busy one for the airfield authorities, with frequent movements, but on this occasion the schedule had been seriously disrupted as the threat of thundery weather had delayed the refuelling and loading of aircraft. Consequently the forecaster was under intense pressure to forecast a lower risk of lightning once the precipitation display showed the trough line clear of Lyneham at 0900 GMT, Plate III. In view of the developing small cell to the south-east he refused to bow to the pressure and his caution was justified when, just after 0930 GMT another thunderstorm crossed the airfield, Plate IV.

This was a good example of the speed with which convective cells decay. At 0915 GMT (picture not reproduced) the maximum precipitation intensity of this cell was 16 to 32 mm h^{-1}, yet by 1000 GMT the cell had completely disappeared.

TREND* forecasts

The usefulness of the precipitation distribution displays in preparing TREND forecasts is rather limited since changes in visibility and/or cloud conditions are normally of prime importance. None the less, improvements associated with the passages of cold fronts have been forecast with accuracy, while in unstable situations preferred shower tracks can be identified and TRENDS forecast accordingly.

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*A TREND is a 2-hour landing forecast which is routinely added to hourly observations at some airfields.

Meteosat data

The Meteosat data, displayed in an array of 10 km pixels, cover an area bounded by approximately 45°N to 56°N and 03°E to 13°W, Fig. 4. As with the network radar rainfall display, the Meteosat display incorporates a background coastline map and a pair of moveable crosswires for reference purposes.

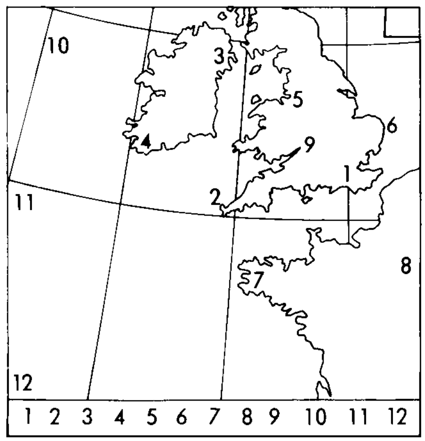

Figure 4. Area covered by Meteosat infra-red imagery. The data time is presented in the top right-hand corner. Spot temperatures for the numbered locations on the map are presented in sequence along the bottom strip.

Although both half-hourly visual and infra-red (IR) Meteosat data are available, it was decided at a very early stage to use hourly IR data only. This decision was based on the following circumstances:

(i) Visual pictures are unavailable during the hours of darkness, whereas IR pictures would provide a continuity of data;

(ii) The limited storage facility of the unit (only 4 pictures can be stored);

(iii) The relatively greater potential of obtaining quantitative detail from IR data (such as inferring cloud top heights from cloud top temperatures).

The mean IR intensity level for each 10 km pixel is displayed as the equivalent black body temperature (in degrees Celsius), each temperature being colour coded. In practice, since the TV monitor is capable of generating only eight colours, each colour must necessarily relate to a wide range of temperatures. Table II shows the colour coding and temperature relationship initially adopted at Lyneham.

Table II. *Temperature–colour relationship adopted at Lyneham for presentation of Meteosat infra-red imagery.*

Colour	Temperature range (°C)	Approximate height band (feet × 1000)
Black	>20	Surface
Yellow	15 to 20	<2
Green	8 to 15	2 to 7
Cyan	-5 to 8	7 to 14
Blue	-20 to -5	14 to 21
Violet	-33 to -20	21 to 27
Red	-45 to -33	27 to 33
White	<-45	>33

Unfortunately this proved too coarse a resolution to relate colours on the display unit with specific cloud top heights with any degree of accuracy, and subsequent modifications to the temperature ranges did little to help matters. The problem has, however, been partly overcome by embedding spot temperature values, coincident as far as possible with radiosonde stations, in a predetermined order, at the bottom of each picture, Fig. 4. Reference to the corresponding upper-air ascent then allows the cloud top height to be determined.

Some idea of the accuracy to be obtained can be gained by referring to the situation on 21 January 1983 when England was covered by a sheet of stratocumulus. Surface observations for 0700 GMT and 0800 GMT indicated a cloud base over Wiltshire of between 2300 and 2500 ft asl (above mean sea level), measured by cloud base recorder. Although a Lyneham aircraft reported the stratocumulus base and tops as 3000 and 4000 ft asl respectively at 0752 GMT, it is believed these figures were too high by 500 ft, in view of the consistent surface observations of cloud base, which implied an observed cloud top of 3500 ft asl.

This would be consistent with the 0724 GMT Larkhill ascent, Fig. 5, which shows a very strong inversion at this level. The temperature of the cloud top at the base of the inversion was –5.5 °C; the corresponding temperature measured by Meteosat was –5 °C. (In a similar situation at 0800 GMT on 7 March 1983 a Meteosat cloud top temperature of –1 °C compared very favourably with a Larkhill measurement of –0.2 °C.)

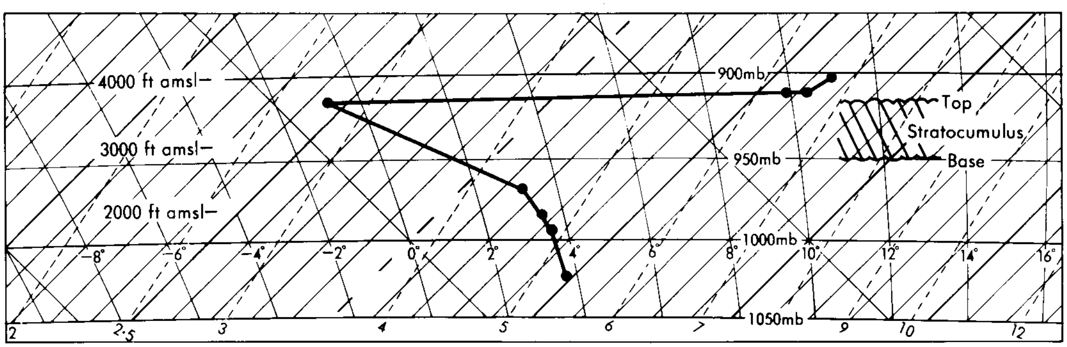

Figure 5. Larkhill ascent for 0724 GMT on 21 January 1983.

As a briefing aid the Meteosat display has time and again proved invaluable, even immediately following its introduction to Lyneham in the early summer of 1982. During this period some crews were receiving intensive training in air-to-air refuelling, which must of necessity be carried out in clear air, either above or between cloud layers. At the time Meteosat was only of limited use since, although totally cloud-free areas could easily be located, the coarse temperature resolution necessarily adopted made it difficult to identify with any accuracy the height of cloud tops.

Even with this limitation Meteosat was of some use when briefing an air-to-air refuelling exercise on 11 July 1982. At the 1300 GMT briefing, the crews were insistent the exercise should take place over south-west England, despite the 1200 GMT Meteosat display showing a large area of slow-moving layer cloud with embedded cumulonimbus just to the west. Having advised the crew that the North Sea would be a more suitable operational location, the forecaster suggested the safest area to the south-west (of Lyneham) to be over Devon or Somerset.

The 1300 GMT Meteosat display (received after the briefing) showed that not only had the cloud mass already reached the proposed area, but additional cumulonimbus development was taking place to the south. All this information was passed to the crews in ample time to allow a change of plan.

In another instance on a fine sunny morning a few days later, on 18 July 1982, the duty forecaster was confidently able to dissuade a glider pilot from attempting a flight from Hullavington to Lincolnshire, as it was clear from the automated Meteosat display that a south-eastwards moving stratocumulus sheet would soon cover the planned route and inhibit thermal activity.

Normally wave cloud would be difficult to identify from the Meteosat display but on 2 September 1982 a stationary detached cloud just to the lee of the Pennines attracted attention, Plate V. The cloud-top temperature was estimated to lie between -20 °C and -33 °C (approximately 21 000 to 27 000 ft), but Met O RRL subsequently assessed it as about -26 °C, ±2 °C (at 24 000 ft).

Although the wind at this level was in excess of 128 km h^{-1}, the leading edge of the cloud remained stationary from 1200 GMT to 1500 GMT, Plates V and VI, and in fact could be identified in the same position for nearly 24 hours, despite being hidden at times by eastward moving cirrus. This lack of movement indicated that the cloud was orographic in origin and, as the 1200 GMT Aughton ascent, Fig. 6, shows, conditions were indeed favourable for lee-wave development.

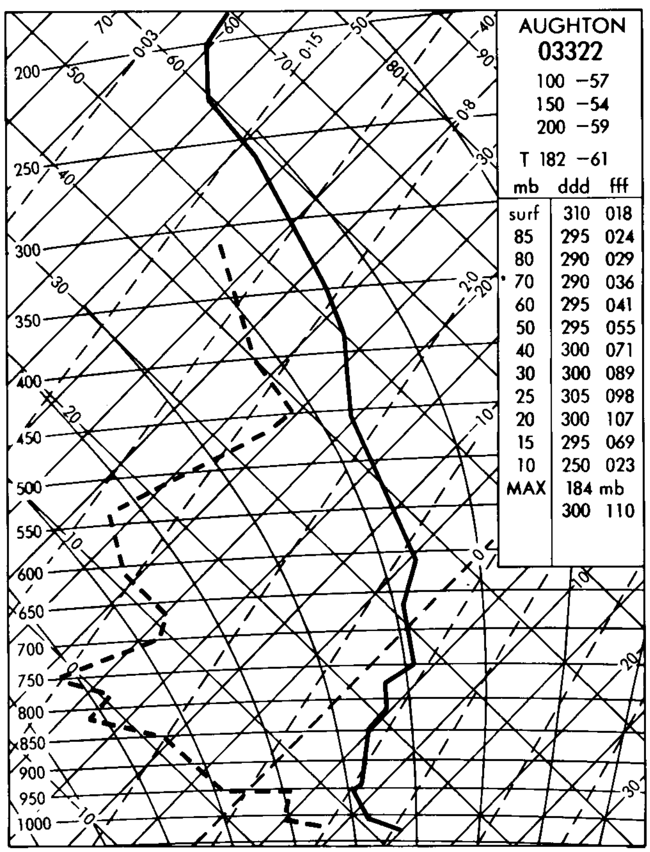

Figure 6. Aughton tephigram for 1200 GMT on 2 September 1982. 400 mb approximately equates to 24 000 ft. Wind data in degrees and knots.

Following Casswell (1966) it has been calculated that the maximum vertical velocity of a secondary wave train would have been found at 24 000 ft (temperature −26 °C) just above a layer of relatively high relative humidity and consistent with the 'observed' cloud-top temperature.

Since the two types of display offer unique data sets which complement routine synoptic observations it would be unwise to suggest that one is of greater use than the other. A case in point was the afternoon of 4 June 1982 when scattered thunderstorms developed in a warm unstable southerly surface airflow.

Conventional surface observations suggest the thundery activity is confined to eastern districts, Fig. 7. (The shower reported at Boscombe Down was unconnected with deep convection and lasted for all of a minute!) The corresponding precipitation display, Plate VII, shows evidence of convective precipitation over North Wales, the Vale of York, north Devon and along a line from Bristol to London, with a suspicion of storms over the Cherbourg peninsula and the Wash. The return over west Cornwall is believed to be spurious.

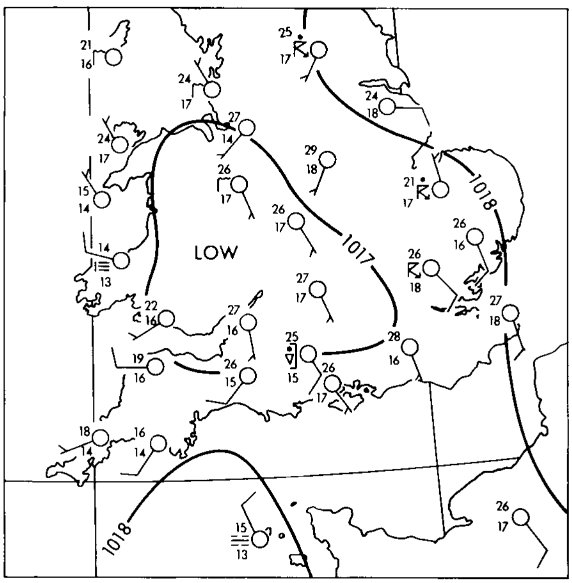

Figure 7. Synoptic chart for 1500 GMT on 4 June 1982. Plotted observations have been abbreviated to show wind, weather, dry-bulb and dew-point temperatures only.

The 1500 GMT Meteosat display, Plate VIII, clearly shows the locations of all cumulonimbus clouds (and hence thunderstorms) over England and Wales as well as France, plus the smaller convective cell over north Devon.

Despite high inland temperatures only small amounts of shallow cumulus developed over south and south-east England (possibly owing to the inland penetration of sea air), hence the black colouring indicating surface temperatures of more than 20 °C (actual screen temperatures 25–27 °C). The yellow colouring over the Midlands is indicative of larger cloud amounts. Although screen temperatures were similar to those further south, the mean areal radiance levels monitored by Meteosat would be lower owing to the presence of convective cloud, hence the yellow colouring (equivalent black-body temperature range 15–20 °C).

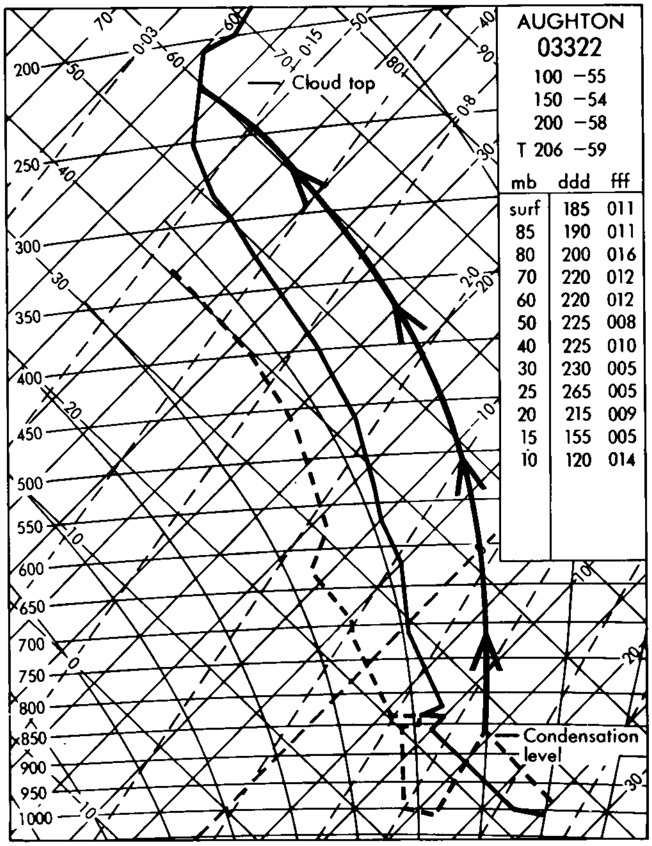

Figure 8. Aughton ascent for 1300 GMT on 4 June 1982. If the surface dry-bulb temperature at 1500 GMT is taken as 27 °C and the dew-point temperature as 17 °C, cloud tops can be estimated as reaching 36 000 ft.

Cumulonimbus cloud-top temperatures over England and Wales were assessed by Met O RRL as −56 °C (±2 °C), a height of 34 000–36 000 ft on the representative radiosonde ascents. This is consistent with cloud tops of 36 000 ft estimated by conventional means, as demonstrated by Fig. 8.

Thus while the precipitation display presents data at frequent (15 minute) intervals, the Meteosat display offers similar data (but less frequently) for a much greater area by inference from the cloud type and distribution, together with a good indication of the cloud-top heights. Additionally, and importantly from the aviation forecaster's point of view, it presents the weather situation with great visual impact.

Conclusion

In the short period that digital Meteosat and precipitation data have been made available to Lyneham all forecasters have found the information invaluable for analysis, while the ability to replay stored data has given much greater impact to their verbal briefings.

Acknowledgements

I am indebted to the staff of Met O RRL in general and to Dr A. Eccleston in particular for the advice they have offered and the provision of the photographs. I would also thank the Lyneham forecasters for bringing the several events to my attention.

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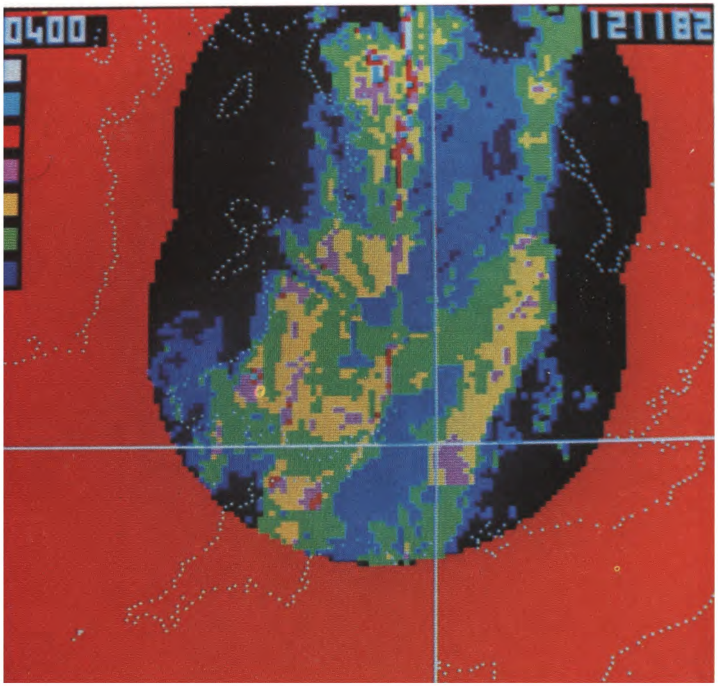

Plate I. The precipitation distribution display for 0400 GMT on 12 November 1982 (Upavon and Camborne radars were unserviceable). The intersection of the cross-wires locates Lyneham. Note the irregular distribution of heavy rain (violet/red/cyan) pixels over Wales. The colour scheme is different from that normally adopted at Lyneham, and on this presentation rainfall intensities (mm h^{-1}) are represented as follows: blue <1, green 1 to <4, yellow 4 to <8, violet 8 to <16, red 16 to <32, cyan 32 to <126, white $\geqslant 126$.

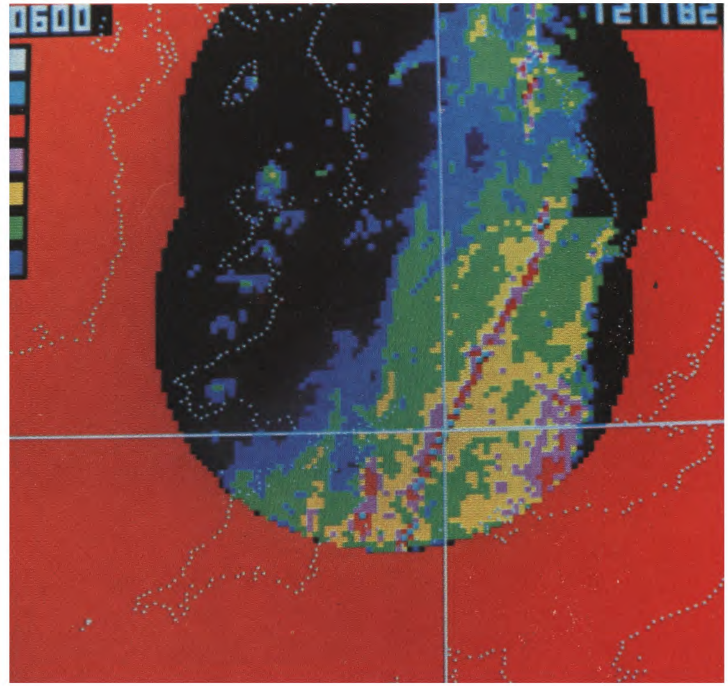

Plate II. The location and extent of the developing squall line is clearly evident in this precipitation distribution display for 0600 GMT on 12 November 1982. See Plate I for details of the colour scheme.

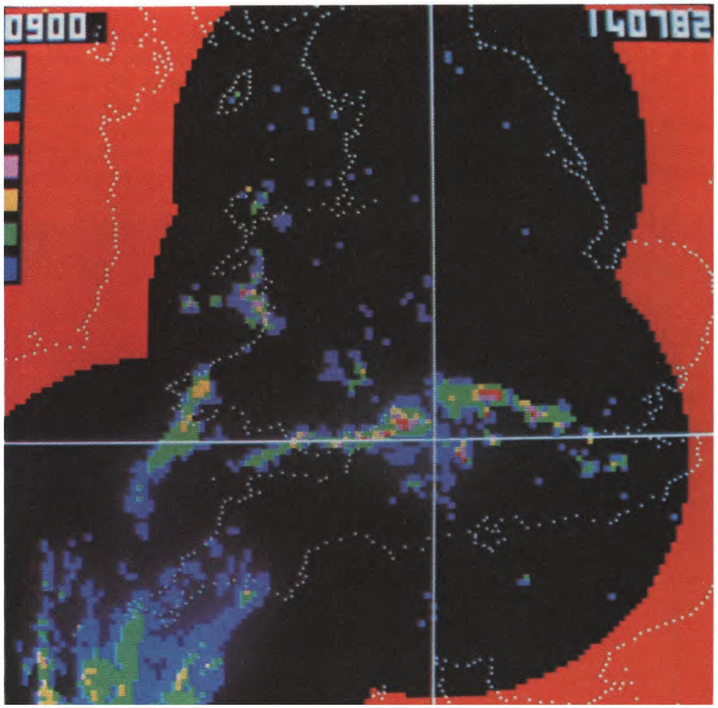

Plate III. The precipitation distribution display for 0900 GMT on 14 July 1982, which shows a significant line of showers and thunderstorms just to the north of Lyneham. However, by this time the forecaster's interest had been transferred to the small, but intense, echo to the south-east of the airfield (the violet/red pixels). This cell was not detectable from conventional surface observations. The blue/green pixels between Lyneham and the south coast are spurious echoes. See Plate I for details of the colour scheme.

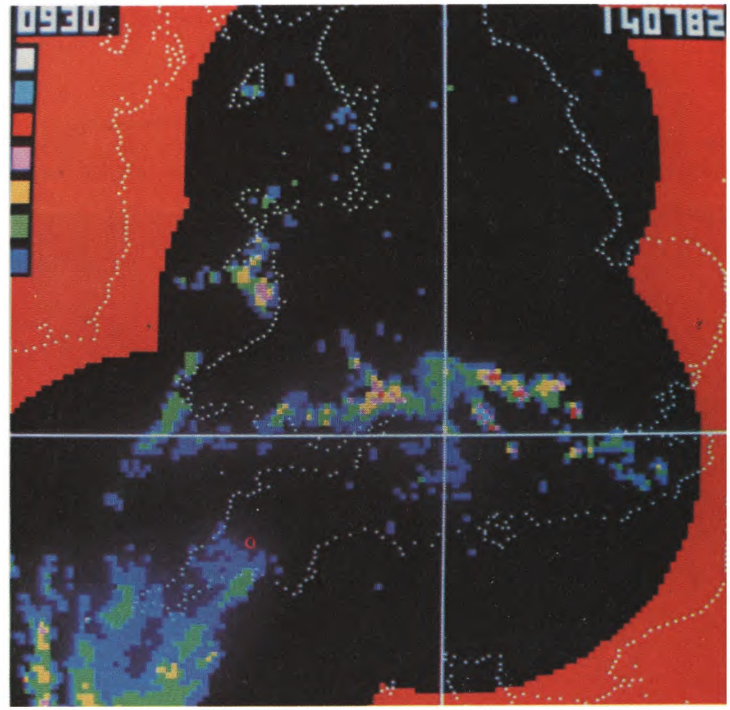

Plate IV. The precipitation distribution display for 0930 GMT on 14 July 1982, showing the echo referred to in Plate III crossing Lyneham. (Because of its limited extent the echo is almost obliterated by the cross-wires.) Although the mean areal rainfall intensity has now fallen to 4–8 mm h^{-1}, thunder and lightning were associated with the cell as it crossed the airfield. See Plate I for details of the colour scheme.

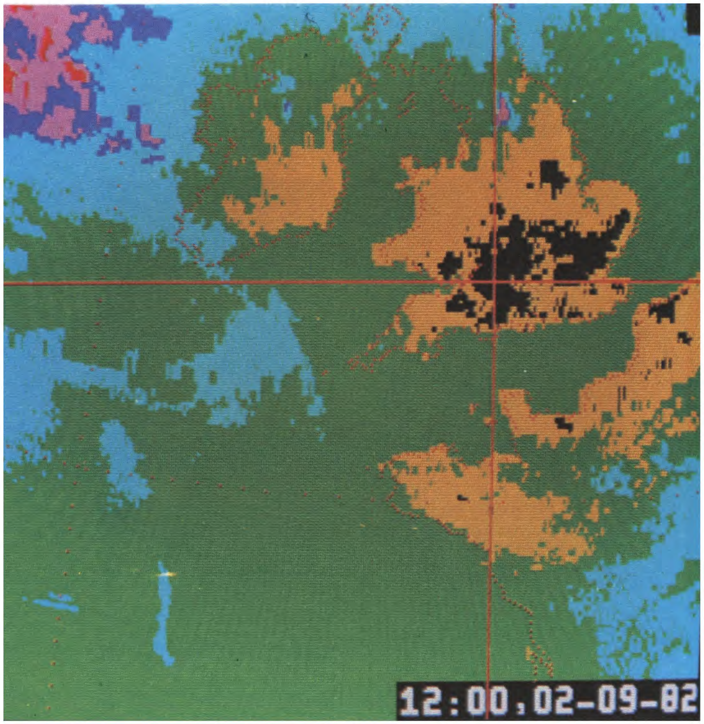

Plate V. Meteosat infra-red image at 1200 GMT on 2 September 1982. The cross-wires intersect over Lyneham, and the leading edge of the orographic cloud over the Pennines is aligned along the N–S cross-wire. The colours represent the following temperature ranges (°C): black >20, yellow 15 to 20, green 8 to 15, cyan −5 to 8, blue −20 to −5, violet −33 to −20, red −45 to −33, white <−45.

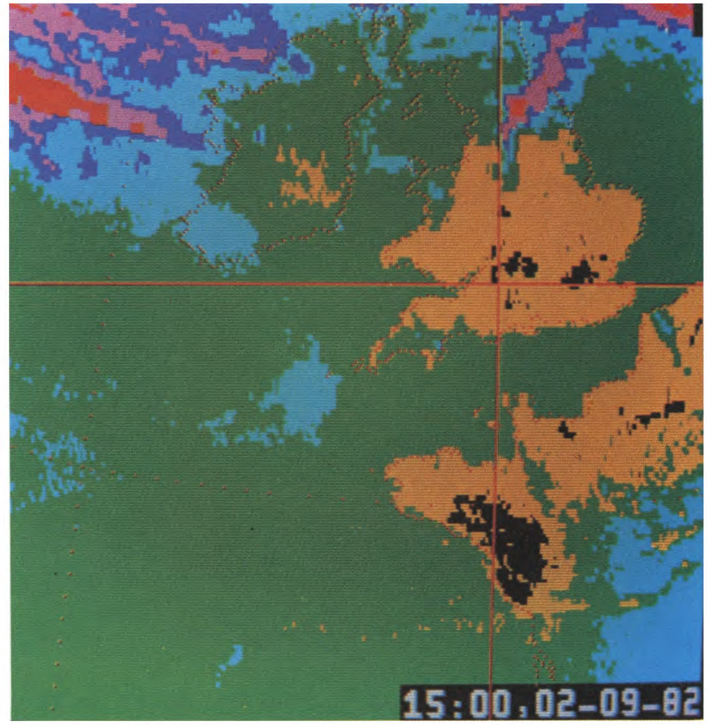

Plate VI. Meteosat infra-red image for 1500 GMT on 2 September 1982. The orographic cloud over the Pennines is still evident despite more widespread cirrus development. See Plate V for details of the colour scheme.

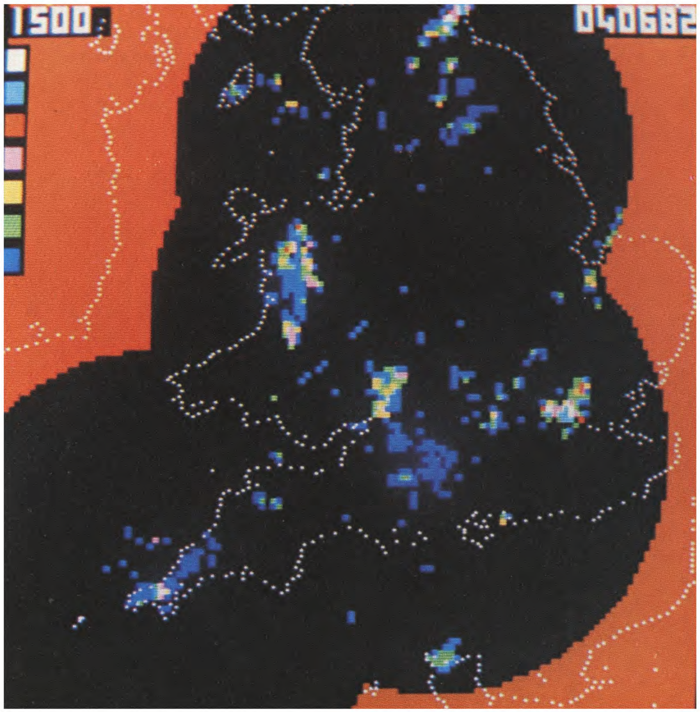

Plate VII. The precipitation distribution display at 1500 GMT on 4 June 1982, showing the locations of thunderstorms and showers. The returns over Cornwall and Salisbury Plain are spurious. See Plate I for details of the colour scheme.

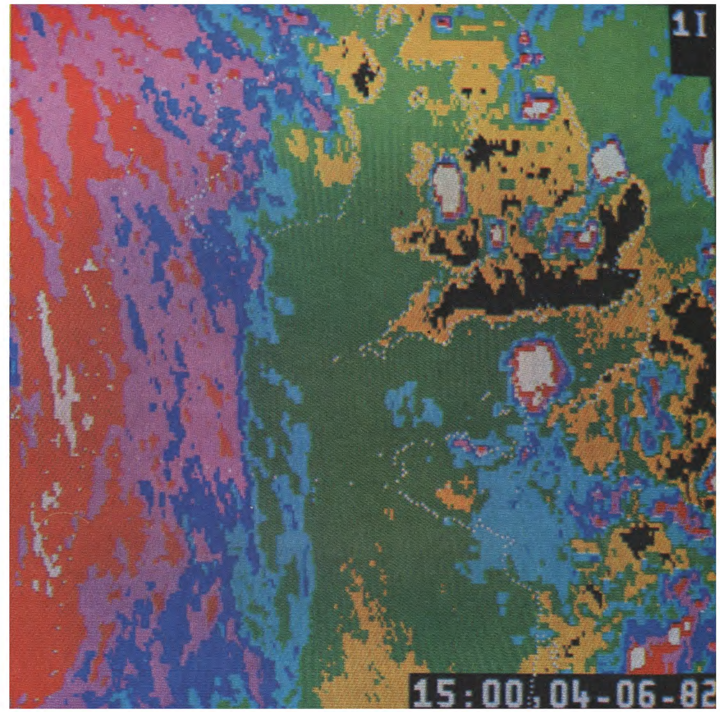

Plate VIII. Meteosat infra-red image at 1500 GMT on 4 June 1982, clearly showing the locations of cumulonimbus clouds over France and the southern North Sea, as well as England and Wales. The white pixels indicate the cumulonimbus tops. See Plate V for details of the colour scheme.

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Correspondence

Comments on 'Extreme value analysis in meteorology' by R. C. Tabony

In his paper on extreme value analysis in meteorology, Tabony (1983a) discusses the problem of seasonal variation and comments on our suggestion (Carter and Challenor 1981) that it can be reduced by analysing monthly maxima instead of the usual technique of analysing annual maxima. Tabony gives a plot of annual maximum wind speed at Scilly in which he includes the distribution derived, as we suggest, by combining distributions of monthly maxima (his Fig. 11, reproduced here as Fig. 1). From this figure he concludes that: 'As the technique 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

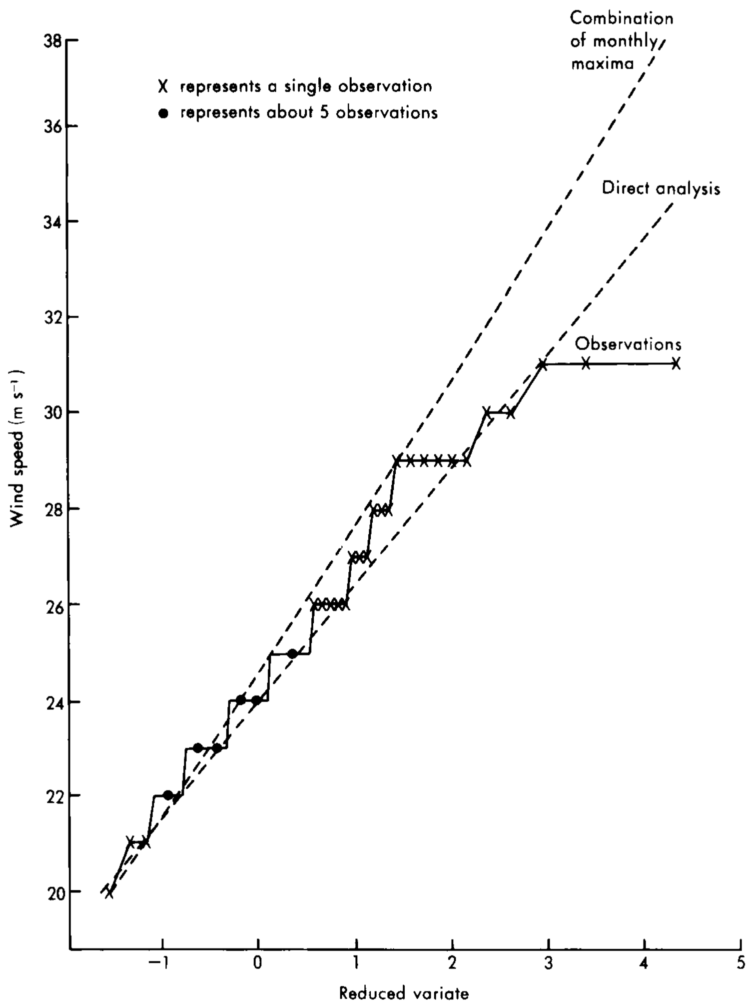

Figure 1. Annual maxima of hourly mean wind at Scilly, 1927–81.

purposes of extrapolation'. This statement would appear on the face of it to be a 'show stopper' worthy of Lady Bracknell. However, in matters statistical it is rarely wise to accept results at face value. It is in fact likely that 'our' distribution is closer to the true distribution of annual maxima than the product of 'direct analysis', and should be used for interpolation as well as for extrapolation, to estimate, for example, the 50-year return value.

Simulations from a simple model will show why this is so.

Simulation model

Suppose that maximum values during month m (m = 1–12) are from a Fisher–Tippett Type I (FT-I) distribution given by

$$\text{Prob}\ (X_{\max} < x) = \exp\{-\exp[-(x - A_m)/B_m]\} \qquad (B_m > 0). \qquad \ldots\ldots (1)$$

So, assuming that monthly maxima are independent, the distribution of maxima throughout the year is given by

$$\text{Prob}\ (Y_{max} < y) = \prod_{m=1}^{12} \exp\{-\exp[-(y - A_m)/B_m]\} \qquad \ldots\ldots (2)$$

Now assuming that A_m, B_m have the same values, A,B, for all months — so there is no seasonal variation in the model — then the distribution of annual maxima is given by

$$\text{Prob}\ (Y_{\max} < y) = [\exp\{-\exp[-(y - A)/B]\}]^{12}$$

which reduces to

$$\text{Prob}(Y_{max} < y) = \exp\{-\exp[-(y-(A + B\ln 12))/B]\} \qquad \ldots\ldots (3)$$

i.e. annual maxima are also from an FT-I distribution with the same value for the scale parameter, B, but with A replaced by $A + B\ln 12$.

If we simulate maxima for each month for N years (i.e. $12N$ values), then the distribution of annual maxima can be estimated by:

(a) Fitting an FT-I to the N annual maxima to obtain estimates $\hat{A}$,$\hat{B}$, giving

$$\text{Prob}\ (Y_{\max} < y) = \exp\{-\exp[-(y-\hat{A})/\hat{B}]\}\ , \text{and}$$

(b) Fitting an FT-I to each of the 12 monthly sets of N maxima to obtain estimates $\hat{A}_m$, $\hat{B}_m$, then using equation (2) to give

$$\text{Prob}\ (Y_{\max} < y) = \prod_{m=1}^{12} \exp\{-\exp[-(y-\hat{A}_m)/\hat{B}_m]\}.$$

These two estimates for the distribution of annual maxima can be compared to the true distribution given by equation (3).

We have carried out such simulations, fitting the FT-I distributions by the method of maximum likelihood, and using A=B=1.

Results

The results of one such simulation run with N=40 are shown in Fig. 2, with probability axis scaled so that the FT-I distribution is linear. The data have been plotted using the same formula as that used by Tabony (1983a) for plotting position, with the ith ordered value of n at $(i-0.31)/(n+0.38)$. Clearly, method (a) gives a closer fit to the sampled annual maximum values — it must do, since this method consists simply of fitting these values; but the distribution obtained by method (b) is nearer to the true distribution of annual maxima.

It must be admitted that the example shown in Fig. 2 was not chosen quite at random, but was selected because of the similarity with Fig. 1. However, such a result is not uncommon. Figs 3(a) and 3(b) show the results of 50 random simulations; these figures give respectively the distributions estimated by method (a) and (b), with N=20. (Note that for clarity a narrow swath about the line of the true distribution has been left blank.) The right-hand edge of each plot, with probability = 0.99, gives the 100-year return value. Method (b) is generally close to the true distribution; the 100-year return value is biased high but its mean-square error is lower than the value from method (a), which suggests that method (b) is preferable. Similar results were obtained from simulations with other values of N (except that for small N, estimates of long-period return values from method (a) tend to be low because the method of maximum likelihood is biased for small N).

The results from these simulations would seem to imply that it is better to divide identically distributed data, analysing subsets such as monthly maxima rather than annual. More data are fully incorporated into the analysis, and the effects of outliers — statistical or accidental — are reduced. However, in practice the population distribution is not known, and the use of the FT-I is only justified asymptotically with increasing number of observations from which the maxima are derived. Unfortunately the rate of convergence to the asymptotic FT-I with increasing number of observations is not known, but Smith (1982) shows it to depend upon the (unknown) population distribution. So it is

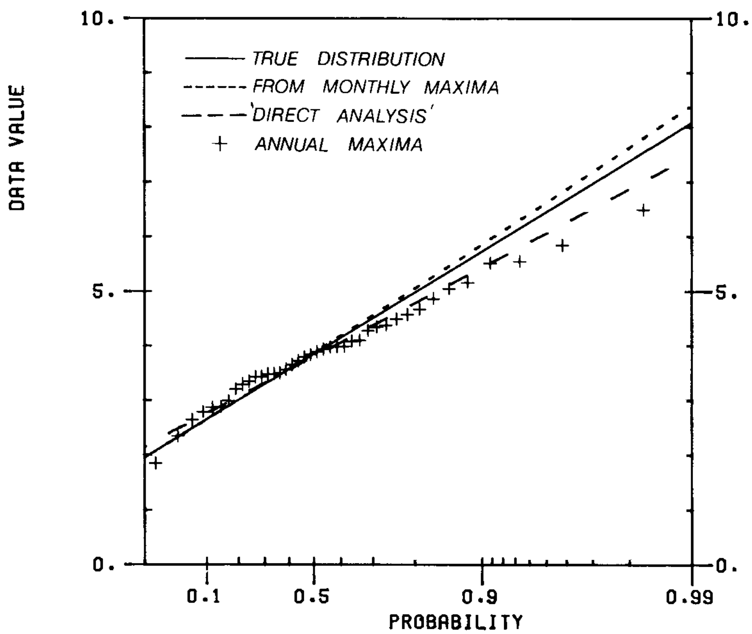

Figure 2. Example of estimates of the distribution of annual maxima from 40 years of simulated data.

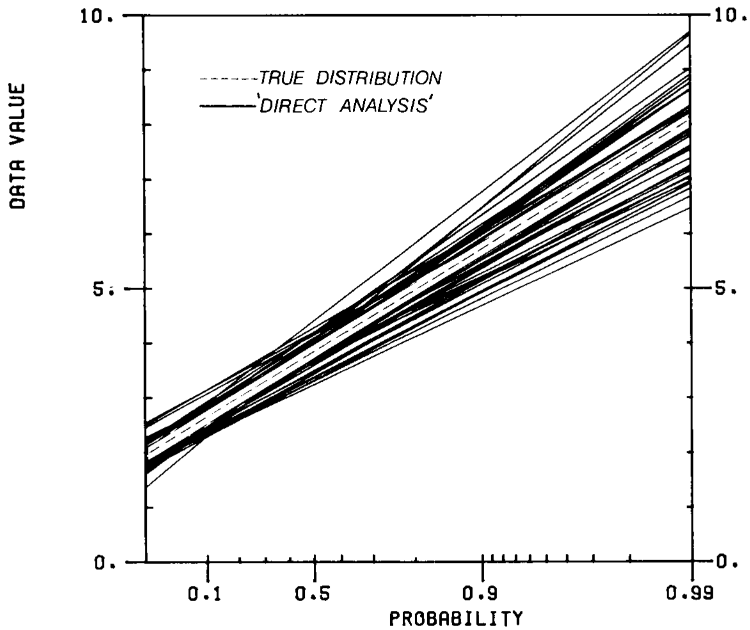

Figure 3(a). Fifty estimates of the distribution of annual maxima each from 20 years of simulated annual maxima.

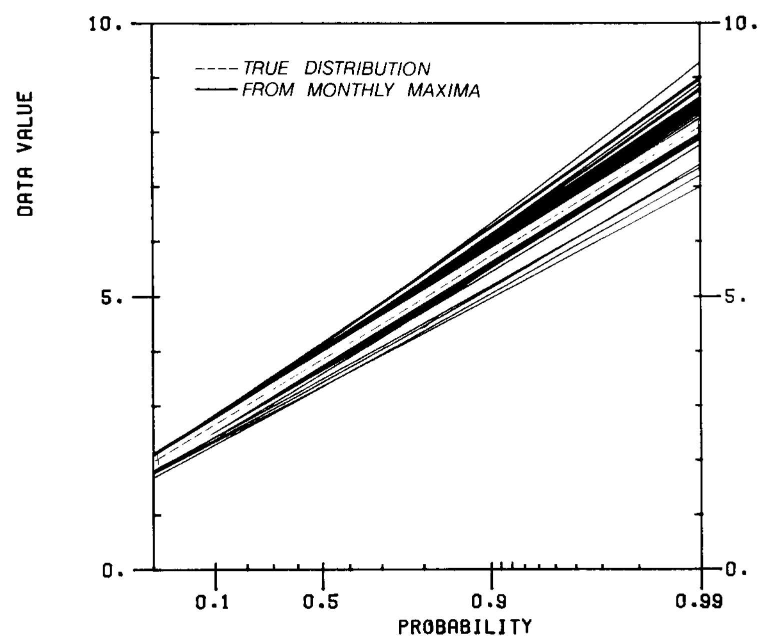

Figure 3(b). Fifty estimates of the distribution of annual maxima each from 20 years of simulated monthly maxima.

not possible to weigh the effect of improving the analysis by dividing the data into subsets against the consequent movement away from the asymptote. On the other hand, analysing annual maxima is not theoretically justifiable because of seasonal variation. In our reply to Tabony (1983b) in the *Quarterly Journal of the Royal Meteorological Society* we illustrate the markedly different distribution of wind speed at Scilly between months and show the effect of ignoring seasonal variation when estimating return values.

Our simulation model does not incorporate seasonal variation; even so the results illustrate why Tabony is wrong to infer from Fig. 1 that combining monthly maxima is an unsatisfactory method of estimating the distribution of annual maxima.

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P. G. Challenor

Institute of Oceanographic Sciences
Wormley, Godalming, Surrey

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Reply by R. C. Tabony

Conventional extreme value analysis of annual maxima requires a large amount of data before reliable results can be obtained. Very often, estimates of 50-year return values are required when only a few years of data are available, in which case estimates derived from annual maxima will have unacceptably wide confidence limits. In these circumstances it is sensible to use other techniques which reduce random errors by making use of more of the data. Such methods, however, may also be associated with larger systematic errors due, for example, to the main body of observations (which are used to reduce the random errors) not belonging to the same population as the extremes. The best technique to use may well be that which minimizes the total (systematic + random) error. Carter and Challenor's proposed technique, by making use of more of the data, produces smaller random errors than an extreme value analysis of annual maxima. They also claim, however, that their approach is associated with smaller systematic errors, and this is where we disagree.

In their comments, Carter and Challenor attempt to show the superiority of their technique by using simulated data. By not incorporating a seasonal variation they ensure that both monthly and annual maxima belong to a Fisher–Tippett Type I distribution and therefore that a direct analysis of the annual maxima will have no systematic errors. They show that estimates of 50-year return values obtained from a combined analysis of monthly maxima have a standard deviation about 70% of that obtained from a direct analysis of annual maxima. They also concede, however, that their technique introduces a small positive bias, although the extent of this is not clear from their diagram. I have performed a similar analysis using real data and a description of this follows.

Monthly and annual maxima of mean hourly wind during the period 1931–80 were extracted for the 9 stations shown in Fig. 1. Changes in effective height were taken into account by using a 0.17 power law relation, but other changes in site and instrumentation could not be allowed for, except during 1975 at Shoeburyness when overlaps were available. Occasional missing values were estimated from neighbouring stations.

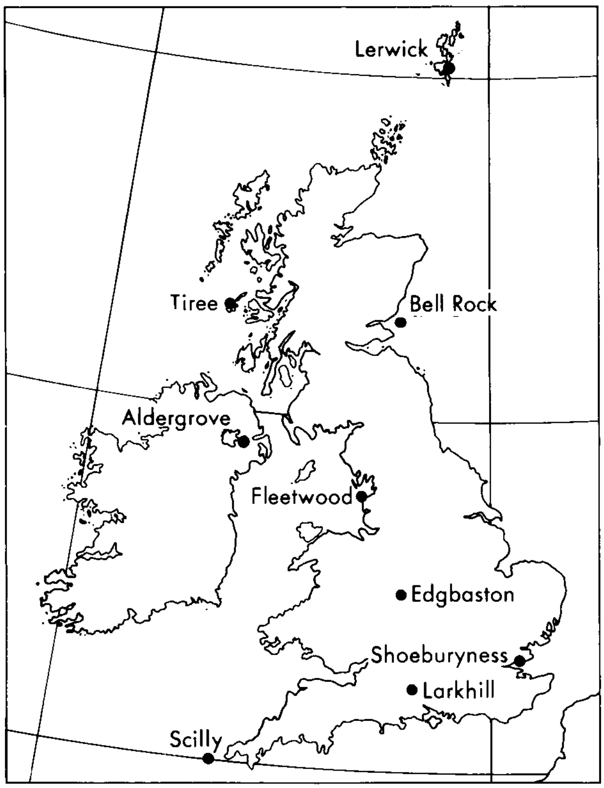

Figure 1. Stations used in the analysis

Return values of annual maxima were estimated both by a direct analysis of the annual maxima and by a combination of analyses of monthly maxima. The technique used was due to Lieblein (1974) and calculates the Gauss–Markov best linear unbiased estimates, which are those with the minimum variance for any linear estimate. The return values were obtained from only 10 years of data and were expressed as a percentage of the median annual maxima observed in the full 50 years of data for the station concerned. This procedure eliminated most of the differences between stations when the return values were expressed in absolute units. Forty-five sets of estimates were obtained (5 decades × 9 stations) and the means and standard deviations for various return periods are displayed in Fig. 2. These estimates are compared with a set of 'observed' annual maxima obtained by averaging the ranked extremes over the 9 stations after they had also been expressed as a percentage of the median value for each station.

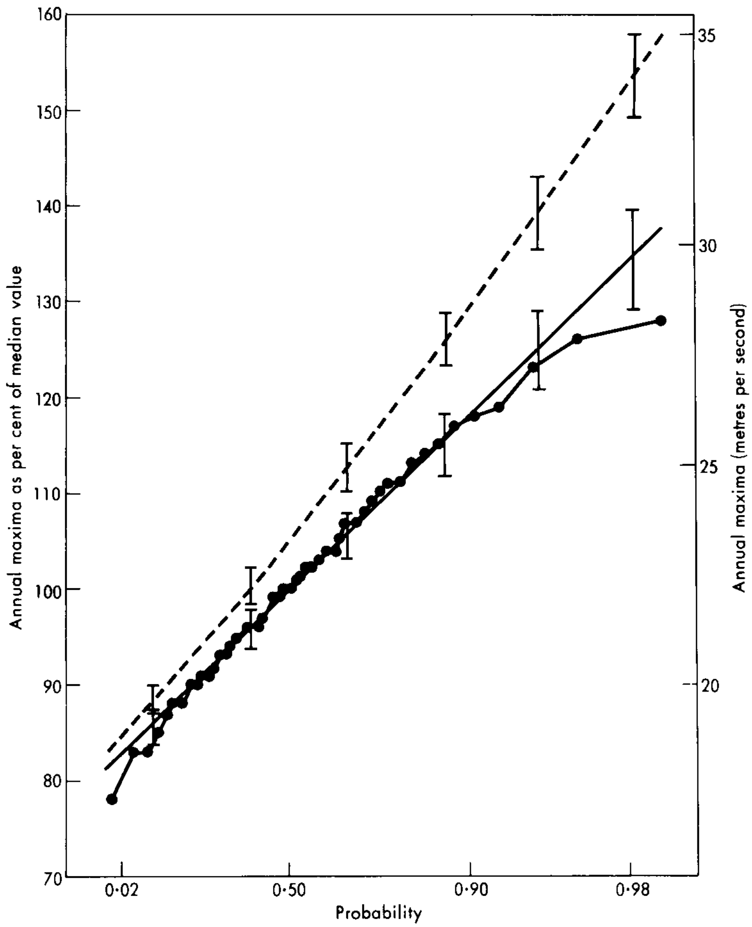

Figure 2. Annual maxima of mean hourly wind: comparison of 45 estimates made from 10 years of data for 9 stations over the period 1931–80.
——— Direct analysis of annual maxima.
– – – Recombination of monthly maxima.
●——● Observed data (meaned over 9 stations).
Vertical bars represent the standard deviation of the 45 sets of estimates.

Fig. 2 shows that a direct analysis of annual maxima provides a very good fit to the observed extremes, with very little systematic error. The presence of seasonal variation — the grounds on which Carter and Challenor criticize the analysis of annual maxima — is clearly unimportant. The combination of monthly maxima, on the other hand, yields estimates which are far too high, although their standard deviation is only 80% of that associated with the direct approach. The estimates in Fig. 2 are being tested against nearly independent data, since the former are derived from only 10 years of data for one station, while the observed values are based on 50 years of data from 9 stations.

There are two main reasons why a combined analysis of monthly maxima produces overestimates of annual maxima. The first may be expressed either as an inability to satisfy the asymptotic requirements of extreme value theory or else as the failure of the wide range of events represented by monthly maxima to conform to a single population. These alternatives are statistically distinct but, as I tried to show in my paper, they are difficult to distinguish between in practice. Carter and Challenor (1983) show that, for certain parent distributions, a sample size of 10 is sufficient to meet the asymptotic requirements of extreme value theory. The number of independent meteorological observations in a month may average around 10, but in any individual month there may be more or fewer than this number, and months with persistent blocking patterns in particular may contain very few degrees of freedom. General meteorological experience indicates that a month is an insufficiently long period of time in which to observe an 'extreme' event.

The second reason why a combined analysis of monthly maxima overestimates annual extremes is essentially a random effect. Consider the case in which there is no seasonal variation, and all the monthly extremes belong to the same Fisher–Tippett Type I distribution. A sample of observations drawn from the population will yield monthly analyses whose slopes will not be equal, but which will be randomly distributed around the true value. The estimates of annual maxima will be asymptotic to the monthly analysis with the largest slope and this dependence on the largest, rather than the true slope, produces return values which are too high.

The question which now arises is: how much of the positive bias produced by the combined analysis of monthly maxima is due to each of the reasons given above? The errors caused by the second factor can be eliminated by ensuring a smooth seasonal progression of the slopes and intercepts of the extreme value distributions fitted to the monthly maxima. Thus the relative importance of the two effects can be determined by repeating the above analysis using smoothed 'regression coefficients' for the monthly analyses.

The slopes and intercepts of the 'Gumbel' distributions fitted to each month were expressed as a percentage of the value meaned over all months for the station concerned, and these values were then meaned over all stations. The results, displayed in Fig. 3, show a clear seasonal variation in the intercepts. The variation does not quite match the sine wave fitted by Challenor (1982), so a 7-point binomial filter was used to achieve the smoothing. This was actually applied to the median values rather

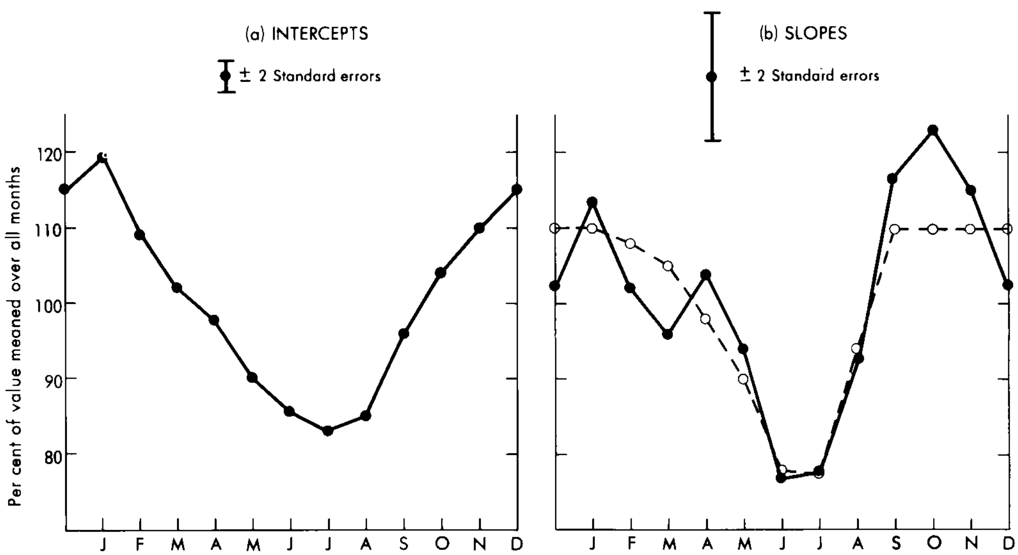

Figure 3. Intercepts and slopes of extreme value distributions fitted to monthly maxima of mean hourly winds (meaned over 9 stations). The dotted line indicates the imposed seasonal variation of slopes.

than to the intercepts, since the latter do not correspond to the centroid of observations. The much larger errors associated with the slopes ensure that the need for smoothing is great, but also that the true seasonal variation is unclear. The variation imposed is marked by the dotted line in Fig. 3(b) and combines a broad maximum from September to January with a sharp minimum in June and July. The true variation will probably change with geographical location, but the large errors involved prevent identification of any such changes.

The effect of smoothing the slopes and leaving the median values unchanged is shown in Fig. 4. It can be seen that the overestimate in the 50-year return value is almost halved and that a further modest reduction in error occurs when the median values are smoothed. The variance of the estimates, however, is unchanged by the smoothing. The general conclusion is, therefore, that random errors in the slopes of the monthly analyses account for nearly half the systematic errors in the return values of annual maxima.

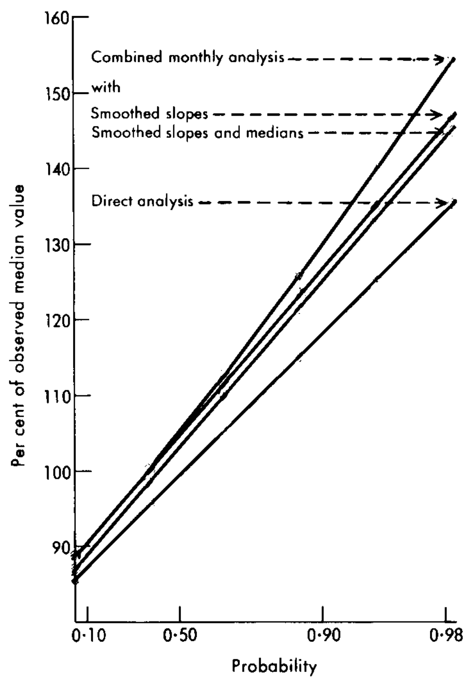

Figure 4. Comparison of estimates of annual maxima.

Despite the small systematic errors associated with the direct analysis of annual maxima, the large random errors involved may make it an unsuitable technique to use if only a small number of years of data are available. Every effort should be made, however, to reduce random errors by making use of covariate information, notably that from neighbouring stations. A comparison of results from neighbouring stations, combined with a sensible interpretation of them, should increase the applicability of extreme value techniques. Despite the fact that the incorporation of covariate information may have to be statistically crude, it still provides a very valuable way of reducing random error.

R. C. Tabony

Meteorological Office, Bracknell

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The Second International Meeting on Statistical Climatology

By R. C. Tabony

(Meteorological Office, Bracknell)

The meeting was primarily sponsored by the World Meteorological Organization and the USA's National Science Foundation and Office of Naval Research. It was held near Lisbon from 26 to 30 September 1983 and was attended by around 100 participants. The organizing committee chairman, Dr A. H. Murphy, worked hard to ensure that the conference program went ahead as smoothly as possible.

The scope of the meeting was wide, but subjects excluded from discussion were those relating to weather modification and forecasting, as these topics attract conferences in their own right. Subjects which featured prominently in this symposium were the economic value of climate information, the impact of climate, principal component and time series analysis, studies of precipitation, and the evaluation of general circulation model experiments. A total of 68 papers were presented, including 14 lead papers from invited speakers.

The standard of the lead papers was mixed. Some were very good, like that from Roger Stern who advocated an increase in the use of the general linear model. Others were poor in that they lacked generality, or covered only familiar ground and failed to highlight new areas of development or interest.

To the writer, some of the most interesting papers were those concerned with principal component analysis, especially the discussion relating to the assignment of variables to points in either space or time. These papers constitute highly recommended reading for the many users of this technique. Another area of interest was the evaluation of general circulation model experiments. There the discussion centred on how to determine the correct number of degrees of freedom from the massive amount of correlated data produced. This is clearly very important in order to avoid the inflated values of significance which have plagued climatology in the past. The last paper was given by Ian Jollife who pointed out that, for small sample sizes, the distribution of the correlation coefficient is flatter than that assumed by the formulae which are generally used for testing their significance. This goes a long way to explaining many of the spurious correlations which have been observed in climatology.

A large number of papers were concerned with simulation. The main reason for the exercise seems to be to reduce the sampling error by generating a long time series. In the writer's opinion, this is false logic. The sampling errors in the real data are converted to systematic errors in the simulation. Having thus generated the data, one is tempted to extend their use to provide information on aspects of the real world which have not been modelled explicitly. Such use of a model is almost always likely to lead to gross errors. A much sounder technique is to fit distributions directly to the data in order to deal with the given enquiries. One then has a much better appreciation of the likely errors involved and there is no danger of using a model outside the area of its validity.

The main purpose of the meeting was clearly to promote an exchange of ideas between statisticians and climatologists, and this was most naturally achieved through lead papers and discussion periods. In general, this interchange of ideas was successful. Nearly half the lead papers were given by statisticians, where they were given the opportunity of recommending techniques suitable for climatologists to use. Papers presented by climatologists had their statistical weakness pointed out by the statisticians, while papers given by statisticians had their physical shortcomings exposed by the climatologists.

The interaction between statisticians and climatologists, however, should not consist solely of a flow of ideas from the former to the latter. In order to advance the cause of climatology, there needs to be a feedback of information to the statistician, and the climatologist cannot afford to adopt a passive role. All the statistical techniques used by the climatologist were developed with other disciplines in mind, e.g. medicine, agriculture, or the social sciences. The onus is on the climatologist to approach the statistician, inform him of his problems, and persuade him to carry out research into techniques of direct applicability to his science.

Statistical climatology has acquired a poor reputation in many eyes in recent decades. This had been mainly because of the low statistical standards of many papers, especially in the area of solar and climatic variability, which led Pittock to make his famous review*. Partly as a result, the era of statistically ignorant papers is largely, although not entirely, over. There are still too many papers, however, which one feels are cluttering the journals with trivia. The reasons are either that the aim is scarcely worth while, the results have no practical value, the scope is too limited, or that no attempt has been made to improve the quality of the data used to the extent that the results are useful. It is to be hoped that future meetings of this kind will have high amongst their aims the enhancement of the status of statistical climatology.

*Pittock, A. B. 1978 'A critical look at long-term Sun-weather relationships', *Rev Geophys Space Phys*, **16**, 400–420.

Notes and news

50 years ago

The following extracts are taken from the *Meteorological Magazine,* February 1934, **69,** 17, 20–21.

Buxton Weather Bulletin

Mr. H. Everard sends us the following copy of a weather bulletin which was displayed in a shop window at Buxton. In explanation of the remark about pressure it must be remembered that Buxton is at a height of 1,000 ft. above M.S.L.

Temperature. — Keeps up a good average.
Pressure. — Finds effort of climbing too much for it.
Rainfall. — Fairly frequent visitor.
Wind. — Speaks with a soft southern accent.
Current noting. — Ridge of high pressure giving way.
Further outlook. — Good, bad and indifferent in turn.
Propitious features. — Rest from their toils.
Ominous symptoms. — Collecting a representative array.

Today's local weather handicap.

Pressure — drooping once more.
Distant influences — still quarrelsome.
Inferences — Bashful sunshine.
Arrogant clouds.
General dampness.
Fair periods.
Fairly mild.

Broadcast Weather Noises

Now that weather noises "off" form such a usual — and vivid — accompaniment of many broadcast plays, meteorologists may be interested in the methods which are used in the studio for reproducing these realistic effects. Mr. J. E. Cowper has kindly supplied the following notes on the subject:—

Wind. — This is done on a cylinder 2 ft. in diameter and 6 in. deep, set in a wooden frame 3 ft. high with a length of canvas stretched over the top. A handle is fixed to this, and by rotating at a normal rate one gets a steady wind, and with a quick motion gusts. It is a most realistic noise, and usually comes over very well.

Rain. — A rose on a water tap is usually used for this, which is turned on fully into a large wooden tank.

Thunder. — This is produced by suspending from the ceiling a huge piece of sheet iron, with a wooden shaft at the bottom where two handles are fixed for the hands. This, when shaken in an intelligent way, produces excellent thunder.

Sea. — A one-sided drum with lead shot inside shaken from side to side and round and round produces waves breaking on the shore, and is quite one of the best noises "off."

May I add that in nearly all cases we use gramophone records of these sounds, and these records will, I think, gradually effect the instruments I have tried to explain to you.

Obituary

We regret to record the death on 7 September 1983 of Mr G. F. McKay, Higher Scientific Officer, who was stationed at London/Gatwick Airport.

Gerry McKay joined the Office as a Meteorological Assistant in 1947 and worked for some years at Castle Archdale in Northern Ireland. In 1952 he was posted to the Marine Branch at Harrow and in 1956 was promoted to Assistant Experimental Officer and became a forecaster. During his forecasting career he worked at a variety of outstations including Wittering, Upavon and Boscombe Down, with two lengthy spells at Heathrow (1956–61 and 1975–81) and an overseas tour at Laarbruch. He moved to Gatwick in 1981.

Gerry McKay had a cheerful and friendly personality and got on well with all his colleagues. He was a keen games player, especially in his younger days, being particularly good at lawn tennis. He used to compete in the Air Ministry championships, and represented Heathrow in matches against other Meteorological Office teams. He was a sportsman in the best sense of the term.

THE METEOROLOGICAL MAGAZINE

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NOTICES

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Reduction in the daily rainfall gauge network in England and Wales

By B. R. May

(Meteorological Office, Bracknell)

Summary

The measurement of daily rainfall totals in England and Wales is made by about 4000 gauges at present. Many of these gauges are administered by the Water Authorities and other organizations, and their observations are sent to the Meteorological Office. These organizations and the Meteorological Office are having to reduce the resources allotted to the handling of these observations and, as a consequence, the total number of gauges is being reduced, but with some redistribution.

This paper describes the reduction procedure, which is designed to preserve the general quality and usefulness of the rainfall archive, and its implementation.

1. Historical perspective

It is not surprising that for many hundreds of years the British people have recorded an interest in the amount of rain that falls on these islands. The variation with locality, reflected in the contrast between the wet highlands of the west and north and the drier lowlands of the south and east, and the variation of duration and intensity, reflected in the contrast between heavy summer showers and the long, unremitting rain of winter storms, has raised scientific curiosity about rainfall as well as making it a subject for daily conversation.

Naturally a phenomenon of such relevance to everyday lives required rigorous and regular observation. Sir Christopher Wren is credited with the invention, about 1660, of two of the earliest known rain-gauges in Britain. There is no evidence, however, that the architect himself ever used the gauges for making regular measurements, which became more the interest of 'gentlemen-philosophers' who wished to use their wealth and leisure in scientific pursuits.

A Mr Richard Towneley (1629–1707), of Towneley Hall near Burnley, is generally acknowledged to be the first British observer to make and record regular observations of daily rainfalls as we understand them today, starting in January 1677 and continuing until his death. He believed in simplicity. His gauge consisted of a funnel to channel rain into a simple graduated measuring cylinder, much the same principle as is still used today in simple storage gauges. He believed in comfort as well. The funnel was mounted on his roof, with a long pipe leading indoors so that he could make his measurements in the dry.

2. British Rainfall Organization

During the 18th and early 19th centuries many different types of gauge were developed with funnels on roofs, towers, walls and on the ground, but there was no central co-ordination of measurements of rainfall and their recording. This was the situation until 1860 when J. G. Symons founded the British Rainfall Organization to collect and publish rainfall data regularly. He also appreciated that for sensible studies of rainfall variation the gauges and methods of observation should be standardized and should not be unduly affected by local effects and procedures. He issued instructions on the correct siting of gauges, e.g. on level ground away from obstructions, and set a standard time of observation of daily rainfall accumulations, 0900 GMT.

The earliest volume of *British Rainfall* was for 1860 and contained data for 500 sites in the United Kingdom (including all Ireland). The rapid growth of the water distribution system during Victorian times was accompanied by a corresponding expansion in the number of rain-gauges so that in 1900 data for 3500 gauges were published. Of these by far the largest percentage, approximately 70%, were maintained by landowners and 'gentlemen', 9% by ladies and 8% by waterworks and local councils; a further 9% of gauges were maintained by parsons, presumably because the time of rainfall observations fitted in with their parochial duties. That total of 3500 gauges far exceeds the number of rain-gauges in many countries even today.

The British Rainfall Organization carried on until 1918, at which time nearly 5000 observers were active. It was now too large for a small semi-professional staff to manage. In that year the functions of the Organization were taken over by the Meteorological Office which continued to collect and to publish rainfall data under the *British Rainfall* title.

It is relevant to the theme of this article that the foreword to *British Rainfall* for 1919 contained the comment that '... due to the Great War the numbers of observers had declined because of disturbance to the routine of their lives but fortunately many of these were in districts where there was a surfeit anyway ...'. The writer goes on to speculate whether '... we are not in some cases actually overburdening ourselves with an unnecessary accumulation of data...'.

In spite of these words the number of gauges continued to increase, reaching about 6000 in the United Kingdom in 1980. Of the approximately 4000 gauges in England and Wales, 70% are now owned or maintained by the ten Regional Water Authorities who took them over from numerous River Boards and Water Companies in the reorganization of the water-supply industry of the early 1980s; the remaining 30% are owned by private observers, or are sited at the Meteorological Office's own stations or co-operating climatological stations.

3. Present-day processing of observations

The observations of daily rainfall made at these 4000 gauges are submitted to the Hydrometeorological Branch (Met O 8) of the Meteorological Office at Bracknell. They arrive at Bracknell on postcards, each of which carries a calendar month's observations. They come mainly via collecting centres for observations at Water Authority sites or directly from private and other observers. Observers in Scotland and Northern Ireland despatch their observations to the meteorological offices in Edinburgh and Belfast respectively.

Met O 8 is responsible for the checking, quality control and archiving of the rainfall observations made in England and Wales. These processes are today computer-controlled, this being the only practical way of handling the 4000 observations made each day (approximately 1.4 million per year). A central key to all of these processes is a comprehensive 'housekeeping' catalogue (called 'RAINMASTER') of the details of all known gauges past and present, totalling 15 000, which enables the organization of the work to proceed. After an initial manual check on rainfall cards (legibility of writing, correct station number, etc.) they are submitted for entry into the computer for quality control. The success of the quality-control procedure depends on three factors: that on any day there is broad similarity in the rainfall measured by neighbouring gauges (on average these are about 6 km apart but in practice range from 1 km to over 30 km apart); that incorrect observations are the exception rather than the rule; and that a large proportion of the observations for any one time can be assembled quickly to allow the quality-control process to begin. Comparisons between measurements at adjacent gauges then reveal suspect observations and from a knowledge of the kinds of errors that are most commonly made, the computer program estimates a more likely value for the measurement which is thought to have been faulty. The most common errors are: completely missing observations, accumulations of rainfall on several successive days reported as one measurement, observations ascribed to the wrong date, and simple clerical and transcription errors. However, some obscure errors defeat the capability of the computer to suggest correction, and experienced staff then need to perform manual quality control; periods of snow or showers often result in this situation. In all cases staff have the final decision in accepting or rejecting computer-recommended amendments. When quality control has finished, the observations are archived in the computer and used to create monthly and annual rainfall totals which are published by the Meteorological Office annually under the title *Monthly and annual totals of rainfall for the United Kingdom* which replaced *British Rainfall* in 1969.

4. Who wants daily data anyway?

Daily rainfall observations are used in many ways, and requirements range from daily values on specific days at an individual station to complex statistical summaries of observations from many stations over many years. The Water Authorities and the Department of the Environment need to know of the characteristics of rainfall over Authority areas and the United Kingdom as a whole because water is an essential basic resource which is usually collected in one area where the rain falls and piped to another area where population and industry are concentrated. The collection and storage of water often involves the use of reservoirs and dams, so the statistics of the incidence of prolonged heavy rains are needed for safe engineering design and efficient operation, and for drainage and flood alleviation works generally. Rainfall often governs crop growth; too much rain requires efficient drainage, while too little rain requires extra irrigation. Thus the agricultural industry has an interest in a knowledge of likely rainfalls, both for long-term planning of capital projects and field-work, and for the cost–benefit assessment of investment. Architects and civil engineers require rainfall statistics so that adequate provision can be made for conducting rain-water away from buildings and built-up areas. The legal and insurance professions take an interest in observations of rainfall in connection with claims for damage or accidents or interruption of construction work caused by rain and flooding. Many institutions with diverse interests in weather-sensitive problems and in the environment require rainfall observations for study and research. In addition to the routine supply of data to the Water Industry and Government Departments, the Meteorological Office receives about 5000 non-routine enquiries for rainfall data each year. There is no indication that the demand for rainfall data will decrease in the next few years.

5. Requirement for reduction in numbers of gauges

Both the Meteorological Office and the Water Industry are under pressure to reduce the effort involved in the making, collection, checking and archiving of rainfall data. At the end of 1981 the National Water Council–Meteorological Office Joint Liaison Group set up a Working Group to make recommendations on how these reductions could be brought about, while recognizing the continuing requirement for adequate or even improved rainfall data. The Working Group, which consisted of representatives of the Water Authorities, the Meteorological Office and other Government Departments, reported at the end of 1982. In summary its recommendations were:

(i) that the number of daily-read gauges in England and Wales whose data are to be stored in a central archive at Bracknell should be reduced from 4000 to about 2800 (this increases the average spacing between gauges from about 6.0 km to 7.2 km), i.e. a net reduction of about 30%;

(ii) that reductions should take place in those areas already well provided with gauges;

(iii) that in some areas which are now devoid of gauges efforts should be made to install gauges so that both generally and locally the recommended density of gauges is achieved;

(iv) that the gauges that are closed down should include a high proportion of those for which past experience indicates that there are difficulties in obtaining regular and reliable observations (for a variety of reasons);

(v) that gauges of particular interest should be retained (for instance those with a long record of observation are of significance to the Meteorological Office, Water Authorities and other institutions such as university research departments).

These recommendations have been accepted by the Joint Liaison Group and implementation has already started.

6. Practical aspects of reductions of the numbers of gauges

Much thought has gone into the implementation of these recommendations. It was known, for instance, that objective methods of 'rationalizing' rain-gauge networks would be very costly in terms of manpower and computer time. This conclusion was based on the experience from such a rationalization study which was carried out in 1978 for the Wessex Water Authority area jointly by the Institute of Hydrology, the Meteorological Office and the Authority. It involved a statement of the required accuracy of daily rainfall estimates following a review of user requirements and an elaborate procedure for estimation of rainfall at ungauged points based on historical rainfall statistics. The result was an indication of those areas where gauges could be removed, and also where a few new gauges were needed; the result was that the total number of gauges could be reduced by about 30%, while maintaining the required accuracy of observation. As a consequence of the effort involved in that exercise it was decided that the present country-wide reduction in gauges would need to use a simpler subjective method but based on the Wessex Water Authority area experience.

The practical procedures for choosing gauges to be retained in the reduced network consist of these steps:

(a) Mandatory gauges are specified by users (e.g. Water Authorities and the Institute of Hydrology for resource planning and flood control design; the Meteorological Office for country-wide rainfall and evaporation monitoring, meteorological studies, enquiries, catchment run-off studies, etc.).

(b) A matrix of grid squares of side x (where x is approximately 7 km) is specified.

(c) The relative importance of gauges is assessed using a scoring system which allots points for standard of exposure and equipment, regularity and quality of observation, length of record, altitude and remoteness of site and whether the site has other hydrometeorological instrumentation.

(d) For each square not containing a mandatory gauge the rain-gauge with the highest score is chosen.

(e) If a square contains gauges with an altitude range of greater than 50 m then two gauges at different heights are selected.

(f) Squares without gauges are noted for future 'gap-filling'.

The result of this procedure is a gauge network of generally no less than the required spacing but with a concentration of gauges in topographically complex areas. A computer program has been written by the Meteorological Office to carry out this design process automatically.

7. Progress in implementation of recommendation

The rain-gauge reductions are being carried out with each individual Water Authority independently. The Welsh Water Authority is the first being considered and this will establish the practicalities of the procedures. Fig. 1 shows the pre-reduction network of daily gauges in south and west Wales and, in comparison, Fig. 2 shows the post-reduction gauges. Note that the concentrations of gauges to the south of Plynlimon, on the Brecon Beacons and on the Black Mountains are considerably reduced. The gauges indicated by circles in Fig. 2 are new gauges in that though they existed previously they were not known to the Meteorological Office and no data were received from them; these gauges help to fill some gaps in the coverage. Inadequately gauged areas are also shown in Fig. 2, indicating where recruitment of rainfall observers should be pursued. The final net reduction in gauges in the Welsh Water Authority area will be about 30%.

Final agreement with the Severn-Trent Water Authority on reductions in their area is near and discussions with the remaining eight Authorities have commenced.

8. Conclusions

Although most of the gauges to be closed down are owned by Water Authorities with observations being made by their staff, inevitably some reports from gauges belonging to private observers will no longer be required, though these closures will be kept to a minimum. The efforts made by that peculiarly British institution — the enthusiastic, knowledgeable and dedicated 'amateur' — will not be discarded thoughtlessly and the nation's gratitude to the many amateur rainfall observers cannot be overstressed. Some individuals, over many decades, and indeed some families over several generations, have contributed to an archive of rainfall data which is a national asset that is the envy of many. Although some individual reports will no longer be included in the national archive, it is hoped that the observers will continue to make observations for their own satisfaction. It is only now, 65 years after the original suggestion, that the number of rain-gauges whose data are to be stored centrally is to be reduced so that the work load of maintaining the national archive can be handled with the available resources. Even after this reduction has been implemented the United Kingdom will still have one of the densest networks of rain-gauges of all countries.

The problems of rainfall assessment may have been largely solved but new crucial problems arise. Water quality, for example, and control of pollution are of concern to us all and new insights and procedures are required for the cost-effective design of safe water supplies and the safe discharge of excess rainfall and stream flow. Rainfall monitoring and data interpretation will have to continue into the foreseeable future and the rationalized reduced network of rain-gauges will be essential in providing the basic information from which progress in this work can be made.

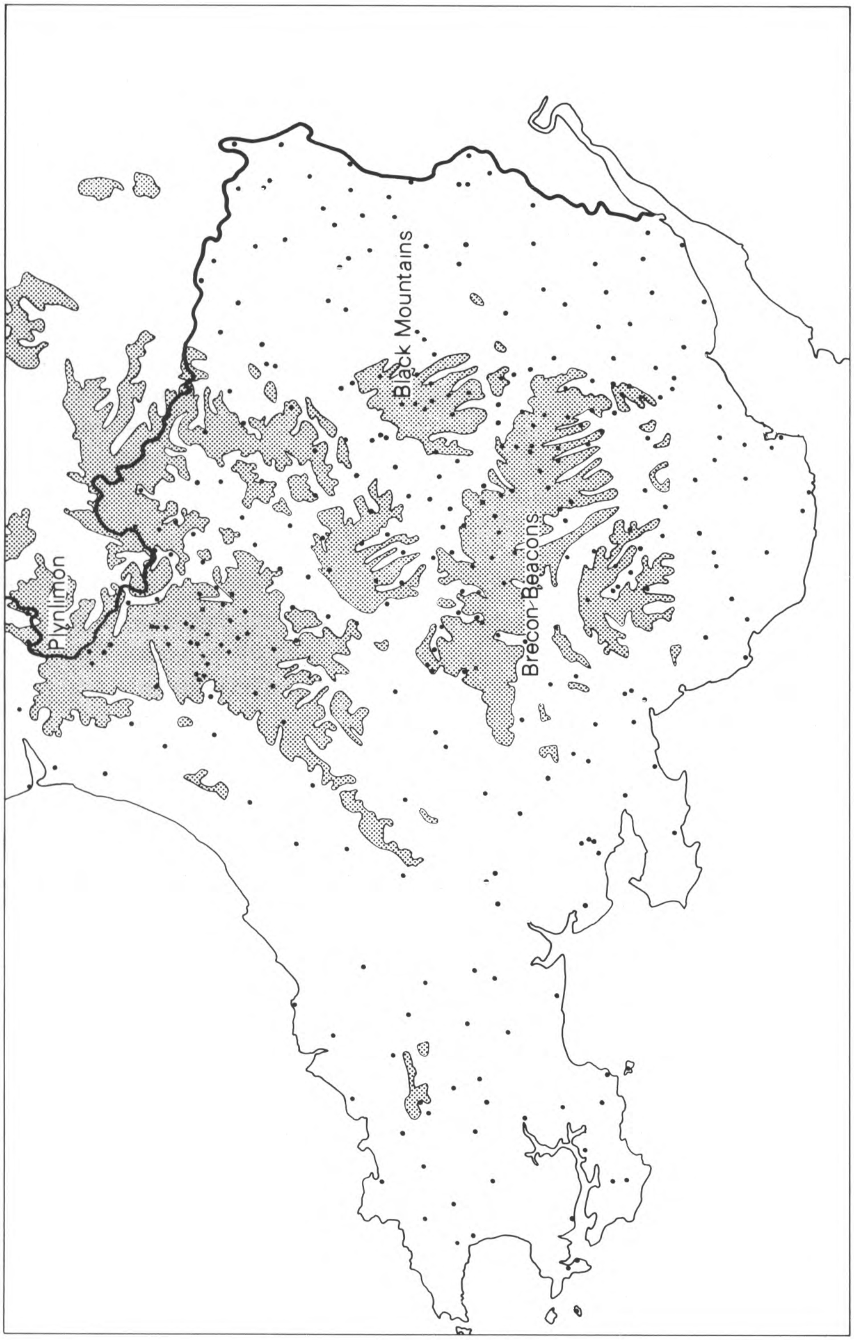

Figure 1. The pre-reduction network of daily rain-gauges in south and west Wales. Stations are denoted by dots.

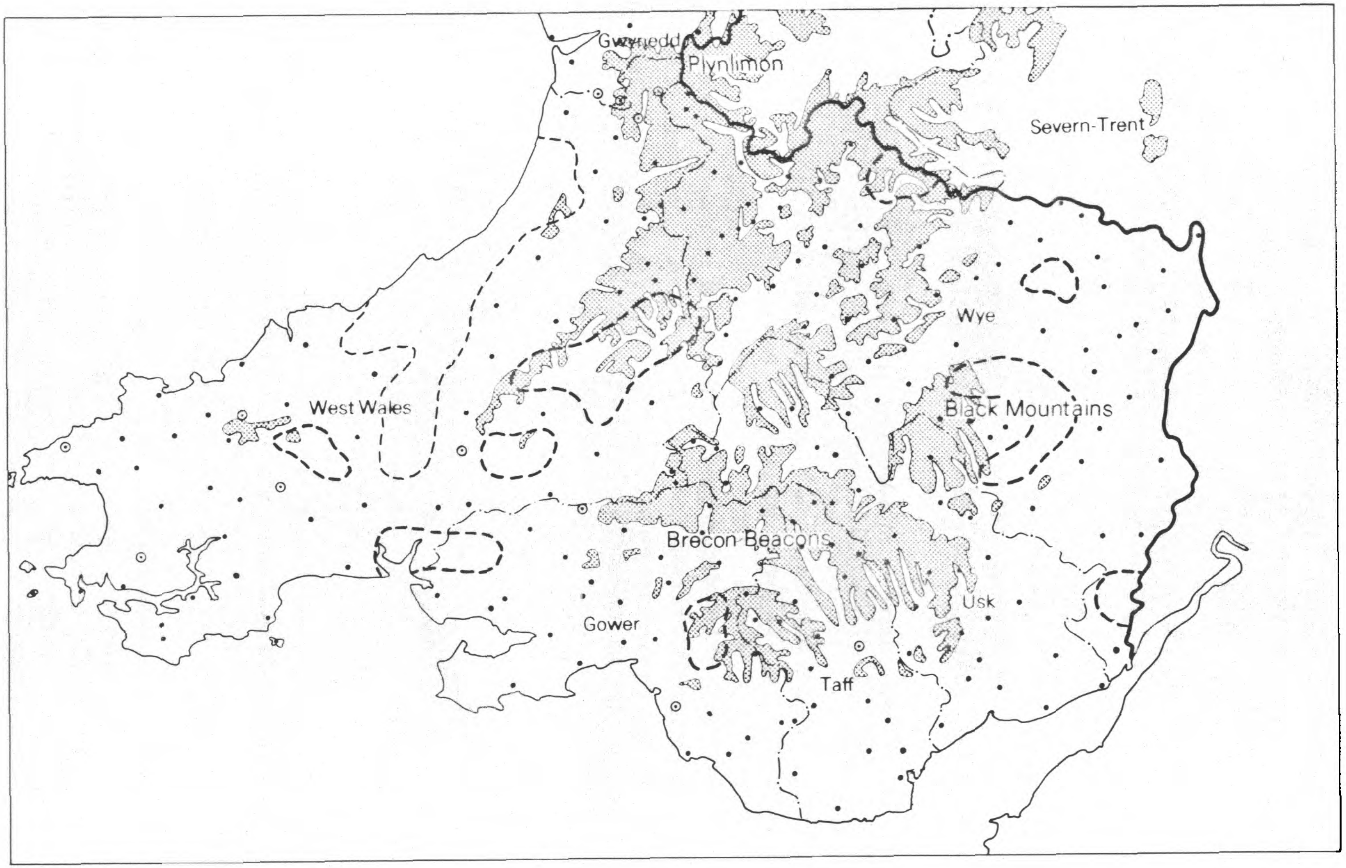

Figure 2. The proposed post-reduction network of daily rain-gauges in south and west Wales. Dots denote stations retained; circles show stations to be 'registered' with the Meteorological Office; and pecked lines enclose areas lacking in gauges. Dash–dot–dashed lines divide River Authority areas.

551.524.32(4/9)

Non-sinusoidal features of the seasonal variation of temperature in mid-latitudes

By R. C. Tabony

(Meteorological Office, Bracknell)

Summary

Reasons for the non-sinusoidal nature of the seasonal variation of temperature in mid-latitudes are discussed. They are then used to explain the geographical and secular variations in the second harmonic of temperature previously found by Craddock and Smith.

1. Introduction

The seasonal variation of temperature in mid-latitudes is mainly, but not entirely, sinusoidal. Relatively well marked asymmetries in the march of monthly mean temperatures are illustrated in Fig. 1

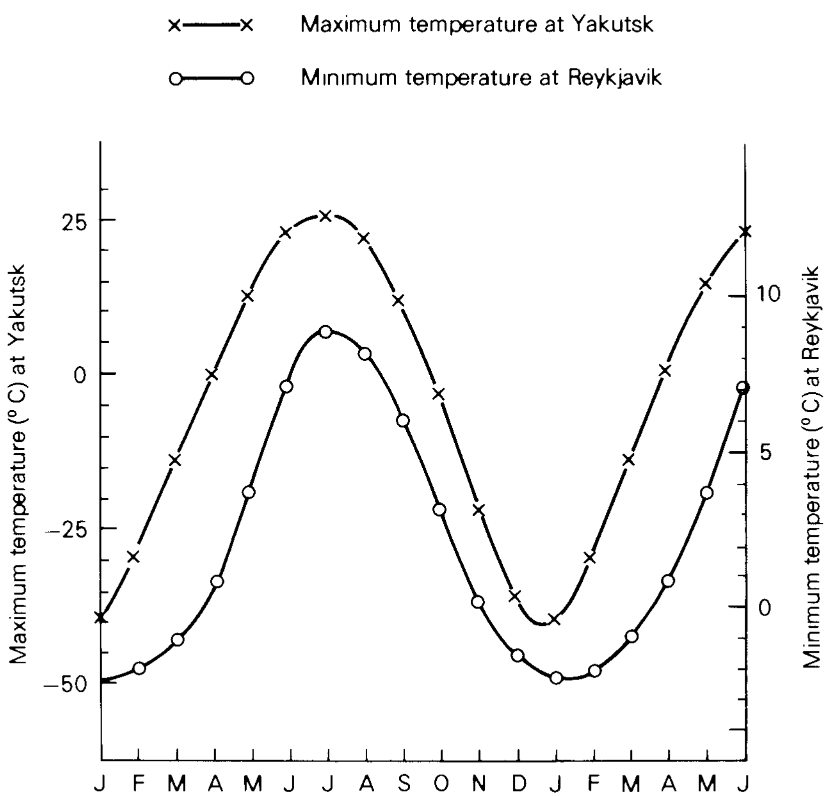

Figure 1. Seasonal variations of temperature at Yakutsk and Reykjavik.

for Yakutsk in Siberia and Reykjavik in Iceland. The departures from a purely sinusoidal annual cycle of temperature may be taken into account by using harmonic analysis and Craddock (1956a) has shown that two harmonics are sufficient to obtain an adequate representation of the seasonal variation of temperature. The non-sinusoidal component will then be represented by the second harmonic.

In a series of papers, Craddock (1955, 1956a, b) examined geographical variation in the first and second harmonics of mean temperature over the northern hemisphere, northern Europe, and the British Isles. Later, Smith (1984) examined temporal changes of these harmonics at Oxford and illustrated the difference between those for maximum and minimum temperature. The purpose of this note is to discuss the reasons for the non-sinusoidal variation of temperature, and to explain the findings of Craddock and Smith.

2. The non-sinusoidal nature of the seasonal variation of temperature

In mid-latitudes, departures from a purely sinusoidal seasonal variation of temperature may be expected for five reasons:

(a) *Solar elevation*

A change in the solar elevation has more effect on the radiation received at the surface when the sun is low in the sky than when it is high. At 50°N, for example, a rise in the solar elevation from 16° at the winter solstice to 21° 38 days later produces a greater change in radiation than the decrease from 63° to 58° as the summer solstice is passed. The changes in radiation received at the surface are therefore greater during the passage of winter months than summer months. The effect on the seasonal variation of temperature is to make the winter trough sharper than the summer peak.

The dates at which mean temperatures reach their highest and lowest values are also affected. The increase in radiation as the sun's elevation increases through January is greater than the corresponding decrease during July. Hence the date of the seasonal extreme of mean temperature lies nearer to the solstice in winter than in summer. A corollary is that the fall of temperature in autumn is more rapid than the rise in spring.

(b) *Lapse rates*

Mean lapse rates of temperature in the atmosphere vary seasonally, especially over the land, where they are greater in summer than in winter. The more stable the atmosphere is, the less the depth of the atmosphere that has to be heated or cooled. Over the continents, this factor contributes towards more rapid changes of temperature in winter than in summer, and hence a winter trough that is sharper than a summer peak.

(c) *Sea temperature*

In winter, the surface layers of the oceans are well mixed and the vertical structure of sea temperature is approximately isothermal. In summer, however, the surface layers are warmer than those below and the depth of ocean which is being heated or cooled is much less than in winter (see, for example, Wells (1982)). It follows that sea temperatures change more readily in summer than in winter, and their seasonal variation is characterized by a summer peak that is much sharper than a winter trough.

(d) *Seasonal changes in the relative importance of radiation and advection*

Compare two locations with different climates, the first calm and sunny, the second windy and overcast. One would clearly expect the first location to have the greater seasonal variation of temperature, with the dates of the maximum and minimum closer to the solstices than those at the second location. Consider next a single location where the summers are calm and sunny and the winters windy and cloudy. The effect on the seasonal variation of temperature is to make the summer peak sharper than the winter trough.

(e) *Seasonal changes in the frequency of northerly and southerly winds*

In the northern hemisphere, a predominance of northerly winds in winter and summer and southerly winds in spring and autumn will make the winter trough sharper than the summer peak. A greater frequency of northerly winds in the first halves of winter and summer compared to the second halves of those seasons may advance the winter trough and delay the summer peak. Although changes in the frequencies of cold and warm winds do occur, they generally have a periodicity of 12 rather than 6 months, and therefore affect the first, rather than the second, harmonic.

3. Interpretation of the harmonics

The combined effects of the first and second harmonics are described by Craddock (1956b), but are repeated here for convenience. Fig. 2 demonstrates the addition of a first harmonic, with trough and peak in January and July respectively, to a second harmonic, whose amplitude is 20% of the first. Figs 2(a) and 2(b) show that when the peak of the second harmonic is in phase with that of the first, the summer peak is sharpened. Figs 2(c) and 2(d) show that when the peak of the second harmonic is delayed by 46 days, the date of the winter trough is advanced while that of the summer peak is delayed. If the second harmonic peaks 92 days after the first, it is the winter trough which is sharpened. Thus if the peak of the second harmonic lags behind the first by up to 46 days, the effect is that of a sharp summer peak combined with an asymmetric rise and fall of spring and autumn temperatures. If the lag of the second harmonic is between 46 and 92 days, the asymmetric rise and fall of temperature is combined with a sharp winter trough.

The second harmonic does not express explicitly the two main features of the non-sinusoidal behaviour of temperature. The amplitude does not distinguish between sharp summer peaks or winter troughs, while the phase compounds this information with the asymmetry in the spring rise and autumn fall of temperature. A description of the non-sinusoidal variations in temperature would therefore be made clearer by the use of two 'second harmonics' with phases fixed at 0 and 46 days with respect to that of the first harmonic. The first of these second harmonics would then measure the relative sharpness of the summer peak to the winter trough, while the second would contrast the rate of spring rise in temperature to the autumn fall.

4. Geographical variations in the harmonics of mean temperature

Craddock (1955) has calculated the first and second harmonics of mean temperature for 305 stations in the northern hemisphere using monthly mean temperatures for 1921–40. The first harmonic simply reflects the increased amplitude and advanced phase of temperature variations over the continents with respect to those over the oceans. The main findings concerning the second harmonic are reproduced in Figs 3 and 4.

Fig. 3 displays the difference in phase between the first and second harmonics of mean temperature. This is shown to lie between 0 and 45 days over the oceans and Arctic, and between 45 and 90 days over the continents. An autumn fall faster than a spring rise of temperature is therefore indicated, combined with a sharp summer peak over the oceans and a sharp winter trough over the continents. These features are in accord with the relative importance of radiation and sea temperatures in determining the seasonal variation of air temperatures. In the Arctic, the long winter night also contributes towards the establishment of a flat winter minimum. Over the oceans and northern continents, the relative importance of radiation to advection in the climate is greater in summer than in winter. This enhances the well-defined summer peak over the ocean, where there is a feedback on sea temperatures, and sharpens the flat summer peak over the continents. Over the more southerly continental areas, the

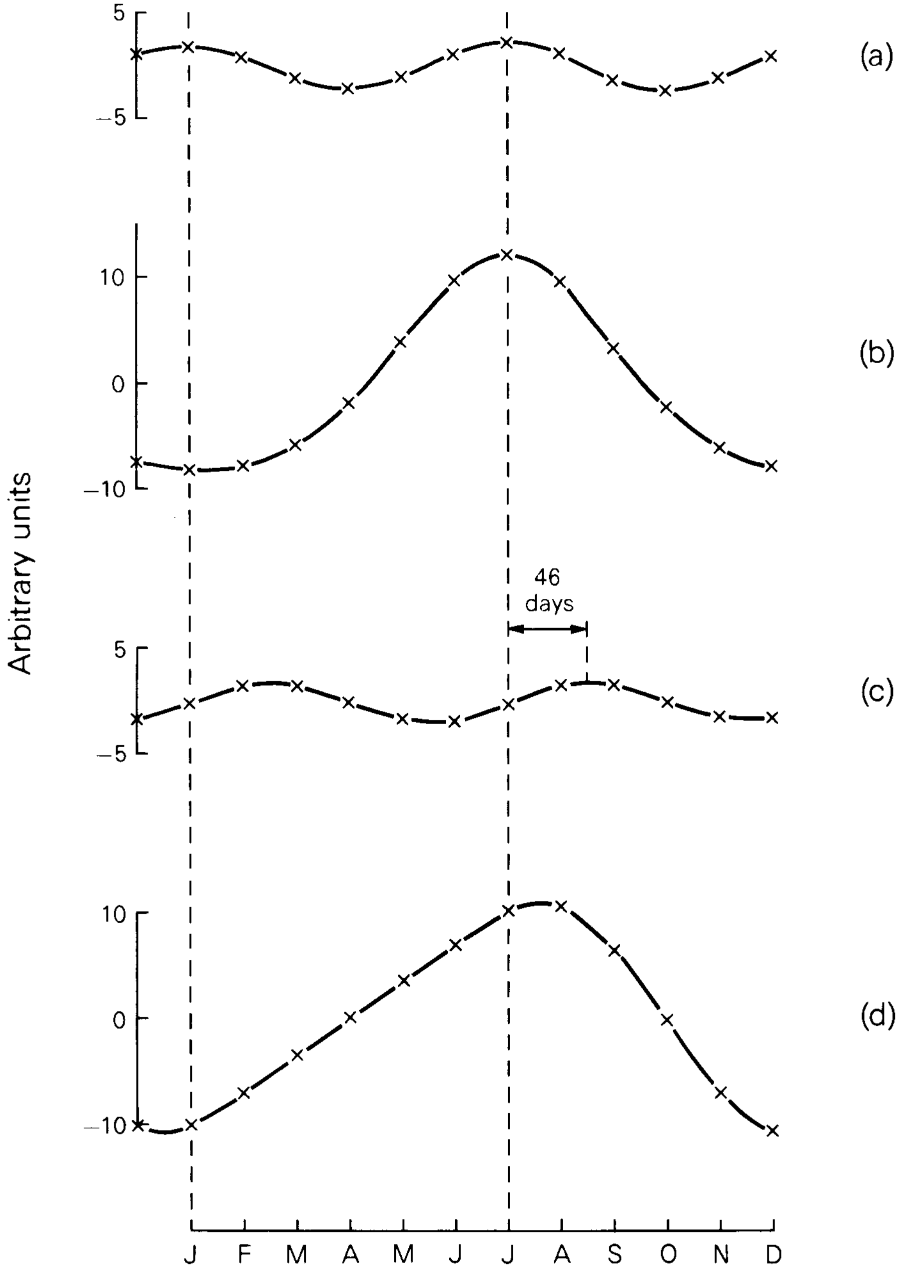

Figure 2. Combinations of first and second harmonics: (a) isolated second harmonic with peak in phase with peak of first harmonic; (b) addition of first harmonic to second harmonic (a) (sharp summer peak); (c) peak of second harmonic 46 days after peak of first harmonic; and (d) addition of first harmonic to second harmonic (c) (slow spring rise and rapid autumn fall). Dashed lines represent trough and peak of first harmonic.

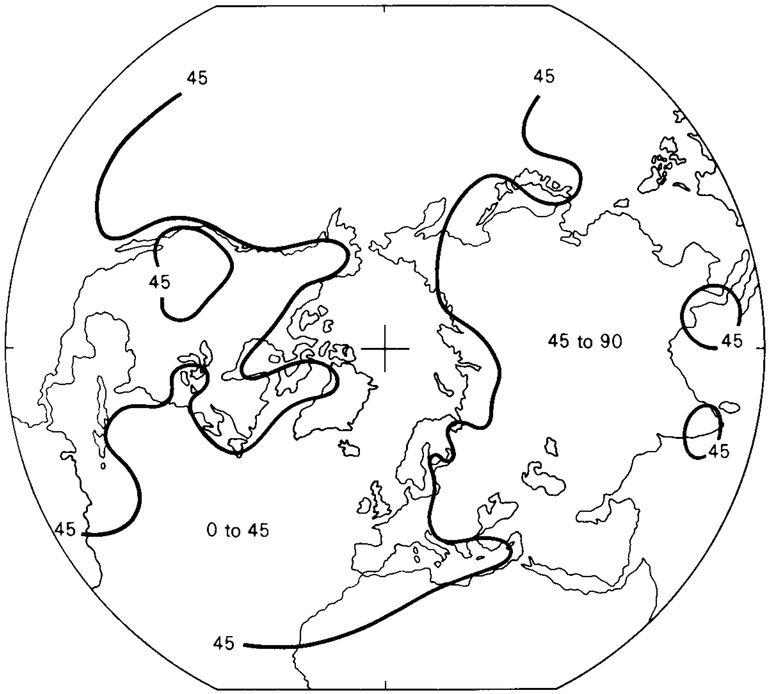

Figure 3. The difference in phase (days) between the first and second harmonics of mean temperature.

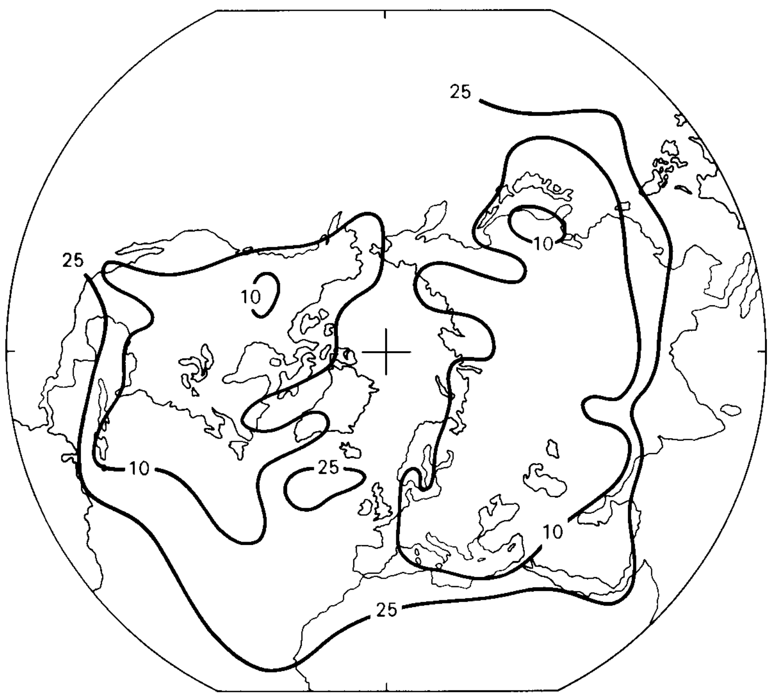

Figure 4. The ratio of amplitude of the second to the first harmonic of mean temperature, expressed as a percentage

monsoonal climate causes the relative importance of radiation to be greater in winter than in summer and this enhances the sharp winter trough in those regions.

Fig. 4 displays the ratio of the amplitude of the second harmonic to that of the first, and shows that the second harmonic is more important over the oceans and towards the tropics than over the temperate continents. The sea temperature is seen to introduce a larger non-sinusoidal component over the ocean than radiation does over the continents. In the tropics, of course, the second harmonic assumes greater importance because of the occurrence twice in a year of the overhead sun.

5. Differences in the harmonics of maximum and minimum temperature

Maximum temperatures respond to solar radiation more rapidly than minima which are more dependent on dew-point and therefore on sea temperatures. These differences can be seen in the findings of Smith (1984) who reports that, at Oxford, for example:

(i) The phase of the first harmonic of maximum temperatures is 8 days ahead of that for minima.

(ii) The phase difference between the first and second harmonics is 30 days for maxima, but only 5 days for minima. This shows that the asymmetry in the seasonal rise and fall of temperature is pronounced for maxima, but almost absent for minima.

(iii) The ratio of the amplitudes of the second to the first harmonic is 13% for minima but only 7% for maxima. This shows that for the maritime climate of the United Kingdom, as exemplified by the records for Oxford, the relative sharpness of the summer peak to the winter trough is greater for minima than for maxima.

6. Secular variations in the harmonics of temperature

Using data from 1861 to 1980, Smith (1984) showed that the amplitude and phase of the second harmonic of temperature at Oxford have undergone considerable changes with time. It will now be shown that these variations are an expression of changes in the continentality of climate at Oxford.

Increasing continentality is associated with changes in the relative sharpness of the winter trough to the summer peak. For minima, in which the asymmetry in the seasonal rise and fall of temperature is small, this will be associated with a decline of a second harmonic which is in phase with the first, followed by the growth of a second harmonic which lags behind the first by around 92 days. For maxima, the asymmetric rise and fall of temperature prevents the amplitude of the second harmonic from falling to zero. Increasing continentality is, therefore, associated with an increase in lag of the second harmonic with respect to the first. As discussed in section 3, a phase lag of up to 46 days combines an asymmetric rise and fall with a sharp summer peak, while a lag of between 46 and 92 days combines the asymmetry with a sharp winter trough.

Smith's results are summarized in Fig. 5. It can be seen that an increase in phase difference between the first two harmonics of maximum temperature is highly correlated with a decrease in the amplitude of the second harmonic of minimum temperature (note the inverted scale), and with the amplitude of the first harmonic of minimum temperature. The last named may be regarded as a direct measure of the continentality of climate.

7. Conclusions

Departures from a purely sinusoidal annual cycle of temperature are due to the effects of solar elevation, sea temperatures, and the relative importance of radiation and advection at a particular

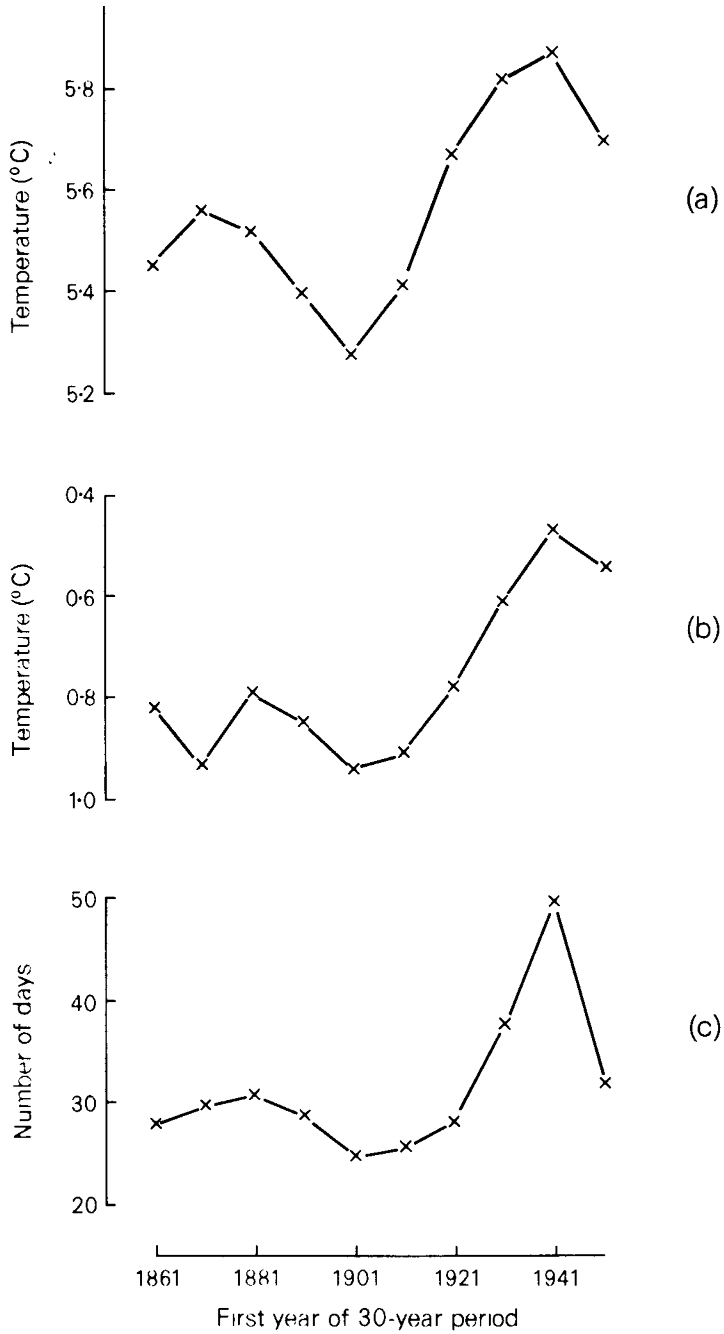

Figure 5. Secular variations of harmonics of temperature at Oxford: (a) amplitude of first harmonic of minimum temperature; (b) amplitude of second harmonic of minimum temperature; and (c) phase difference between peaks of first and second harmonics of maximum temperature.

location. The non-sinusoidal behaviour is characterized by two main features, namely a difference in the sharpness of the summer peak compared to the winter trough, and an asymmetry in the spring rise and autumn fall of temperature. These features are best represented by two 'second harmonics' with phases fixed at 0 and 46 days with respect to that of the first harmonic. These characteristics can, however, also be related to the phase and amplitude of the conventional second harmonic, and used to explain the geographical and secular variations in these parameters found by Craddock and Smith.

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Awards

L. G. Groves Memorial Prizes and Awards

The award of prizes, the first under the new arrangements forecast in the account of last year's prize giving, took place on Tuesday 8 November 1983 at the Main Building, Ministry of Defence, Whitehall. The Vice-Chief of the Air Staff, Air Marshal Sir Peter Harding, KCB, presided.

Under the will of the late Mrs Dorothy Groves, who died in June 1980, a further large sum of money was added to the previous endowment of the L. G. Groves Memorial Prizes and Awards. Over the following two years discussions were held involving the Trustees, the Royal Air Force, the Meteorological Office, M.o.D. Headquarters, and the Charity Commissioners in order to reorganize the terms of the Awards, and new rules were finally agreed and promulgated early in 1983. The main change from the previous arrangements was that teams, as well as individuals, became eligible for awards, and each member of the team would receive an individual prize.

Air Marshal Sir Peter Harding opened the proceedings and expressed the thanks to Mr Nicholas Abbott of all those concerned with the arrangements for his services in presenting the awards since the death of Major Groves. He announced that Mr Abbott was now standing down in favour of his cousin, Mr Robin Wight. He gave a resumé of the new regulations, explaining that the monetary value of the annual prizes was now substantially increased, and congratulated the winners. Mr Abbott acknowledged the remarks of Sir Peter Harding and, after referring to his late great-uncle, Major Groves, introduced Mr Wight. Mr Wight, who is a director of a private commercial firm, said that he had been reading through the citations for the various awards since they were introduced, and had been much impressed by the detail they went into and the evidence they gave of the great importance to aircraft safety of the work for which the awards had been given. Air Commodore T. H. Stonor (Inspector of Flight Safety, RAF) then read the citations for the prize-winners, and Mr Wight presented them with their prizes and certificates, adding his own personal congratulations.

The 1982 Aircraft Safety Prize was awarded to Senior Aircraftman E. B. Govan of RAF Chivenor in recognition of his inventiveness and initiative in designing and producing a modification to the Personal Survival Pack Line Assembly of the Hawk Parachute Harness. This facilitates easy release especially in water. This modification may have a wider application to other aircraft equipped with a similar ejection seat. It is very simple in concept and is comparatively inexpensive.

The 1982 Meteorology Prize was awarded jointly to Dr P. W. White, Dr T. Davies, Dr A. Dickinson and Dr W. H. Lyne, of the Meteorological Office with the following citation:

'Dr White was the Project Officer for the development of a new numerical weather prediction system to provide improved forecast guidance for the Meteorological Office. Within the project team, the groups dealing with the forecast model were led by Drs Davies and Dickinson, and that with analysis by Dr Lyne.

The operational numerical analysis and weather prediction system is the heart of the Meteorological Office's forecasting activities. It incorporates much of our understanding about the behaviour of the atmosphere, as well as extensive knowledge about observations and observing systems. To replace the previous highly developed system with an improved version was a major undertaking calling for outstanding scientific expertise and technical and managerial skills of a high order.

The new system differs from the old in providing higher resolution over the whole globe. Consequently numerous scientific and technical problems were experienced, which had not previously been encountered. A basic feature of the new design is that the analysis scheme assimilates observations by modifying the forecast model's atmospheric variables as the model is integrated

L. G. Groves Memorial Prize and Award Winners standing (left to right: Mr B. Greener, Sergeant R. Clay, Dr W. H. Lyne, Dr T. Davies, Dr A. Dickinson, Dr P. W. White, SAC E. B. Govan and Sqn/Ldr M. K. Allport) with, seated left to right, Mr Robin Wight, Mr Nicholas Abbott, Air Marshal Sir Peter Harding, KCB, and Air Commodore T. H. Stonor.

Dr P. W. White, Project Officer for the team which won the Meteorology Prize, receives his prize from Mr Robin Wight.

forward in time. The method is inherently extremely flexible, able to deal with a wide variety of types of observation, such as those from satellites and commercial aircraft with reporting and error characteristics quite unlike those of the conventional synoptic network. Work on the model and analysis techniques had therefore to be carefully co-ordinated, particularly to ensure that the whole system maintained dynamical consistency as the effects of new observations were incorporated.

The results from the new system have been notably successful. Although new and untried features were involved, a clear superiority over the old system was soon established. It was particularly fortunate that the development proceeded quickly enough for a version of the system, albeit not fully tested and evaluated, to be used as a basis for forecasts in support of the Task Force during the Falklands Campaign. The usefulness of the predictions at that time vindicated the basic design. Subsequently real-time testing led to further improvements in various aspects, including the analysis and prediction of jetstreams which are crucial for aircraft operations.'

The Meteorological Observer's Award for 1982 was awarded jointly to Squadron Leader M. K. Allport, HQ, RAF Support Command and Mr B. Greener of the Meteorological Research Flight, Royal Aircraft Establishment, Farnborough, with the following citations:

'Sqn/Ldr Allport completed a three-year tour as officer commanding the RAF unit of the Meteorological Research Flight (MRF) in September 1983. He very quickly demonstrated his interest in, and appreciation of, the meteorological objectives of MRF, and has played a very active and enthusiastic role with research scientists in the planning and execution of their experiments. Particularly notable was his contribution to an international meteorological research project (KONTUR) carried out over the German Bight in autumn 1981. Sqn/Ldr Allport's leadership and dedication have been major factors in the accomplishment of meteorological research objectives, often involving demanding flying requirements.'

'Mr B. Greener joined MRF in 1971. He has worked on electronic aspects of experimental instruments of specialized navigational equipment and, most recently, as head of the electronics section, on the new data recording system for the Hercules. In addition to these technical tasks, he took a very active role in the flying program, and became one of the most experienced observers on the Canberra aircraft. Through his outstanding technical ability and skill as a meteorological observer in the air, Mr Greener has made a remarkable and wide-ranging contribution to the success of many MRF projects'.

The 1982 Second Memorial Award was made to Sergeant R. Clay of RAF Chivenor (late of the Institute of Aviation Medicine, Farnborough) in recognition of his achievement in developing an aeromedical stretcher harness which has been tried and tested successfully, particularly in recent operations, and has now been introduced into service.

Notes and news

Retirement of Mr P. Graystone

Mr P. Graystone, Assistant Director, Data Processing, retired from the Meteorological Office on 25 January 1984 after a career lasting nearly 43 years. After initial training in 1941, he held a commission in the RAFVR from November 1942 to May 1947, a period which included three years' service in India and the Middle East.

He returned as an Assistant Experimental Officer to aviation forecasting at Hendon and Northolt and, after promotion to Experimental Officer in 1950, moved to Cranwell. He gained an external Honours Degree in Mathematics from London University in 1951 and became a Scientific Officer the following year.

Paul Graystone's first spell of research began with a move to Victory House in 1953, to work on equivalent head winds, and he was promoted to Senior Scientific Officer a year later. Between 1956 and 1958, he was associated with the planning and organization of the Christmas Island experiments, and produced an early analysis of upper winds near the equator.

The year 1959 saw his introduction to research on numerical weather prediction at Dunstable and with it his first taste of computing. He was promoted to Principal Scientific Officer in 1960. By 1963, now at Bracknell, he was developing the procedures for introducing operational forecasting on the KDF-9, and a couple of years later moved to the Forecasting Techniques Branch (Met O 8a) to work on the operational aspects of automatic data assimilation, analysis and output.

A second interlude of overseas service, as Chief Meteorological Officer Bahrain, lasted from 1967 to 1969. Back at Bracknell, Paul was immediately involved with the introduction of the 10-level model on the IBM 360/195. In 1972 he joined the Committee on the Meteorological Effects on Stratospheric Aircraft group in the Dynamical Climatology Branch (Met O 20), and played an active part in modelling the stratospheric phenomena of relevance to supersonic transport operations, as well as in the many organizational aspects.

In 1974 he was promoted to Senior Principal Scientific Officer and spent three years as Assistant Director, Forecasting Research, and a further three years as Assistant Director, Dynamical Climatology, where his ability to handle the organizational aspects of complex scientific programs was well demonstrated. Paul's last assignment, in 1979, as Assistant Director, Data Processing, has made good use of his computing experience and unobtrusive management skills, and has seen the successful introduction of the Cyber 205 and IBM 3081.

In recent years, Paul Graystone has not always been in the best of health, but we hope that this will neither inhibit his golfing pursuits nor distract from the individual style of competitive bridge which he has pioneered. We wish him and Mrs Graystone a long and happy retirement.

M. J. Blackwell

50 years ago

The following extract was published in the *Meteorological Magazine*, March 1934, **69**, 38–39.

In Lighter Vein

Many inquiries have been made as to the cause of the abnormal drought: and various tentative suggestions have been put forward to explain it. One school attributes it to a change in the volume of the Gulf Stream drift: another suggests that radio-broadcasting has used up most of the ions previously available as nuclei of condensation.

A more plausible reason has recently come to my notice. It is well known that rain in England is mainly derived from evaporation from the Atlantic Ocean; and further that evaporation from spray is much more effective than evaporation from a water surface. A most effective producer of spray is a spouting whale: but there has been so great a reduction in the number of whales in the North Atlantic that this source of rainfall has been nearly cut off — hence the drought.

E. Gold

THE METEOROLOGICAL MAGAZINE

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Climatological network design

By F. Singleton

(Assistant Director (Climatological Services), Meteorological Office, Bracknell)

and E. A. Spackman

(Meteorological Unit, ADAS, Cambridge)

Summary

Generalized requirements are stated for climatological networks on the basis of regulations and recommendations as published by WMO. Proposals are made for the objective assessment of climatological station network densities for the United Kingdom relative to the WMO recommendation for 'geographically fairly uniform' areas.

Introduction

One of the major problems in designing networks of observations for meteorological purposes is to define the station density required. For synoptic use the spacing of stations should be commensurate with the size and lifetime of those meteorological features which it is possible to identify and forecast for periods of a few hours upwards. In the past there have been constraints in the capacities both of communication channels to handle and of forecasters to assimilate the data, but with the advent of high speed communications and computer processing it may become possible to deal with larger quantities of data for real time purposes than hitherto. Currently there are about 200 stations within the United Kingdom producing synoptic reports with schedules varying upwards from one observation per day.

For climatological purposes much higher station densities are both needed and practicable. There may be significant climatological differences between sites only a few kilometres apart but having quite different topographical characteristics. At the time of writing, the climatological network in the United Kingdom comprised 600 stations while the number of stations in the rain-gauge network was ten times greater. The climatological network has developed in a haphazard fashion rather than been planned, and consists of much of the synoptic network supplemented by stations manned by voluntary climatological observers. Traditionally, and regardless of need, the Meteorological Office has archived all readily available climatological data as long as the quality was acceptable. Because archiving and quality control are expensive operations it has become necessary to know where stations are redundant and where, therefore, it is unnecessary to take action to replace any which close. It is also necessary to be aware of requirements for data to help decide upon, and justify the expenditure of, resources in seeking new voluntary observers or in making use of automatic equipment. Such decisions should be capable of being made by different people in a consistent and reasonably objective manner.

The requirement for a climatological network can be stated quite simply as being to provide just enough data to permit the climate of a particular area to be defined within specified limits. Guidance on the density of stations needed to fulfil this requirement can be found in the *Guide to climatological practices* (WMO No. 100) in which it is stated that, 'where the geographical conditions are fairly uniform, then one ordinary climatological station* per 1000 km^2 will normally be sufficient for most climatological purposes'. The *Guide* also says that care must be taken to ensure that all types of terrain are represented satisfactorily and that the demand for information should be taken into account. This means, for example, that there would be a need for a greater density of stations in or near industrial regions and that there is likely to be little requirement for stations above heights where man normally lives or works.

Ideally, the number of stations at which any particular climatological element is observed should be large enough to permit a complete analysis to be made of the geographical distribution of mean values, frequencies, extremes and other characteristics of the element. This means, according to the *Guide,* that the station density depends very much upon the element in question and on the geographical features of the area. A sparse network may be sufficient for the study of surface pressure reduced to mean sea level but, on the other hand, a fairly dense network will normally be required for the study of the wind regime and maximum temperatures, while a very dense network may be required for the study of minimum temperatures or frequencies of frost and fog.

The WMO *Guide* does not quantify what is meant by the words 'sparse', 'fairly dense' and 'very dense'. No indication is given as to what is meant by the term 'geographically fairly uniform' nor any guidance on how many more ordinary climatological stations are required in areas that are geographically complex. It is assumed that an area that is geographically uniform will be climatologically homogeneous. This latter term is taken to describe an area throughout most of which the various meteorological variables behave in similar ways in a given synoptic situation.

In this paper the possibility of trying to determine climatologically homogeneous areas is examined and rejected. A methodology is proposed whereby the climatological complexity, or otherwise, of an area may be determined and, therefore, an estimate made of the optimum number of stations.

Climatological areas

Before the introduction of computer techniques into climatological station quality-control procedures the 'hand and eye' subjective methods depended upon the definition of 80 or so areas which were assumed to be climatologically homogeneous. Each observation within an area was compared with observations from the other stations within the same area. Although defined by experienced staff these areas were inevitably results of subjective judgements which were, no doubt, heavily influenced by individual experience or impressions. To some extent the size of each area was also determined by the need to have sufficient stations within it for quality-control purposes. Fig. 1 shows these areas. Another, still subjective, attempt to define climatologically homogeneous areas may be found in the Ministry of

* The definition of an ordinary climatological station can be found in the *Manual on the global observing system* (WMO No. 544). The minimum requirement is to report daily extreme temperatures and amount of precipitation.

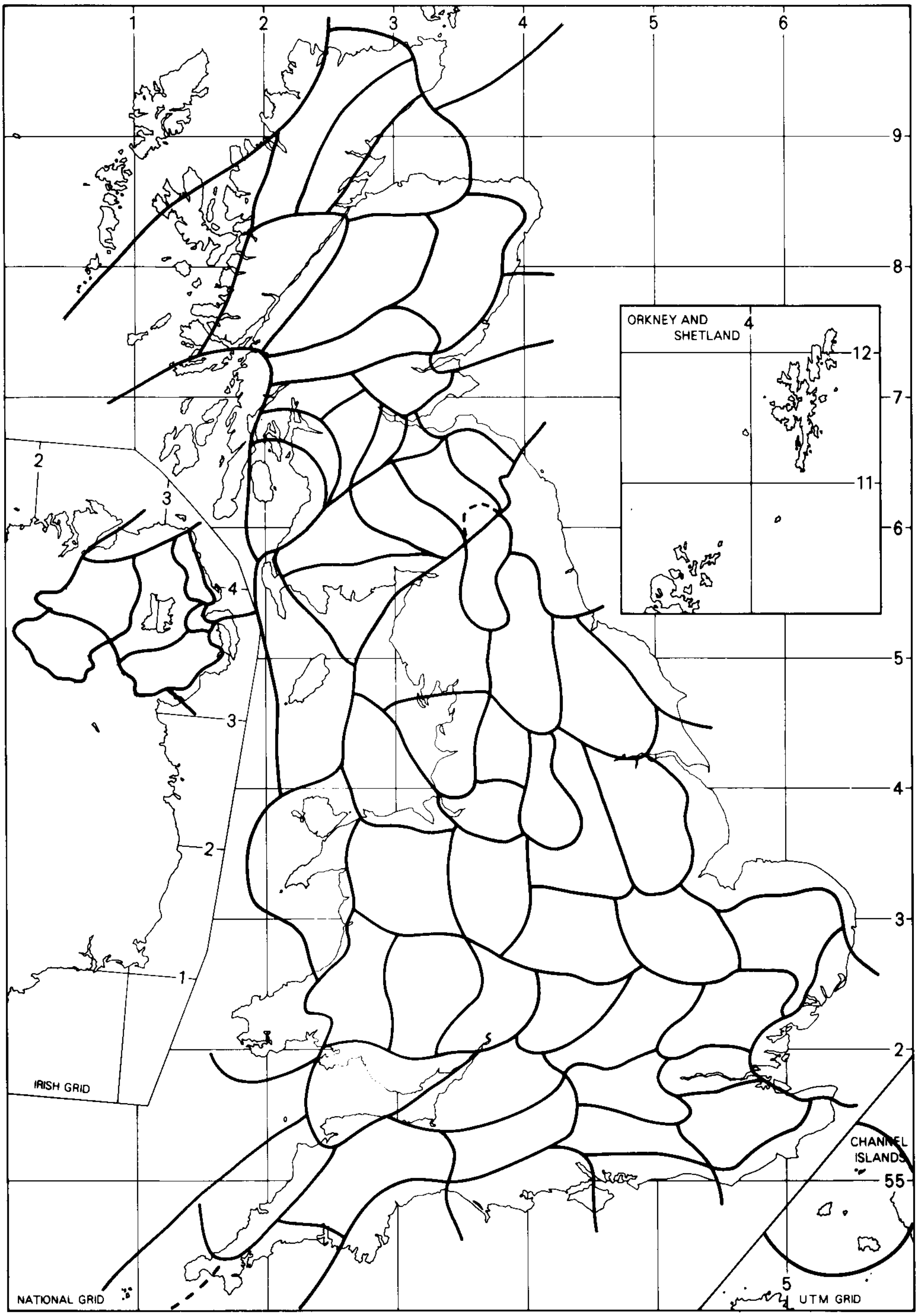

Figure 1. Climatological areas formerly used for subjective quality-control work.

Agriculture, Fisheries and Food Technical Bulletin No. 35, entitled *The agricultural climate of England and Wales.* This publication defines agro-climatic areas primarily on the basis of agricultural land use, although the boundaries of the 52 areas for England and Wales were made to coincide with parish boundaries and, where possible, with those of the Agricultural Development and Advisory Service districts also. Other possibilities include the delineation of areas of the United Kingdom from an essentially topographical point of view. For example, lines could be drawn on a map around the coastal plains, inland mountainous areas, low-lying inland areas, moors, plateaux and major conurbations.

The three possibilities above for defining climatological areas for network design may or may not be equally viable but all leave unresolved the question of the determination of numbers of stations in the more complex areas.

Factor analysis for the determination of climatologically homogeneous areas

Spackman and Singleton (1982) have described the use of factor analysis in areal quality control. The basis of the areal quality-control process is the representation of a climatological element X on day i at station j as being

$$X_{ij} = a_{i1} f_{1j} + a_{i2} f_{2j} + \ldots + a_{in} f_{nj} + r_{ij}$$

where $f_{1j} \ldots f_{nj}$ are factors at station j, $a_{i1} \ldots a_{in}$ are factor loadings on day i and r_{ij} is the error or the residual on the specific day. It was found that 85% of the total variance of X_{ij} can be described by means of the first 15 factors ($f_{1j} \ldots f_{15j}$) and the corresponding factor loadings ($a_{i1} \ldots a_{i15}$).

The factors are station-dependent and result from physical features (or combinations of physical features) at each station while the factor loadings depend upon the synoptic situation. Thus in a westerly situation, when considering temperatures, the latitude factors would be important and the corresponding factor loadings would be high. On the other hand, in an anticyclonic situation there would be high loadings of the factors representing night-time radiation when minimum temperatures are considered. Stations that behave in similar ways in similar synoptic situations will have similar factors. It would, therefore, seem logical to try to define regions that are climatologically homogeneous by looking for groups of stations that have similar factor values. This selection or grouping can be achieved in a number of ways and that chosen was by means of a 'clustering' algorithm.

The basis of the clustering process is the definition of distances of stations from each other in 15-dimensional factor space, i.e.

$$d_{ij}^2 = \sum_{k=1}^{15} (f_{ik} - f_{jk})^2$$

where d_{ij} is the 'distance' apart of stations i and j, and f_{ik} and f_{jk} are the kth factors at those same stations. The clustering algorithm produces a predetermined number of groups, the stations in each being nearer to each other in factor space than to stations in any other group.

Lines can then be drawn around stations grouped together using either subjective or objective analysis methods. Fig. 2 shows, for various elements, analyses of the results of clustering into 40 groups. For temperatures and rainfalls over 700 stations were used in the clustering analysis but only around 460 for sunshine. The stations used were the climatological stations and not the rainfall only stations. On three of the maps analysed there are more than 40 areas delineated because stations may be near in factor space and yet be well separated geographically. This happens, for example, with headlands exposed to a common wind direction, and frost hollows. Such locations can be climatologically similar for particular elements even though they are some considerable distance apart and separated by areas that are climatologically different. The varying complexity of the analyses in Figs 2(a), (b), (c) and (d) for the

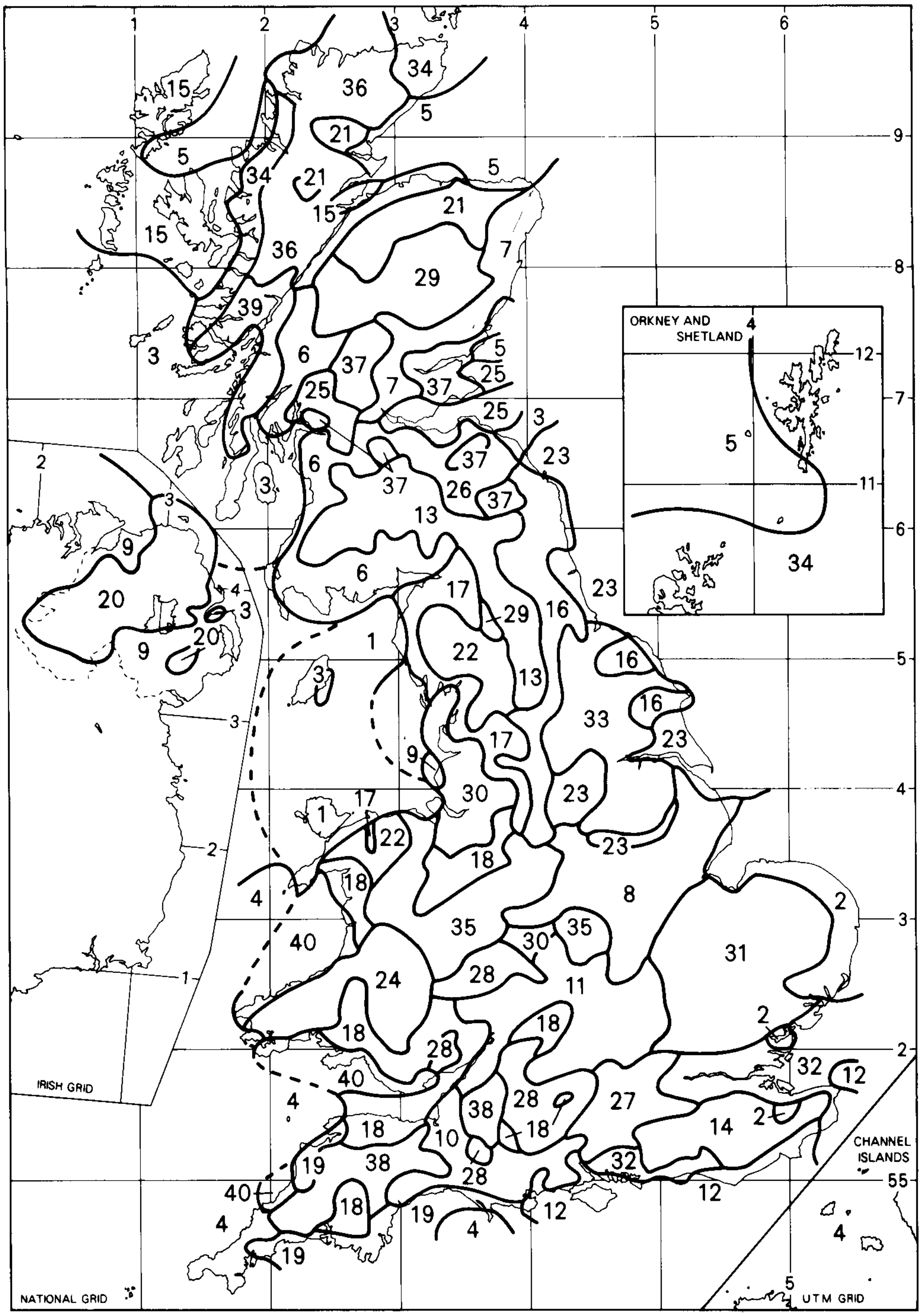

Figure 2(a). Climatologically homogeneous areas for minimum temperatures derived from clustering analysis into 40 groups. Areas with the same number belong to the same group.

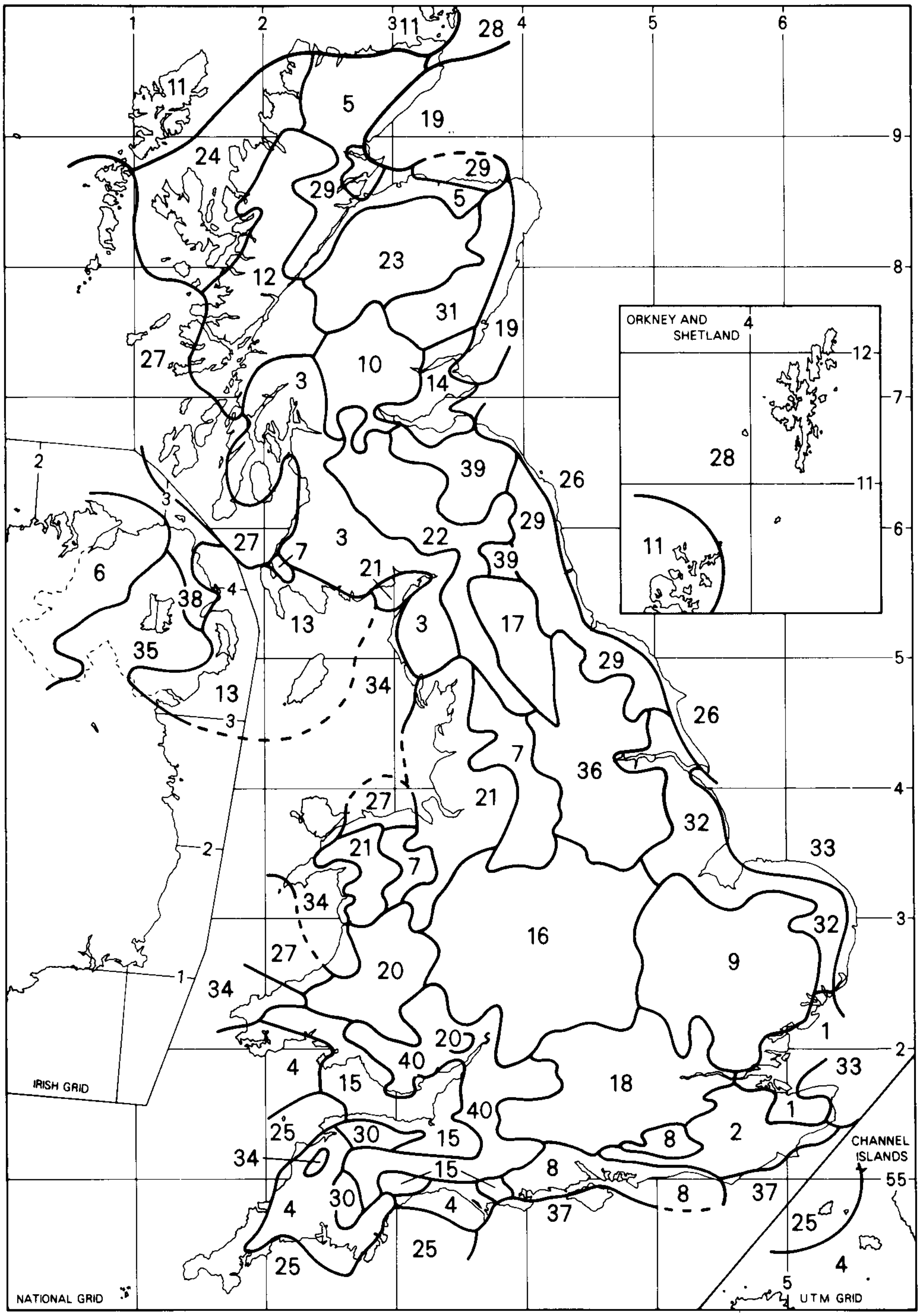

Figure 2(b). Same as Fig. 2(a) but for maximum temperatures.

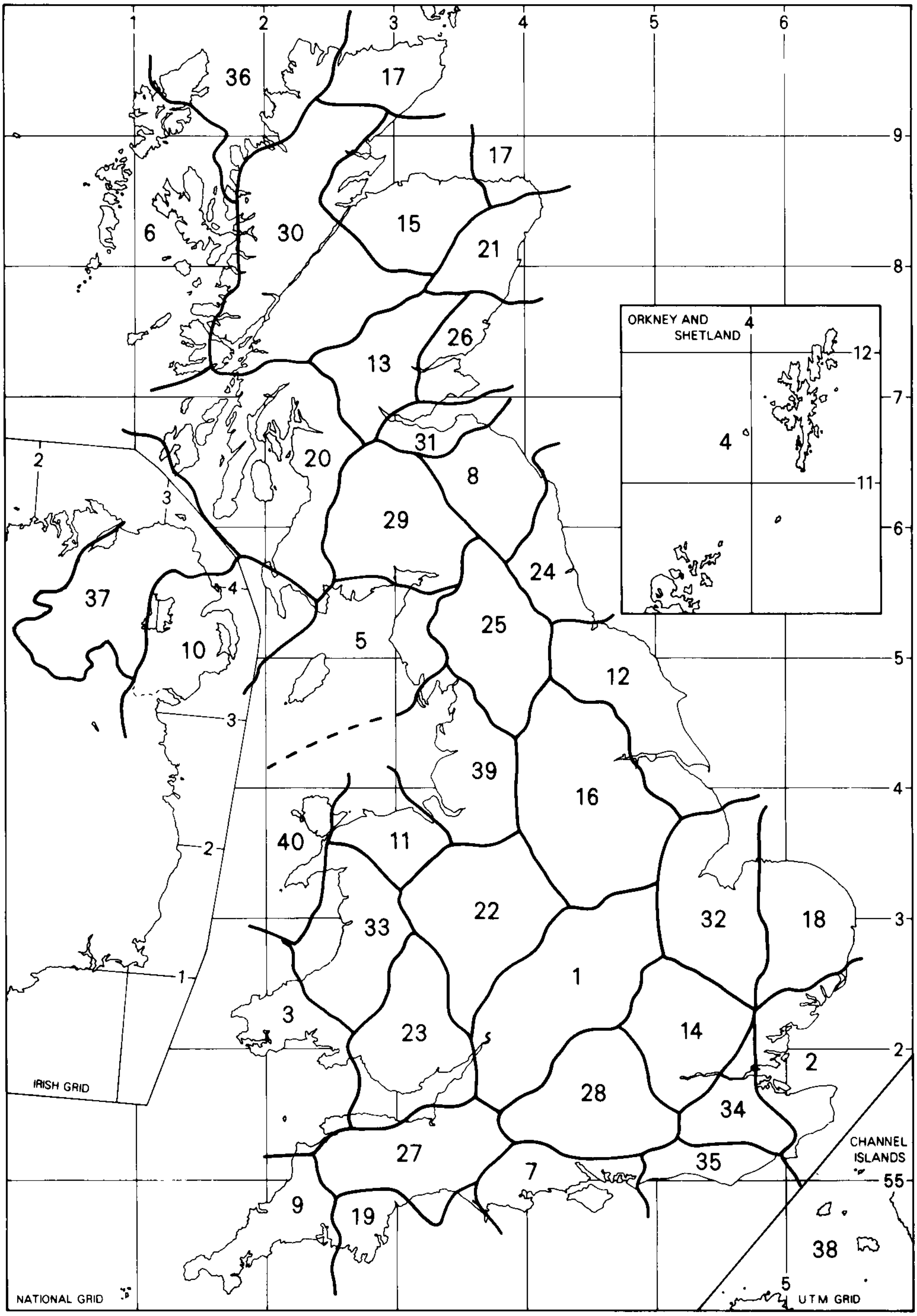

Figure 2(c). Same as Fig. 2(a) but for daily sunshine.

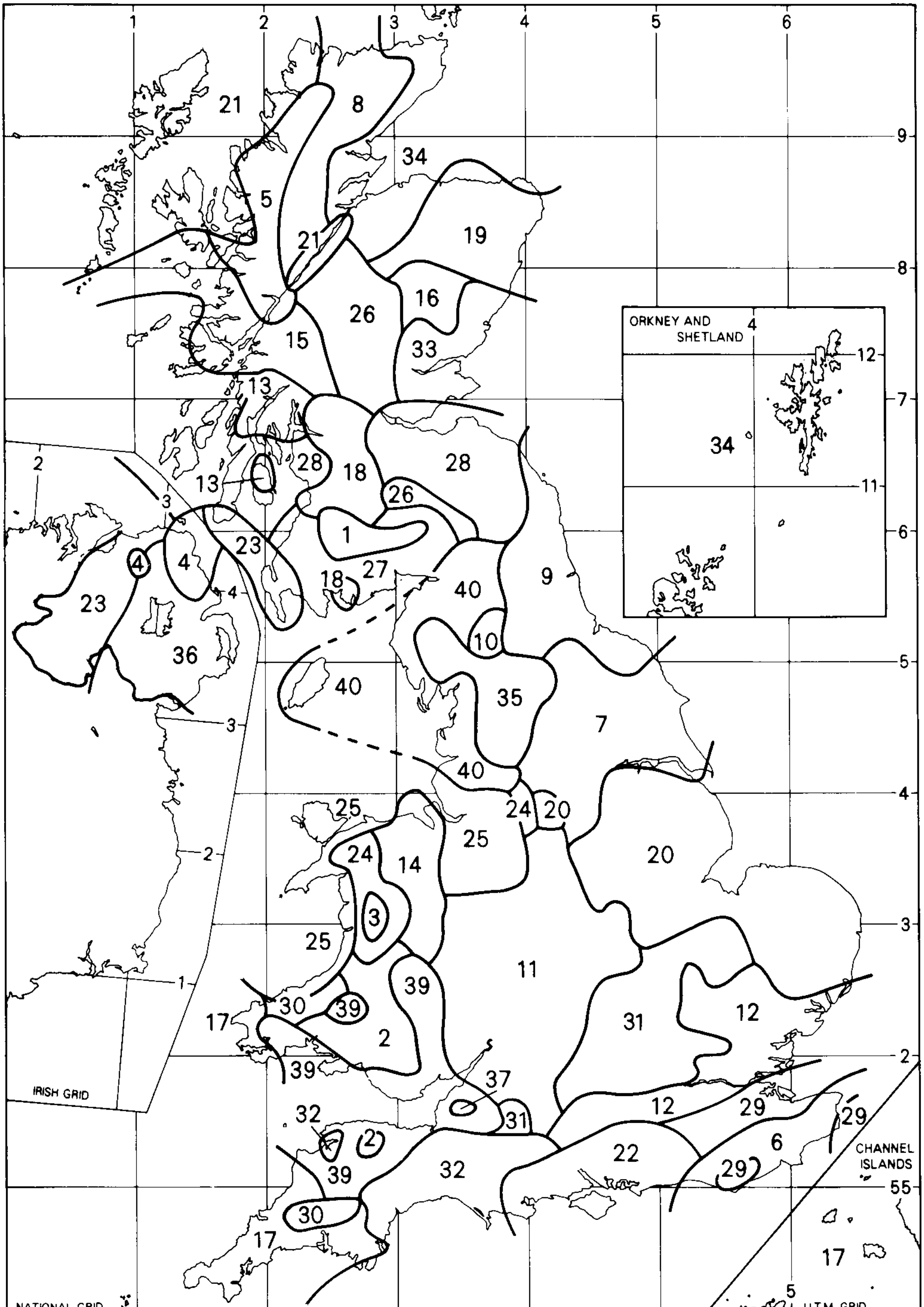

Figure 2(d). Same as Fig. 2(a) but for daily rainfall.

different elements depends partly upon the number of stations with data available for the study and partly upon the effects of topography on the element in question. From these maps it can be seen that while some quite large areas can be defined as being climatologically homogeneous for one element or another there are other areas where the patterns are complex and where topography is very important. Figs 2(a), (b), (c) and (d) also show that areas where the patterns are simple for one element may be complex for another and, therefore, that areas climatologically homogeneous for one element are not necessarily homogeneous for another.

The approach of trying to define climatologically homogeneous areas by means of factor analysis was therefore discarded, mainly because it was impossible to define a unique set of areas for all elements. However, it should be noted that for individual elements it might be expected that network requirements could be defined on the basis of one station per 1000 km^2 in each area of the maps in Figs 2(a), (b), (c) and (d). Some rounding up would be necessary so that each area, however small, would have at least one station, an area between 1000 km^2 and 2000 km^2 at least two, an area between 2000 km^2 and 3000 km^2 at least three stations and so on. This assumes, of course, that there are sufficient data to define the areas adequately in the first instance. In view of the coverage in some parts of the United Kingdom this is patently not the case. The use of the analysis to determine network requirements for single elements can thus only be practicable in areas where there is a large enough number of stations to determine the cluster groups.

Use of factor analysis to determine climatological complexity

Because, as has been shown above, one set of climatological areas cannot be defined for all elements an alternative approach depending upon the definition of the climatological complexity of fairly large predefined geographical areas was examined. For simplicity it was decided to use areas based upon the national grid, partly because the selection of areas and boundaries between stations can be made objectively and partly because this simplifies the writing of computer programs for such purposes as listing numbers of climatological stations in the various areas and analysing their height distributions. Other possibilities considered included using the four countries of the United Kingdom with their respective regions, or topographically defined areas such as the lowlands, highlands, coastal regions and so on. These were discarded as being either too subjective a definition or too complex for the purpose of this work and with no consequential perceivable benefits. The areas chosen are shown in Fig. 3. In order to avoid small land areas with few stations, contiguous grid squares or parts of grid squares were grouped as shown. The size of each area and the number of stations used for the analysis in each area are shown. Apart from Orkney and Shetland the smallest area of land was grid square SH with 4500 km^2 and the minimum number of stations in any area was 13. The minimum density of stations for any area was in square NN with 1.4 stations per 1000 km^2. In no area, therefore, was the station density less than the WMO recommended minimum for geographically simple areas although it should be pointed out that station distributions are by no means uniform within any particular area. The results of the clustering exercise for minimum and maximum temperatures are shown with the number of cluster groups recorded in each area. Extreme temperatures were chosen since these gave the most complex patterns and, rainfall apart, the largest quantity of data. (The analysis of rainfall used only the climatological stations and not the 6000 or so stations of the rainfall network.)

The smaller the number of groups represented in any one area then, presumably, the simpler is that area climatologically, while higher densities of groups indicate increasing climatological complexity. The simplest areas are Northern Ireland, where there are some 14 400 km^2, a station density of 4.6 stations per 1000 km^2 and only 3 (4) distinct groups for minimum (maximum) temperatures and the mainland area TL/TM (part of eastern England and East Anglia) with 13 100 km^2, a station density of 3

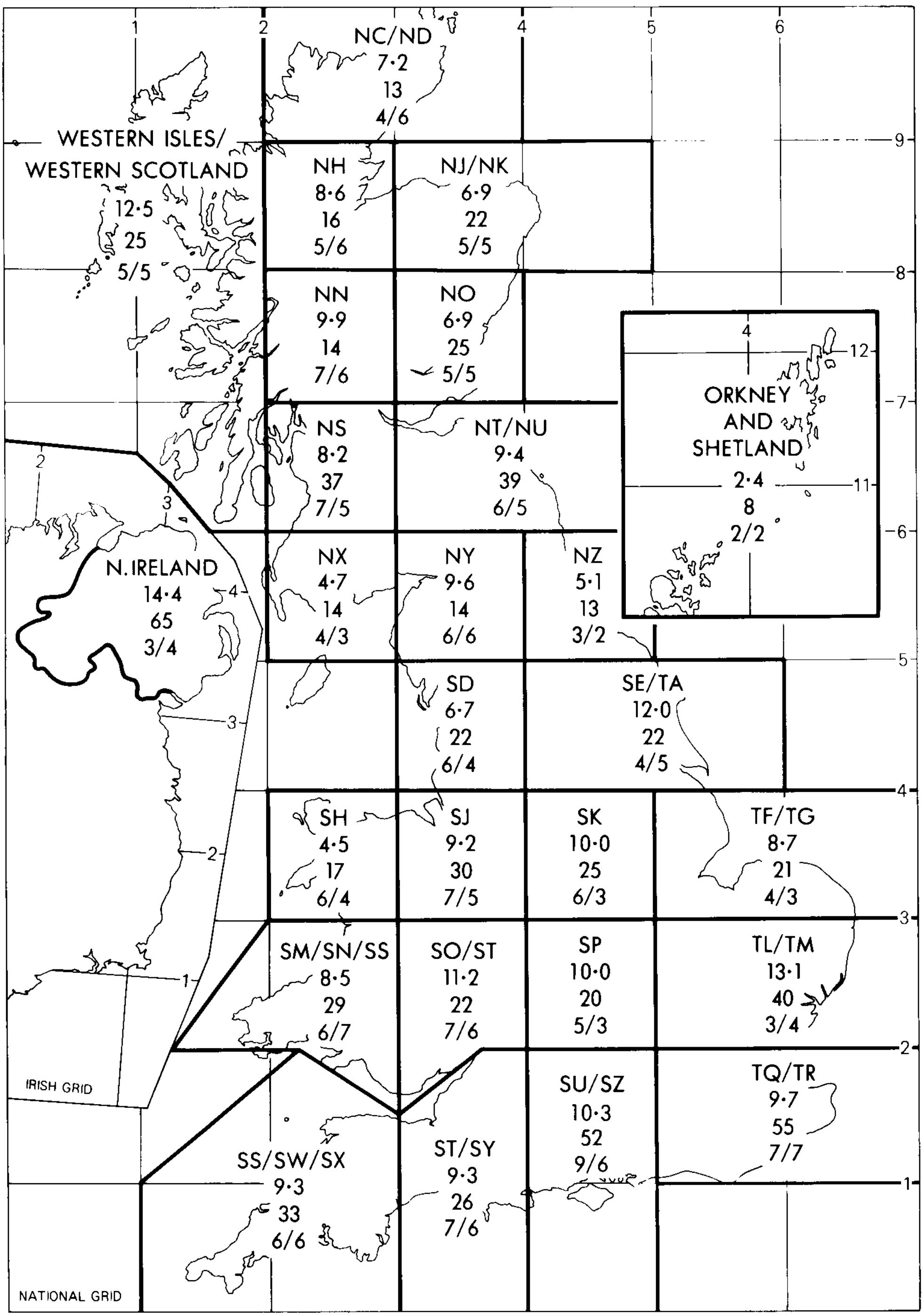

Figure 3. Areas and national grid squares showing code letters and size of land area (in units of 10^3 km^2) together with the number of ordinary climatological stations and cluster groups for minimum/maximum temperatures within each area.

stations per 1000 km^2 and only 3 (4) cluster groups. One of the more complex areas is central southern England, grid squares SU/SZ, with 10 300 km^2, a station density of 5 stations per 1000 km^2 and 9 (6) cluster groups.

An empirical measure of climatological complexity can be defined as the number of cluster groups per unit area. Taking the higher value of the maximum and minimum temperature cluster groups represented in each area then examples of 'complexity values' are 4/14.4 for Northern Ireland, 4/13.1 for TL/TM, 9/10.3 for SU/SZ, 6/4.5 for SH, and 7/8.2 for NS.

The quantitative effects of differing station density are difficult to ascertain and it is not possible to estimate how many more groups would have been produced in any particular area by increasing the number of stations. For Northern Ireland and those areas of the mainland with 30 or more stations it is fairly unlikely that many more groups would have resulted. For those areas with fewer than, say, 20 stations then it is quite possible that more groups would have resulted, particularly had different types of topography and a wider range of heights been represented by the climatological stations used in the analysis. The fact that fairly large areas of the Scottish highlands can apparently be homogeneous for maximum and minimum temperatures may simply be because many of the stations reporting are in glens, and the climate of one glen is similar to that of its neighbours. It is difficult to draw any really objective quantitative conclusions about network requirements simply because of the differing station densities and differing degrees of representativeness of the station network from area to area. In other words the 'complexity values' are somewhat uncertain in the more data-sparse areas.

Starting from the basis that Northern Ireland and grid squares TL/TM seem to be simpler climatologically than anywhere else in the United Kingdom then the climate of these areas could probably be adequately represented by the WMO minimum of one station per 1000 km^2, assuming that is that these areas comply with the WMO definition of being geographically fairly uniform. In other words, if the WMO guidance is correct then 14 stations evenly distributed over Northern Ireland or grid squares TL/TM should be sufficient to define the cluster groups derived from the analysis described above. It is not too much to argue that areas of greater geographical (or climatological) complexity require more stations to define the cluster groups deduced from the analysis described. To determine the nature of the relationship between station density required and climatological complexity would necessitate an experiment starting with many more stations than at present and repeating the clustering exercise with different numbers of stations. Future work could perhaps look at specific areas such as Northern Ireland for temperature and, perhaps more profitably, the whole of the United Kingdom for rainfall. For the time being, and pending such work, it is suggested that climatological station density-needs should be defined as being in direct proportion to the climatological complexity values derived above.

Table I shows the resultant numbers of stations and their densities for each of the areas on this basis. The application of this rule with an underpinning minimum of one station per 1000 km^2 gives some very high station densities in places, for example north-west Wales, square SH, would need 21 stations or about 4.7 per 1000 km^2. This, however, is a complex area topographically with coasts facing in all directions, coastal plains, valleys, mountains and plateaux. The calculated densities for some of the Scottish squares, NH and NN for example, could well be too low relative to some other areas because of underestimation of the number of cluster groups represented in NH and NN arising from the fairly low number of observations available for the cluster analysis.

The numbers of stations shown as a requirement makes no allowance for the uncertain future of many of the co-operating climatological stations. Even with 600 climatological stations there are relatively few with long periods of record. Some measure of redundancy is therefore desirable in the network and the actual requirement has been arbitrarily set at some 10% over and above the numbers shown.

Table I. *Number of ordinary climatological stations (OCS) and their height distribution relative to the height of the ground within the area, and the OCS requirement and density in direct proportion to the complexity value of the areas shown in Fig. 3*

Area or national grid square	Number of OCS			Station density (Number of OCS per 10^3 km^2)		Percentage of OCS at a level lower than 25, 50, 75 and 95% of total ground			
	Required	Actual	Deficit	Required	Actual	25%	50%	75%	95%
Orkney and Shetland	7	5	2	2.9	2.1	20	60	80	100
Western Isles/ Western Scotland	18	23		1.4	1.8	83	100	100	100
NC/ND	21	12	9	2.9	1.7	62	92	100	100
NH	21	15	6	2.4	1.7	73	93	93	100
NJ/NK	18	19		2.6	2.8	63	84	95	95
NN	25	10	15	3.0	1.2	90	100	100	100
NO	18	19		2.6	2.8	58	79	100	100
NS	25	34		3.0	4.1	68	82	97	100
NT/NU	21	28		2.2	3.0	39	75	100	100
NX	14	15		3.0	3.2	47	87	100	100
NY	21	11	10	2.2	1.1	45	73	82	91
NZ	11	10	1	2.2	2.0	45	80	100	100
SD	21	13	8	3.1	1.9	46	85	92	100
SE/TA	18	18		1.5	1.5	17	56	78	100
SH	21	13	8	4.7	2.9	61	92	100	100
SJ	25	26		2.7	2.8	27	54	81	100
SK	21	20	1	2.1	2.0	22	55	80	100
TF/TG	14	15	–	1.6	1.7	40	53	73	93
SM/SN/SS	25	25	–	2.9	2.9	60	84	92	100
SO/ST	25	14	11	2.2	1.3	57	78	86	100
SP	18	17	1	1.8	1.7	56	89	100	100
TL/TM	14	30		1.1	2.3	13	42	80	94
SS/SW/SX	21	37		2.3	3.5	59	70	79	94
ST/SY	25	21	4	2.7	2.3	43	62	81	95
SU/SZ	32	43		3.1	4.2	51	62	78	96
TQ/TR	25	43	–	2.6	4.4	36	60	84	99
N. Ireland	14	64	–	1.0	4.4	No height data on data set			
Total	539	600							

Monitoring the climatological network

The data given in Table I can be used to give a first indication of those parts of the United Kingdom where there are either too many climatological stations or not enough. It is, of course, also necessary to take into account the actual locations and spatial distribution of the stations and, in particular, the height distribution which is currently by no means ideal. Where there are deficiencies in the network then positive action can be taken by the Meteorological Office to recruit co-operating observers in order to open new stations or to ensure the continuation of existing ones. The data can also be used as an aid to decisions regarding the siting of automatic equipment for climatological purposes. Table I shows, for each of the areas of Fig. 3, the actual number of climatological stations, and the height distribution of those stations relative to the heights of ground within each area. It can be seen that the total number of climatological stations exceeds the total requirement. However, the distribution is by no means ideal, even when considered simply as numbers of stations in areas as large as those in Fig. 3 and without regard to the spatial distribution within each area. Similarly, the height distribution of stations leaves a lot to be desired. Some 20% of the land surface of the United Kingdom is above 300 metres but only 3% of the climatological stations are above that height.

Some areas have a satisfactory height distribution of stations, for example area SK with 80% of stations situated at locations representing the lowest 75% of the ground and 22% of the stations the lowest 25% of the ground. Other areas have a poor distribution, for example area NN with 90% of the stations situated at locations representing the lowest 25% of the ground and all stations the lowest 50% of the ground. (Note: areas with an adequate number of stations may have a poor height distribution, for example area NJ/NK where 63% of the stations are situated at locations representing the lowest 25% of the ground.)

The station densities given as requirements in Table 1 may, of course, be incompatible with the demand for data. In some areas it may not be sensible to try to achieve the prescribed coverage when considered in terms of cost to benefit ratios. What is scientifically or meteorologically desirable may not be economically necessary. Conversely, in some areas the demand for data to answer queries regarding weather details on special occasions may entail having a greater density of stations than is necessary just to determine climatological parameters. For example, an area may need a certain number of stations to define the rainfall climatology but many more to define rainfall associated with specific convective situations.

Conclusions

The use of factor analysis can lead to increased objectivity regarding the definition of climatologically homogeneous areas for individual elements and, as such, can be used to determine requirements for specific instruments. This could be of value in helping to decide optimum dispositions of new sensor systems to replace existing ones. Factor analysis does not define areas that are homogeneous for all climatological parameters. It can, however, be used to help define network densities in predetermined geographical areas of the United Kingdom. This information is of use in introducing some objectivity to the allocation of resources to the network as a whole and to maximize the benefit of any such expenditure.

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A rain–snow discrimination study for Jerusalem

By L. M. Druyan and H. Berger

(Department of Geography, Bar-Ilan University, Ramat-Gan, Israel)

Summary

Rain–snow discrimination for Jerusalem is studied by examining upper-air meteorological variables observed over Israel, Cyprus and Lebanon. Scatter diagrams of snow events plotted according to pairs of variables observed usually 3–15 hours prior to the onset of snow show generally different distributions from rain events. The differences show the importance of local flow patterns, as well as the lower-troposphere temperature north-west and north of Israel, to subsequent snow. Interpretation of the snow frequency by area (on the two most successful graphs) as an indication of future probability suggests application of the results to rain–snow discrimination forecasting.

Introduction

Snowfall in Israel is confined mostly to the higher elevations of which Jerusalem (800 m) is the most populous. Jerusalem's mean minimum temperature for the coldest month (January) is a moderate 5 °C so that snowfall there requires the penetration of anomalously cold air. Although forecasting precipitation in general is by no means a trivial problem, rain–snow discrimination presents a particular challenge because a synoptic regime that provides efficient cold air advection will quite often bring rain or possibly sleet to Jerusalem and not snow.

There is considerable interest generated by the particular charm of Jerusalem, the Holy City, blanketed with the white of snow, for thousands of tourists and residents alike. The city is, however, also a bustling urban centre so that an accurate forecast of the infrequent snow event is of great importance to the municipality when preparing crews and equipment for snow removal.

The statistics of snow occurrence over mountainous and hilly regions in Israel are given by Bitan and Ben-Rubi (1978) and for Jerusalem in particular by Batz (1981). Batz shows, for example, that since 1948 snowfall has been observed, on average, in three out of four years. Moreover, although the snow depth once reached 50 cm, the median of maximum seasonal depths is only about 7 cm for this period. Both the studies review the synoptic weather patterns favourable for snow in Israel: a typical pattern shows cold advection from the north or north-east around the western side of a sharp trough or low of great vertical extent; the axis of the system usually extends toward the north-east from Israel. Precipitation can be initiated by low-level convergence within sea-level troughs, some of which are cold frontal zones, and is often enhanced by destabilization due to warm coastal waters and by the orographic influence of the Judean Hills.

A graphical method for rain–snow discrimination was previously based on upper-air observations from Israel's single radiosonde station (Druyan 1977, 1980). A summary of the second of these papers, which were published in Hebrew, is given in the Appendix. While results of the earlier work can provide useful forecast guidance, it is apparent that an important proportion of snow events are ambiguously predicted by the graph. This shortcoming prompted the present research.

No doubt conditions beyond Israel's borders are important in creating the environment that determines whether or not snow falls in Jerusalem during subsequent hours. The present study widens the search for predictors to include upper-air data from over Cyprus, Lebanon, Turkey and Syria.

Data

For the purposes of the study a snow episode is defined as a 12-hour period during which at least one observation of falling snow was made at the Jerusalem observatory atop the downtown Generali Building. This definition of course qualifies a maximum number of events. Although we did not examine the conditions for mixed rain and snow, we assume that they occur for borderline snow indications; here such situations are classified as 'snow'. Application of the above definition yielded 63 snow events from the meteorological archives for the period 1959–80. Control data consist of some 47 events during which only rain fell in Jerusalem on days when the surface temperature fell below 5 °C.

A search was made for the meteorological variables that best reflect differences in the atmospheric conditions preceding snow and rain respectively. These variables, which have potential as predictors, were chosen from synoptic upper-air observations made at least three hours before the initial snow observation and usually not more than 15 hours earlier; since radiosonde releases in Israel before 1964 were made only once per day, the data include 13 snow events for which the atmospheric conditions were observed 15–22 hours before the commencement of snowfall. The Israeli stations (Be'er Yacov before 1964, then Bet Dagan) are located in the central coastal plain near Tel Aviv. The variables over Israel included observations of 1000–500 mb and 1000–850 mb thicknesses, geopotential at 1000 mb, 850 mb and 500 mb, and 850 mb wind speeds and directions. Temperatures and wind directions were taken from operational 850 mb charts over the stations Nicosia (Cyprus), Beirut (Lebanon), Ankara (Turkey) and Latakia (Syria).

Results

The meteorological variables were tried in all possible combinations on scatter diagrams to examine which of them showed the most efficient rain–snow discrimination for subsequent precipitation over Jerusalem. As in Druyan (1980) the most important single parameter proved to be the Israel 1000–500 mb thickness (Z).

This parameter was previously used for predicting precipitation type (Wagner 1957) and is one of three predictors for automated rain–snow discrimination guidance provided for US cities (Glahn and Bocchieri 1975). The latter uses the so-called Model Output Statistics procedures and the predictors are therefore themselves derived from numerical forecasts.

The analysis showed that results are considerably improved by considering the 850 mb wind direction over Nicosia (D_N) simultaneously with Z. Fig. 1 shows all the events plotted according to their corresponding observations of Z (horizontal axis) and D_N (vertical axis). The scatter diagram shows that in the area labelled A snow followed the observation every time. The value of Z was here less than about 5350 which corresponds to a mean layer temperature of −9 °C. Although these are the conditions some 3–15 hours before snow onset, it is interesting to estimate the height of the 0 °C isotherm implied. For example, a moist adiabatic lapse rate with mean 1000–500 mb temperature of −9 °C intersects the 0 °C isotherm at about 850 mb. This pressure level is about 50 m above the ground over Jerusalem. We note, however, that the temperature structure over this elevated region is probably somewhat different from that of the free-air column measured by the radiosonde over the adjacent coastal plain. Glahn and Bocchieri (1975) found that a 50% probability of snow is indicated by thicknesses of 5360–5430 gpm over the US cities that are at approximately the same altitude as Jerusalem. Judging by the relative occurrence of snow and rain events for these thicknesses as shown in Fig. 1, the Jerusalem data are quite consistent with these findings.

It can be seen from Fig. 1 that the predictor D_N becomes important when Z is initially too high; a more northerly flow undoubtedly expedites the advection of cold air into the region. Thus, the proportion of snow events in area B_1 is 77% while in area B_2 41% of the events are snow; southerly or south-easterly flow over Cyprus, not uncommon before even 'cold' rain, seems to preclude subsequent snow in Jerusalem (events in area C). Reference to the characteristic maps for snow situations recalls the importance of a strong northerly wind component over the eastern Mediterranean Sea (Bitan and Ben-Rubi 1978, Batz 1981). We determined also that better discrimination is achieved by using the Nicosia wind rather than the wind over Israel, perhaps because the former is upstream from the forecast target area.

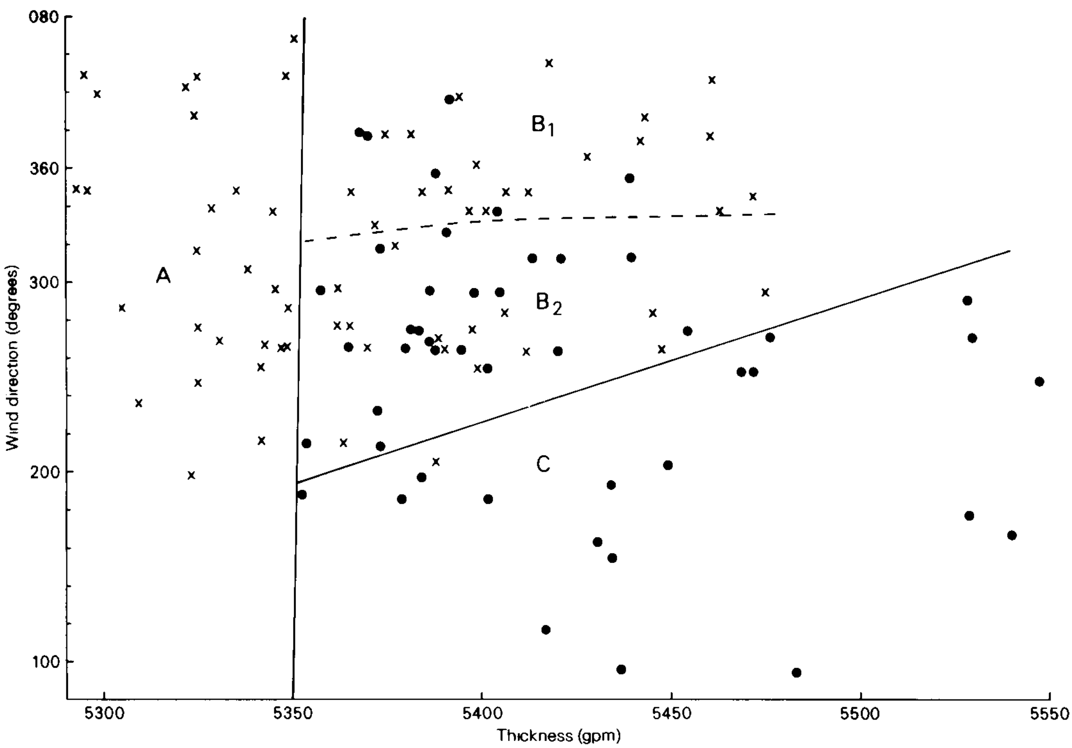

Figure 1. Distribution of snow (x) and rain events (dots) plotted according to earlier observations of 850 mb wind direction over Cyprus and 500–1000 mb thickness over Israel.

The mixture of snow and rain occurrences followed by the conditions prescribed by area B (Fig. 1) means that these two predictors sometimes cannot provide complete discrimination. The remaining predictors were tried via scatter diagrams for all the events appearing in areas B_1 and B_2. Fig. 2 shows the most successful of these plots; here the vertical axis gives the 850 mb wind direction over Beirut (D_B) and the horizontal axis the 850 mb temperature (T_B), also over Beirut. Many of the snow cases for which the first two predictors (Z and D_N) were not decisive are conveniently relegated to the cold left side of Fig. 2. The data show that $T_B < -2$ °C is a sufficient condition for subsequent snow in Jerusalem (area D of Fig. 2(a)). Rather surprisingly, there is strong evidence that at warmer values of T_B, rain, rather than snow, is favoured by north-westerly winds over Beirut (the events in area E of Fig. 2(a)) while snow is more frequent following south-westerlies (area F).

This indication becomes even more apparent when the data from the mixed-event area B_2 (of Fig. 1) are isolated on a similar plot (Fig. 2(b)). The slopes of the boundaries between areas E and F and H and J (Figs 2(a) and 2(b)) imply that the warmer T_B is, the more southerly the wind over Lebanon must be for eventual snow. Why should north-westerly flow virtually preclude snow at these warmer temperatures

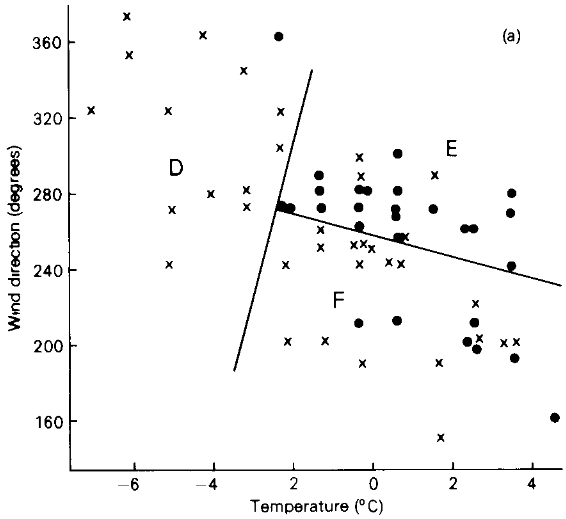

Figure 2(a). Snow (x) and rain events (dots) from areas B_1 and B_2 of Fig. 1 plotted according to earlier observations of 850 mb wind direction and temperature both over Beirut.

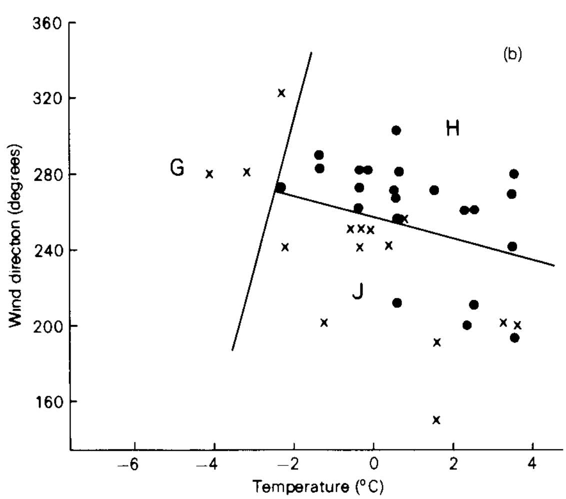

Figure 2(b). Same as Fig. 2(a) but for events from area B_2 of Fig. 1 only.

while south-westerlies presage a high snow frequency? By way of explanation we point out that north-westerlies indicate a likely trough position downstream (to the east) of both stations and it is possible that in these situations the coldest air has already reached the Israel–Lebanon longitude. North-westerlies at both stations may also reflect a too-shallow trough with insufficient advection from the cold air reservoirs of northern Europe. This situation is depicted schematically in Fig. 3(a). On the other hand, a veering of wind direction from Lebanon to Cyprus implies a trough upstream of Israel and a likelihood of an additional surge of air, cold enough for subsequent snow in Jerusalem, as depicted schematically in Fig. 3(b).

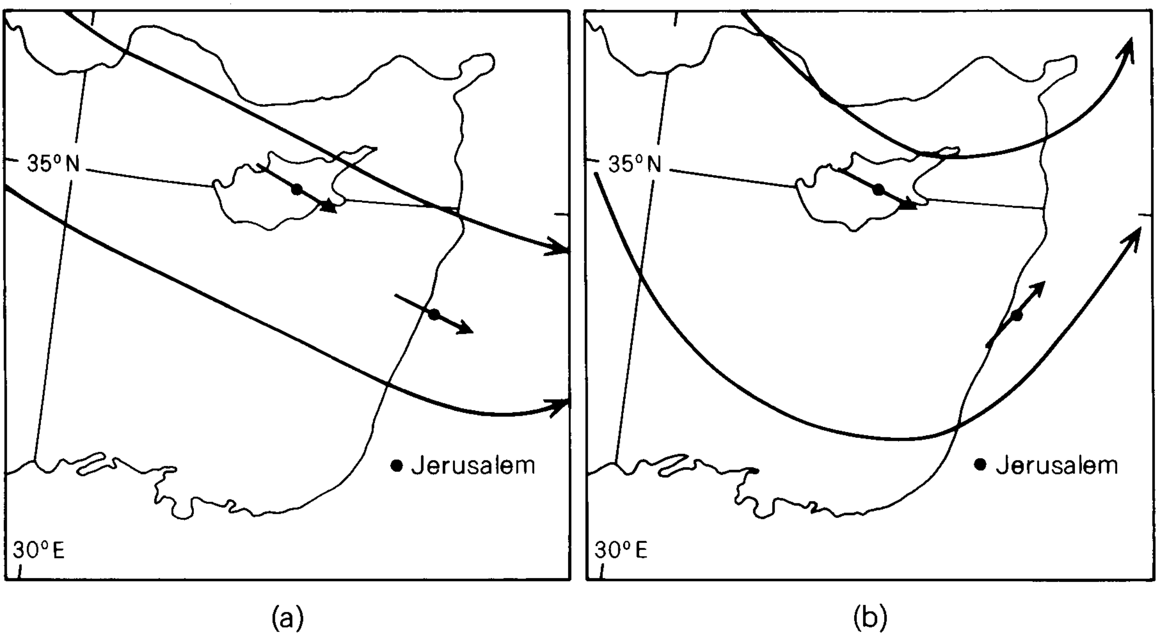

Figure 3. Schematic representation of 850 mb flow for north-westerlies over Cyprus and Lebanon (a), and for south-westerly flow over Beirut (b).

Application

The results suggest the following procedure for assigning a probability (conditional on the expectation of precipitation and surface temperature below 5 °C) of snow in Jerusalem. Observations of Z and D_N determine the primary category for use with Fig. 1:

observations qualifying for area A ... 100% probability of snow,
observations qualifying for area C ... 5% probability of snow,
observations qualifying for area B_1 ($T_B < -2$ °C) ... 100% probability of snow,
observations qualifying for area B_1 ($T_B > -2$ °C) ... 77% probability of snow, and
observations qualifying for area B_2, refer to Fig. 2(b) where:

area G ... 100% probability of snow,
area H ... 5% probability of snow, and
area J ... 73% probability of snow.

By way of comparison we note that during the period January 1976–March 1980, Jerusalem experienced 63 precipitation days during which the local surface temperature fell below 5 °C. On 16 of these at least one observation of snow was reported, implying a climatological expectation of only 25.4% for cold precipitation days; for precipitation days in general, the climatological expectation of snow is, of course, much lower.

Conclusion

We have considered 21 years of data and have used the most liberal definition of a snow event to maximize the data base. Differences have been documented between the atmospheric conditions which precede snow and rain in Jerusalem on cold days (surface temperature below 5 °C). During the period under study snow occurred following 1000–500 mb thicknesses over Israel less than 5350 gpm and was considerably more frequent than rain following even greater thicknesses whenever 850 mb winds over Cyprus were from the north through north-east. Rain without snow in Jerusalem was associated with 850 mb temperatures north of Israel warmer than −2 °C combined with west to north-west low-level flow over Cyprus and Lebanon.

The scatter diagrams which demonstrate the relative importance of selected upper-air variables in rain–snow discrimination at Jerusalem can be useful for prediction. They are, however, somewhat uncertain over certain ranges of several variables that occurred infrequently in the data set. To use the diagrams for forecasting, the indicated frequency of snow within appropriate ranges of the 'predictors' is interpreted as probability; the boundaries between radically different probability categories should be regarded as transitions representing intermediate probabilities.

The present study adds to the findings published in Druyan (1980) in that it considers upstream conditions. The results suggest that multiple regression or discriminant analysis could quantify the relative importance of each meteorological variable. Here the relationships between atmospheric conditions and rain–snow discrimination are shown qualitatively and in a graphical presentation which is suitable for operational forecasting.

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Appendix—Summary of Druyan (1980)

Fig. A.1. shows the distribution of snow and rain events in Jerusalem taken from the years 1959–77. These data have been plotted as in Figs 1–3 but here the observations that precede the events are the height of the 0 °C isotherm (vertical axis) and the 500–1000 mb thickness (horizontal axis), both over Israel's central coastal plain (Bet Dagan or Be'er Yacov). The symbols, the definition of snow and rain and the time interval between the upper-air parameters and snow onset in Jerusalem are the same as in the present study. The strong relationship between the height of the 0 °C isotherm and the 500–1000 mb thickness notwithstanding, the scatter of the events suggests that an advantage is gained by considering them in concert. The trend of increasing frequency of snow following low heights of the 0 °C isotherm and low thicknesses which is documented by the diagram undoubtedly offers useful information to the forecaster. Unfortunately, rain-snow discrimination remains ambiguous for certain intervals presumably because both predictors reflect only local conditions.

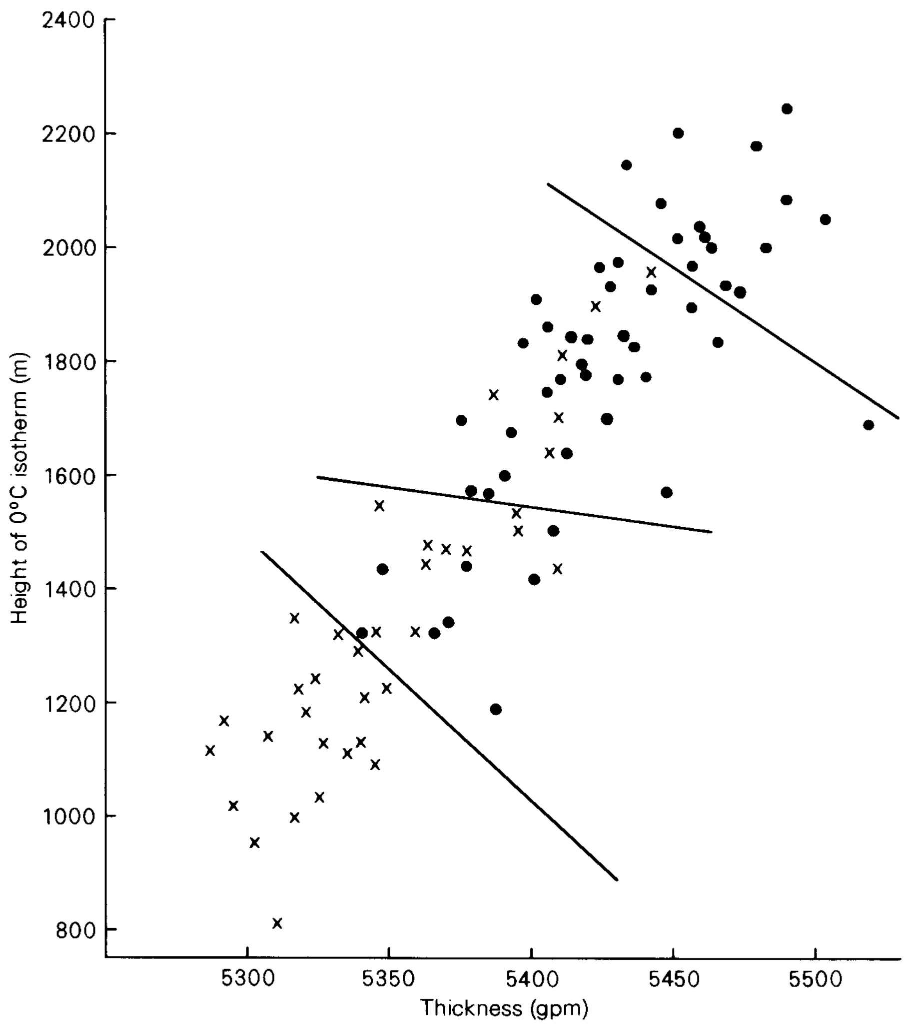

Figure A.1. Snow (x) and rain events (dots) from the years 1959–77 at Jerusalem plotted according to height of the 0 °C isotherm and 500–1000 mb thickness observed over Israel (from Druyan 1980).

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Oscillations of wind at Edinburgh due to travelling gravity waves

By K. J. Weston

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Summary

Cases in which the surface wind exhibits periodic oscillations are examined to establish the conditions under which they are most commonly observed. All oscillations were found to occur at night in polar or arctic airstreams when a stable layer was present at about 850 mb above a layer of almost neutral static stability.

1. Introduction

Oscillations within a stably stratified layer of air — gravity waves — are extremely common at all levels in the troposphere. The most familiar type, and those which have been most intensely studied, are stationary gravity waves, or lee waves; but travelling gravity waves have also received attention. Travelling waves are commonly observed on microbarograph records as periodic pressure variations of amplitude up to about 1 millibar and periods generally between 5 and 15 minutes. Keliher (1975) analysed 280 gravity wave events and concluded that about half were shear-induced in layers where the Richardson number was small. Gedzelman and Rilling (1978) detected 88 examples of gravity waves during a two-month period using a network of four microbarographs. Their results also suggested that such waves are often generated by dynamic instability of the wind profile in the upper troposphere and that their pressure amplitudes are greatly enhanced by the presence of a layer of high static stability in the lower troposphere.

Rather less frequently observed are regular periodic oscillations of surface wind due to gravity waves. An early analysis of such events was performed by Gossard and Munk (1954), who analysed seven occasions of waves in California all of which occurred in the presence of a low-level stable layer with base at 300 m or below. The oscillations often followed a reversal of a land- and sea-breeze circulation. More recently Richner and Nater (1981) analysed observations obtained at sites near Zurich, Switzerland and compared observed phase velocities with theoretical values. The present article is a study of cases of oscillations of wind speed or direction, or both, over a five-year period at Edinburgh to establish the conditions most likely to give rise to such occurrences. Data from Shanwell radiosonde station are used to examine upper winds and temperatures on wave occasions.

2. Characteristics of the oscillations

During the period studied (1978–82 inclusive), nine occasions of well-defined oscillations of surface wind were identified, all occurring in arctic or polar maritime air masses. In addition to these, there was a similar number of identifiable, but minor, oscillations which were not included in the study. Fig. 1 shows the clearest example: there are pronounced oscillations that are in phase and have amplitudes of about 2.5 m s^{-1} and 40° respectively in speed and direction.

Table I summarizes observations from all nine cases. On six occasions there were clear oscillations in both speed and direction while the remaining three displayed regular variations only in direction.

Fig. 2 shows a satellite photograph taken over Scotland at a time when oscillations of surface wind were occurring (same occasion as for Fig. 1). Two cloud layers can be seen, the levels of which can readily be identified from humidity and temperature soundings taken over Scotland. There is a layer of closed cells of stratocumulus at about 850 mb over and to the north of Scotland, and rather dense cirrus at about 400 mb over and to the west of Scotland; this cirrus is associated with a warm front approaching from the Atlantic. Waves can be seen in both these cloud layers over much of Scotland. Of particular interest are those in the stratocumulus over north-east Scotland where there are two sets of waves with different orientations. One set has an orientation approximately north to south, as have the waves downwind (eastward) of the Faeroes (F) and Shetland (S). All these waves are perpendicular to the wind at stratocumulus level and are likely to be stationary gravity waves. However, the second set of waves has an orientation approximately south-west to north-east with a distinct curvature and they are probably travelling gravity waves.

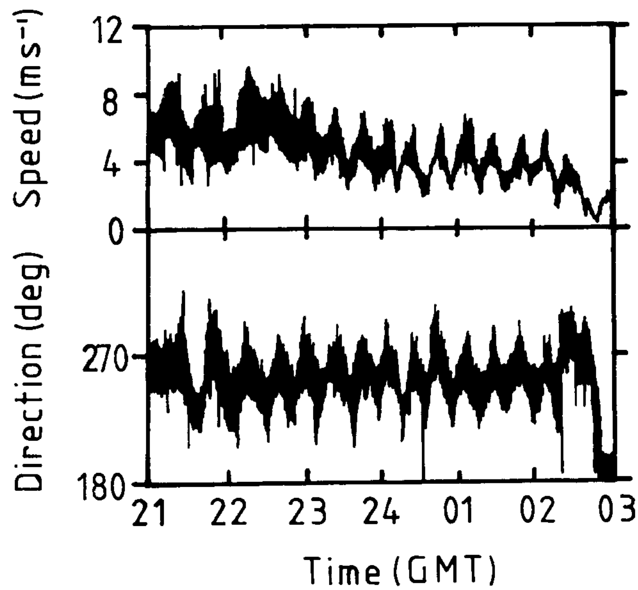

Figure 1. Anemogram for 22/23 March 1982 recorded at the University of Edinburgh.

Table I. *Amplitude and period of oscillations of surface wind at Edinburgh*

Date	Time (GMT)	Amplitude Direction (degrees)	Amplitude Speed ($m\ s^{-1}$)		Period (minutes)
30 Aug 1978	0300 - 0730	40	1.0	in phase	25
8 Feb 1979	0400 - 0800	90	2.0	in phase	26
18 Jul 1979	2000 - 2400	30			40
11 Sept 1979	1930 - 2200	30	2.0	in phase	28 (speed) 14 (direction)
21 Sept 1979	2130 - 0030	30			22
29 Feb 1980	2000 - 0100	60	3.0	in phase	irregular
3 Mar 1980	0000 - 0700	90	2.5	in phase	28
23 Apr 1981	0230 - 0530	40	–		29
22 Mar 1982	2130 -0330	40	2.5	in phase	20

Photograph by courtesy of Dundee University

Figure 2. NOAA 5 satellite picture, 0335 GMT, 23 March 1982; AVHRR infra-red image. The north arrow is aligned along the Greenwich meridian. Waves can be seen to the east of the Faeroes (F) and Shetland (S) and over much of Scotland.

All nine cases of pronounced wave motion occurred during night-time, as did all other cases of identifiable waves in this data set. Table I shows the time of occurrence of waves, as identified from anemograms. The non-occurrence during day-time is, no doubt, partly due to the greater difficulty of identification caused by a more variable wind with a higher gust amplitude; but this cannot be the whole explanation because many of the waves are of sufficiently large amplitude to stand out against this variability. Significantly, on all nine occasions, lee waves were visible on images from polar-orbiting satellites during the pass prior to the occurrence of the wind oscillations.

3. Thermal structure

As most of the waves occurred at or near midnight, the 00 GMT radiosonde soundings from Shanwell (about 50 km north-north-east of Edinburgh) are fairly representative of conditions during wave occurrence. Fig. 3 is an analysis of the thermal structure on wave occasions and shows the levels of stable layers in which the lapse rate is less than half that of the dry adiabatic. The figure represents stability in terms of the increase of potential temperature in °C per km. On all nine occasions there was a markedly stable layer between about 850 and 750 mb. Below these stable layers the lapse rates were close to the dry adiabatic, ranging between 7.5 and 9.3 °C per km, with an average of 8.4 °C per km.

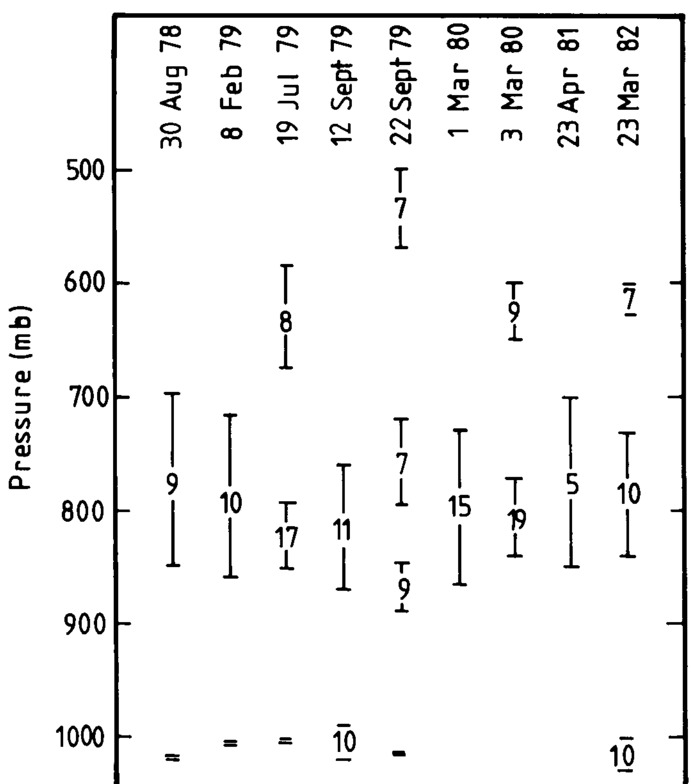

Figure 3. The extent of layers with a lapse rate less than half the dry adiabatic lapse rate. Figures show the increase of potential temperature in °C per km but values are not shown for very shallow layers at the surface.

It can be seen that there was only a small variation in height of the base of the stable layer so that a composite temperature sounding, with height normalized with respect to the height of this base, can readily be drawn; this is shown in Fig. 4. Thus the thermal stratification typical of wave occasions is a shallow stable layer at the surface with a layer above, in which the lapse rate is close to the dry adiabatic, which in turn is capped by an inversion.

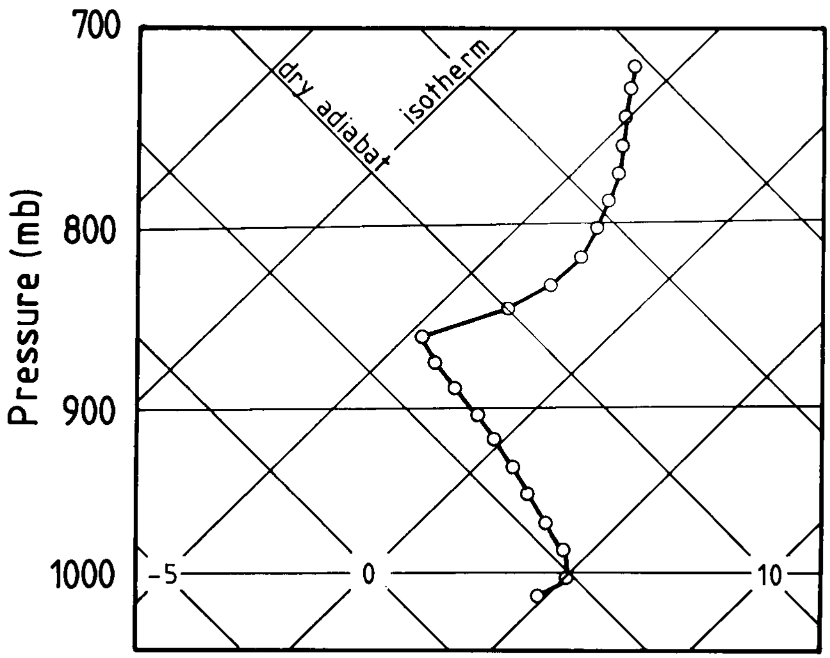

Figure 4. A composite sounding for nine occasions of gravity waves. Values of potential temperature were averaged at heights normalized with respect to the level of the base of stable layers near 850 mb. Isotherms and adiabats are shown at intervals of 5 °C.

4. Concluding remarks

Gravity waves in the lower troposphere of sufficient amplitude to give marked oscillations of surface wind appear to occur on occasions with a marked temperature inversion, beneath which there is a layer with a lapse rate close to the dry adiabatic. All cases in this study occurred at night in polar or arctic maritime airstreams, so that a shallow stable layer at the surface was probably present on all occasions. Lee waves were observed on all occasions prior to the oscillatory wind events.

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551.521.16

Measurement of low levels of daylight on 6 August 1981

By P. J. Littlefair

(Building Research Establishment, Department of the Environment, Garston)

Summary

Armstrong (1983) has presented radiation data for 6 August 1981, a day when intense darkness enveloped much of southern England around midday. At Bracknell global irradiances were well below the 1% percentile for most of the day. At the same time daylight measurements were continuously being made at Garston, Hertfordshire, and these are reported briefly here.

Since February 1981 daylight illuminances have been recorded continuously at Garston, Hertfordshire (51.7° N, 0.4° W). Measurements are made on vertical external planes and inside model rooms, as well as the more usual measurements of horizontal total and diffuse external illuminance. The purpose of the work is to improve methods for predicting daylight availability and lighting energy consumption inside buildings (Littlefair 1983).

During normal working hours each illuminance is measured every minute; the variation with time of horizontal total illuminance on 6 August 1981 is plotted in Fig. 1. The overall outline of the graph is

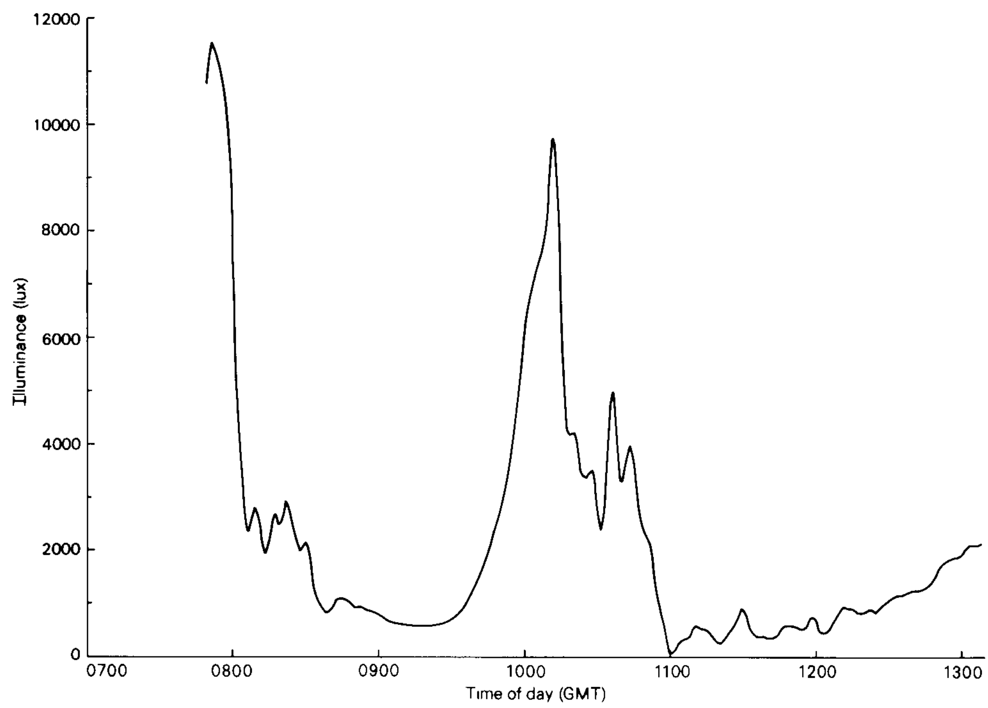

Figure 1. Horizontal unobstructed daylight illuminance under heavily overcast skies at Garston on 6 August 1981.

similar to the variation in irradiance presented by Armstrong (1983). However, the greater sensitivity and fast response time of the daylight sensors enable a detailed analysis of the lowest illuminance levels to be carried out.

This is presented in Fig. 2, which shows the variation in horizontal total illuminance between 1050 and 1210 GMT. The lowest value recorded was 89 ± 7 lux just after 1100 GMT. Between 1100 and 1200 GMT the unobstructed horizontal illuminance did not exceed 1000 lux. Under overcast skies 1 W/m^2 corresponds approximately to 115 lux (Krochmann and Seidl 1974).

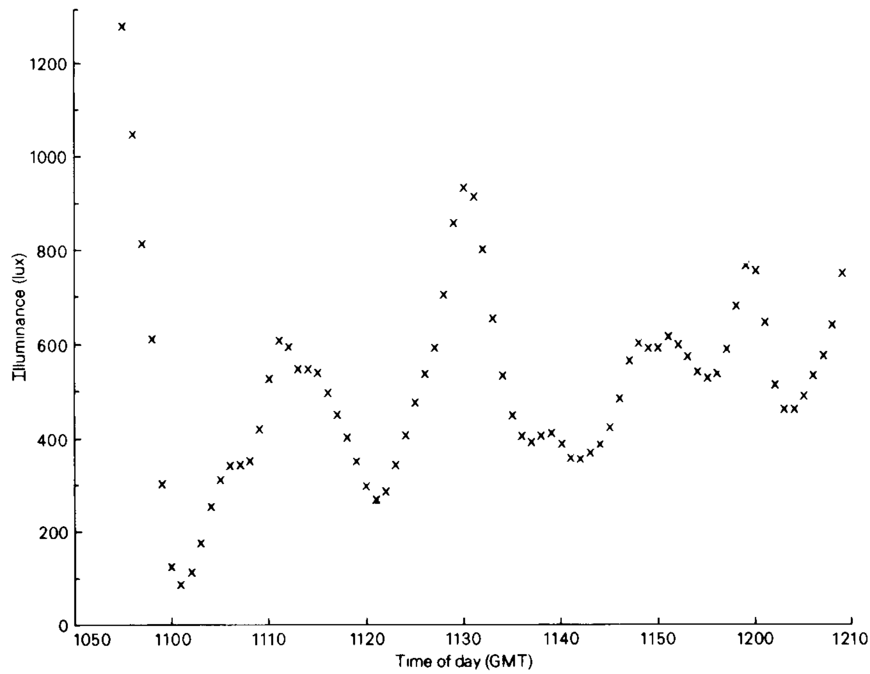

Figure 2. Minimum values of horizontal unobstructed daylight illuminance at Garston on 6 August 1981.

Krochmann and Seidl also give formulae for the average illuminance from an overcast sky; that due to Krochmann gives a value of 16 500 lux for this time of day and year.

Acknowledgement

The work described forms part of the research program of the Building Research Establishment of the Department of the Environment, and is published by permission of the Director.

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Operational forecasting of a 'wind-chill' factor for young lowland lambs

By J. R. Starr

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Summary

As part of a study to obtain detailed veterinary and economic information on lamb mortality in a commercial lowland sheep flock, meteorological observations were made at Rushall Manor Farm, near Reading, between 1976 and 1979.

The data were interpreted in terms of critical environmental heat demands likely to lead to lamb mortality 'in the field'. Since 1980 these 'critical demands' have been used as a basis for lamb 'wind-chill' forecasting trials in south and south-west England in collaboration with forecasting offices.

Introduction

'... there is hardly an expense equal to the effects, both to fields and livestock, of a gnawing or destroying air.' (L. Bain, *Q J Agric,* 1839).

Early in 1976 the Divisional Veterinary Officer (Veterinary Investigations) for South East ADAS at Reading approached the recently established Regional Agrometeorological Department with a view to a collaborative study of the veterinary and economic aspects of lamb mortality in a nearby commercial lowland sheep flock.

Lamb mortality, during and soon after birth, is thought to be a major source of loss to the world's sheep industry. Various studies have been made in Australia, New Zealand and Scotland (e.g. Scottish Agricultural Colleges, 1975). Although some figures are available from the Meat and Livestock Commission for 504 commercial lowland sheep flocks in 1970 and 1971 (suggesting a lamb birth-to-weaning mortality of 13%), and a Ministry of Agriculture, Fisheries and Food survey in the south of England for 1974 and 1975 indicated that on many farms lamb losses from birth to six weeks were considerable (20% or more), little detailed information has been published on the situation in England and Wales.

Farm livestock can be affected by climate both indirectly, through the influence of climate upon the availability of food, and directly, as a result of exposure to the rigours of climate (e.g. Blaxter 1964, Obst and Ellis 1977). The rate of metabolic heat production in homeothermic animals such as lambs increases

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

in response to an increase in heat loss to the environment and represents an attempt to stabilize body temperature. Heat loss increases as environmental temperature falls and as air movement and evaporation from the coat increase (Joyce *et al.* 1966). The environment becomes potentially lethal for the lamb when its heat loss exceeds its 'summit metabolism' — the maximum rate of heat production that the lamb can sustain.

Clearly the total environmental effect experienced by a lamb will fluctuate from hour to hour and follows variations in air motion, temperature, radiative effects and the intensity and duration of rainfall, as has been demonstrated, for example, by Slee (1977) and McArthur and Monteith (1980) in measurements of the (electrical) energy required to maintain the temperature of a simulated animal; by Alexander (1964) in climate-chamber research; and by Sykes *et al.* (1976) in field observations. Such investigations imply that almost all new-born lambs are subject to cold-stress (and a high metabolic demand) which is compounded by low body (energy) reserves with which to meet the demand. An erosion of energy reserves from an already undernourished or sick lamb, particularly in breeds with short birth-coats, is recognized as contributing to the incidence of death in young lambs. In severe climates, associated with, for example, hill farms, cold-stress might be the primary cause of death in new-born lambs (Munro 1962).

Such weakling stock might be at risk even in apparently moderate weather conditions such as those generally encountered in south-east England; it is this hypothesis that was investigated and from which the wind-chill forecasting system developed.

Materials and methods for the investigation

The farm

Rushall Manor Farm lies mainly on a south-facing, undulating slope of the Berkshire Downs (some 17.5 km west of Reading) leading down to the River Pang. Of the 250 ha a large part is under cereals, about 40 ha are temporarily under grass (leys) and 16 ha are permanent pasture.

The flock

The sheep flock in 1976 consisted of 400 breeding ewes of four different types (mainly Cadzows and Suffolk Crosses). In 1977 the flock size was increased to 486 by a batch of Scott half-bred gimmers (ewes lambing for the first time); in 1978 it was further increased to 550, and in 1979 to 567.

All dead lambs were submitted for autopsy; careful records being kept of date of death, age, and ewe of origin. Where death was attributed to chilling or starvation in the field, carcases showed general congestion of the viscera, especially the lungs, and in most cases the stomachs were empty or contained only a little milk. Table I presents the numbers and percentages of total lamb losses due to chilling or starvation in the field over the years of the study.

Table I. *Analysis of lamb losses over the period of study, 1976–79*

	1976	1977	1978	1979
Ewes	400	486	550	567
Total lambs born	745	943	1150	1133
Total field and house losses	85	116	209	238
Chilling/starvation losses in the field	6 (7%)	20 (17%)	36 (17%)	77 (32%)

Equipment

In field investigations designed to evaluate the effect of meteorological factors on livestock, long-term interdisciplinary studies are commonly desirable. Equally, an agriculturalist will commonly require a swift resolution of a production problem which is having, or could have, important economic consequences. Logistically, too, there are difficulties in supervising and maintaining site-monitoring equipment and in achieving adequate data-recovery regularly over an extended period (Smith 1970). Changes from year to year in grazing facilities, husbandry techniques, etc., add further dimensions of difficulty. However, it was Gloyne's conviction (Gloyne 1967) that, given a sufficiency of 24-hour runs, it should at least be possible to infer the basic features of the surface wind regime at any site after periods of study reckoned in weeks rather than years.

'Run-of-wind' measuring equipment (cup anemometers) exposed at 2 m height and minimum thermometers at 1 m were established in several fields near ewe feed and watering areas and near significant hollows. Surveys with hand-held anemometers helped to establish a preliminary view of the association between local land form and local wind speed and direction. Data were related to a 'reference site' which housed a rain-gauge, a run-of-wind anemometer, a grass-minimum thermometer, maximum and minimum thermometers and a thermograph housed in a large (Stevenson) screen at lamb height, and a minimum thermometer, screened simply and exposed at 1 m as in the other fields. During the critical neonatal period daily readings were made. Subsequently, in 1978 and 1979, continuous meteorological recordings were made at lamb height using automatic equipment. The representativeness of such fixed-point data in the present context may be open to question. The data can only provide an approximation to the actual environment experienced by a lamb possibly protected by its ewe or otherwise sheltered. However, such data, even if not correct on an absolute scale, still provide a means of estimating days of relatively high or low environmental stress.

Heat loss from lambs

Data obtained by Alexander (1964) and Smith (1973) provided the basis for expressing the environmental variables in terms of heat loss from the young lamb. From Fig. 1 of Alexander (1964) it may be deduced, for example, that the rate of heat loss (M) from a young, dry, 2 kg lamb, with a fine coat, in still air at $-32\,°C$ ($M = 160$ W m^{-2}) is the same as that from the same lamb with a dry coat in a 5.5 m s^{-1} (12 miles per hour) wind and at an air temperature of $-4\,°C$, or with a wet coat in a 5.5 m s^{-1} wind when the air temperature is $+13\,°C$. The influences of wind and particularly a wet birth-coat are clear. Corrections to the environmental temperature T_a can be made to allow for a 'radiative environment' most apparent under clear-sky conditions. Smith (1973) suggests decreasing T_a by up to 5 °C depending on cloud cover, and such corrections were applied before estimating M. Although Alexander's work was on young merino lambs, the results were taken as applicable to the Rushall Manor lamb flock, a not unreasonable assumption according to Alexander (personal communication 1978).

In 1978 the environmental heat demand from the lambs over four-hourly periods was estimated as a multiple of the basal 'metabolic' rate of heat loss per hour (the rate of heat production for the lamb in its 'thermal comfort zone'), M_B, from the observed combination of wind, temperature and rainfall (it being assumed that rainfall wetted the coat instantly and that the cessation of rain similarly marked the return of the birth-coat to the dry state). The heat loss estimates were accumulated for one, two and three days prior to lamb death and tabulated against the total numbers of lamb field deaths occurring within equal increments of the cumulative energy demand M_p over the appropriate period, p. If the observed deaths are not weather related, every day would hold an equal probability for the death of lambs. M_p was therefore calculated for every day and deaths allocated in proportion to the number of days with a given range of energy demand to give an 'expected' death distribution. Since the dead lambs were recovered only once daily in 1978, the time of death is in question; the assumption was made that all lamb deaths occurred overnight. In 1979 hourly estimates of the heat demands were made — and lambs were recovered twice daily (confirming that deaths indeed occurred predominantly overnight).

A full description of the weather and details of lamb mortality over the years 1976–79 is to be found in Starr (1981). The tables presented there may be summarized as follows:

(i) Field deaths are predominantly in twins and triplets and are highly correlated with the heat loss accumulated 24 hours before death.

(ii) Negative (or only small positive) weight gains are generally recorded in lamb deaths where the animal is under 10 days old.

(iii) Mortality is not confined predominantly to any one field.

It is of interest to study the energy considerations for lamb survival. Alexander (1964) states that summit metabolism in young merinos (3 kg lambs) is 58 W or 232 W m^{-2} (i.e. about four times the basal metabolic rate M_B). In the present study, the maximum hourly energy demand was estimated to be 4.4 M_B and the corresponding demands over 12 and 24 hours to be 49 and 94 M_B respectively, environmental demands which, over the day, are close to the summit demand and which exceed this demand over short periods. Total useful energy reserves in lambs from adequately fed ewes are about 1083 J kg^{-1} (i.e. 3.135 kJ for a 3 kg lamb); the time to exhaust fat and glycogen reserves is hence of the order of 15 h. Eales (1980) further points out that twins each weighing 3 kg have something like 30% more surface area through which heat is lost than a single 6 kg lamb; in addition the twins have to compete for the available milk supply.

The low, generally negative, liveweight gains in the young lambs point to the energy intake being unable to match the energy lost to the environment; this continual erosion of energy, even if not fatal, is reflected in low liveweight gain and hence in the sale weight of the fat lamb.

The Rushall Manor lambs were housed during the critical first day and in general were subjected to an altogether more moderate climate than that which can give trouble to upland flocks. Nevertheless, the data indicated that there is a difference between observed and expected young lamb mortality. The implication is that young lambs (particularly twins or triplets), less than 10 days old, can be at risk even in quite moderate weather.

Being more specific, the 1979 analyses showed that some 60% of lamb deaths were attributable to days when the integrated heat demand over 24 hours (M_{24}) exceeded 80 times the basal rate (M_B); the corresponding demand above which 75% of deaths occurred was 70 M_B. Taking the total mortality in day-old lambs over the eight 24-hour periods with M_{24} greater than 80 M_B, the mortality of light (less than 3 kg), medium (3–5 kg) and heavy (more than 5 kg) lambs is found to be 14.5, 5.2 and nil (expressed as percentages of their respective populations of 48, 171 and 35). On one night, 13/14 March, 6 of the 14 (i.e. 43%) light lambs died; only 6 out of 51 medium lambs died. None of the 4 heaviest succumbed.

The practical implications of the critical 24-hour heat demand of 80 M_B mentioned for young lambs may, by reference to Alexander's (1964) Fig. 1, be summarized as follows.

Wet lambs may be in danger in winds of about 5 m s^{-1} even at a temperature of about +20°C; the corresponding 'danger' temperature for dry lambs under these windy conditions is 0 °C. Even a wind of below 2.5 m s^{-1} can cause distress to wet lambs when the temperature is below 10 °C (clear skies accentuate the danger). The temperature must be below −10 °C if dry lambs are to be at risk in tranquil conditions. (Calculations show that this 24-hour heat demand of 80 M_B was attained on at least 15 occasions in northern England and the Borders in March and April 1979.)

The forecasting of the heat loss factor ('wind-chill') and field assessments

1980 and 1981 seasons

In the springs of 1980 and 1981, trial daily forecasts of likely hazardous weather for young lambs were prepared for the Rushall Manor area with the co-operation of the meteorological offices at RAF Benson

(Oxon) and RAF Upavon (Wilts). Briefly, the 24 hours beginning 0800 local time were divided into 6 four-hourly periods, for which temperatures and wind speed (reduced to lamb height in the Rushall Manor area) and the occurrence or not of rain were forecast. Wind-chill indices were totalled (Table II(a) and (b)) and passed by telephone to the farm manager, Mr Bishop, whose initiative it was to make contact. Should a 'danger' level be attained (M greater than or equal to 80 M_B) the decision might be, for example, to keep young lambs housed for a further day or so. An example of the forecast (and actual) wind-chill for 27 March 1980 is shown in Table II(c). The forecasts were followed meticulously in 1981; the farm manager reported only 1% field losses in 1000 lambs. In particular, on the severe night of 21 March, 43 deaths occurred at an elevated farm near Marlborough; no fatalities occurred at Rushall Manor Farm. Upavon forecast the high wind-chill factor of 99 and Mr Bishop reacted accordingly.

Table II. *Wind-chill indices for wet coat and dry coat*

Wind speed at Rushall Manor Farm	(a) Wet coat indices				(b) Dry coat indices		
	Temperature (°C)						
(m s^{-1})	5	5 to 0	0 to −5	< −5	>0	0 to −5	< −5
>10	17	18	19	20	12	13	15
5–10	16	17	18	19	11	12	13
<5	14	15	16	17	10	11	12

(c) Forecast and actual wind-chill on 27 March 1980 for Rushall Manor Farm

	Period (local time)						Total
	08–12	12–16	16–20	20–00	00–04	04–08	
Temperature (°C)							
forecast	10	10	10	7	7	7	
actual	12	11	9	7	6	7	
Wind speed (m s^{-1})							
forecast	8	6	5	5	5	5	
actual	8	8	6	4	2	5	
Rain							
forecast	yes	no	yes	yes	yes	yes	
actual	yes	yes	no	no	yes	yes	
Wind-chill*							
forecast	16	11	14	14	14	14	83
actual	16	16	11	10	14	14	81

*Add the six scores to give the forecast 24-hour heat-loss factor M_{24}. If $M_{24} > 90\ M_B$ conditions may be critical; $M_{24} = 80$ to $90\ M_B$, danger; $M_{24} = 70$ to $80\ M_B$, warning; $M_{24} < 70\ M_B$, little danger.

It was evident from these initial trials that the main divergence of 'actual' from 'forecast' wind-chill factors could be attributed to the difficulty of forecasting the onset and cessation of precipitation, a problem likely to be accentuated, as will be seen, under showery conditions. Further, Mr Bishop suggested that, since the lamb coat tended to remain moist under 'dry' conditions in high humidity and low winds, future forecasts should allow for continuing coat wetness under appropriate conditions.

1982 season

The 1982 trial operated through RAF Benson and Bristol Weather Centre; the benign weather of early spring meant that the system was not given an adequate test. Only the first half of March yielded several high index days and it was during this period that Mr Dartnall's ewes began lambing near Marlborough.

Mr Dartnall commented subsequently as follows:

'... there were two periods when the indices were over 85, 9–12 March 1982 and the 14–17th. Several of the days in these two periods started dry and bright and during other lambings we would have turned some out. The high readings prevented us doing that and the weather duly turned bad in the afternoon. There is no doubt that if we had turned any out some would have been lost.'

At a meeting of all farmers involved in the 1982 trials Mr Dartnall referred to his loss of 43 lambs in a night in the 1981 season. A consequence of this was his adoption of the following choice of priorities for turning out lambs when there was pressure on housing in 1982.

Wind-chill factor	81–90	Turn out only single lambs
	71–80	Turn out twin lambs
	70 or less	Turn out triplet lambs.

'The result was an acceptable level of losses considering the high number of triplets born and a severe fox problem:

Ewes put to ram	2200
Lambs turned out	4048 (184%)
Lambs at inoculation	3855 (175.2%)
Lambs lost	193 (4.8%).'

Other farmers, although starting lambing in a mild period in the spring of 1982, also adjusted their management to take account of wind-chill. Mr Harbottle of Faccombe near Newbury, with fields at elevations of 150 m and 300 m, normally put stock out of a morning. He often delayed until the afternoon in the light of wind-chill forecasts and kept in triplets for several days, eventually putting them out in the more sheltered field at 150 m. Mr Hawes (Horton-cum-Studley, Oxon) found two occasions of high chill index when he did not turn out. He remarked, however, that if a flock is held in too long, virus infections can result. Mr Brown (Beckley, Oxford) said his mind was not altered by the forecasts. He felt that he could judge for himself when lambs should be put out.

Mr Soanes (Beckley, Oxford) felt the forecasts potentially useful but he began lambing in late March during the mild period.

Mr Bishop again found the forecasts 'extremely useful'.

1983 season

With the agreement of the Public Services Branch of the Meteorological Office trials were continued in 1983 free of charge and on a modestly increased scale. Several farmers from Hampshire, Surrey and West Sussex areas that fell in the Southampton Weather Centre catchment were involved, together with a Devon farmer (by local arrangement with Plymouth Weather Centre). The withdrawal of Benson from public service commitments meant that farmers in the Oxford, Berkshire and Wiltshire areas were served entirely by Bristol Weather Centre.

The weather of the season produced testing sequences for the system. To quote Mr M. J. Bibb, Bristol Weather Centre: 'It was a particularly difficult year with much of the precipitation being showery and as such it must have been a searching test of our effectiveness'.

The requirement on the forecasters to make a Yes/No forecast for rainfall over the 6 four-hour periods is, of course, the most demanding aspect of the forecast procedure. If the farm misses out on the showers, the actual wind-chill factor will be much less than the forecast value. This was partly resolved by taking:

(i) the probability of *light* showers as meaning 'NO' rain since the lamb could well shelter from a light shower or at least dry out quickly, and

(ii) the probability of *heavy* showers forecast as 'YES' rain.

As the season progressed Bristol decided to provide two wind-chill factors appropriate to this forecast shower severity. The farmer could interpret the factors accordingly.

Some comments by farmers on the 1983 season were as follows.

Mr N. M. Bridges, farm manager, Cirencester, wrote to Mr M. J. Bibb: '... we have reduced our mortality due to hypothermia this year in what is arguably one of the worst spells of weather at lambing for some years. I found it very useful to have very detailed weather forecasts and wind-chill forecast data to hand when making decisions on turn-out.'

In his report on lambing, Mr Bridges noted: 'Without doubt this service was a major aid in making the decision on when and what to turn out.

'Fourteen of the thirty-six days gave us forecast wind-chill factors of 80 or less, indicating it was of low risk to turn out ... we were forced to turn out ewes and lambs on days when the forecast factor was 81–88 although only strong lambs were put out on these days.

'Records show we only lost two lambs in the field due to exposure. We have without doubt reduced the number of deaths attributable to exposure following turn-out. A fair measure of credit must go to the staff of Bristol Weather Centre for their help.'

From Mr D. Harbottle, Faccombe Estates, near Andover, Hants: '... the trial forecast proved far more useful then last year although on several occasions what was forecasted failed to materialize and we held lambs in when they could have easily gone out.

'... we (Mr Harbottle and his new shepherd) felt that overall it was a very worthwhile exercise. Obviously it is very difficult for Bristol Weather Centre to be entirely specific some 60 miles east of them and therefore they must be inclined towards generalizations and this does fall down from time to time.

'However, I am sure that anyone lambing a considerable number of ewes with limited holding space must find the services beneficial.'

Writing to Mr K. Best of Southampton Weather Centre, Mr Janaway of Basingstoke commented: 'I found the figures you gave most helpful ...' (He suggested that a forecast for up to three days would be valuable since he had enough space to hold ewes and lambs for up to three days.)

The problems that can be posed by showery weather are highlighted in the pertinent comments of Mr Dartnall of Temple Farm, near Marlborough: '... Unfortunately I did not find the lamb wind-chill factor anywhere near as accurate this year as it was last. In many cases the figure was too high for the conditions that developed later that day; for example, on 29 March 1983 the factor was 97, when in fact we only actually had 2.5 mm of rain. There were several occasions when there was a very high figure and yet it was warm, humid and misty and yet on other occasions the same figure was followed by much colder, wetter weather. To me there was no comparison between the two days and yet Bristol Weather Centre forecast that they would be roughly the same. However, there was one advantage in actually physically talking to a meteorological officer. Whether the problem was in the interpretation of the data but it seemed to me that the quality of advice wasn't the same as the year previous.

'I think this system still has potential but needs refinements ...'

Bristol subsequently developed the 'two-index system' for the showery situation to minimize the likelihood of such errors.

The meteorological office at Plymouth responded to a request by Mr Allen, Lane End Farm, Honiton, Devon, who had read of the trial wind-chill forecasts in the farming press. He received these forecasts for three weeks from 20 March on a repayment basis. He reported the forecasts to be 'very, very useful — the timing too was spot on. I hope the service will continue'.

He considered the value to lie in aiding his decision to put out lambs, born in house, since the following night's weather was critical.

Verification exercise

A verification exercise was carried out by Southampton Weather Centre for the recipients, who were all in the north-east of Hampshire. Interpretations of maximum and minimum temperature from Long Sutton were therefore appropriate, together with subjective assessments of wind strength and rainfall from Southampton Weather Centre records and London Weather Centre's *Daily Weather Summary.*

Briefly, 7 of the 51 forecasts issued predicted the index exactly whilst the error of the remainder did not show a particular bias.

'As one would expect', commented Mr Best, 'the greatest forecast errors occurred on occasions when this precipitation prediction was unsuccessful ... the forecaster is faced with a Yes/No decision regarding rainfall and he is often uncertain whether intermittent precipitation is significant with respect to the wetting of a young fleece.'

(Bristol Weather Centre partly resolved this problem, as discussed earlier.)

Conclusion

The forecasting scheme has been tried out under a variety of conditions from benign (most of spring 1982) to severe (several nights in 1980, 1981 and 1983). In particular, the showery spring of 1983 highlighted difficulties, since the wind-chill factor is critically dependent on rainfall and its duration. Nevertheless, the availability of a forecaster to discuss such problems with the farmer and to suggest 'limits' for the wind-chill factor (depending on whether showers were likely to be heavy or prolonged or light and infrequent) was vital and was appreciated by several farmers. Over the three seasons of the trial it was clear that farmers were prepared to adjust their management in the light of the wind-chill forecasts and on several occasions lamb mortality due to exposure was apparently dramatically diminished.

The scheme will overestimate the wind-chill under daytime conditions of strong insolation (conditions in which the index is likely to be low). It is under severe night-time weather that the index is more realistic, integrating as it does the effects of rain, wind and temperature.

The scheme tests the forecaster, yet does not make unreasonable demands upon him. It offers the opportunity for the forecaster to become involved with the participating farmer in his decisions, since interpretation of the wind-chill index (e.g. partitioning into day/night accumulation or the assessment of the consequences of showery conditions) may well be necessary.

At the current price of fat lambs, a charge for the service of about £100 (with possibly a reduction for those farmers who take the Meteorological Office Forecast Consultancy Service) must be seen as cost effective, representing as it does the value of perhaps three lambs.

The wind-chill forecast service was promoted in the area served by Bristol Weather Centre, through ADAS, for the 1984 lambing season.

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ADAS Livestock Husbandry Officers Mr G. Hughes, Miss R. Cox and Miss A. Perez recruited interested farmers — 10 farmers co-operated in the trials and many made constructive oral or written comments which are summarized in the article. The encouragement of the Public Services Branch of the Meteorological Office is acknowledged.

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551.586:612(53)

Discomfort in Sharjah

By N. A. Shehadeh

(University of Jordan)

Summary

Three years' wind, temperature and humidity data at Sharjah International Airport are used to provide a climatology of 'effective temperature', interpreted as a 'discomfort index' including monthly means and diurnal variation. The summer climate (May to October) of Sharjah is shown to be more uncomfortable than that of Singapore and is worst in July and August when the effective temperature reaches dangerously high values. Regression equations are found for daily mean values of effective temperature as a function of dry-bulb temperature, wet-bulb depression and wind speed for all summer months. The 'accumulated physiological strain' of successive uncomfortable days is discussed.

Introduction

Sharjah is the third largest city in the United Arab Emirates. It is located less than 10 kilometres to the north-east of Dubai and is almost connected with Ajman. The city, which is situated on the south-eastern shore of the Arabian Gulf at 25° 19'N 55° 31'E, has grown very rapidly in the last few years.

The climate of the Arabian Gulf is known for its high temperature and relative humidity (see Fig. 1), truly considered as one of the most oppressive climates in the world. Two previous studies by Watt (1967) and Turner (1978) discussed climatic discomfort in Bahrain. This paper is an analysis of discomfort in Sharjah, especially in the six summer months.

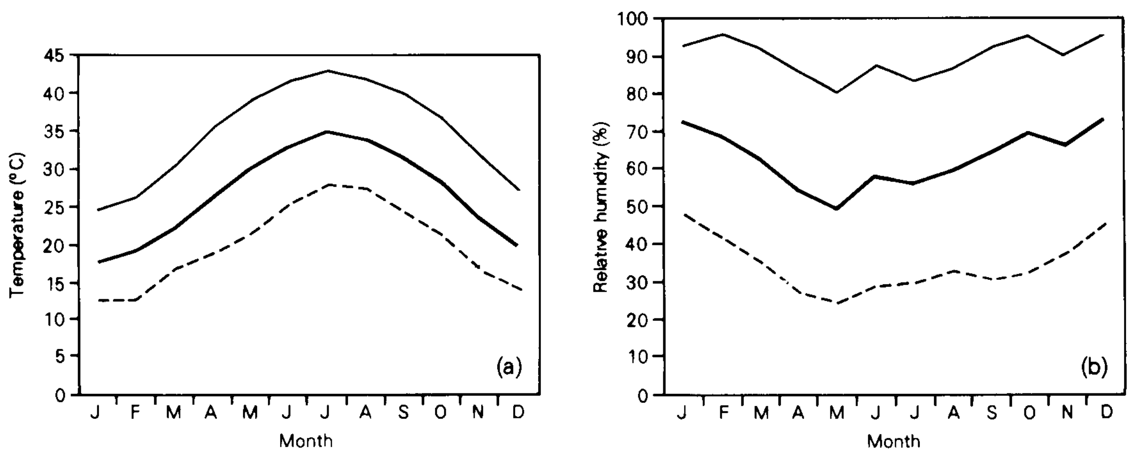

Figure 1. Annual variation of temperature and relative humidity at Sharjah. Graphs display (a) mean daily maximum, mean daily and mean daily minimum temperatures, and (b) mean daily maximum, mean daily and mean daily minimum relative humidities.

The climate of Sharjah

Sharjah is located in the hot arid desert climatic zone of the Arabian Gulf (BWh Köppen classification). Average annual rainfall, which does not reach 125 mm, is confined mainly to the winter months. The year is generally divided into two parts; winter (November – April) and summer (May – October). The climate in winter is normally pleasant with a mean temperature of 21.5 °C. Mean daily maximum temperature is 29 °C and mean daily minimum is 15 °C. The coldest month is January which has an average temperature of 17.9 °C and a mean minimum temperature of 12.6 °C. Average relative humidity of the winter months is 66% and average wind speed is 7.95 knots. Average wet-bulb temperature is 17.2 °C and average 'effective temperature' (T_e), defined later, is 14 °C.

Climate in the summer months is extremely unpleasant with an average temperature of 32.4 °C and a mean relative humidity of 58% (Table I). Mean daily maximum temperature reaches 42.9 °C in July and on individual days the temperature not infrequently exceeds 49 °C.

Table I. *Monthly, seasonal and yearly means of dry-bulb temperature (T), wet-bulb temperature (T_W), relative humidity (RH) and effective temperature (T_e) at Sharjah International Airport for the period 1977–80*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Winter (Nov.–Apr.)	Summer (May–Oct.)	Year
T (°C)	17.9	19.1	22.4	26.3	30.4	33.3	35.3	34.5	32.0	28.9	24.4	20.0	21.5	32.4	26.9
T_w (°C)	15.0	15.8	17.6	19.7	22.0	26.2	27.4	27.4	26.2	23.9	18.7	16.7	17.2	25.5	21.3
RH (%)	73	69	63	54	49	57	55	58	64	67	65	73	66	58	62
T_e (°C)	10.0	11.0	15.0	19.0	22.5	25.9	27.4	27.3	25.5	22.6	16.0	13.0	14.0	25.2	19.6

Summary of data used

Climatological data used is from Sharjah International Airport which is located about two kilometres from the sea in the south-west of the city at an elevation of 33.3 metres above mean sea level. The means of daily dry-bulb and dew-point temperatures for the four summers of 1977–80 were used to estimate means of daily wet-bulb temperature from a hygrometric chart. Then, means of daily dry-bulb temperatures and means of daily wind speed were used in computing means of daily T_e from a nomogram of T_e. Readings of a three-hourly interval of dry-bulb temperature and relative humidity were used to compute the diurnal change of wet-bulb temperature.

The discomfort index

Of the many discomfort indices, T_e is the most widely used. It is a stochastic model that was formulated by the American Society of Heating and Ventilating Engineers (1944) and since then it has been used in many studies of human discomfort in tropical and semi-tropical areas. Several examples of these studies can be cited: Stephenson (1963), Wycherley (1967) and Finkelstein (1971). T_e, as defined by Stephenson, is 'that temperature of saturated motionless air which would produce the same sensation of warmth or coolness as that produced by the combination of temperature, humidity, and air motion under consideration'.

The scale of T_e is based on the reactions of groups of middle-aged people in Pittsburgh, Pennsylvania, to varying conditions of air temperature, relative humidity and wind speed in a controlled climatic chamber. The original scale was intended to be used for indoor conditions, but its use had been extended to outdoor environments provided that people are not exposed to direct sunshine, are suitably dressed and are not engaged in strenuous work.

It is recognized that the use of T_e as a discomfort index has several shortcomings, but a number of studies have shown that it depicts physiological reactions to atmospheric environment reasonably well.

It was found that physical impairment at high T_e has a parallel in mental performance. The following scale, which was considered by earlier authors to be suitable for acclimatized people in tropical regions is used in this study:

Comfort range	T_e (°C)
Above acceptable	>24.4
Upper acceptable	22.9 - 24.4
Optimum	20.5 - 22.8
Lower acceptable	18.9 - 20.4
Below acceptable	<18.9

Analysis of results

Annual variation of T_e

Monthly means of wet-bulb temperature and T_e are given in Table I.

It is clearly shown that winters in Sharjah are usually mild, comfortable for living and suitable for vacations and outdoor sports, not only for acclimatized people of the area but for Europeans and other peoples of the temperate regions. Winter period requires no further comment and all subsequent analysis is directed to the summer months.

Summers in Sharjah are extremely unpleasant and uncomfortable. Mean T_e reaches 25.2 °C and average wet-bulb temperature exceeds 25.5 °C. The two most oppressive summer months are the hot and sticky July and August. Average T_e of these two months reaches 27.4°C and frequently exceeds 30°C on a number of days*. On 4 August 1979 mean dry-bulb temperature was 36.6 °C and average relative humidity was 71%. The mean T_e on that day exceeded 31.5 °C which is commonly reported as a probable level at which heat stroke is likely to occur. Discomfort in May and October is considerably lower than its average in the rest of the summer months. The mean T_e in May is 22.5 °C, which makes it one of the relatively comfortable months. The expected number of uncomfortable days in May if 4.25 compared to 31 in August. The remarkable drop of relative humidity from 54% in April to 49% in May associated with the change in direction of the winds from the prevailing westerly or north-westerly Shamal winds to the southerly and south-easterly winds seems to be an important factor in this decrease of discomfort. The mean T_e of October is 22.6 °C and the expected number of discomfort days is 4.5.

Monthly means of T_e for Bahrain, Sharja and Abu Dhabi are shown in Table II. The most unpleasant month in the three places is August. Discomfort is highest in Bahrain and is lowest in Abu Dhabi. Means of T_e in August, September and October are higher in Bahrain than in Sharjah. However, they are higher in Sharja during May, June and July. The extreme oppressiveness of the climate in the coastal areas of the Arabian Gulf during the summer is clearly shown when means of T_e for these three Gulf cities are compared with those of an equatorial station like Singapore (Table II).

Table II. *Means of effective temperature (°C) at Sharjah, Abu Dhabi, Bahrain and Singapore*

	May	June	July	Aug.	Sept.	Oct.	Summer
Sharjah	22.5	25.9	27.4	27.4	25.5	22.6	25.2
Abu Dhabi	22	24	26	27	25	22	24.3
Bahrain	22	25	27	28	26	23	25.2
Singapore	25	24	24	24	24	24	24.2

Accumulated physiological strain

One of the main factors of discomfort that is insufficiently illustrated in the index of mean monthly T_e is accumulated physiological strain that results from a succession of days of discomfort. Table III gives four simple measures of monthly accumulated physiological strain. The first measure is the percentage

*Body temperature begins to rise when T_e exceeds 30 °C.

of the mean monthly number of days in which average daily wet-bulb temperature exceeds 25.5 °C. The second measure is the percentage of the mean monthly number of days in which T_e exceeds 24.4 °C. The third measure, which is the expected number of days of discomfort per month, is computed by use of the binomial distribution and treatment of the discomfort day as a Bernoulli variable. The fourth measure is computed by daily accumulation of the excess of T_e above 24.4 °C. Because the purpose of this measure is to assess accumulated physiological strain, days in which T_e is lower than 24.4 °C are ignored. To facilitate comparison between months of different lengths, the average monthly accumulated excess of T_e above 24.4 °C is multiplied by a correction factor that depends upon the ratio of a 30-day month to the actual number of days in the month. Another measure of accumulated physiological strain is given in Table IV. This measure is a matrix of probabilities of having different successions of uncomfortable days in a ten-day period. Probabilities in Table IV are computed for each month according to the binomial distribution.

Table III. *Measures of monthly accumulated physiological strain in Sharjah*

Accumulated physiological strain	May	June	July	Aug.	Sept.	Oct.
Percentage of days $T_w > 25.5$ °C	3	64	85	82	66	25
Percentage of days $T_e > 24.4$ °C	14	80	93	100	78	15
Expected number of uncomfortable days per month	4.3	24	28.8	31	23.4	4.6
Accumulated monthly averages of $T_e > 24.4$ °C	3.4	50	92.4	86.2	38.5	5.1

Table IV. *Probabilities of different successions of uncomfortable days in a ten-day period*

Month	Probabilities of different days (x) $x \geqslant 1$	$x \geqslant 2$	$x \geqslant 3$	$x \geqslant 4$	$x \geqslant 5$	$x \geqslant 6$	$x \geqslant 7$	$x \geqslant 8$	$x \geqslant 9$	$x = 10$
May	0.80	0.46	0.16	0.05	0	0	0	0	0	0
June	1.0	1.0	1.0	1.0	0.97	0.88	0.78	0.68	0.68	0.11
July	1.0	1.0	1.0	1.0	1.0	1.0	0.99	0.97	0.85	0.48
Aug.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Sept.	0.72	0.36	0.13	0.03	0	0	0	0	0	0
Oct.	0.80	0.46	0.16	0.05	0	0	0	0	0	0

The two months of least discomfort are May and September and the two most uncomfortable months are July and August. Although every day in August is an expected day of discomfort, the accumulated measure of discomfort in July (Table III) is larger than in August. Table V gives a frequency distribution of the uncomfortable days in July and August during the period 1977–80.

Table V. *Frequency distribution of T_e (°C) in July and August 1977–80*

T_e	<20.4	20.5–22.8	22.9–24.4	24.5–26.9	27.0–29.4	29.5–32
July	0	1	8	31	68	16
Aug.	0	0	0	52	63	9

Factors of discomfort

Multiple regression offers an easy stochastic model for analysis of the relations between T_e and other related variables. It also results in a series of regression equations that can be used in computing T_e from these variables. A stepwise regression model is used in this paper to investigate the relations between average daily T_e and means of daily dry-bulb temperature, wet-bulb depression, relative humidity and wind speed. The correlation coefficients between T_e in each month and the other variables in the same month are given in Table VI. The resulting regression equations for each month are listed in Table VII as are the F-ratios and the coefficients of determination which measure the percentage of explained variation in T_e.

Table VI. *Correlation between effective temperature (T_e) and dry-bulb temperature (T), wet-bulb temperature (T_W), wind speed (V), wet-bulb depression (T_{WD}) and relative humidity (RH)*

	T_e	T	T_W	V	T_{WD}	RH
May	1	0.90	0.68	0.09	0.40	0.29
June	1	0.62	0.66	0.49	0.03	0.14
July	1	0.73	0.79	0.15	0.10	0.22
Aug.	1	0.60	0.78	0.09	0.33	0.39
Sept.	1	0.56	0.78	0.13	0.25	0.16
Oct.	1	0.85	0.85	0.47	0.27	0.33

Table VII. *Regression equations, coefficients of determination (R^2) and F–ratios of mean daily effective temperature (T_e) upon daily means of dry-bulb temperature (T), wet-bulb temperature (T_W), wet-bulb depression (T_{WD}) and wind speed (V)*

Month	Equation	R^2	F*
May	$T_e = 0.91T - 0.31T_{WD} - 0.34V - 1.12$	0.95	827
June	$T_e = 0.78T - 0.41T_{WD} - 0.90V + 4.4$	0.78	139
July	$T_e = 0.94T - 0.48T_{WD} - 0.37V - 0.28$	0.92	475
Aug.	$T_e = 0.98T - 0.44T_{WD} - 0.35V - 2.0$	0.88	300
Sept.	$T_e = 0.91T - 0.49T_{WD} - 0.33V + 0.3$	0.80	159
Oct.	$T_e = 1.04T - 0.57T_{WD} - 0.31V - 3.9$	0.97	1380
Summer	$T_e = 0.96T - 0.43T_{WD} - 0.37V - 1.5$	0.94	4396

*All F-ratios in this table are significant at the 0.01 level of significance.

The general variability of T_e during the summer season is caused mainly by variability in dry-bulb temperature (Table VIII). Relative humidity is the second important variable but wind speed is a variable of minor importance. However, the relative importance of each variable changes considerably from one month to another; the discomfort in May and October is caused mainly by high temperature but in July and August by a combination of high temperature and high relative humidity. Wind speed remains a secondary variable during May, July and August but it becomes more important than relative humidity in June, September and October.

Table VIII. *Percentages of variation in effective temperature that are explained by variation in dry-bulb temperature (T), relative humidity (RH) and wind speed (V).*

R^2	May	June	July	Aug.	Sept.	Oct.	Summer
T	82	38	53	36	31	72	75
RH	07	13	29	31	06	17	13
V	06	17	11	08	22	17	03

Diurnal variation of wet-bulb temperature

As can be seen from Fig. 2, for the diurnal variation of wet-bulb temperature, there is no noticeable discomfort in the average days of May and October. While nights are generally comfortable in June and September, most of the day is uncomfortable in July and August. The least uncomfortable time of the day in July and August is early morning between 4.00 a.m. and 7.00 a.m. Wind speeds of three to four

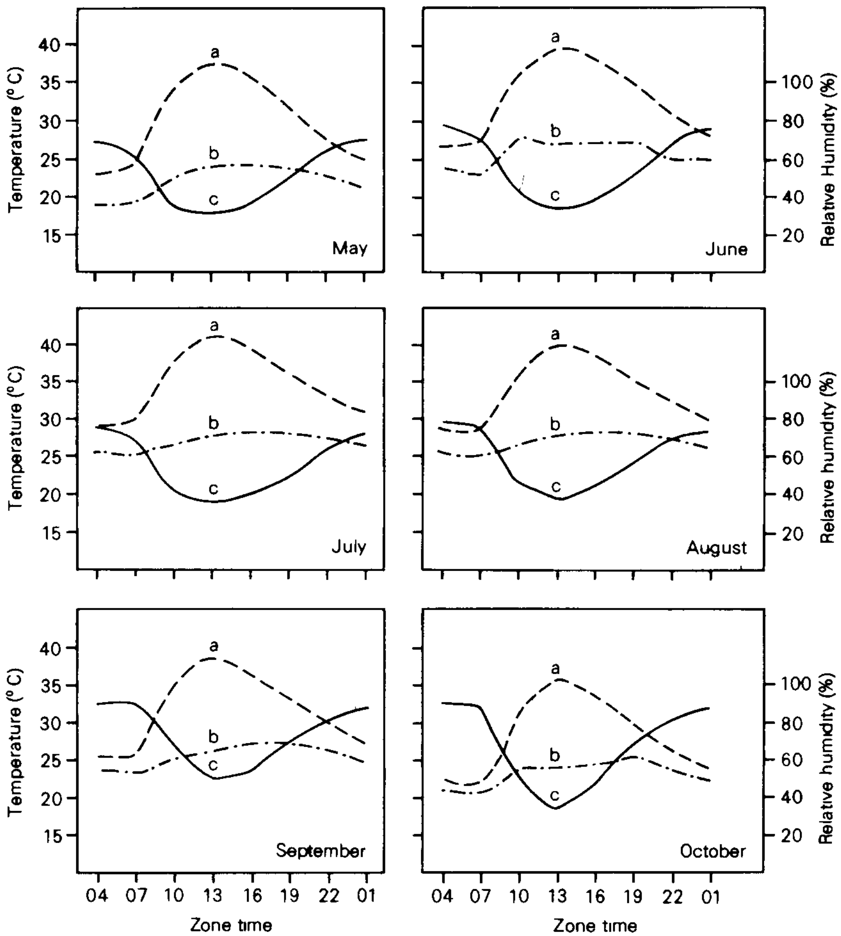

Figure. 2 Diurnal variation of (a) dry-bulb temperature, (b) wet-bulb temperature and (c) relative humidity at Sharjah.

knots are adequate for producing comfortable conditions in the early morning hours of July and August but winds of 15 knots are incapable of dealing with the more extreme conditions during most of the day (Fig. 3).

Conclusions

(1) The two most uncomfortable months in Sharjah are July and August and the least are May and October.

(2) Discomfort in May and October is caused mainly by high temperature, but in July and August it is caused by a combination of high temperature and relative humidity.

(3) Wind speed remains a secondary variable in the explanation of variability of T_e in May, July and August but it becomes more important than relative humidity in June, September and October.

(4) Summers in the Arabian Gulf region are more uncomfortable than summers in a typical equatorial area as represented by Singapore.

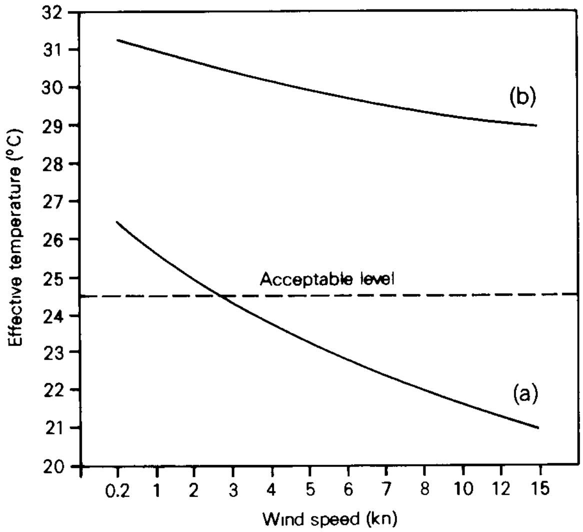

Figure 3. Variation of effective temperature with wind speed at Sharjah at (a) 0700 zone time and (b) 1300 zone time for an average August.

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The use of meteorological data in plant disease warning schemes

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Summary

The agricultural section of the Meteorological Office has for a number of years provided an automated plant disease warning scheme to the Ministry of Agriculture, Fisheries and Food. An account is given of the comprehensive warning service now offered and is illustrated by a description of one of the most recent additions to the service, the combined plant disease program. Future developments are also discussed.

1. Introduction

It has long been realized that plant diseases are greatly influenced by the weather. Theophrastus (370–286 BC), for example, recognized that cereal crops growing in upland areas exposed to the wind were not so liable to rust (a fungal disease) as crops grown on the lowlands (Colhourn 1973).

Work carried out in recent years by plant pathologists and agricultural meteorologists has identified links between weather and the development of a number of plant diseases. In some cases it has been possible to define criteria for potential infection periods in terms of readily available meteorological variables. By combining this information with a knowledge of the growth stage of the crop and existing disease levels (including carry-over from previous years) plant pathologists are in a position to advise on both the need for spraying and its timing to achieve optimum effect.

2. Plant diseases and the influence of weather

Empirical relationships that identify weather conditions suitable for disease development have been established for several of the most important diseases including apple scab, barley mildew, eyespot, fireblight, net blotch, potato blight, *Rhynchosporium* and *Septoria.* All, apart from fireblight, are fungal diseases and have in common a sensitivity to weather at critical stages in their life cycle.

Temperature, humidity, rainfall and wind speed are the most important quantities in assessing disease risk. With apple scab, for example, the impact of raindrops causes spores to be released from fallen leaves into the air; these spores can then infect new tree growth by settling on the growing leaves so long as these remain wet (Adams and Seager 1977). This requirement is reflected in the criteria: a possible infection period starts when precipitation is reported, and continues as long as there is precipitation, or a dew-point depression of 1 °C or less is reported (taken to represent leaf surface wetness (Hearn 1961)). A so-called 'Smith period' occurs when this period satisfies a certain temperature/time condition (allowing for breaks of no more than one hour) as noted by Mills and La Plante (1954).

During 1982 a complex mathematical model of potato blight was introduced operationally to replace the existing empirical scheme. The new model (Sparks 1980) monitors, in simplified terms, the environmental effects on every stage of the life cycle of the disease from the growth of spores to the formation and senescence of lesions. The scheme is a significant step forward in disease-weather modelling and is the first of a new generation of sophisticated models which will gradually replace the existing empirical models.

3. Operational schemes

A number of computer programs incorporating associations between weather and plant disease have been written over a number of years, the first being for barley mildew in 1975. The programs are mostly run about mid-morning each day during the season of interest, accessing data for the previous 24 hours which have been passed into the synoptic data bank from stations throughout the United Kingdom. Output from the programs is in the form of a telex message which is dispatched to the Ministry of Agriculture, Fisheries and Food (MAFF) computer at Guildford about midday for subsequent access by their ADAS plant pathologists in each region. The data are also sent direct to the Crop Pest and Plant Disease Intelligence Unit at Bristol for interpretation (see Fig. 1). Certain routine messages are similarly telexed direct from Bracknell to the East of Scotland College of Agriculture and to the Department of Agriculture, Northern Ireland.

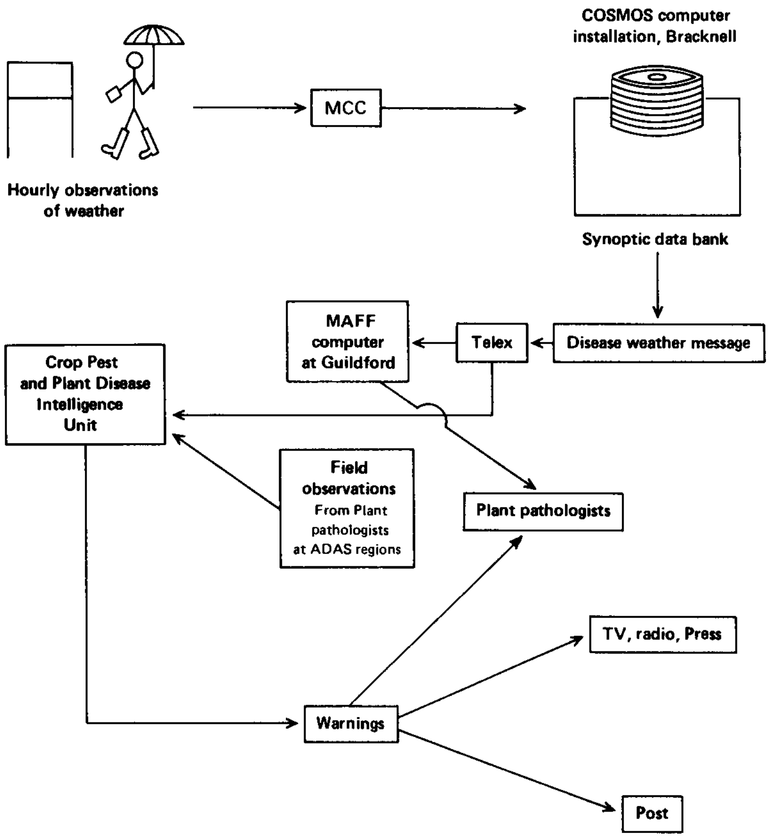


Figure 1. Flow of weather information to and from the Crop Pest and Plant Disease Intelligence Unit at Bristol. (MCC — Meteorological Communications Channel)

4. The combined plant disease program

In 1982 it was decided to rationalize the information provided and so a new plant disease message with the code-name HERDS was introduced on 1 January 1983. This message incorporates the most useful information from each of the four existing plant disease messages in a more convenient form.

A shortened version of the telex output is shown in Fig. 2 and the salient features are described in the Appendix. The full message contains data for almost 100 stations in the United Kingdom, of which 55 or so report hourly and can be used to derive the full complement of disease indices; the locations of these are shown in Fig. 3.

The HERDS program is run daily on COSMOS, the Meteorological Office's computer installation, at about 1045 GMT by which time four other programs producing the component data have already run. The steps involved are shown in Fig. 4. A paper copy of the output is produced for local quality control and storage in addition to the telex output. Output from HERDS is directed to an on-line data set which is then accessed by communications computers that dispatch the message to recipients with the assistance of an automated 'telex manager'.

PLANT DISEASE INFECTION					CRITERIA ON 21/05/1983										
	APPLE	RHYNCO	SEPTOS	NETBOL	RAIN	09DPD	BARLEY MILDEW		EYE SPOT	POTATO BLIGHT MODEL			WET PERIODS TIME OF END	LEN	MEAN TEMP DEG
STN NO					MM		SMTH	POL	WD	SM	SR	AIN	HRS	HRS	C
LER005	/	R2	S	2	0.4	1.6	33.4	1		/	0	13.1	12	022	6.2
KIR017	/	R1	/	2	+ 0.0	2.2	29.9	1		/	0	10.7	13	015	6.8
BEN022	/	/	/	2	0.3	2.2	34.7	1	56.3	/	0	11.2			
STO026	A	R3	S	1	1.9	0.4	29.5	0	96.0	/	0	11.9	18	024	6.8
KIN066	NM	R2	S	2	2.7	3.9	40.6	0	59.6	/	0	8.4	C .	017	7.2
GLE070					2.3	3.3	40.2								
WIC075	/	/	/	3	0.1	1.9	28.3	1		/	0	10.3			
DYC091	/	R1	/	2	2.3	4.1	36.6	0		/	5	6.9	22	011	8.3
FRA093					1.1	2.0									
TIR100	/	/	/	2	+ 0.0	3.5	41.4	2	92.2	/	0	18.4			
MCH111						0.0									
PRE135	/	/	/	1	+ 0.0	4.3	49.6	1	51.9	/	0	7.6			
WHI137					0.0	4.7	51.3								
ABT140	/	/	/	2	1.8	2.8	45.7	0	62.2	/	0	6.2			

Figure 2. An extract from a HERDS telex message.

5. Future developments of the disease warning scheme

Plant disease warnings are only one of a wide range of operational services based on recent weather data that are offered to MAFF and other sectors of the agriculture industry by the Meteorological Office. Other 'agromet' schemes include advice on certain weather dependent animal diseases, such as liver fluke and parasitic gastroenteritis, and advice on the airborne dispersion of virus diseases, e.g. foot-and-mouth. There is also a computerized service which provides weekly estimates of potential evaporation and soil moisture deficits for 40 km squares in the United Kingdom. Operational advice based on weather forecasts deals with certain insect pests and the hazards faced by animals owing to snowfall or windchill.

New applications for agromet data are continually being found and it is apparent that the present system of writing individual programs to meet each new requirement is not the most efficient way to satisfy the increasing demand for such data. The plant disease programs, for example, were written over a number of years and can be run totally independently of each other. This has the disadvantage that large program segments (and often the ones requiring most frequent change) are repeated in many of the programs. From a programmer's point of view, it is often easier to write a completely new program in order to compute a new index rather than add a few statements to one already in existence.

An alternative to the present system that is under development is illustrated in Fig. 5. The central feature is a large agromet data base containing, for a given period, both basic weather elements and derived parameters, such as the plant disease indices. Data are input to the data base via a series of data extraction and parameter-deriving programs. Once filled, the data therein would be accessible by any number of specific programs, e.g. ones to produce a telex message, paper or fiche copy of data, etc. The inherent advantage of this system is that changes can be made in one area without disturbing other areas, whilst new programs will only require the minimum of programming effort, using existing data extraction, telex formatting routines, etc.

One is aware of the limitations on the quality of advice attributable to the uneven distribution of the observing network (Fig. 3), especially in Scotland and Wales. These gaps will be filled as new observing sites occupied by Synoptic Automatic Weather Stations (SAWS) are established to provide synoptic data for forecasting and other purposes.

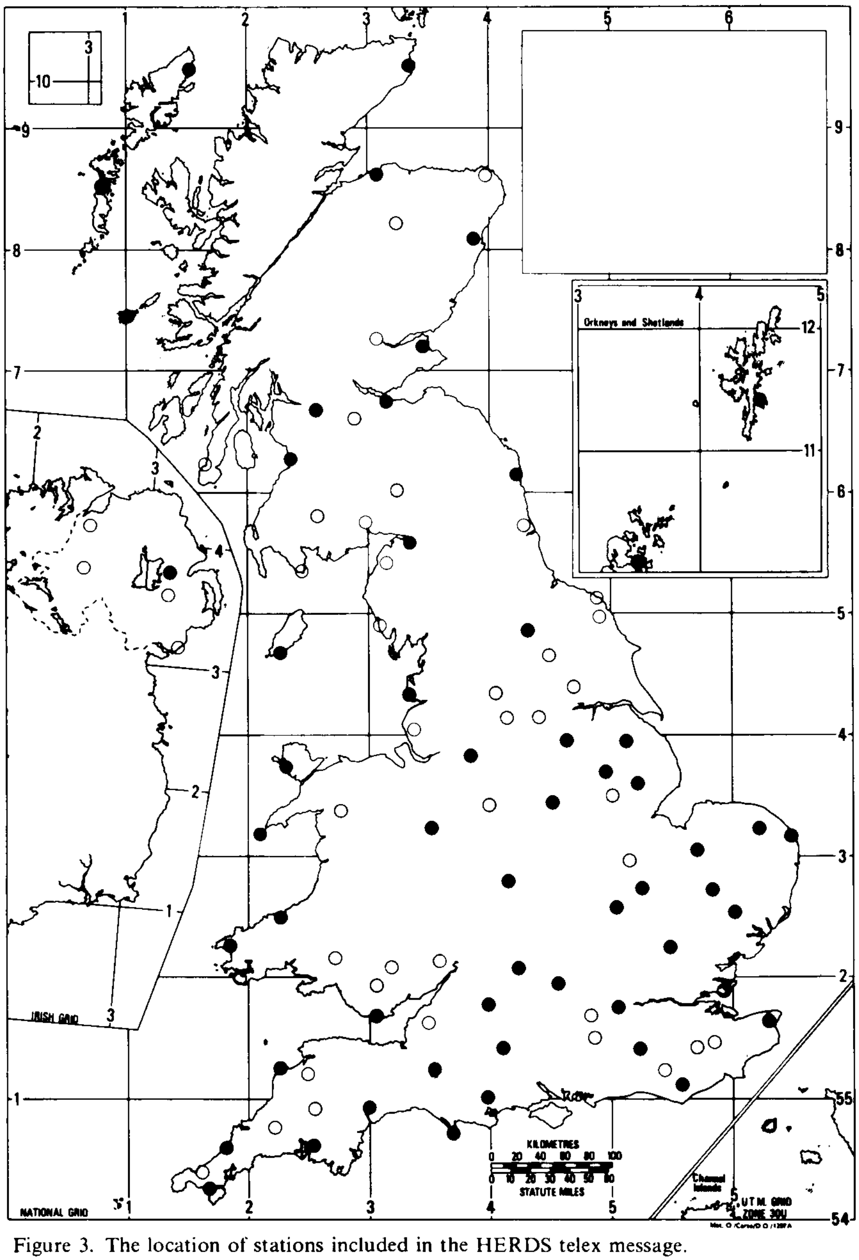
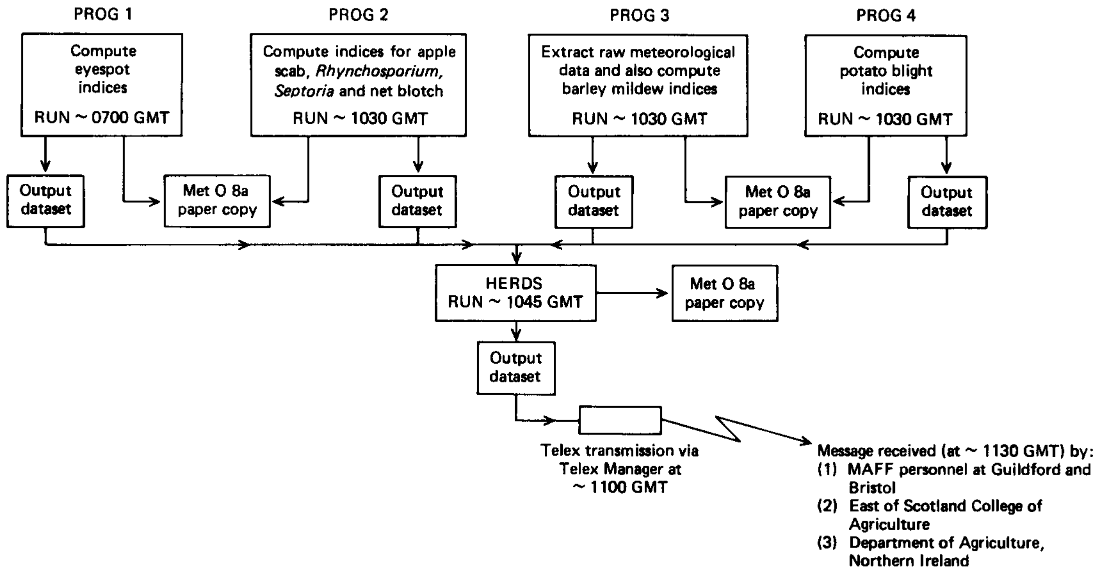


Figure 3. The location of stations included in the HERDS telex message.
• Stations with full complement of disease indices, o stations with a reduced complement.



Notes

PROG 1 — Daily for the period from 15 January to 30 June.
PROG 2 — Daily for the period from 15 January to 31 July.
PROG 3 — Daily all year.
PROG 4 — Daily for the period from 15 May to 30 September.

These timings are subject to alteration. When 'out-of-season' a series of blanks will appear on the HERDS message under the headings for that particular disease.

Figure 4. Daily sequence of events in producing a HERDS telex message.

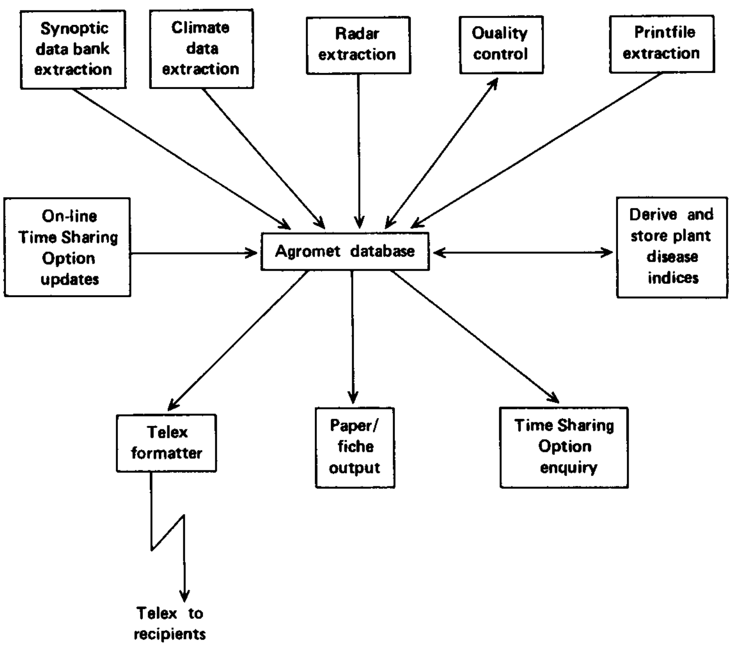


Figure 5. An alternative to the present agrometeorological data system.

6. Conclusions

The advice offered by the meteorologist forms an essential link in the chain of events that leads to timely and effective crop protection measures. Since the introduction of the first warning scheme for barley mildew in 1975 agrometeorologists have striven to increase the range and quality of the services they provide to the farming and horticultural community. This effort is reflected in the wide range of services now offered and by the increase in clientele who take advantage of them.

Major improvements in the advisory system are likely in years to come. The contrast between the open observing network of Fig. 3 and the crop environment information potentially available from satellites is considerable. The latter requires the Meteorological Office to develop the facilities to gather such data and also the software to turn the data into meaningful operational advice.

Acknowledgements

Thanks are given to Dr J. R. Starr, Regional Agrometeorological Officer at ADAS, Aberystwyth and to Dr N. Thompson, Head of the Agriculture Section, Meteorological Office, Bracknell for their constructive comments in the writing of this paper. Thanks also to Mr. R. D. D'Costa of the Agriculture Section for his assistance in programming the HERDS message. The information provided by Mr. W. R. Sparks, Regional Agrometeorological Officer at ADAS, Bristol helped greatly in the compilation of the Appendix.

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Appendix — Description of HERDS telex message

1. STN NO: The station identification code.
2. APPLE: The apple scab index.
   - A — indicates that the requirements for at least light infection have occurred.
   - NM — a 'near miss'. The criteria for light infection were not quite satisfied.
   - / — conditions unsuitable for infection.
3. RHYNC: The *Rhynchosporium* index. R1, R2 and R3 indicate that conditions suitable for slight, moderate or severe infection occurred respectively. (/ takes the same meaning as before.)
4. SEPTO: The *Septoria* index. The symbol S indicates the possibility of *Septoria* infection.
5. NETBL: The net blotch index. 0, 1, 2 or 3 may appear, where 3 indicates the highest risk of infection.
6. RAIN: The total rain (millimetres) over the rainfall day. (+0.0 indicates trace)
7. 09DPD: The 0900 GMT dew-point depression (°C) on the day of the message.

8. BARLEY MILDEW: Two indices are calculated:

   SMITH — The Smith index involves the combination of several relevant weather variables. Interest is in the departure from some threshold value of the index.

   POL — The Polley index. The scale 0, 1, 2 or 3 is used to indicate an increasing risk.

9. EYESPOT: WD is a measure of the infection risk. Again threshold values are significant.

10. POTATO BLIGHT MODEL: Several variables are derived.

    The Smith period calls for suitable weather on two successive days.

    SM — The indicator P (partial) in the daily weather bulletins is used to show weather consistent with disease build-up. NM indicates a near miss. / indicates criterion not met.

    SR — an index of viable spore release from each active lesion.

    AIN — a measure of the accumulated infection.

11. WET PERIODS.

    Certain plant diseases require an obligatory period of leaf wetness for part of their life cycle.

    TIME OF END — the time of end of the wet period to the nearest hour. '00' signifies a period ending at midnight and 'C' a period continuing into the next day's message.

    LEN — duration (length) of wet period in hours. This observation accumulates continuously wet periods over several days if necessary.

    MEAN TEMP — the average temperature (°C) for the wet period.

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Onset of the summer monsoon over India and its variability

By I. Subbaramayya, S. V. Babu and S. S. Rao

(Department of Meteorology and Oceanography, Andhra University, Waltair, India)

Summary

The 'northern limit of the monsoon' (NLM) on a daily basis is determined using the principle stated by Subbaramayya and Bhanukumar (1978) with a slight modification for the period 1 May to 15 July in the years 1956–80. Thence the average dates of onset of the monsoon and their variances have been evaluated for several places. The advance of the monsoon is critically examined. Periods and places of stagnation of the NLM recurring regularly every year have been noted. Three significant phases in the advance of the monsoon over south peninsula, north peninsula and central north India respectively have also been identified.

The dates of onset in different parts of the country and the stagnation of the NLM are statistically investigated.

Abnormalities in the onset of the monsoon, either late or early, have been noted to be similar in general in any year over north peninsula, central India, Gujarat and north-east India, while in other areas it may not be the same.

Introduction

A chart showing the normal dates of onset of the summer monsoon over India was published by the India Meteorological Department (IMD 1943). The dates of onset at any station for the purpose of preparation of this chart were determined from the characteristic rise in the cumulative curve of the five-day mean rainfall totals. This so-called characteristic rise, however, is not clear at several of the stations. Therefore, Ananthakrishnan *et al.* (1967) inquired into the details of the procedure — adopted by the India Meteorological Department — and found that the onset date was determined subjectively by three experienced meteorologists for every year by keeping some other factors also in view and probably the mean of these dates was also taken into consideration in finalizing the normal dates of onset.

With the view of evolving a specific guiding principle to determining the onset date and the 'northern limit of the monsoon' (NLM) in any year, Subbaramayya and Bhanukumar (1978) studied the changes in different weather parameters one week on either side of the officially declared onset dates at a number of stations. It was observed that substantial changes in the weather do occur around the time of the onset, but not simultaneously. It was noted that the changes occur, in general, in the order: (1) medium and high cloud amounts, (2) low cloud amount, (3) rainfall, (4) maximum temperature and diurnal range of temperature. The changes were spread over four or five days and sometimes they were gradual too. Therefore, it was concluded that it may not be possible to have a simple criterion for fixing the onset involving several weather parameters. Hence they suggested that the onset of the monsoon at any place should be associated with the first westward moving rain storm of the season, for the reason that the monsoon rains are caused by easterly disturbances, in contrast to the winter and pre-monsoon rains which are associated with westerly disturbances.

It was, however, seen that easterly disturbances are present in the extreme south of India even in the pre-monsoon period (Subbaramayya and Ramanadham 1981), but the equatorial westerlies as a broad belt are not observed with those systems in the pre-monsoon season. Therefore, the presence of a belt of equatorial westerlies over the neighbouring oceanic area should also be considered as an additional condition in fixing the date of onset of the monsoon in the extreme south.

In the present study, the authors determined the NLM, based on the above guiding principle, every day from the beginning of May in the years 1956–80. Thence a revised chart of the mean dates of onset of the south-west monsoon for the Indian region has been prepared and the variability of the onset dates also has been studied.

Data and analysis

Daily rainfall amounts at about 300 stations during the period 1 May to 15 July in the years 1956–80 have been plotted on charts to study the rainfall distribution and the spreading of the rain areas day by day. To understand the synoptic systems, if any, that have contributed to the widespread rains on any day, the surface pressure and wind charts published in the *Indian daily weather reports* have been consulted. Rain areas associated with the westward progression of synoptic systems are demarcated. The NLM on any day is then obtained by joining the northernmost segments of the rain-area demarcation lines till that day. As an example the chart showing NLM on different days in the year 1969 is presented in Fig. 1.

About 200 stations uniformly spread over the country have been selected and the dates of onset of the monsoon at every station in every year from the NLM charts have been obtained. The average and the standard deviation of the dates of onset at every station have been evaluated. Correlations between the dates of onset at different stations also have been evaluated to study if there are any regional relationships.

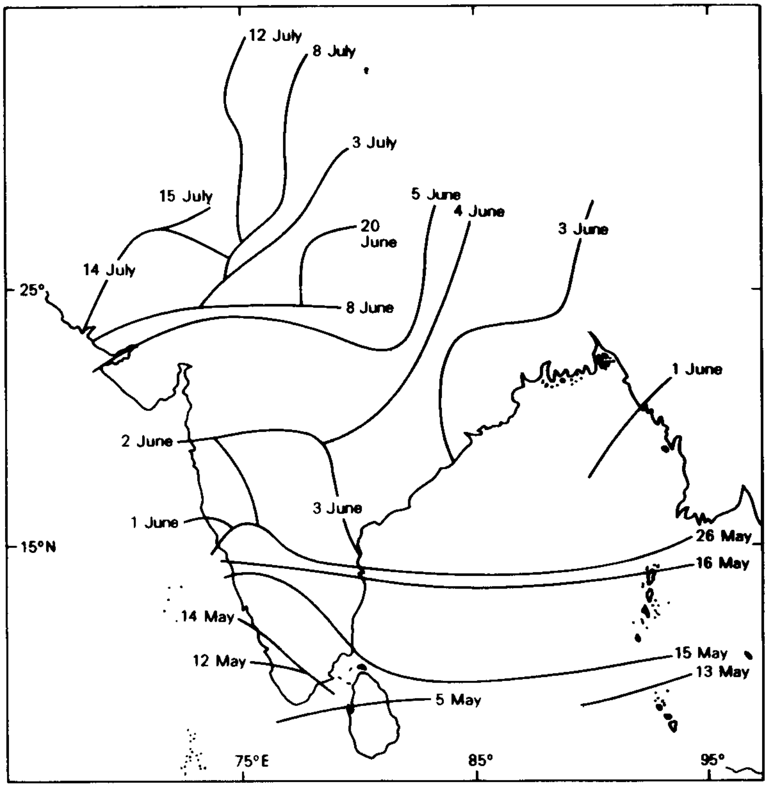

Figure 1. Advance of the monsoon in 1969, showing the northern limit of the monsoon on different days.

Results and discussion

The average dates of onset of the monsoon in different parts of the country evaluated by the above procedure are presented in Fig. 2(a). The normal dates chart published by IMD in 1943 is presented in Fig. 2(b) for purpose of comparison. Though the charts are similar, there are significant differences too. The average dates of onset on the present chart are early compared with those given by IMD over south peninsula and Sri Lanka by five to ten days. This difference could be due to the fact that the onset in the present study is considered to have been associated with the first westward moving rain storm while the IMD meteorologists were probably waiting to ensure the persistence of the rains. However, over central India and the adjoining northern parts, the dates agree, while over northern India the average dates of onset are later than those given by IMD. The IMD meteorologists in this case might probably have mistaken some of the rain spells caused by westerly troughs as monsoon rain when fixing the dates of onset over north-west India and hence the difference over the north-western region.

The monsoon advances mainly northwards over western India and westwards over the northern parts of the country. The orientation of the lines of dates of onset over peninsular India shows that the monsoon sets in earlier over the west coast than over the east coast at the corresponding latitudes. This feature is contrary to that in the IMD chart. The onset over eastern Bay of Bengal is, however, earlier to

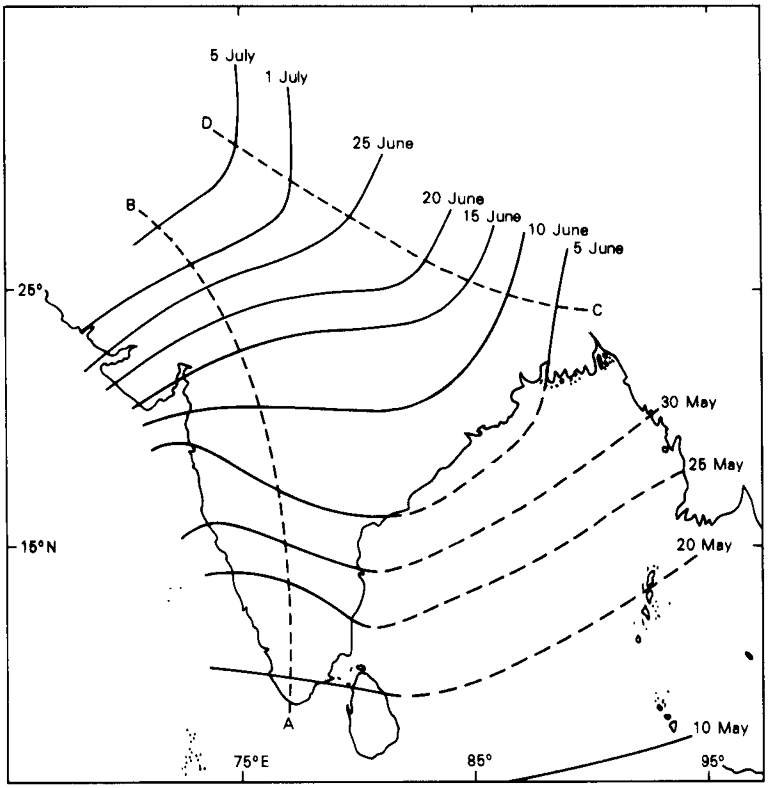

Figure 2(a). Average dates of onset of the south-west monsoon.

that over the west coast. The advance of the monsoon near the west coast was in general associated with northward movement of cyclonic disturbances over east Arabian Sea while the advance over the east coast was associated with development of low-pressure systems over north-west Bay of Bengal. The former event, in general, preceded the latter.

It can be seen that the advance of the monsoon is quick in the south but slow over central peninsula near 15°N. It is again quick over north peninsula and slow over Gujarat area in the north-west. The advance is also slow over Bihar in the north-east. The slow advance in the above areas was in fact due to stagnation of the northern limit of, or break in the advance of, the monsoon by one to two weeks in individual years. It is only in the averaging process that it appears as a slow advance. The northward progression of the monsoon over India in individual years along the lines AB and CD (shown in Fig. 2) is presented in Fig. 3. It clearly shows the breaks in the advance of the monsoon. The average period of the stagnation in different regions and the average latitude/longitude of occurrence of stagnation have been evaluated. The stagnationof the NLM over central peninsula occurs at 14°N from 22 May to 6 June (15 days) on the average while that over the Gujarat area is at about 24°N from 13 to 30 June (17 days).

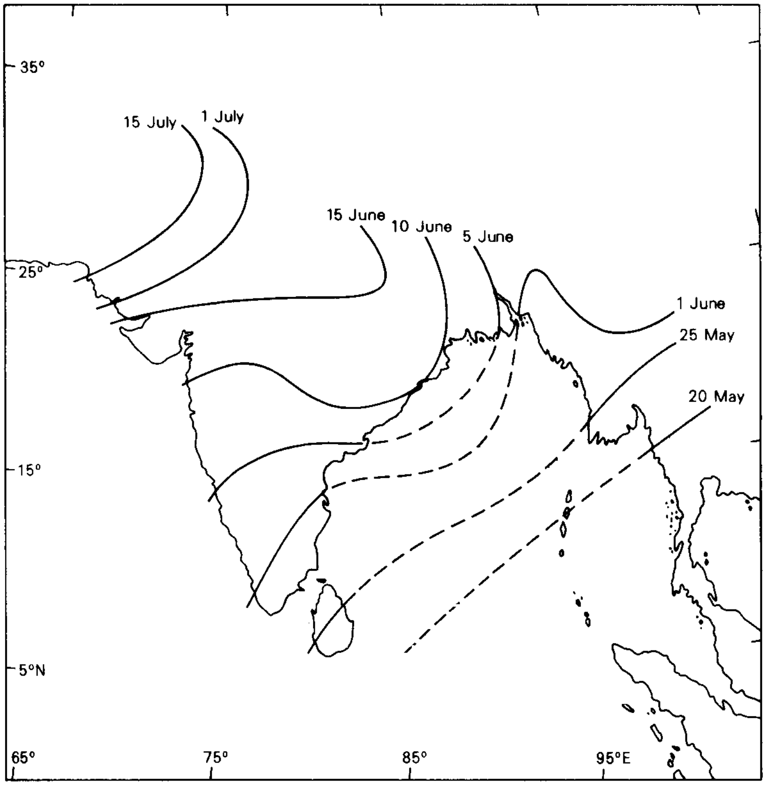

Figure 2(b). Normal dates of onset of the south-west monsoon (India Meteorological Department 1943).

The break in the westward advance over north-east India occurs on the average at 86°E from 6 to 17 June (11 days). There is a less conspicuous break of 12 days duration in the westward advance at 79°E. These features of the advance of the monsoon are represented in Fig. 4.

Stagnation of the NLM over Sri Lanka was also observed in some years. It may be a regular yearly feature, and occurring in other years further south of Sri Lanka, which could not be identified because of lack of data south of Sri Lanka. One can thus see that there are mainly three spurts or phases in the advance of the monsoon over the Indian subcontinent; first over south peninsula, second over north peninsula and central India and the third over the central parts of north India.

The variability of the onset of the monsoon as expressed by the standard deviation of dates of onset is presented in Fig. 5. It is large (ten days) over the west coast and north-east India and relatively small (eight days) over the monsoon trough area. There were, however, instances when the monsoon was delayed by even three weeks in individual years.

The correlations between the dates of onset at 15 stations spread over the whole country showed that they are in general positive, but large significant correlations appeared at some adjacent stations only.

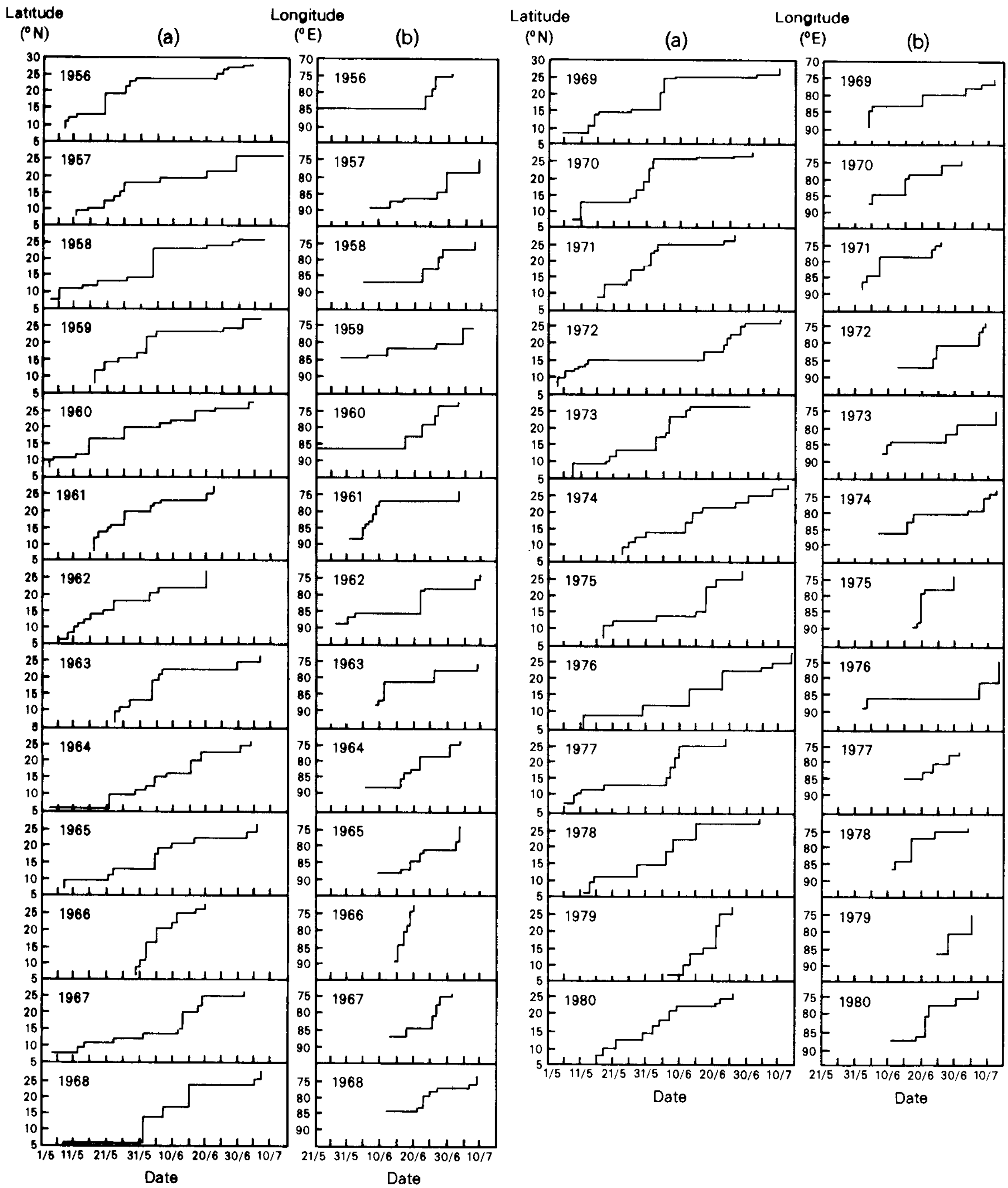

Figure 3. Advance of the monsoon along (a) the line AB and (b) the line CD shown in Fig. 2 (a) in the years 1956–80.

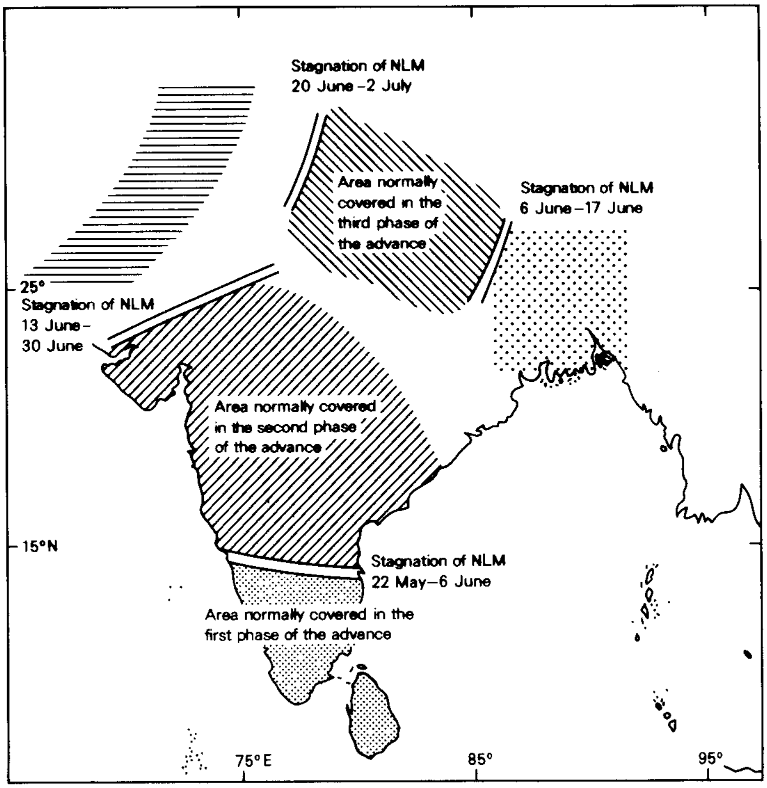

Figure 4. Areas and periods of different phases in the advance of the monsoon.

These stations fall into three groups, and area-wise they are in south peninsula, north peninsula and north-east India and north-west India. These are the areas where the three phases in the advance of the monsoon have been found to occur and this explains the large correlations between the stations in each area.

Further, correlations between the onset dates, P_1', P_2', etc., at representative stations in different phases of quick advance of the monsoon, and duration of the stagnation of NLM, S_1', S_2', etc., at different places also have been evaluated and are presented in Table I. It can be seen that the onset date in any phase of advance bears large negative correlation with the duration of the following stagnation period and positive correlation with the proceeding one. This means late/early onset in any phase is partly caused by an earlier prolonged/short stagnation, while the same causes short/prolonged stagnation later. It is interesting to note that there are significant positive correlations between (i) dates of onset over south peninsula, P_1, and north-east India, P_1', (ii) period of stagnation over Gujarat, S_2, and that over Bihar, S_1', as well as the onset date over central north India, P_2', and (iii) dates of onset over north peninsula, P_2', and central north India, P_2'. The latter two indicate that the advance over north peninsula and central north India and the stagnation over Gujarat and north-east India are affected by a common factor. The stagnation, S_2, over Gujarat has significant negative correlation with that over central peninsula, S_1, and the onset date over north-east India, P_1'.

Table I. *Correlations between dates of onset and periods of stagnation of the monsoon*

	P_1	S_1	P_2	S_2	P_3	P_1'	S_1'	P_2'	S_2'	P_3'
P_1		-0.49	0.33	-0.23	0.04	0.43	-0.27	0.13	-0.28	-0.10
S_1			0.69	-0.48	0.08	0.20	0.06	0.29	-0.08	0.23
P_2				-0.71	0.12	0.03	-0.16	0.48	-0.30	0.16
S_2					0.61	-0.66	0.45	0.45	0.33	0.27
P_3						-0.21	0.45	0.25	0.12	0.57
P_1'							-0.20	0.16	-0.21	-0.09
S_1'								0.62	-0.28	0.36
P_2'									-0.33	0.39
S_2'										0.52

P_1 — Date of onset over south peninsula (Bangalore)
P_2 — Date of onset over north peninsula (Parbani)
P_3 — Date of onset over north-west India (Jodhpur)
P_1' — Date of onset over north-east India (Tura)
P_2' — Date of onset over north India (Lucknow)
P_3' — Date of onset over north-west India (Patiala)
S_1 — Duration of stagnation period over central peninsula
S_2 — Duration of stagnation period over Gujarat
S_1' — Duration of stagnation period over Bihar
S_2' — Duration of stagnation period over Punjab.

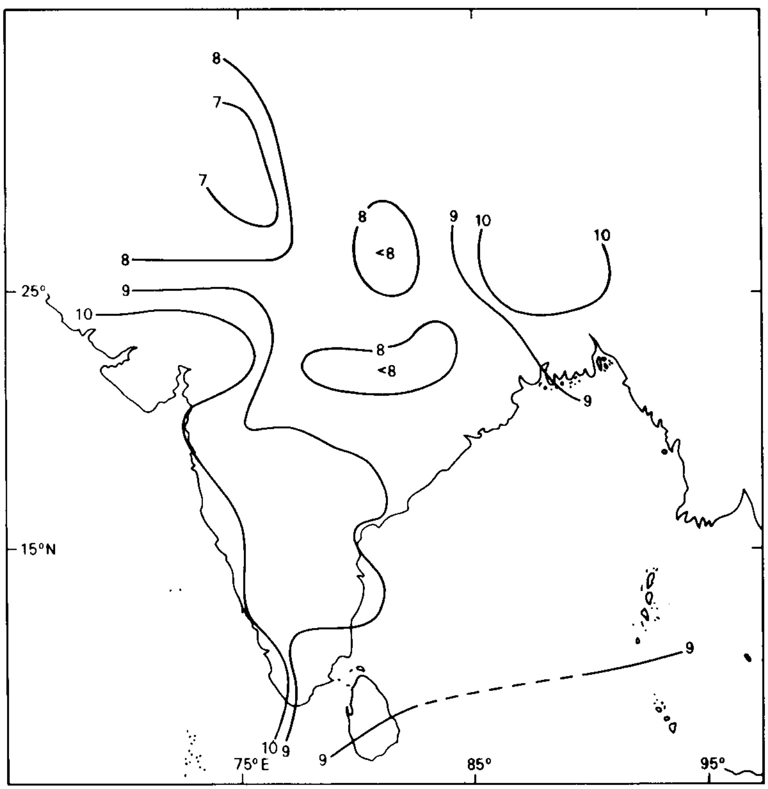

Figure 5. Variability of the onset of the south-west monsoon as expressed by the standard deviation of the dates of onset.

Conclusions

(1) According to the principle proposed by Subbaramayya and Bhanukumar for identifying the monsoon rains, the average dates of onset of the monsoon are five to ten days ahead of the dates given by IMD over south peninsula and late over north-west India.

(2) The advance of the monsoon takes place mainly in three phases, the first one being over south peninsula, the second over central India, both occurring in the northward direction, while the third is in the westward direction over north India.

(3) Stagnation in the advance of the monsoon for periods ranging from one week to two weeks occurs over central peninsula, Gujarat and Bihar regions.

(4) The variability of the onset of the monsoon in terms of standard deviation ranges from eight to ten days. Minimum variability is over central India.

(5) Correlation between the dates of onset of the monsoon in different parts of the country indicate that the onset and advance of the monsoon over north peninsula, central India, Gujarat and north-east India are generally uniformly affected in any year.

(6) It is, therefore, desirable to consider places situated over central India for the study of year to year variations of the onset of the monsoon, but not over Kerala area.

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Notes and news

A weather radar for flood warnings and improved short-period forecasts over London and south-east England

A contract has been placed with Plessey Radar Limited for the purchase and installation of a weather radar which will be used to help in detecting and forecasting potential flood situations in the Thames Water Authority, GLC and Southern Water Authority areas and to improve the accuracy of short-period weather forecasts in south-east England. A Consortium consisting of the Meteorological Office, the GLC, Thames Water Authority and Southern Water Authority are sharing the cost of the radar which will be sited to the north-west of London at RAF Chenies, near Amersham, Bucks. The site was chosen because it allows a clear radar view of London and the south-east of England.

A tower on which the radar antenna is to be mounted was completed recently. Installation of the antenna and its protective radome began on 6 February 1984 and should be completed by late April. The radar will come into operation in the early summer.

The total cost of the scheme will be about half a million pounds and it consists of a weather radar, data processing equipment and telemetered rain-gauges. The radar will scan continuously, detecting rain, hail or snow over a range of up to 130 miles and quantitative measurements of rainfall will be made up to a range of about 50 miles. Rainfall measurements over river catchment areas will be sent to the Water Authority control centres, and to the GLC Thames Barrier Control Centre where they can be presented on colour television monitors and are available to use in computer models as an aid to flood forecasting and to help in deciding on actions to be taken. These radar-derived data can also be used in the Water Authority operational hydrological control systems to help in the management of the water within rainfall catchment areas, as further information in river level regulation activities, and to obtain early warning of particularly heavy rainfall or thunderstorm events.

The measurements will also be transmitted back to the Meteorological Office Radar Research Laboratory at Malvern where they will be integrated with data from the existing network of four weather radars covering most of England and parts of Wales. There the information is combined in a central computer and a picture of the rainfall is produced displaying the weather in every 3 mile (5 km) square within range of a weather radar. A new picture is formed every 15 minutes, and by following these detailed pictures combined with other forms of weather observations from weather stations and satellites and the coarser scale computer predictions, the weather forecaster should be able to produce greatly improved short-period weather forecasts over the following two to six hours. It is hoped to illustrate the usefulness of the radar data in weather forecasting by including the display in national television weather presentations later this year.

A press facility will be provided at RAF Chenies when the radar system is brought into service. Further information can be obtained from the Chairman of the London Weather Radar Project Consortium Steering Group, Dr P. Ryder Tel: Bracknell (0344) 420242 Ext 2575.

Obituary

We regret to record the death on 17 January 1984 of I. H. Simpson, Higher Scientific Officer, Eskmeals. Ian Havron Simpson — always known as Sandy Simpson — joined the office as a Scientific Assistant in 1947. After a period of initial training and service with the RAF, he was posted to the Falkland Islands at the end of 1950 and in January 1954 he was seconded to the Falkland Islands Dependencies Survey for a further 18 months before his first posting to Eskmeals. In 1963 he was promoted to Senior Scientific Assistant and moved to Porton. Promoted further to Experimental officer in 1968 he had postings to Upavon and Larkhill before returning to Eskmeals in 1976 as Senior Meteorological Officer.

Sandy Simpson was a member of IPCS Branch Council in the 1960s and 70s, serving as Overseas Secretary and Editor of the Branch Bulletin. He was a keen fell-walker and a strong supporter of outdoor activities of all sorts, and also did a great deal for the young people of the village of Bootle where he lived.

With a keen appetite for work and a strongly marked personality, Sandy was not always the most peaceful of colleagues, but his generous nature and good humour usually smoothed out difficulties quickly.

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NOTICES

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The diurnal range of temperature over the United Kingdom

By R. C. Tabony

(Meteorological Office, Bracknell)

Summary

Geographical and seasonal variations in the diurnal range of temperature over the United Kingdom are examined. Variations due to differences in climate and topography are seen to change in relative importance as less common events are considered.

1. Introduction

The frequency and severity of frosts are important aspects of climate for a wide variety of activities, especially those in the agricultural and construction industries. As the proneness to frost is very sensitive to local site details, a good knowledge of the relationships between minimum temperatures and topography is required. In this context, the word 'topography' is used in the widest possible sense to include all relevant physical factors such as aspect and slope, soil and vegetation, degree of urbanization, distance from the coast, etc.

The effects of topography on frost are best investigated when variations due to other factors, e.g. latitude and altitude, have been minimized. One way of doing this is to choose the diurnal range of temperature (hereafter referred to simply as the 'diurnal range') as the relevant climatic parameter. There are disadvantages in this approach. Topographic effects on maximum temperatures will be included, for instance, and in winter the largest diurnal ranges may be caused by advection rather than radiation. The lowest temperatures in winter may not be associated with large diurnal ranges, as the surface inversion present during periods of cold weather gradually increases its strength day by day. One of the main applications, however, will relate to frosts in spring, and for this purpose the diurnal range is an appropriate climatic parameter to use.

Although the average diurnal range is easily obtained from means of daily maxima and minima, most practical applications will be concerned with more extreme events — the largest diurnal range in a month, for instance. This is a parameter that is not recorded explicitly in tabulations of meteorological data, and hence very little is known about it. As a preliminary to an investigation into relationships between diurnal range and topography, some simple analyses of the diurnal range were made, and these are presented here for their general climatological interest.

2. Creation of a data set of the highest diurnal range of temperature in a month

Daily values of 24-hour (09–09 GMT) maximum and minimum temperatures in the period 1959–79 were accessed for all stations with less than 120 months of missing data in that period. The number of stations was about 570, and their distribution is shown in Fig. 1.

Daily values of diurnal range were calculated from the 24-hour maximum on day i and the 24-hour minimum on day $(i + 1)$. This represented the night fall rather than the day rise of temperature, as this is the main parameter of interest. It also has the advantage that in winter, when large changes of temperature can be caused by advection rather than radiation, sudden falls of temperature (due to advection) are less common than sudden rises. The arrangement of data into monthly blocks, however, made this procedure inconvenient on the last day of the month, so on this day the daily rise in temperature was used instead. If any daily maximum or minimum temperature was missing, preventing the calculation of the night fall in temperature, then the day rise was used in preference to the acceptance of a missing value.

The highest diurnal ranges in a month were derived from the daily values as follows. In any month in which more than one daily range was missing, the highest value for that month was also regarded as missing. The highest daily ranges in the remaining months were then averaged over all years for each calendar month, and any values that exceeded the mean for the appropriate calendar month by more than 12 °C were rejected. Before 1972, the original daily maximum and minimum temperatures had not been subjected to any quality-control procedures. Any missing values of the highest diurnal range were then estimated using the methods described by Tabony (1983).

3. The effect of climate

The relationships between topography and diurnal range will depend on the climate, and particularly on the wind and cloud. The differences in diurnal range between a valley and a hilltop, for instance, will be greater where the climate is clear and calm than where it is cloudy and windy. The influence of climate will also depend on the return period of the event under consideration. Compare, for example, the diurnal ranges at topographically similar sites in the north-west and south-east of the United Kingdom. The average diurnal range would be expected to be greater in the south-easterly location because of the smaller mean amounts of cloud and wind. The largest diurnal range recorded over a period of 20 years, however, would be expected to be similar at both locations, because in that length of time even a most disturbed climate would include some good radiation nights. The question therefore arises as to what extent the highest diurnal range in a month is likely to be affected by changes of climate across the United Kingdom.

A guide to the answer was obtained by examining the highest daily sunshine totals recorded in a month at about 380 stations in the United Kingdom with fewer than 120 missing values in the period 1959–79. The missing data were again estimated using the procedures described by Tabony (1983).

As the sunshine totals were being used as a guide to cloud amounts, they should clearly be expressed as a percentage of the maximum possible. One of the problems in this respect is that of obstructions. Although site details are documented sufficiently well to enable the effect of obstructions to be calculated, they are not held in machinable form. An alternative means of obtaining relative sunshine was therefore adopted. It was assumed that at least one day of unbroken bright sunshine would occur in each calendar month in the 21 years of data examined and that this would be taken as the highest value recorded for that calendar month. The highest daily sunshine totals were then expressed as a percentage of that figure.

For each station the 21 values of highest daily sunshine for each month were ranked and the median values extracted. Geographical variations in these median values, meaned over all months, are

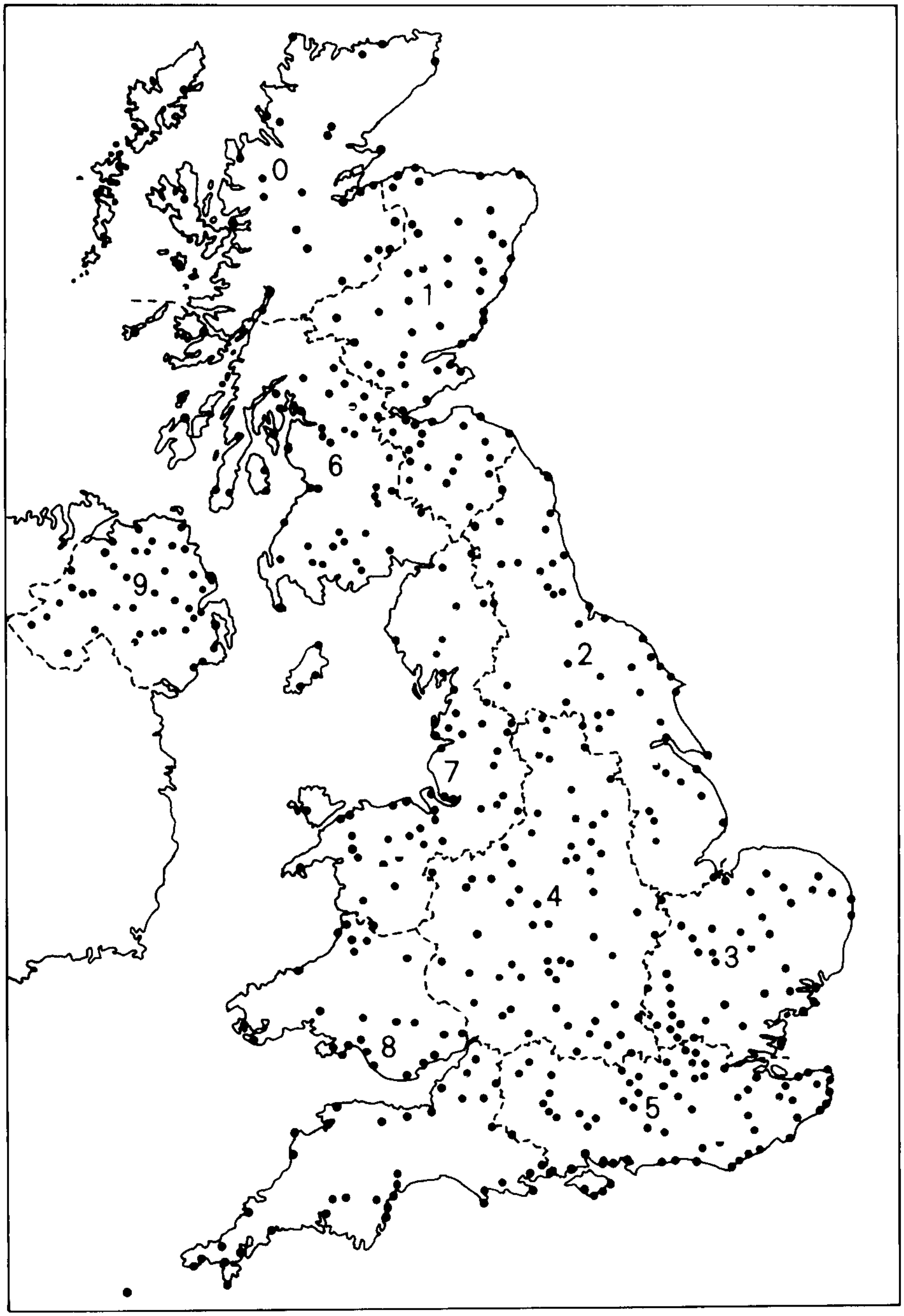

Figure 1. Distribution of stations used to obtain daily values of maximum and minimum temperatures for the period 1959–79. Districts referred to in Figs 9–11 are also shown. (Not all stations can be indicated by separate dots.)

illustrated in Fig. 2. All the maps presented in this paper are generalized in the sense that the station values, to which the isopleths have generally been drawn, show a wide scatter due to the dependence (especially for diurnal range) on local topography. A little smoothing has been employed, but no significance should be attached to the small-scale detail. The main features, however, are well represented, and in Fig. 2 a decrease from around 92% on the south coast of England to less than 82% in the interior of Scotland can be seen. Seasonal variations at ten stations are displayed in Fig. 3. Median values in summer are seen to be higher than in winter, and in the north-west this seasonal variation is pronounced.

Some qualifications have to be made on the implications of these results for the diurnal range of temperature. For any given cloud amount the amount of sunshine recorded will decrease with solar elevation, and this effect will tend to produce low values of sun in Scotland in winter. Large diurnal ranges are not necessarily associated with good visibility, and in winter cold nights may be followed by mornings with mist or fog. However, large diurnal ranges require light winds as well as clear skies and it seems unlikely that good radiation nights will occur much more frequently than sunny days, with or without wind. It therefore seems fair to conclude that at all times of the year, and especially in winter, most monthly maxima of diurnal range will be observed under more favourable radiation conditions in the south of the United Kingdom than in the north-west.

4. Geographical variations in diurnal range of temperature

The mean diurnal range, meaned over all months, is displayed in Fig. 4. It is similar to the map first produced by Ashmore (1939) and the main features are:

(i) A general increase from north-west to south-east as the climate becomes less cloudy and windy.

(ii) Coastal gradients on the east coast that are sharper than on the west coast, where the prevailing winds are on-shore.

(iii) Coastal gradients that are also intense in the south-east, where the sunnier climate enables the potential differences between land and sea to be more fully realized than elsewhere.

The mean monthly maximum diurnal range, meaned over all months, is presented in Fig. 5, and shows that topography has replaced climate as the most important variable. The considerably decreased effect of the prevailing wind means that coastal gradients are limited to a few tens of kilometres and are relatively uniform along all coasts.

The largest diurnal range observed in each month in 21 years of record, and meaned over all months, is illustrated in Fig. 6. Differences due to climate have been practically eliminated, and the highest values are observed near the high ground in Scotland. Dight (1967) points out that large diurnal ranges in Scottish glens in winter are associated with high maxima as well as low minima. Maximum temperatures rise above freezing even in the presence of snow cover. Dight ascribes this to the turbulence set up by the high ground breaking down nocturnal inversions which would persist over lower ground, especially if it were protected by more distant hills (as at Abbotsinch, for example).

One of the features of Figs 4–6 is the way that, as the return period of the event increases, the diurnal range in Scotland increases more rapidly than in the south of England, especially in winter, as the prevailing climate decreases in importance and the effect of topography increases. This phenomenon can be represented by the slope of an extreme value analysis of diurnal range.

5. Extreme value analysis of diurnal range of temperature

The 21 years of monthly maximum diurnal ranges were plotted on extreme value paper using the

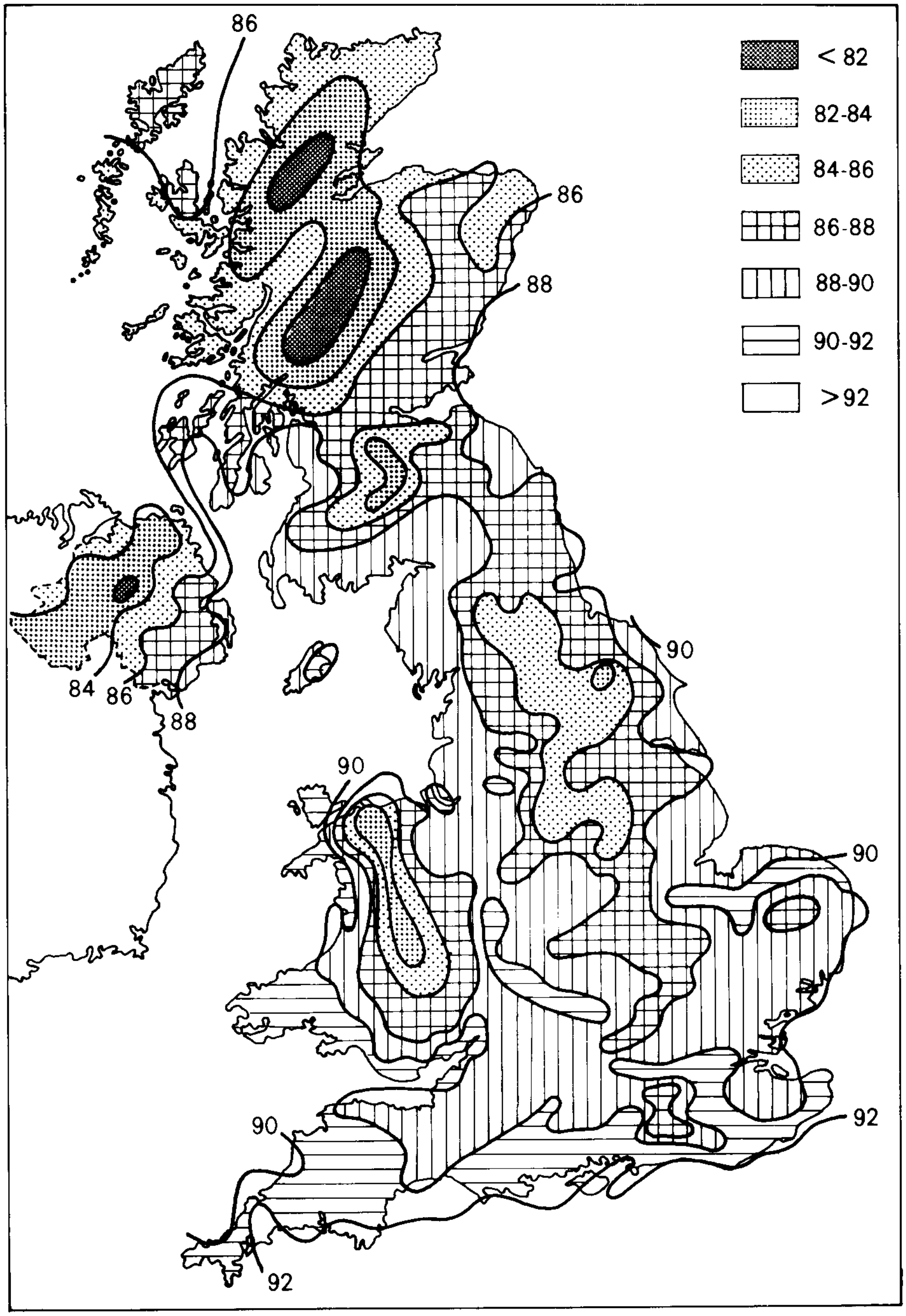

Figure 2. Geographical variation of the median highest daily sunshine in a month. Figures are expressed as a percentage of the sunniest day in each calendar month for the period 1959–79, meaned over all calendar months.

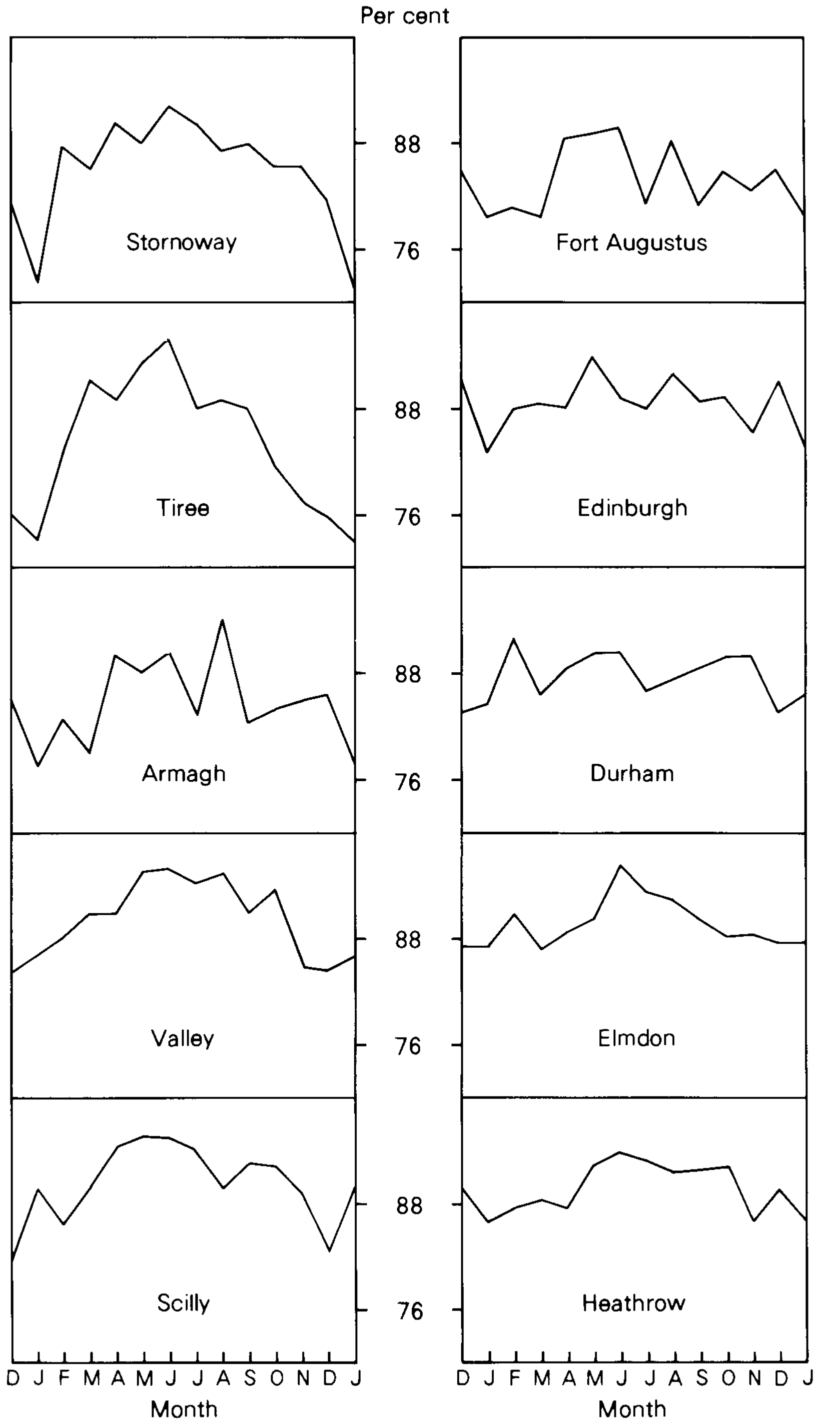

Figure 3. Seasonal variation of the median highest daily sunshine in a month. Figures are expressed as a percentage of the sunniest day in each calendar month for the period 1959–79.

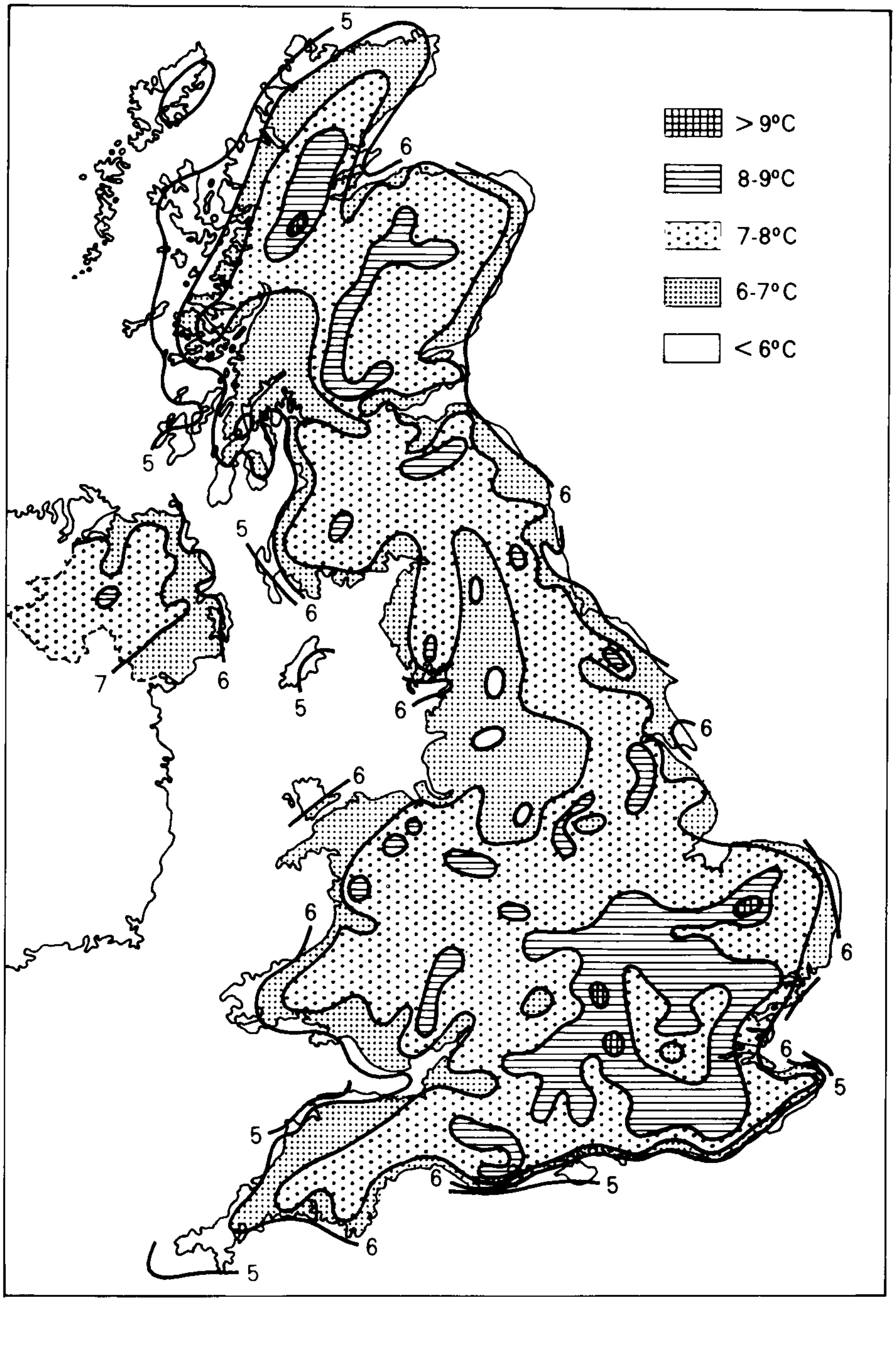

Figure 4. Geographical variation of the mean diurnal range for the period 1959–79 (meaned over all months).

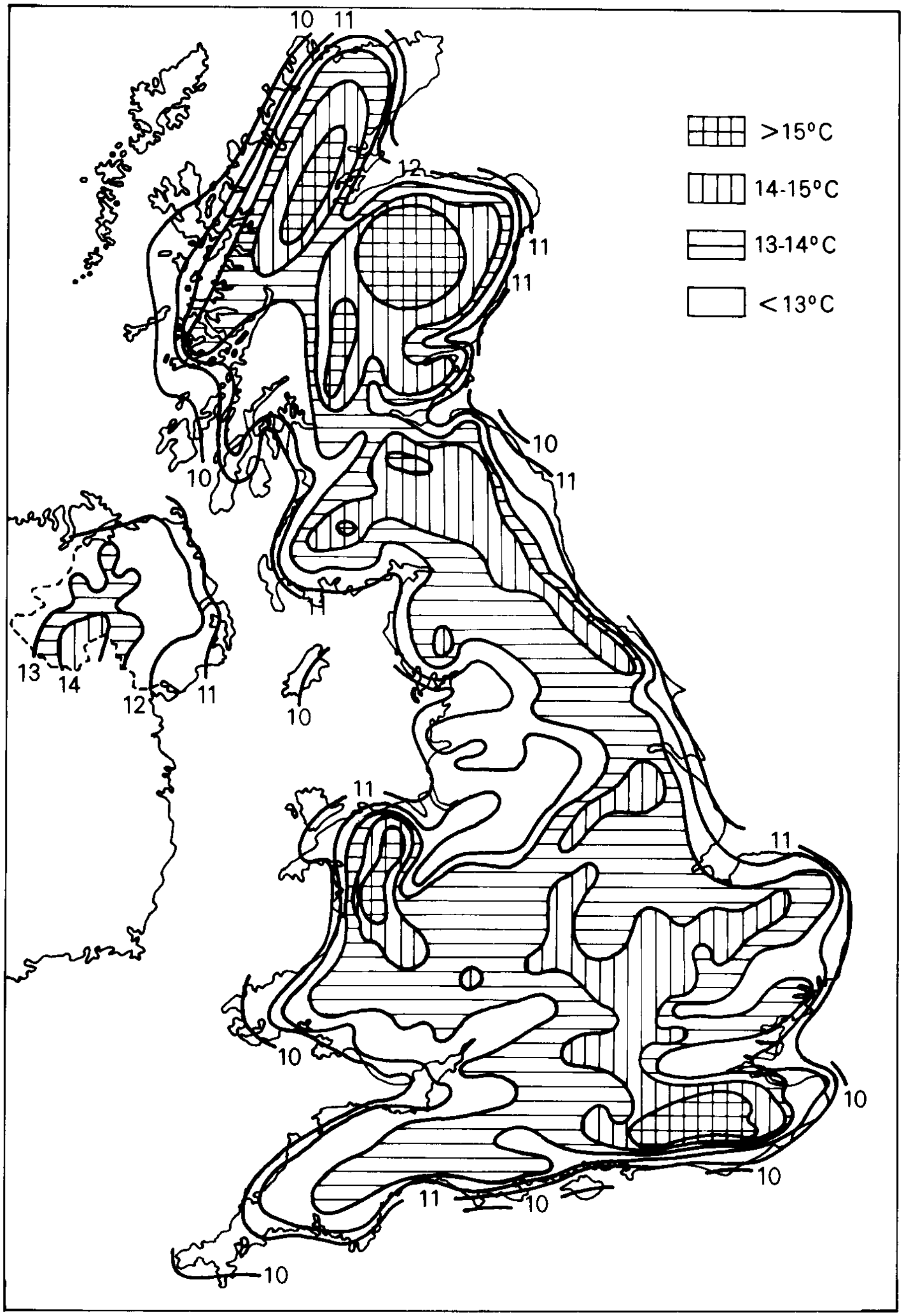

Figure 5. Geographical variation of the mean monthly maximum diurnal range for the period 1959–79 (meaned over all months).

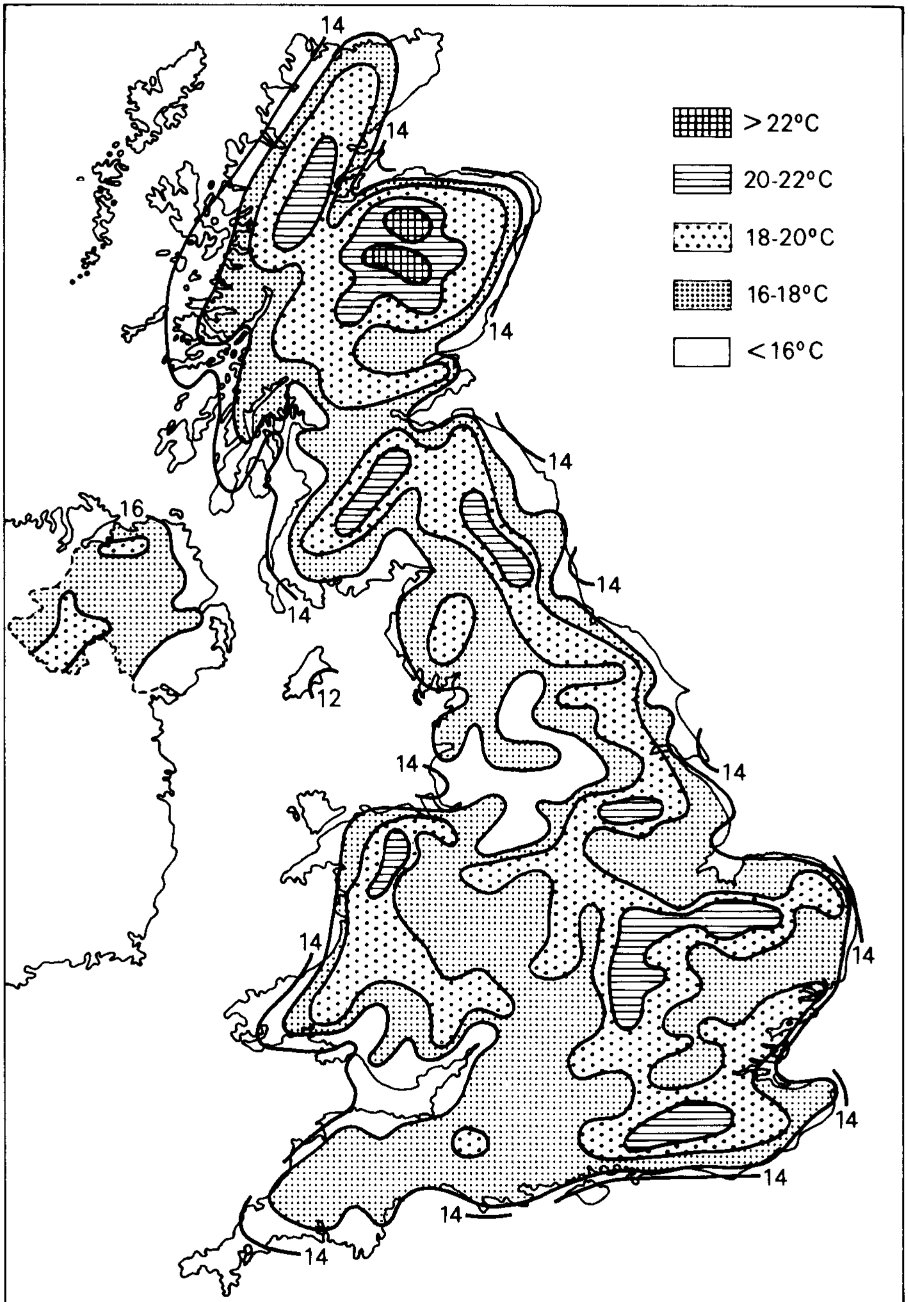

Figure 6. Geographical variation of the largest monthly diurnal range for the period 1959–79 (meaned over all months).

plotting position recommended by Jenkinson (1969), namely

$$p = \frac{m - 0.31}{N + 0.38} \quad \ldots \quad (1)$$

where p is the probability ascribed to the mth ranked of N observations. The observations do not in general lie on a straight line, but appear bounded above. Nevertheless, a straight line was fitted to the observations using a program devised by Jenkinson (1977) which gave extra weight to the more extreme observations. An example of its application is shown in Fig. 7 using data from Corwen in North Wales.

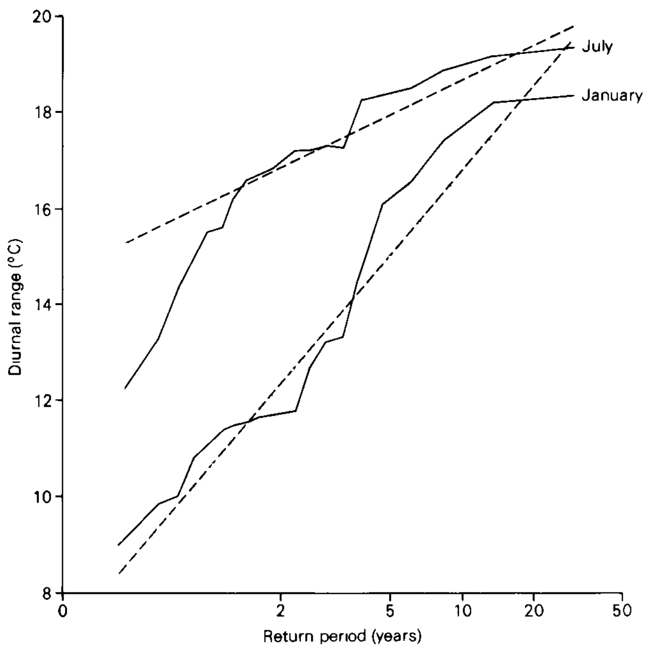

Figure 7. Extreme value analysis of diurnal range at Corwen for the period 1959–79. Dashed lines represent Gumbel distributions obtained by weighting observations according to Jenkinson.

Use of equation (1) yields a return period of around 30 years for the largest event in a sample of 21.

As the observations selected only represent the highest values from the small samples of independent diurnal ranges available in a month, there is no question of the theory of extreme values being satisfied. Neither is there any question that fitting a linear relation to the values obtained is physically realistic. The procedures described above are used simply as a convenient means of introducing a new variable — the slope of the extreme value analyses — which describes an important feature of the climatology of diurnal range.

The slope of the extreme value analysis of diurnal range was calculated as described above, and the geographical variations of the values meaned over all months are displayed in Fig. 8. The large values associated with high ground in Scotland are well illustrated.

6. Seasonal variations in diurnal range of temperature

The diurnal range will increase with solar elevation; in winter the power of the sun is often unable to destroy the nocturnal inversion, whereas in summer superadiabatics can be produced. Greater equality

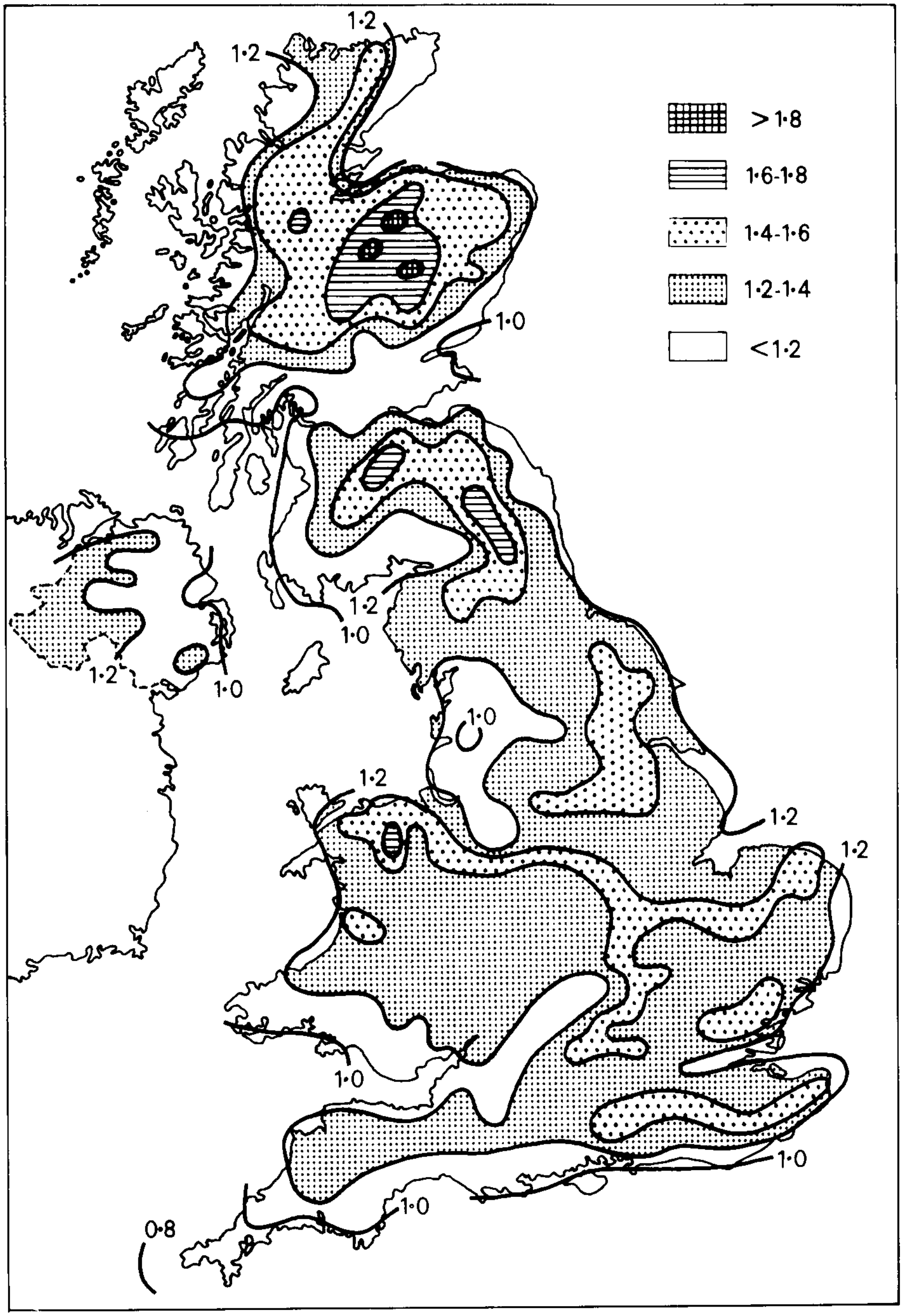

Figure 8. Geographical variation of the slope of an extreme value analysis of diurnal range for the period 1959–79 (meaned over all months).

in the length of day and night is also a factor in favour of large diurnal ranges. The net result is a seasonal variation in diurnal range that is characterized by a broad summer maximum and a sharp winter minimum. This is illustrated in Fig. 9, which displays the diurnal range to be expected once every two years. For climatological purposes the Meteorological Office has divided the United Kingdom into ten districts, and the diurnal ranges shown in Fig. 9 have been meaned over the five stations with the largest diurnal ranges in each district. In Fig. 9 the districts are positioned according to their approximate geographical location, i.e. with north at the top of the page and east to the right. Geographical variations are seen to be small, but the difference in sharpness between the summer peak and winter trough is smaller in the north than in the south.

The slopes of an extreme value analysis were calculated as described in section 5, smoothed over a number of months using a 7-point binomial filter (Lee 1981), and meaned over the same stations as in Fig. 9. The results are illustrated in Fig. 10 and show that over most of the United Kingdom there are only small seasonal variations, but that in northern Scotland there is a pronounced peak in March. These results have to be interpreted in the light of the standard errors involved. If the standard error of a quantity q is denoted by SE(q), then for the intercept (U), slope (α), and ordinal value X of a Gumbel distribution fitted to N observations we have

$$\mathrm{SE}(U) = 1.05\,\alpha\,(N)^{-\frac{1}{2}}$$

$$\mathrm{SE}(\alpha) = 0.78\,\alpha\,(N)^{-\frac{1}{2}} \qquad (2)$$

$$\mathrm{SE}(X) = (1.11 + 0.52Y + 0.61Y^2)^{\frac{1}{2}}\,\alpha(N)^{-\frac{1}{2}} \qquad (3)$$

where Y is the value of the reduced variate corresponding to an estimate of X (NERC 1975). The standard error indicated in Fig. 10 has been calculated from equation (2) using $\alpha = 1.8$ and $N = 21$. This will be an underestimate of the error associated with the Jenkinson fit, since the weighting procedure reduces the number of independent observations used. As the values presented in Fig. 10 have been smoothed over a number of months and averaged over five stations, however, the errors obtained from equation (2) are probably close to the true values.

The standard errors are large enough to indicate that the peak in the slope in March in northern Scotland could have occurred by chance. Nevertheless, the feature is a surprise as a maximum in winter had been expected. As discussed earlier, however, the lowest temperatures in winter are not necessarily accompanied by high diurnal ranges, and the slope of an extreme value analysis of minimum temperatures may well peak in winter. The peak in March for diurnal range may be due to the increased power of the sun in raising day maxima combined with a snow cover at higher levels to nourish nocturnal katabatics. The long record available for Braemar could be used to assess whether the March peak is real, but the data are held only in manuscript form.

The two-year values of diurnal range were seasonally smoothed using a 7-point binomial filter, and these, together with the smoothed values of the slope, were used to estimate values of the diurnal range with a return period of 30 years. The results, illustrated in Fig. 11, show that over England and Wales, the highest values occur in the late summer, possibly because the ground is driest then. In northern Scotland highest values occur in the spring, but the standard errors (as calculated from equation (3)) are large.

7. Conclusion

The average diurnal range of temperature over the United Kingdom is greatest in the south-east, and decreases to the north-west in response to the cloudier and windier climate. As more extreme events are

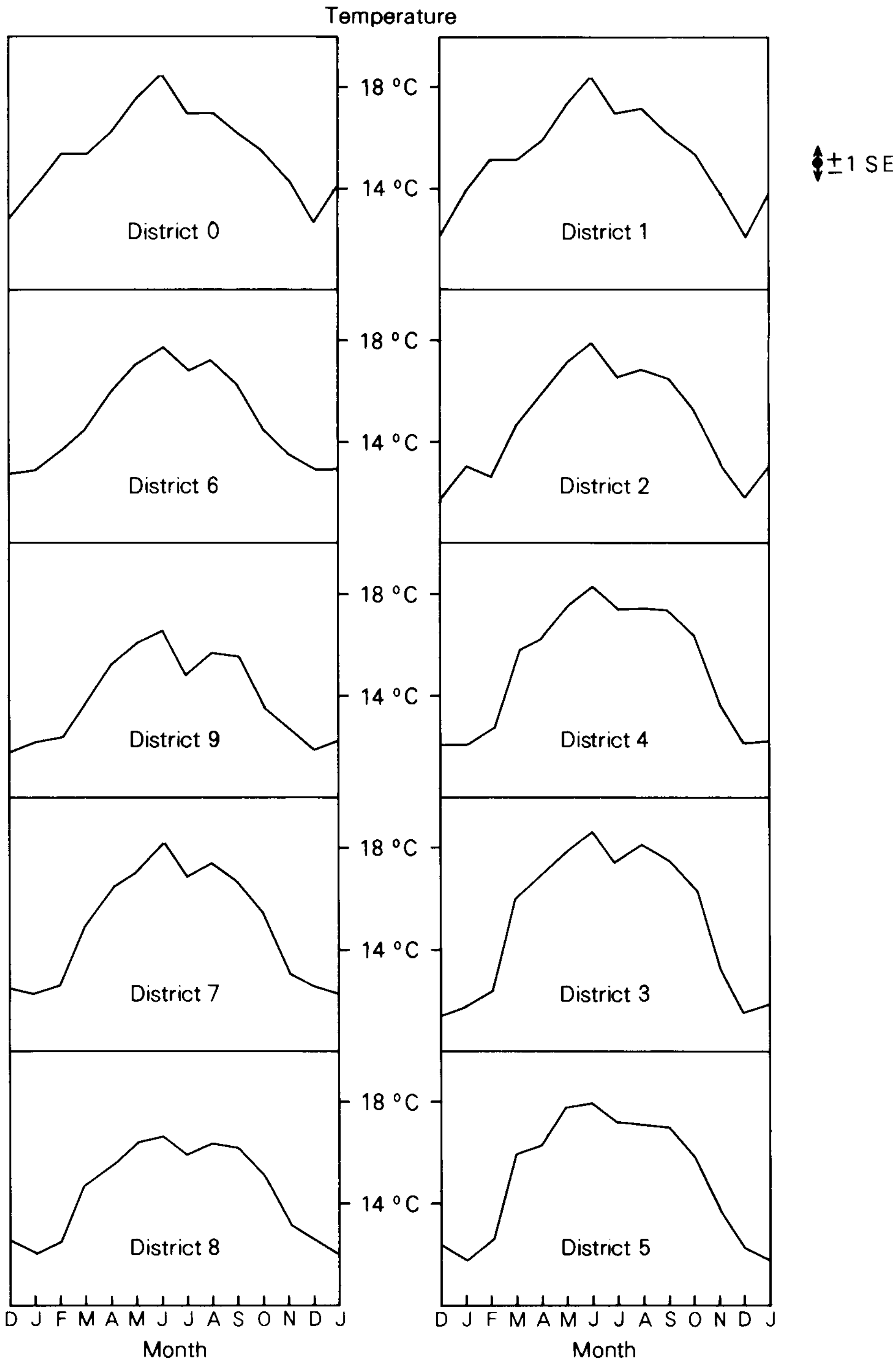

Figure 9. Seasonal variation of diurnal range with a return period of two years (mean of five most extreme stations in each district). ± 1 SE denotes a rough estimate of the relevant standard error, here and in Figs 10 and 11.

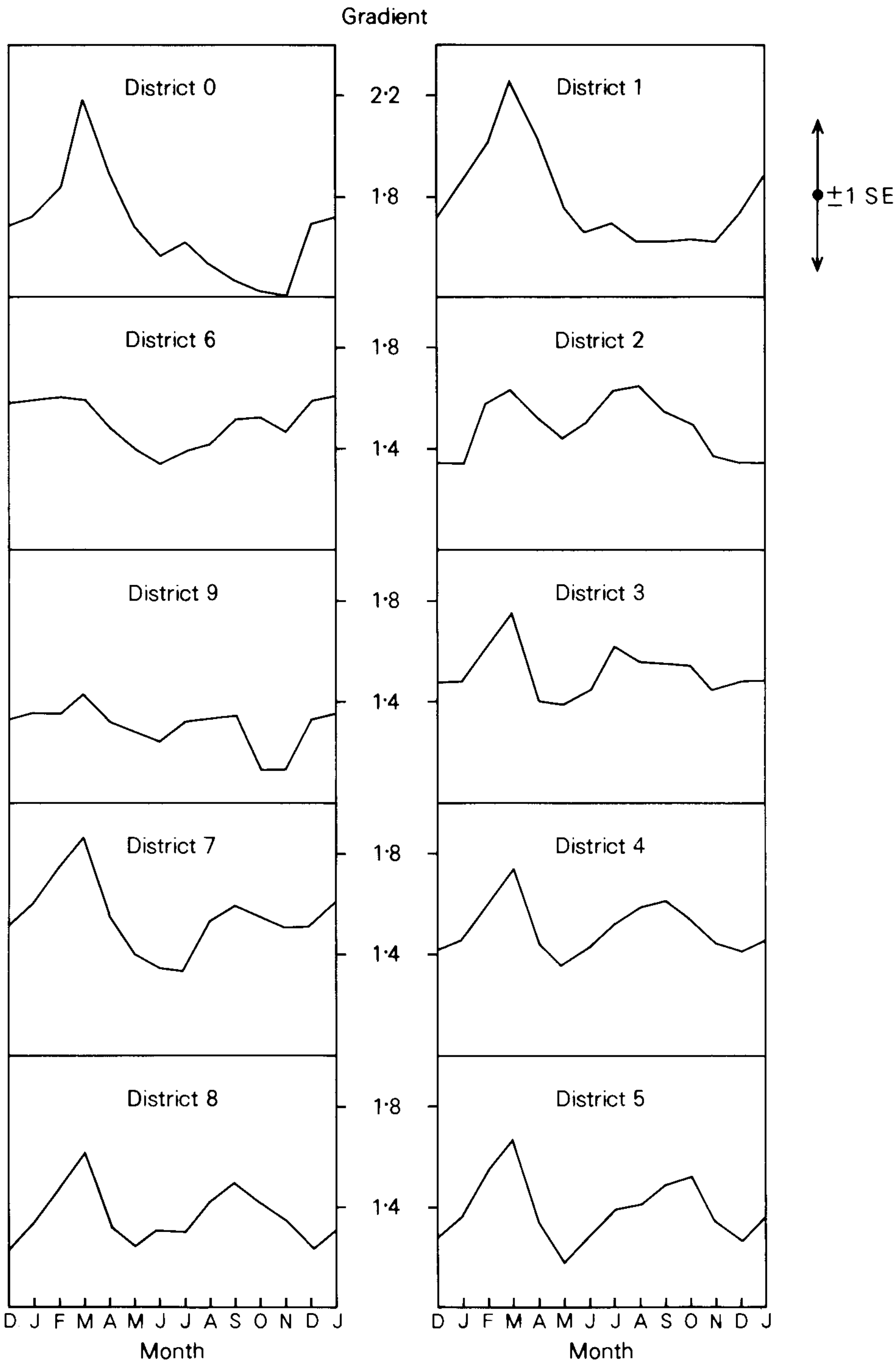

Figure 10. Seasonal variation of the slope of an extreme value analysis of diurnal range. Values represent the mean of the five most extreme stations in each district for the period 1959–79 and have been smoothed.

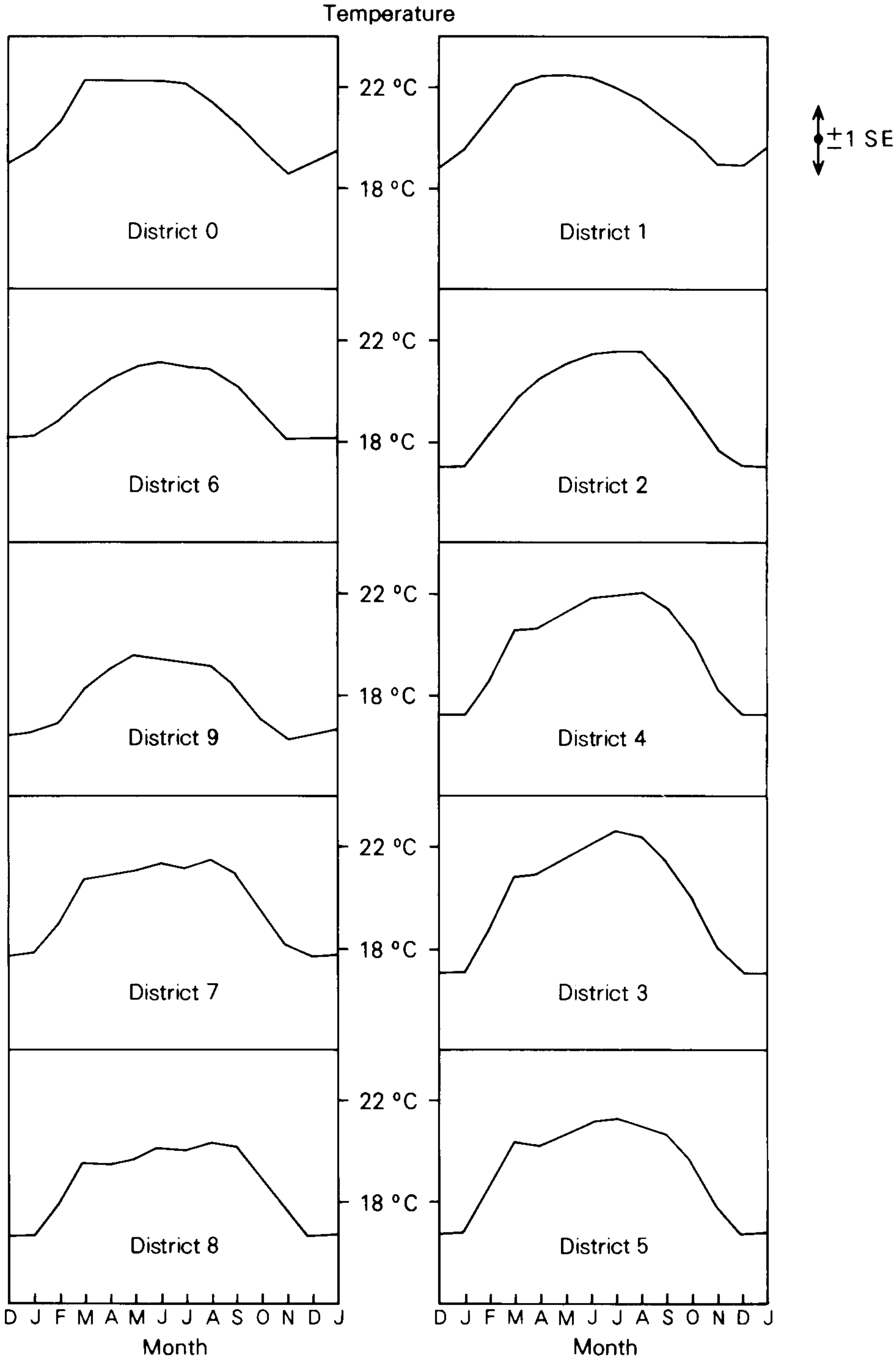

Figure 11. Seasonal variation of diurnal range with a return period of 30 years. Values represent the mean of the five most extreme stations in each district and have been estimated from smoothed values of the two-year diurnal range and slope of the extreme value analysis.

considered differences in climate become less important, and the largest diurnal ranges are likely to occur in Scotland, where the topography is more favourable for the development of extremes of temperature. Diurnal ranges tend to be smaller in winter than in other seasons, and the largest values are liable to occur between March and September.

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Physical modelling of surface windflow over Cyprus

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Summary

The construction and use of a simple wind-tunnel, incorporating an 'inversion surface'* adjustable to 3 levels, and of a crude model of the island of Cyprus are described. Model wind direction data obtained from 4 of the 28 sampling points, with inversions at each of 3 levels, for upstream flow at 10-degree intervals, are compared with surface wind directions observed at 00 GMT throughout 1980 and with corresponding, estimated, upstream 950 mb wind directions, using inversion data sampled by a (daily) 19 GMT radiosonde ascent from one of the four places. The observed and model data are processed in an attempt to validate the latter's predictions, and the model's flow patterns are discussed in the light of experience and of simple physical reasoning.

Introduction

It is well known by meteorologists and seamen alike that the surface winds around Cyprus form complex patterns in space and time. The former are aware that these patterns result from synoptic-scale pressure systems, from anabatic and katabatic systems, from land- and sea-breeze components and from flow diverted by topography (especially the mountain ranges), and that the vertical lapse-rate of air temperature and the existence and heights of inversions therein are also of great importance.

*'Inversion surface' — horizontal lid modelling an atmospheric temperature inversion.

Many studies have been carried out into the intensity, direction and times of onset and cessation of land- and sea-breezes and of katabatic winds. Forecasters are accustomed to use the results of such studies in combination with first-principle reasoning, experience and an understanding of the three-dimensional structure of the atmosphere and of time changes therein to predict surface winds. This simple experiment and related study, which have various unavoidable limitations, have been carried out in an attempt to gain an objective insight, however coarse, into the purely topographical aspects of low-level airflow over and around the island.

Wind-tunnel and model

A wind-tunnel (Fig. 1) was constructed from scrap materials, mostly stout packing cardboad, the design being based on a simple diagram of the Meteorological Office wind-tunnel and on a most helpful briefing (Kiff, personal communication).

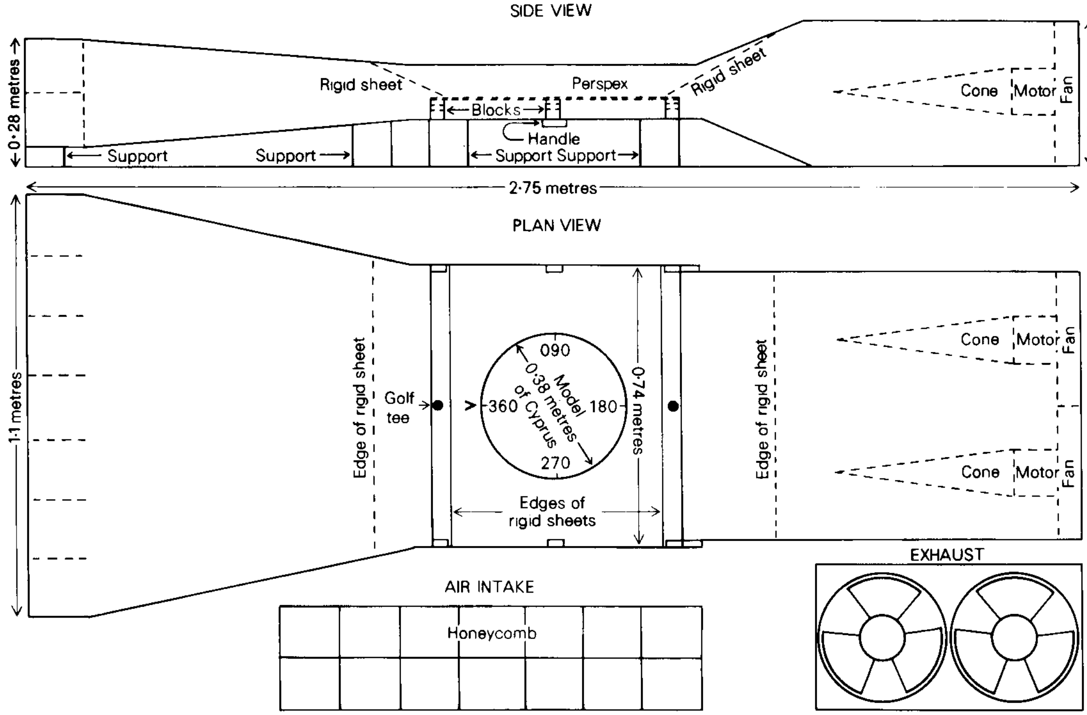

Figure 1. Detail of the wind-tunnel.

The model of the island, on a horizontal scale of 1:750 000, was based on a map the simplified topography of which is employed in various forms by the Cyprus Meteorological Service. The contours were used to shape balsa-wood sheets which were glued together and to a baseboard. The model was then completed using a commercial filler. Because it was decided to use tracing-paper flags 5 mm in height, swinging around pins and resting upon 2 mm diameter metal beads (to reduce friction) it was necessary to enhance the vertical scale very considerably and a factor of ten was selected. This is, in some ways, a fundamental weakness in the experiment and must, to some extent, result in an aerodynamic caricature of flow over and around the island. The turntable upon which the model stands is turned from below by a handle, so that any wind direction can be applied to the model, and fits into a recess in the floor of the working section of the tunnel so that floor level represents sea level. The edge of the turntable is marked at ten-degree intervals. Each of 28 wind direction sampling positions, some at sea, is provided with a 20 mm diameter compass rose (true directions). These positions are shown in Fig. 2. A rigid transparent plastic inversion surface can be set at 2000, 3000 or 4000 m above sea level. These heights correspond roughly to 850, 750 and 650 mb levels. No lower level is practicable because of the height of Mount Olympus (1936 m). With the inversion at 4000 m the cross-section of the working volume is considerably less than one quarter of the cross-section of the air intake. The lengths of the intake and exhaust sections are one-and-a-half times that of the working section and, if the tip of the panhandle of Cyprus is ignored, the model is only one third of the width of the working section. Two three-speed domestic fans (the most powerful available) set at maximum speed produce a four-knot flow across the model (measured by hand anemometer). Three pairs of golf tees of appropriate lengths, are used (one pair at a time) on the centre line to prevent the plastic inversion from sagging under its own weight. Space available for the construction and use of the wind-tunnel limited its size which, in turn, limited the size of the model.

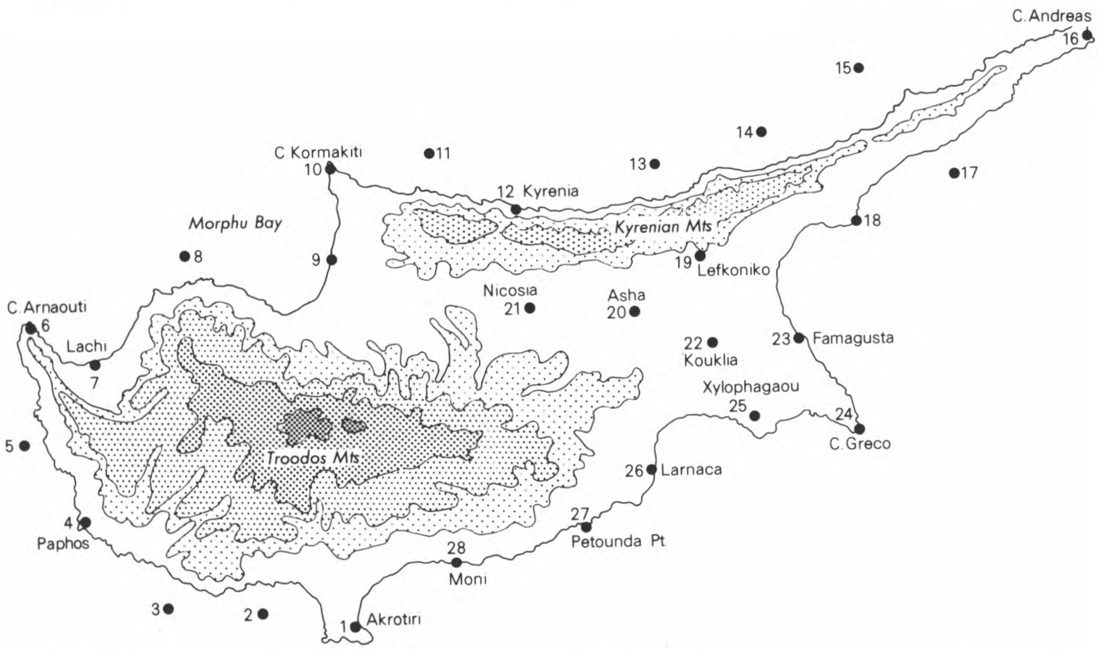

Figure 2. Plan of the model showing basic land contours and the 28 sampling positions. (The map reproduced here is not the one employed by the Cyprus Meteorological Service and was not used in the construction of the model.)

Wind direction data from the model

Three 'runs' were carried out, twice each, for inversions at 2000, 3000 and 4000 m. The sampling-position flag directions were tabulated against the direction of the turntable. Directions at position 12 (Kyrenia) were interpolated from positions 11 and 13 because the model island prevented the flag from turning through 360 degrees. The data for the 2000 m inversion were plotted on maps of approximate scale 1:2250000 and quality control was imposed only to remove 'noise' obviously due to very occasional flag sticking and only those values which could be rejected with confidence were amended. The final values were plotted on maps of the above scale and simple streamlines drawn. To save space only enough of those of the 2000 m map series needed to illustrate this text are reproduced (Figs 3(a)–(i)).

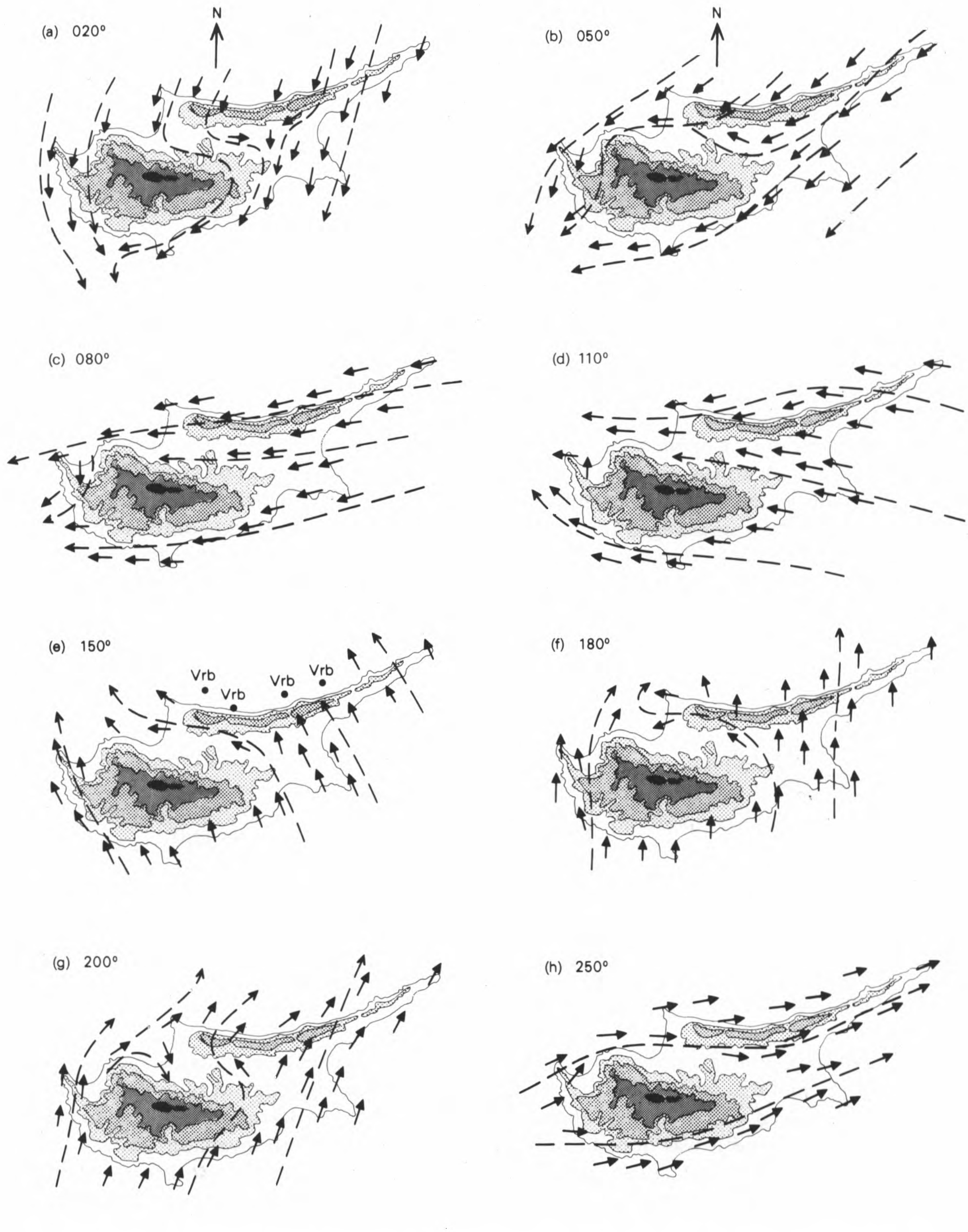

Figure 3 (a)-(i). Streamline patterns drawn from spot wind directions recorded by the model's flags, with inversion at 2000 m and upstream flow direction as shown. Vrb—variable.

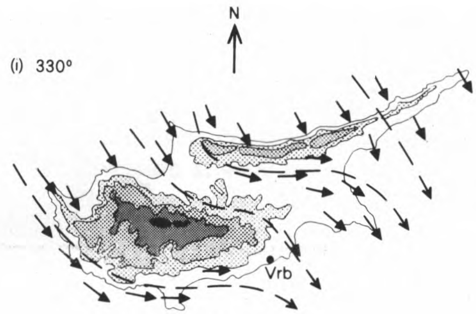

Figure 3 continued.

Real wind and inversion data

The sampling time for real data was chosen as 00 GMT because it is the closest main synoptic chart time to radiosonde time (19 GMT) at which sea-breezes would never be expected, and because it is an upper-air chart time in case upper-wind data were found to be required. The 950 mb wind direction over and upstream of the island was estimated from the mean-sea-level isobars. This simplification, however necessary, introduces the implied assumption that the gradient wind over and upstream of Cyprus always remains virtually unchanged for long enough to allow topographical controls on windflow to become effective all over the island. It ignores the existence and transit across the island of fast-moving, short wavelength synoptic systems. Surface wind direction data for 00 GMT were available from Nicosia, Akrotiri, Larnaca and Paphos only.

Tephigrams of the daily radiosonde ascents, then made from Akrotiri, were examined and details of inversions were extracted. Here reference is made only to inversions in broad classes of height.

Wind direction and inversion data were tabulated to the format:

I_t	Main flow	Nicosia	Akrotiri	Paphos	Larnaca
	dd_{950}	dd	dd	dd	dd
		(dd)	(dd)	(dd)	(dd)
		Diff	Diff	Diff	Diff

where I_t — inversion type,
dd_{950} — estimated 950 mb wind direction over and upstream of Cyprus,
dd — observed surface wind direction at 00 GMT,
(dd) — model surface wind direction for dd_{950} and I_t,
Diff — difference between dd and (dd) (0 to 18, i.e. tens of degrees).

There were 299 cases of inversions below 750 mb (perhaps with higher inversions), 17 cases of inversions only between 750 and 650 mb and 50 cases of inversion only above 650 mb or of no inversion. The last mentioned were classed with inversions above 650 mb because the wind-tunnel flags would not operate with the lid removed and it was hoped to obtain model values for 'no inversion' cases.

The island has an irregular shape, but if the panhandle is ignored its west-to-east extent is some 80 nautical miles. Hence a ten-knot airstream would have to persist and remain virtually steady in direction for up to eight hours to cross the main bulk of the island for topographical controls to take effect everywhere. Table I is a sequential plot of day-to-day changes in estimated 950 mb wind direction at 00 GMT in 1980 (in tens of degrees). The convention has been adopted that the wind never changed

Table I. *Changes of estimated 950 mb wind direction, in tens of degrees, immediately upwind of Cyprus at 00 GMT in 1980 for the previous 24 hours*

	Day 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Jan.	6	10	5	5	9	16	2	3	6	2	12	2	0	1	2	7	7	2	5	7	1			9	4	2	0	14	2	7	
Feb.	0	2	5						1	3	4			4	7	2	5	4	9	3			3	1				16	0	—	—
Mar.	2	6	2	11	1			1	18	5	4	13	1	17	12	5			3				4	1	10	12	0	16	1		
Apr.	2	0	15	4	2	16	3	18	17	18	1	0	3	1	4	1	8	9	14	7	14	2			3	1	13	8	9	6	—
May			12	4			8	11	1	1			18	5	6	4	2	15	8	5	16	1	1	15			4				6
June	8	6	4	6	3	3	2	0	5	3	5	2	2						4	1	3	2	0	3							—
July	0	4				0	7	3	8	2			1	3								8	4	1	3	1			3		
Aug.				1	2	2	5	4	9	10			3	2	11	6	7	4	0	8	9	4	6	12	8	8				3	0
Sept.	1	2	2	0					1	2	3			1	3	2	2	6	4	0	4	0			7	7	0	3			
Oct.	2	2	1	0	1	9	0	5	6	2	1	1						3	1	3	0	5	17				10	8	6	6	10
Nov.	8			7	3	8			12			2	17	1	5	1	0	6	1			4	11	1	3	3	5	1			—
Dec.		4	6	2	10	1	7			1	6						4	7	5	4	4	3	1	12	1			2	4	10	1

through more than 180°. Breaks in the sequence are due to calms. The table gives an impression of the variability of 950 mb wind direction in 1980. It shows 68 occasions when the estimated wind direction did not change by more than 20° in 24 hours for from 24 to 120 hours and there must have been many other occasions when the wind speed was sufficiently strong and the 'pre-00 GMT' direction sufficiently constant for topographical controls to operate by 00 GMT. Hence it seems reasonable to assume that the data are adequate for an attempt at simple verification of the model in terms of there being enough occasions when a steady flow lasted long enough. It is also necessary to be sure that all 950 mb wind directions are represented in the real data. Fig. 4 shows numbers of cases estimated from each ten-degree point with calms at the centre. It could reasonably be argued that some of the 22 cases of 360° probably belonged to 350° and 010°. Accordingly, numbers of cases in 36 overlapping 50° sectors were averaged to give the smoothed totals. It can be seen that the most frequently occurring directions were well sampled but that the infrequent southerlies were less well sampled; there are, however, probably enough for the present purpose.

The processes of data extraction and processing are extremely time-consuming and only one year's data are presented. This is probably not a serious drawback because local wind components (other than topographical ones) occur at 00 GMT and at the other three major synoptic hours and hence the chance of direct verification of purely topographical effects is unlikely to increase significantly with quantity of data.

Data analysis and discussion

Twelve scatter diagrams were plotted as listed in Table II. Numbers 1 to 4 are straightforward comparisons of model-predicted versus observed wind directions at the 4 locations for all cases (inversion at any level or none at all). Numbers 5 to 7, for Akrotiri only (the location from which the radiosonde ascents were made), make the same comparison but for three separate classes of inversion level. Numbers 8 to 11 compare the estimated 950 mb wind direction for inversions at 750 mb and below with the observed (surface) wind directions at the four locations. Number 12 makes the same comparison, for Akrotiri only, for cases when the inversion was at some level higher than 750 mb and when there was no inversion at all. The data tabulated are, firstly, numbers and percentages of total cases where the directions agreed to within 30°, secondly, any tendency for points to cluster in defined parts of the diagrams and, thirdly, any tendency for observed surface wind directions to cluster when the model-predicted or estimated 950 mb wind was calm. Clustering on the scatter diagrams was assessed by inspection. The total ranges of direction are given in the clockwise sense.

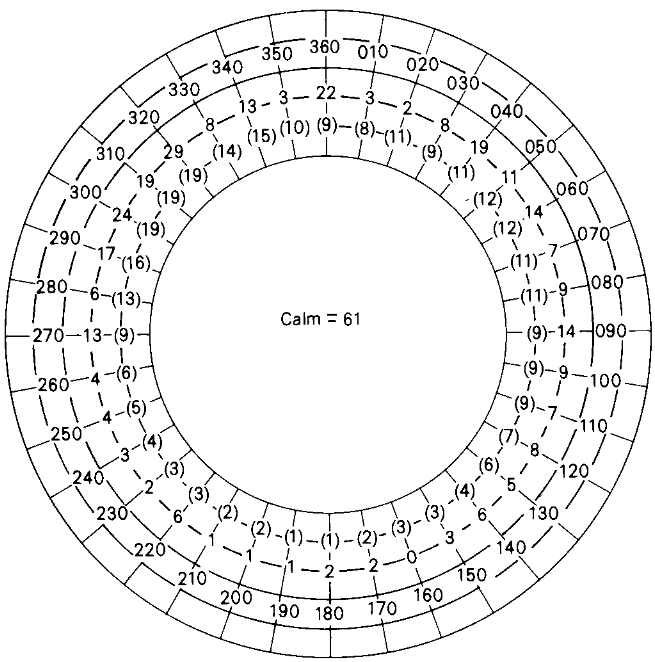

Figure 4. Numbers of cases of estimated 950 mb wind direction immediately upwind of Cyprus at 00 GMT in 1980 from every 10° direction. Values in brackets are meaned over overlapping 50° sectors. (Monthly distributions of estimated daily 950 mb flow reflected the dominance of the seasonal trough from June to September when all directions fell between west and north-east (through north)).

Starting with comparisons 8 to 11 only 36% or less of observed surface winds were within 30° of estimated 950 mb winds and there was marked clustering. This shows that local effects, including topographical controls, are important at all four locations and that the results of such effects are systematic. Taking comparisons 1 to 4 and 8 to 11 in pairs (i.e. one place at a time) there are marked similarities between the clustering characteristics when the model predicted a wind direction.

The contents of the first four blocks in the last column of Table II should explain much of the difference between observed winds and model winds. The observed winds in the ranges given in these blocks occurred when no synoptic-scale pressure gradient could be identified and should, therefore, be due to temporary thermal gradients set up over the island and surrounding sea. The first step was to examine the distributions of reported directions on these 61 occasions, separating from the others those which appear to have been katabatic winds; this is done in Table III.

Table II. *Summary of 12 scatter diagrams*

Station	Comparison	I_t	Cases	No. of cases within 30°	Percentage	Clustering (degrees true) (dd) vs dd	(dd) calm vs dd
1. Nicosia	(dd) vs dd	Any level or none	359	116	32	090–120/200–260 270–310/080–220	calm/180–260 calm/100–170
2. Akrotiri	(dd) vs dd	Any level or none	366	149	41	060–120/240–010 220–270/320–350	calm/300–050 calm/060–100 calm/230–290
3. Paphos	(dd) vs dd	Any level or none	366	139	38	110–130/010–060 300–320/010–070	calm/350–100 calm/270–340
4. Larnaca	(dd) vs dd	Any level or none	366	90	25	040–070/310–360 080–140/310–030 310–360/220–260	calm/260–320 calm/330–010
5. Akrotiri	(dd) vs dd	750 mb and below	299	113	38	As 2	As 2
6. Akrotiri	(dd) vs dd	750–850 mb	22	10	45	Too few cases	-
7. Akrotiri	(dd) vs dd	Higher than 750 mb or none	67	36	54	Too few cases	-
						dd_{950} vs dd	dd_{950} calm vs dd
8. Nicosia	dd_{950} vs dd	750 mb and below	294	42	14	310–140/240–260 290–320/220–230 040–140/220–230	As 1
9. Akrotiri	dd_{950} vs dd	750 mb and below	299	86	29	310–360/240–260 360/270–300 030–110/320–360 030–050/240–290	As 2
10. Paphos	dd_{950} vs dd	750 mb and below	299	108	36	280–360/010–040 010–070/330–360	As 3
11. Larnaca	dd_{950} vs dd	750 mb and below	299	76	25	300–360/230–250 030–140/310–360	As 4
12. Akrotiri	dd_{950} vs dd	Higher than 750 mb or none	67	25	37	Too few cases	-

dd — observed surface wind direction at 00 GMT, (dd) — model surface wind direction for dd_{950} and I_t, dd_{950} — estimated 950 mb wind direction over and upstream of Cyprus.

Table III. *Distributions of observed surface wind directions (degrees true) at four locations in Cyprus at 00 GMT in 1980 on 61 occasions of indeterminate surface pressure gradient*

Station	Katabatic winds Direction (degrees true)	No. of cases	No. of calms	Other winds Direction (degrees true)	No. of cases	Percentage of total
Nicosia	180–260	40	1	060	1	
				100–170	8	
				270–300	10	
				360	1	33
Akrotiri	300–050	27	6	060–100	13	
				180	1	
				230–290	14	45
Paphos	350–100	28	15	130–140	3	
				220	1	
				240–250	2	
				270–340	12	29
Larnaca	260–320	24	17	030	1	
				200	1	
				220	2	
				250	2	
				330–010	14	33

As the wind-tunnel and model were unable to measure wind speeds at the sensing locations there was no point in extracting speeds at the four test stations. In an attempt to obtain rough estimates of the direction of the assumed 'thermal wind' components relating model winds to observed winds it was assumed that all model winds blew at five knots and that all observed winds blew at ten knots. A simple vector device was used with the data from the first four blocks in the next to last column in Table II. The directions limiting ranges of 'thermal wind' obtained by this method are given in Table IV which also contains the katabatic wind ranges of Table III.

Table IV. *Limits of ranges of approximated directions (degrees true) of local, thermal components assumed present in winds measured at four locations in Cyprus at 00 GMT in 1980. (Katabatic wind direction ranges are also given.)*

Station	Directions of estimated thermal winds			Katabatic wind range
Nicosia	080–190	220–270		180–260
Akrotiri	240–350	340–010		300–050
Paphos	350–030	040–090		350–100
Larnaca	280–330	300–360	200–240	260–320

Assuming that the reasoning so far is broadly valid and accepting that, whilst katabatic winds have preferred directions, the direction of flow on an individual night often owes much to other causes, the components still to be explained are:

Nicosia 080–170°, 270°,
Akrotiri 240–290°,
Paphos nil,
Larnaca 200–240°, 330–360°.

Wales-Smith (1984) has demonstrated that the average mean-sea-level pressure at Nicosia is higher than

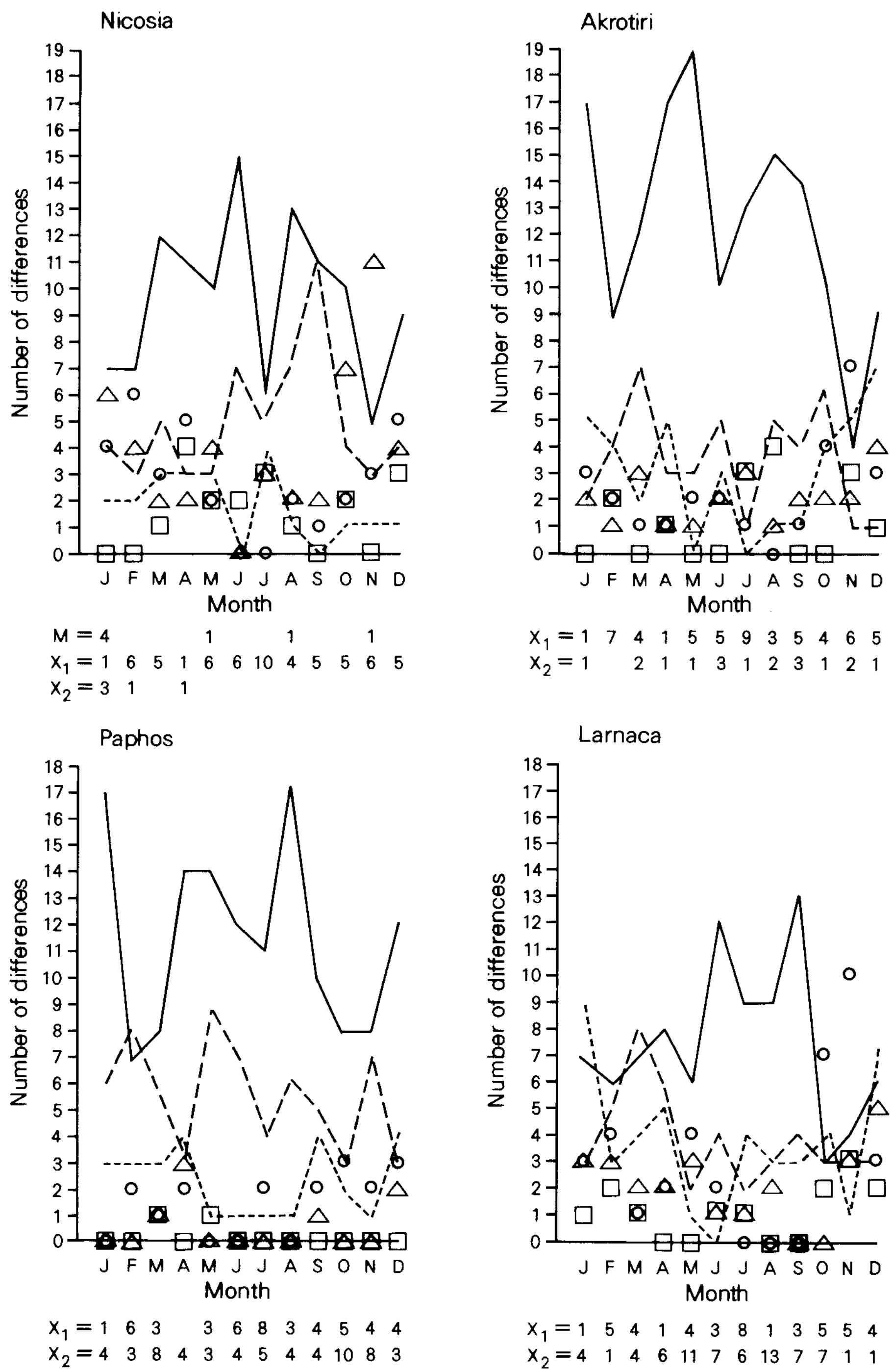

Figure 5. Monthly comparisons between model-predicted and observed surface wind directions at four stations in Cyprus. (——— cases of 0–30° difference, — — — 40–60°, - - - - - 70–90°, ○ 100–120°, △130–150°, □160–180°, M = no observation, X_1 = wind observed when model predicted calm, X_2 = calm observed when model predicted wind.

at three well-separated coastal places at 00 GMT throughout the year. The 14 cases of flow 330–010° at Larnaca (from Table III) occurred throughout the year, and thus may be explainable as land-breeze phenomena.

Unexplained occurrences of other 'thermal winds' in Table III nearly all occurred in the summer months and may have been due to exceptional differences of surface temperature persisting into the night; they are summarized as follows:

Nicosia:	Six out of eight cases of 100–170° occurred in June and July.
	Seven out of ten cases of 270–300° occurred in May, June and July.
Akrotiri:	Eight out of fourteen cases of 230–290° occurred in June to September.
Larnaca:	Four out of five cases of 200–250° occurred in July and September.

Although there were no cases to be explained at Paphos there remain 15 cases in Table III from directions between 220° and 240°; 8 of these occurred in the months from May to September. Presumably those in the cooler months occurred due to weak synoptic-scale gradients not revealed by the sparse data network of the region.

Whilst it is clearly impossible to produce the above arguments in rigorous form it is suggested that they offer considerable support for the purely aerodynamic results obtained from the model.

It is interesting to examine these results from the point of view of level of lowest inversion. From comparisons 9 and 12 it can be seen that, as would be expected, the agreement between estimated 950 mb direction and observed surface direction improves when low-level inversion cases are removed. From comparisons 2,5,6 and 7 it appears that the model's predictions are best when the lowest inversion is above 750 mb or when there is no inversion, second best when the inversion is in the 750–850 mb layer and worst when inversions below 850 mb are included. These results are reasonable since local effects (other than purely topographical ones) would be expected to become increasingly important with inversions near the surface. Caution must be employed, however, in interpreting results obtained from small numbers of cases.

The final section of this simple analysis is included in order to show the degree of success of the model's predictions when thermal components are ignored, to highlight the need for forecasters to take account of thermal components when using the model's predictions, and finally, to provide a compact conspectus of all the comparisons including seasonal differences.

Fig. 5 compares the model-predicted and observed surface wind directions at the four locations in 1980. The quantity shown is difference in direction (from 0° to 180°). Cases where calm was predicted and occurred are counted as 0° difference. Cases when no wind measurement was recorded (M), wind flow was recorded but the model predicted calm (X_1), and where a calm was recorded but the model predicted flow (X_2) are shown separately. The diagram shows that the 0° to 30° class was almost always the largest. It can be seen that Akrotiri and Paphos had similar 0° to 30° graphs and that the Larnaca graph had some resemblance to those at the other three locations. The diagram can be summarized as follows:

Percentage occurrence of various types of comparison between model-predicted and observed wind directions.

Station	0–30° (1 class)	40–90° (2 classes)	100–180° (3 classes)	Wind observed Model calm	Calm observed Model wind	No observation
Nicosia	31	23	27	17	1	1
Akrotiri	41	21	18	15	5	
Paphos	38	26	7	13	16	
Larnaca	25	25	20	12	18	

Cases when the estimated 950 mb wind direction did not change by more than 20° in 24 hours (for from 24 to 120 hours) were examined. Successive differences between model and observed directions were checked to see whether they reduced (improved) or increased (deteriorated) with time. 303 cases were found of which 131 showed 'improvement', 126 showed 'deterioration' and 46 showed no change. This probably means that local effects involving thermal processes were too strong to allow this test to be made.

Comments on the flow maps (Figs 3(a)–(i))

Members of directional groups (here identified by range of wind-tunnel flow direction) have similar characteristics as follows:

010–030° Show a lee trough to the Kyrenia mountains, air flow hugging the Troodos mountains and a confluent area in their lee.
040–050° Show a weak trough in the lee of the Kyrenias, hugging of the Troodos range and confluence downstream of the range.
060–090° Very simple patterns but a tendency for flow to hug the Troodos.
100–130° Very simple patterns but with a tendency for flow to hug the Troodos and for a slight perturbation in the lee of the Kyrenia range.
140–170° Very simple patterns with range-hugging but with a suggestion of a lee trough north of the Kyrenia range.
180–190° Southerlies established north of the Kyrenia range with signs of some perturbation across the range itself. Otherwise a simple pattern.
200–210° A generally simple pattern but with signs of convergence between Morphou Bay and Nicosia.
220–290° Very simple patterns.
300–360° Simple flow patterns. The lee trough to the Kyrenias becomes re-established. A zone of confluent winds south-east to south of the Troodos moves west or east as the main (950 mb) flow veers or backs.

Therefore only nine of the 2000 m inversion streamline maps, out of a total of 36, have been shown.

The above features are all familiar to meteorologists. The service provided by the model system is that of offering evidence that the effects operate strongly over and around Cyprus. No physically unreasonable or unrealistic patterns appear.

Conclusion

Absolute verification of the results obtained from the model is, probably, possible only with a very large and meticulously scaled model, a huge wind-tunnel and sophisticated ancillary equipment. The analysis of real data, presented here, offers considerable support to the model's predictions but can not be claimed as a thorough verification. The model demonstrates patterns which would be expected from first principle physical reasoning. The large-scale roughness of the model island is broadly correct because care was taken to incorporate major peaks, valleys and changes of slope. Any relationship between the small-scale roughness of the model and of the island itself is mainly due to chance. All that can be said is that the plaster was carefully shaped but was smoothed only to the extent necessary to remove unwanted irregularities. The model wind speed and the ten-fold exaggeration of vertical scale were, as explained, consequences of the materials and equipment available. The model and wind-tunnel are crude but are better than an amusing toy. It is probably as good a model system as anyone is likely to have the opportunity to make in the near future under the present-day constraints affecting the interested meteorological agencies.

With no previous experience of wind-tunnel studies the writer was delighted to obtain coherent and apparently meaningful results from so coarse a model. The known occurrance of a zone of indeterminate winds separating a western zone of north-westerlies from an eastern zone of north-easterlies off the south coast of Cyprus was explained to fellow yachtsmen using only the model island and flags, applying a series of winds to the island as a whole, from various northerly points, by blowing! It seems likely that other problem areas could usefully be studied with similar simple and inexpensive equipment.

The important, outstanding practical question is that concerning the usefulness of the model's results to the forecaster working in Cyprus and, indirectly, to forecasters working in other broadly similar locations. The writer would suggest that the results be used as follows. In cases where a short wavelength pressure system is crossing the island quickly the model can offer no more than confirmation that suspected topographical controls are powerful and should be given due weight in forecasting surface winds. Similar remarks apply to occasions when the east–west orientated, seasonal pressure trough of summer is moving quickly northwards or southwards. When the 950 mb flow is expected to remain steady long enough for topographical controls to become established, then, even though the wind veers or backs gently, the forecaster is offered an important component of the resultant surface flow at any place or time.

Acknowledgement

The writer has pleasure in thanking the Cyprus Meteorological Service for its excellent, basic topographical map and for providing data for Nicosia and Larnaca, and the Head of Service for his interest and encouragement.

Reference

Wales-Smith, B. G. 1984 Diurnal and seasonal trough-induced surface pressure gradients and winds over Cyprus (*Meteorol Mag.* In press).

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Radar wind profiler observations of mesoscale wind systems

By M. A. Shapiro, T. Hample and D. van de Kamp

(NOAA/ERL*/Wave Propagation Laboratory, Boulder, Colorado)

Summary

Observations from rawinsondes and UHF and VHF radar wind profilers are used to provide mesoscale contour, cross-sectional and time-series analyses of a sharp trough containing upper-level frontal and jet stream structure. The results demonstrate the great potential value of UHF and VHF profilers for this type of work.

1. Introduction

Recent technological advances in UHF–VHF radar wind profiling† represent a major breakthrough in obtaining accurate, low-cost, temporally continuous, high vertical resolution wind profiles. Whereas past reports (e.g. Gage and Balsley 1978; Röttger 1980; Little 1982; Strauch *et al.* 1983) have focused upon instrument design and performance characteristics, the present article presents mesoscale meteorological analyses derived from this new observing technology. Examples depicting a surface front, an upper-level front and its associated jet stream serve to illustrate the potential application of wind profiler networks for describing and forecasting the spatial and temporal evolution of synoptic and mesoscale wind regimes.

2. The NOAA wind profiler network

The NOAA Wave Propagation Laboratory maintains a network of one UHF (900 MHz) and four VHF (50 MHz) Profilers. The UHF system is located at Stapleton International Airport, Denver, Colorado; the VHF systems are at Platteville, Cahone, Lay Creek and Fleming, Colorado. The Platteville VHF system (operated jointly with the NOAA Aeronomy Laboratory) is an outdated design that gives wind fields with only 1.5 km vertical resolution and for this reason was not incorporated into the analyses that follow. All profilers are programmed for one profile per hour (an average of 12 individual profiles within the hour) with varying vertical resolution. The UHF system has 100 m resolution from 0.34 km to about 2.56 km above ground level (AGL), 300 m resolution from 1.64 km to about 8.30 km AGL and 900 m resolution between 2.70 km and about 14.00 km AGL. The outlying VHF systems provide wind data with 300 m resolution from 1.69 km to 8.35 km AGL and 900 m resolution between 2.61 km and 17.39 km AGL. Changes in vertical resolution are accomplished by changing the pulse length of the radar.

3. The upper-level front and jet stream of 13–14 June 1983

During 13 and 14 June 1983 an unusually strong (for the time of year) trough containing upper-level frontal and jet stream structure passed over the Colorado profiler network. The 12 GMT 300 mb wind analysis for 13 June (Fig. 1) based upon rawinsonde and profiler data shows the $\geqslant$50 m s^{-1} jet stream

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*NOAA/ERL National Oceanic and Atmospheric Administration/Enviromental Research Laboratories.

†For a recent account see e.g. P. K. James (1980), The WPL Profiler: a new source of mesoscale observations, *Meteorol Mag*, **112**, 229–236.

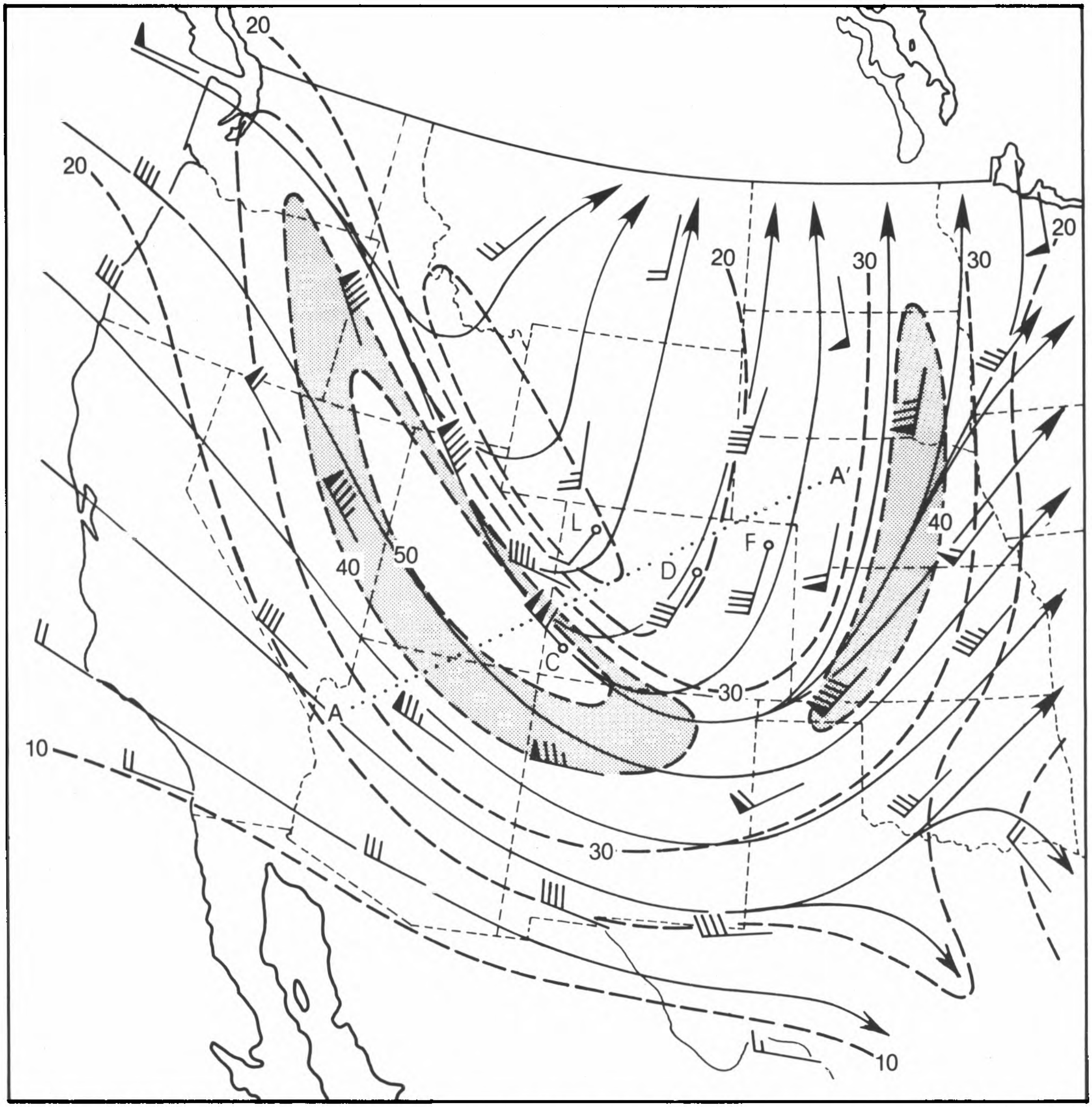

Figure 1. 300 mb wind velocity analysis at 12 GMT 13 June 1983. Wind speed (m s^{-1}), dashed lines; streamlines, thin lines; solid pennants = 25 m s^{-1} full feathers = 5 m s^{-1}; half feathers = 2.5 m s^{-1}. Radar wind profilers are designated by open circles at tip of wind vectors. VHF profilers are located at Fleming (F), Lay Creek (L), and Cahone (C), and the UHF profiler is at Denver (D).

entering south-western Colorado. The Cahone profiler provided a key observation for this analysis, by measuring the 55 m s^{-1} wind speed over the south-west corner of Colorado.

Fig. 2 presents the cross-sectional analysis of wind speed and potential temperature along the line AA′ of Fig. 1 prepared from a composite of conventional rawinsondes and four radar wind profilers. In the analysis, the Cahone profile intercepted the upper-level and jet stream core between the Winslow, Arizona and Grand Junction, Colorado balloon sounding sites. The wind profiles from Lay Creek, Fleming, and Stapleton, and the Denver raob documented the weak wind speeds near the trough axis and the 20 m s^{-1} south-westerly flow in advance of the trough near 300 mb.

After 12 GMT on 13 June, the trough and jet stream (Fig. 1) and front (Fig. 2) continued eastward and passed over the Lay Creek profiler which is located in north-western Colorado. The hourly sequence from Lay Creek (Fig. 3) shows the appearance (after 21 GMT) of the frontal shear layer and its intensification and descent from 9.2 km to 6 km by 10 GMT. The jet core passed overhead at 03 GMT.

4. The surface frontal passage on 12 June 1983

On the day before the passage of the upper-level front, a low-level (surface) front passed over the Rocky Mountains and was observed with the high-vertical-resolution Stapleton UHF profiler. The time-series analysis of the 100 m vertical resolution wind profiles (Fig. 4) contains two-hour resolution because computer failure did not permit the usual one-hour data archiving. The analysis shows weak easterly flow below 3 km before 00 GMT 12 June. By 04 GMT, this flow became southerly and increased in speed just before frontal passage. The Stapleton surface winds documented frontal passage at about 0420 GMT. A low-level southerly wind speed maximum appeared above the leading edge of the front between 04 and 06 GMT. After 06 GMT the winds beneath the frontal layer were northerly to north-easterly, becoming easterly up to 2.8 km by 18 GMT.

5. Conclusion

The case study analyses illustrate the ability of VHF and UHF wind profilers to document the vertical, horizontal and near-continuous temporal structure of front and jet stream mesoscale windflows. It remains for future construction of continental profiler networks with spatial separation of about 300 km to facilitate the monitoring of upper- and lower-tropospheric wind systems and fronts with temporal continuity comparable with that of present satellite and weather radar observing systems. When compared with the present two soundings per day of operational rawinsondes, the profilers represent a major advance toward obtaining wind observations for improved depiction, physical process diagnosis, very-short-term ($\leqslant 6$ hour) prediction (statistical and by extrapolation) and numerical prediction ($\geqslant 6$ hour) of synoptic-scale and mesoscale weather events. Observations from a network of wind profilers would be especially useful in forecasting the motion and intensity of fronts as they propagate across the United Kingdom and influence the evolution of mesoscale precipitation systems over the region.

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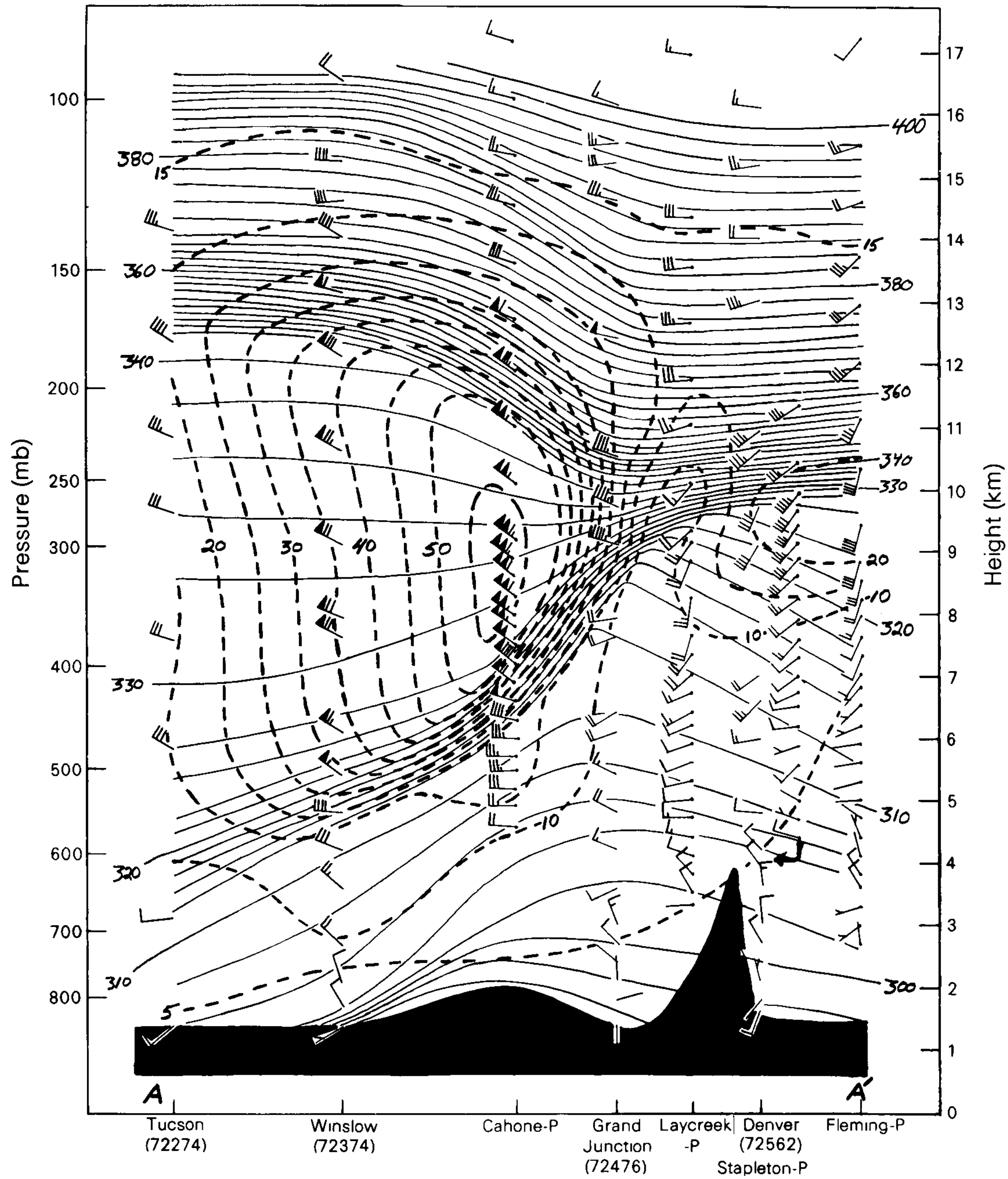

Figure 2. Cross-sectional analysis of wind speed (m s^{-1}), dashed lines, and potential temperature (K), solid lines, at 12 GMT 13 June 1983 along the projection line AA′ of Fig. 1. Analysis is a composite of conventional rawinsonde soundings and radar wind profiles. Profiler soundings are designated by the letter P at the horizontal axis. Solid pennants and feathers represent the same values as in Fig. 1.

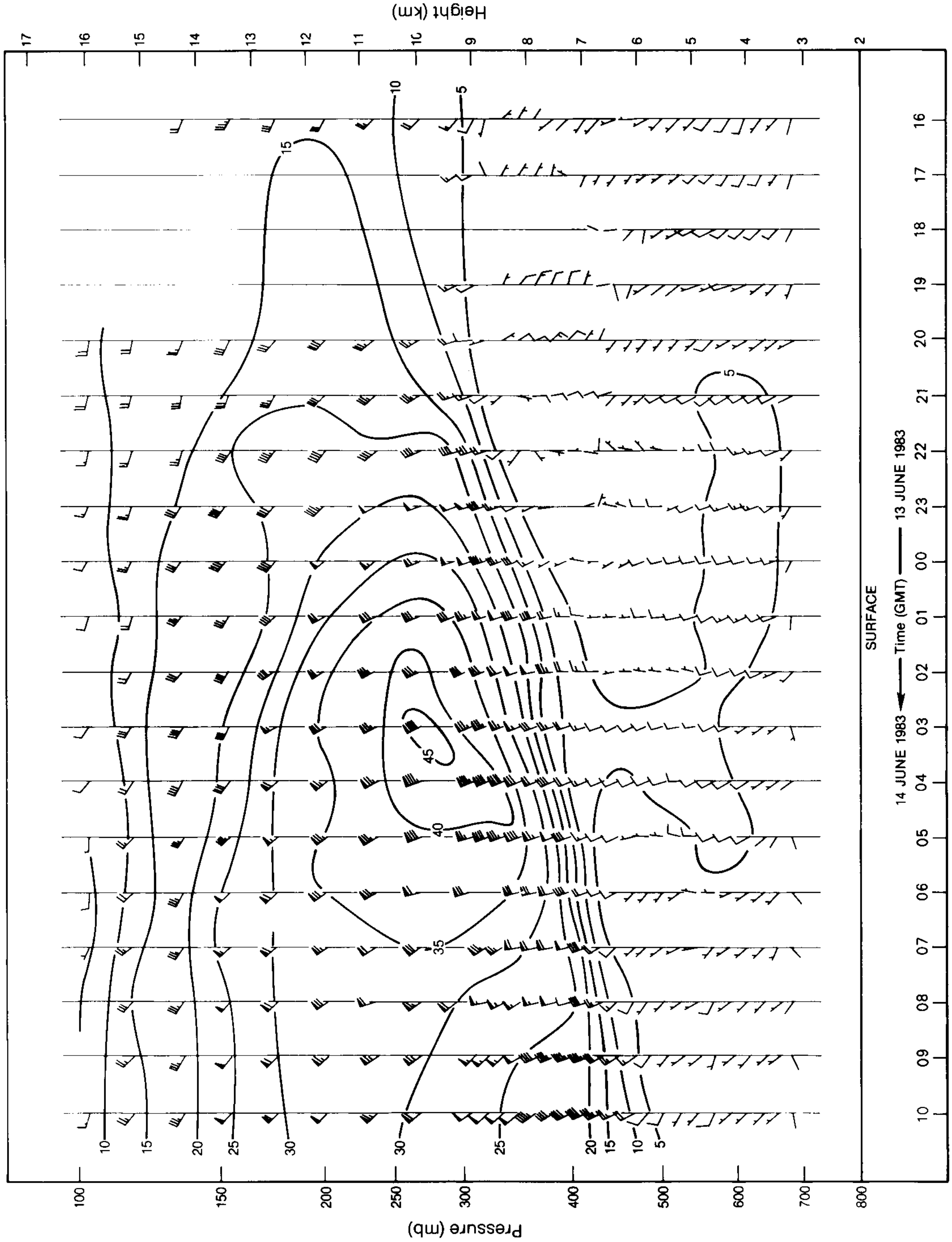

Figure 3. Time-series analysis of wind speed (m s^{-1}) and wind vector plot for the Lay Creek, Colorado VHF radar wind profiler between 16 GMT 13 June and 10 GMT 14 June 1983. Solid pennants and feathers represent the same values as in Fig. 1.

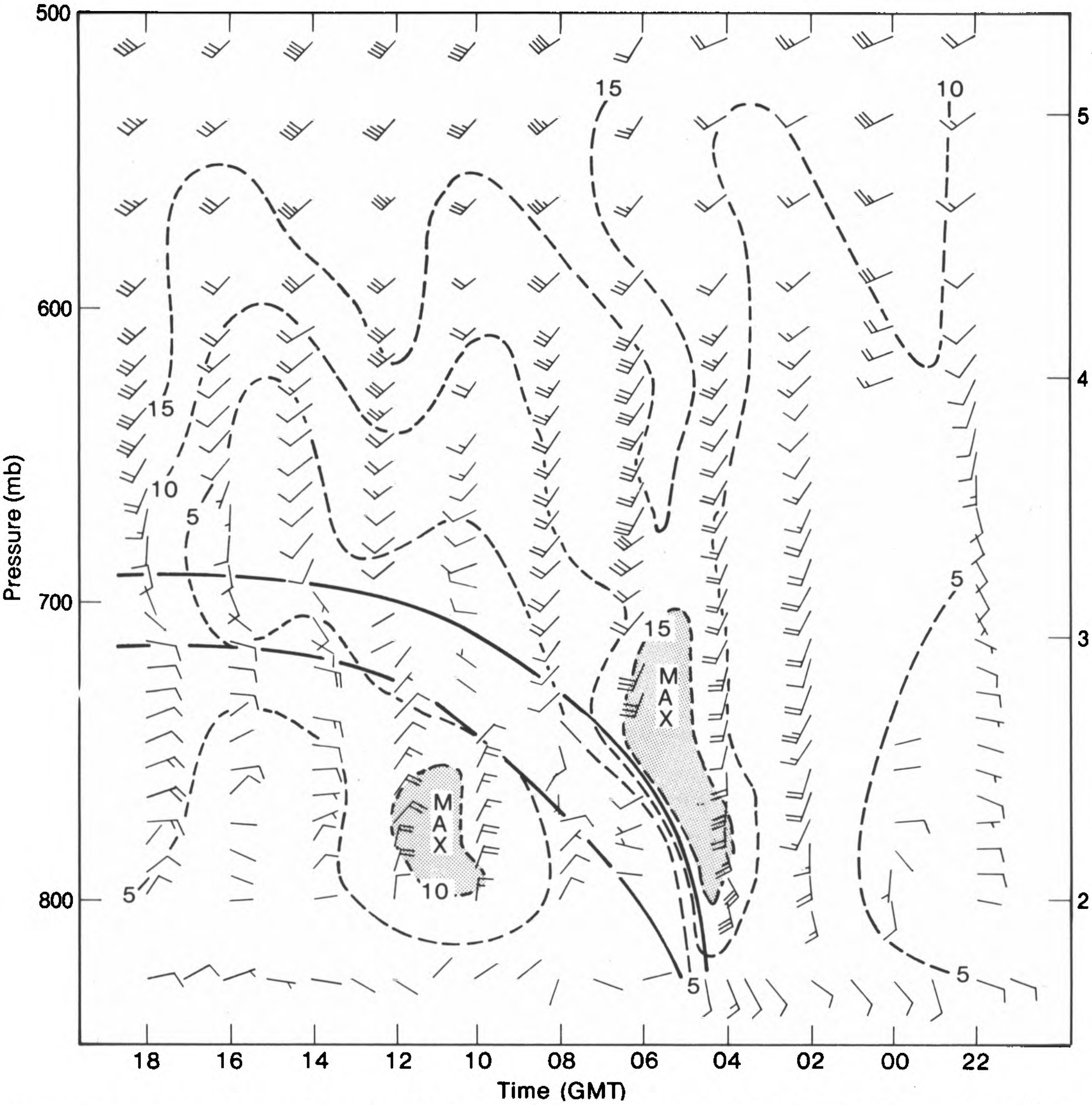

Figure 4. Surface frontal passage time-series analysis of Stapleton, Denver, Colorado UHF high-vertical resolution (100 m) radar winds between 22 GMT 11 June and 18 GMT 12 June 1983. Wind speed (m s^{-1}), dashed lines, and frontal boundaries, heavy solid lines. Solid pennants and feathers represent the same values as in Fig. 1. Surface winds are plotted at lowest height level.

Letter to the Editor

Civil Defence — meteorological advisers to local authorities

I would like to repeat a successful call to your readers that was made in the winter of 1980 for meteorological officers without a likely war role, or those who have recently retired, to volunteer for training as Local Authority Scientific Advisers under a joint Home Office and County Council scheme.

Some twenty meteorological officers volunteered their services in 1981 to various county authorities in England and Scotland. The Royal County of Berkshire was fortunate in securing five, all of whom have become valued Team Leaders with the County and District Councils. Volunteers who make up local authority Scientific Adviser Groups can come from a very wide scientific background, but it has been found that meteorological officers have the highest aptitude and degree of skill for the tasks involved.

Scientific Advisers are responsible for advising the Local Authority Chief Executives in a major civil disaster or in the event of war, including a possible nuclear strike against this country. There is an obvious relevance of meteorological conditions to a developing industrial disaster, e.g. Flixborough, the USA Three Mile Island disaster or the Canadian chemical train derailment and fire at Mississauga in 1980. The prediction of radioactive particle deposition and the spread of toxic gas clouds would have the greatest importance to the enhancement of public survival.

I would therefore like to appeal through your columns to those interested in offering their services to their nearest local authority to contact myself or the County Emergency Planning Officer of their own County Council. Not only qualified meteorological officers are wanted, but any numerate officer who would like to undertake this very worthwhile and humanitarian task. The commitment is not a heavy one and the accent is on the word 'volunteer'.

I will be pleased to answer any queries by letter or telephone and I undertake to pass on any written queries to the appropriate County Emergency Planning Officer, depending on place of work or residence.

J. P. Whittaker
(County Emergency Planning Officer)

Royal County of Berkshire,
County Emergency Planning Team,
Shire Hall, Reading.

Notes and news

60 years ago

The following extract was taken from the *Meteorological Magazine*, June 1924, **59**, 111–112.

The Meteorological Office Exhibit at Wembley

THE British Empire Exhibition at Wembley was opened by H.M. the King, on April 23rd, with all the pomp and ceremony befitting such an occasion. Unfortunately, the brilliance of the spectacle was somewhat marred by the gloominess of the weather, the sun being obscured by low cloud during the whole ceremony.

The apparent preparedness of the greater part of the Exhibition on the morning of the 23rd was a surprise to those who had visited the grounds only a few days previously. Gardens and trees seemed to have grown up in the night as if by magic, more especially so in the vicinity of H.M. Government Pavilion. In the less conspicuous parts of the grounds, however, there was still much to be done and the annexe to the Government Pavilion in which, according to the official guide, the meteorological exhibit was said to be housed, was still in a state of incompleteness. For reasons over which the Meteorological Office had no control, three weeks elapsed before this part of the building was opened to the public. The entrance to the meteorological section is to be found at the back of the Government Pavilion. It is self-contained, and the walls are hung with specially prepared diagrams illustrating the work of the Office with regard to Weather Forecasting, Climatology, Marine Meteorology, Upper Air Investigations and British Rainfall. Numerous instruments used in meteorological work are on view, amongst these being a Dines Pressure Tube Anemograph, which gives a continuous record of the speed and direction of the wind over the building. There is also an Autographic Rain Gauge to show the intensity of rainfall. In a glass bell is exhibited a specimen of a Balloon Meteorograph, together with a large working model of the same instrument. [So reliable is this instrument in use that in spite of its small size, it can record temperature without an error of more than one degree centigrade, and pressure to within a few millimetres of mercury. The record is inscribed on a small piece of silvered plate about the size of a postage stamp and has to be deciphered by the aid of a microscope].

The preparation of forecasts is demonstrated by members of the Meteorological Office Staff who are on duty there. By means of a wireless installation, data from a great part of the Northern Hemisphere are collected. These are plotted on weather maps and deductions are drawn regarding the coming weather. Two large weather charts, each measuring 10 feet by 9 feet are to be seen in the main building near the front entrance, one of the western part of Europe and the other of a large part of the Northern Hemisphere extending from America to Russia. The chart for western Europe is drawn twice daily, for 7h. and for 13h., and that for the Northern Hemisphere once daily, so that visitors may see the current meteorological situation and at the same time realise the rapidity with which meteorological data are collected from very wide areas.

On May 14th, Their Majesties the King and Queen, accompanied by Their Majesties the King and Queen of Roumania, honoured the Meteorological Section with a visit. The Royal Party were received by Dr. G. C. Simpson, C.B.E., F.R.S., Director of the Meteorological Office, and inspected the exhibit with much interest. The King was particularly interested in the current weather map and in the meteorological log which was kept on board H.M.S. "Thrush," when His Majesty, as Prince George, was in command of that vessel. His Majesty immediately recalled the name of the officer who was responsible for the entries.

Judging from the interest shown by the numerous visitors who inspect the exhibit it would appear that the importance of meteorology is being increasingly recognised by the general public.

Call for papers for the WMO* technical conference on urban climatology and its applications with special regard to tropical areas

Urbanization is proceeding with great rapidity in the developing (tropical) world, including the growth of some extremely large cities. Population pressures are great but resources are limited. This may lead to a deterioration of environmental conditions for a large proportion of mankind. However, if simple climatic principles are incorporated in the plans of these settlements they can be made safer, healthier, more comfortable and efficient.

In order to accomplish this it is necessary to gather the available expertise in urban, applied, and tropical climatology to review existing knowledge, consider its relevance to the design and operation of tropical cities and to formulate the most effective means of ensuring its use.

*WMO World Meteorological Organization

These are the objectives of the WMO technical conference on urban climatology and its applications with special regard to tropical areas, which is co-sponsored by the World Health Organization. The conference will be held in Mexico City from November 26 to 30, 1984. Topics of relevance to the meeting include all aspects of urban climatology (e.g. processes, effects, models, methods and case studies) especially those relating urban applications (e.g. hazards, health, comfort, air pollution, energy/water conservation and use) to urban planning (e.g. climate factors in the siting, layout and operation of settlements) and to tropical locations.

Papers are invited on the above topics, and abstracts (less than 500 words) should be sent by July 15, 1984 to:

Professor T. R. Oke
c/o World Climate Programme Department
World Meteorological Organization
41, Giuseppe-Motta
Case postale No. 5
CH-1211 Geneva 20
Switzerland

It is intended that the conference will include considerable discussion amongst the participants. Therefore only those papers deemed most important to the objectives of the meeting will be selected for presentation in the main sessions. Provision will be made for the others to be presented as short lectures or as posters (please indicate your preference). The conference will be conducted in English, French, Spanish and Russian. Abstracts may be submitted in any of these languages.

Reviews

Catalogue of European industrial capabilities in remote sensing. 250mm × 175mm, pp. x + 310, *illus.* A. A. Balkena, Rotterdam, 1982. Price £13.00.

The aim of this catalogue as stated in the preamble is to provide information on equipment, services and design capabilities available from European companies in order to support earth observation campaigns.

The initiative for the catalogue comes from an international association called EUROSPACE, which has been set up by some 80 European aerospace and electronic firms. The declared aim of EUROSPACE is the promotion of European space activities.

A short introductory section (incorrectly titled 'The theory of remote sensing') categorizes sensors and platforms, and outlines data handling facilities. After a brief section on European-related remote sensing activities, the various governmental organizations involved in this field and their remote sensing activities are detailed. The next two sections form the main bulk of the catalogue. These are specification type descriptions of the equipment or service available and a description of the activities and potential activities of some 80 European companies (presumably mainly the sponsors of EUROSPACE). The final section consists of 24 preformatted blank 'Update' pages.

This catalogue is a useful availability guide for those persons planning remote sensing exercises on any scale from elaborate field experiments to extraction of specific data from a communal facility (though I would also have expected their organizations to have received a complimentary copy). It is however unlikely to be of much interest to the more general reader of the Meteorological Magazine.

D. R. Pick

Geophysical fluid dynamics, by Joseph Pedlosky. 150 mm × 235 mm, pp. xii + 624, *illus.* Springer-Verlag, New York, Heidelberg, Berlin, 1982. Price DM 63.00, approx. US $26.30.

This book is a paperback version of an original hardcover edition (published in 1979). That original has already become a standard, if not a classic, in its field, and the availability of a paperback edition will be generally welcomed. Pedlosky's themes are the derivation and analysis of mathematical models of nearly geostrophic motion in the atmosphere and oceans; and the text is aimed at those engaged — or preparing to engage — in research into such motion.

Two introductory chapters deal with basic matters — rotating coordinate frames, vorticity and geostrophy, for example. The discussion of vorticity (and associated theorems) is the highlight here. In Chapter 3, the notion of quasi-geostrophic approximation is thoroughly explored in the simple case of divergent barotropic flow. Poincaré and Kelvin waves are examined before the main subject, the Rossby wave, is introduced, the equivalence (in barotropic flow) of planetary vorticity gradients and sloping lower boundaries being clearly indicated. Chapter 4 contains a useful treatment of viscous boundary layers and their effects on barotropic flow. Chapter 5 deals with homogeneous models of the wind-driven oceanic circulation, and illustrates the concepts and techniques introduced in the previous two chapters. Quasi-geostrophic approximation for the case of baroclinic flow on a sphere is treated in Chapter 6. This leads to the important approximate potential vorticity equations of geostrophic dynamics. Aspects and applications examined include forced stationary waves, wave/mean interaction, layer models and thermocline modelling. Instability theory is considered in Chapter 7. Much attention is given to linear baroclinic problems, but sections on non-linear developments and barotropic and mixed instabilities are also notable. The concluding chapter briefly discusses some ageostrophic phenomena — principally continental shelf waves, frontogenesis and equatorial modes.

Throughout, the emphasis is on analytical technique and underlying physical concepts. The inclusion of detailed mathematical derivations will not appeal to all tastes, but is perhaps the most valuable feature of the book. Meteorological and oceanographical theory are inescapably technical subjects, and anyone who would contribute to progress in the field must acquire particular analytical skills. For those doing research into geostrophic motion in the atmosphere and oceans, Pedlosky's book is an invaluable aid to the learning and refinement of these skills. Its philosophy, admirably, is that of the workshop manual rather than the sales brochure.

Given such a realistic approach, exercises and examples would not have seemed out of place — but there are none. Perhaps an opportunity has been missed here: carefully drafted exercises could have served the dual purpose of challenging the reader and extending the scope of the text. Many important topics are indeed not covered — and the omissions will be felt more acutely by meteorologists than by oceanographers. Acoustic modes are not examined, and hardly any attention is paid to the special coordinate systems which are commonly used in meteorological dynamics. Internal gravity waves and adjustment to geostrophic equilibrium are also not covered. The concern with quasi-geostrophic dynamics is so great that the derivation (in Chapter 6) of the relevant equations from the original, unapproximated forms does not pause to recognize the hydrostatic primitive equations! Neither is much said about the observed atmospheric circulation, beyond what is necessary to introduce theoretical developments. Sadly, these omissions may deter many meteorologists — especially numerical modellers — from studying the book and assimilating the valuable material that it contains.

A strange feature is the almost total lack of reference to laboratory experiments on rotating flow. While it can be easily appreciated that a thorough discussion would have been long and perhaps diversionary, the presentation would surely have been eased in places by brief consideration of simple laboratory systems. This is especially so in Chapter 4 (which in fact contains much material that is helpful in the analysis of laboratory flows).

Inevitably, developments since 1979 make the book appear outdated in a few respects. Thus the recent interest in atmospheric blocking, and the general question of the maintenance of zonal asymmetries in the time-averaged flow, are not anticipated. However, the emphasis of the text on concepts and techniques equips it well to maintain underlying relevance to recent or foreseeable developments. A good illustration is the treatment of wave kinematics given in Chapter 3: a lucid exposition of group velocity and related quantities here provides a useful starting point for anyone wishing to follow current developments in Rossby wave propagation theory. Again, the central theoretical importance of potential vorticity — which becomes ever more apparent — is stressed in Chapters 6 and 7.

One elementary notion which is given inadequate attention is that of the apparent vertical. In Chapter 2, gravitational and centrifugal potential are combined in the usual way, but without comment that the direction of the implied vertical then depends on the rotation rate of the chosen coordinate system. The absence of Doppler-shift properties in rotating flows, which is noted for the barotropic case in Chapter 3, is intimately related to this conceptually important feature. The appearance of the 'non-Doppler effect' in baroclinic flows is obscured in Chapter 6 because the horizontal boundary conditions are not considered in the appropriate parametric limit.

The presentation of the text is good. Clearly laid out equations, in conjunction with a familiar and reasonable notation, greatly ease the task of the serious reader. Intending purchasers should be warned, however, that pages 437–468 were missing from the review copy.

Pedlosky's book can be recommended to everyone working in dynamical meteorology or oceanography — students and professional researchers alike. It is not, nor is it intended to be, about general circulation theory or numerical modelling strategy and method. It is a specialized text which sets out to illuminate the fundamental concepts and techniques of geophysical fluid dynamics, and is highly successful in that endeavour.

A. A. White

Books received

Consequences of climatic change, edited by Catherine Delano Smith and Martin Parry (Department of Geography, Nottingham University, 1981. £3.50) is a collection of papers as a consequence of a conference of the Historical Geography Research Group of the Institute of British Geographers convened at the University of Nottingham in July 1980. These papers have been published as an attempt to link two extremities of the research spectrum — the archaeological and the climatological — in the context of climatic change.

Atmosphere, weather and climate, by R. G. Barry and R. J. Chorley (London and New York, Methuen & Co. Ltd., 1982. £6.50 paperback, £14.50 hardback) is the fourth edition of this book first published in 1968. Important changes to the present edition include substantial rewriting of the chapters on 'Small-scale climates'; the addition of chapter summaries; the updating and standardization of units; the addition of more than 30 figures and plates; and changes to material on solar radiation, thunderstorm mechanics and drought, the characteristics of mesoscale rainfall systems and tornado structures, and the climatic features of disturbances occurring within continental high pressure cells.

World-climates: with tables of climatic data and practical suggestions, by Willy Rudloff (*Books of the Journal Naturwissenschaftliche Rundschau*. Stuttgart, Wissenschaftliche Verlagsgesellschaft mbH, 1981. DM 180) contains 50 figures, 1474 climatic tables and 116 hygrothermal diagrams as well as other tables and reviews and is aimed at the general public and tourism for a work on climatology suitable for practical use. The introductory chapters provide information on weather and climate, the global atmospheric circulation, bioclimatic relations, and a classification of climate which the author considers a revised and consistent development of a climate classification system published in 1931 in the second edition of Köppen's *Outlines of climatology*.

Finite-difference techniques for vectorized fluid dynamics calculations, edited by David L. Book (New York, Heidelberg and Berlin, Springer-Verlag, 1981. DM 72) is from the *Springer series in computational physics.* The book describes several finite-difference techniques developed recently for the numerical solution of fluid equations. Both convective (hyperbolic) and elliptic (of Poisson's type) equations are discussed. The book is intended for specialists in computational fluid dynamics and related subjects. It includes examples, applications and source listings of program modules in Fortran embodying the methods.

Evaporation into the atmosphere. Theory, history, and applications, by Wilfred H. Brutsaert (Dordrecht, Boston and London, D. Reidel Publishing Co., 1982. Dfl 80) is the first in a series entitled *Environmental fluid mechanics* intended for professional scientists and engineers who apply their scientific knowledge to practical goals. An introductory chapter provides an account of the history of the theories on evaporation, the central part deals with the conceptualization and the mathematical formulation of water vapour transport in the lower atmosphere, while the final chapters provide a survey of currently available techniques for measuring and calculating the rate of evaporation.

Mr E. W. C. Harris, Librarian of the National Meteorological Library, being presented on 16 February 1984 by Lt. Col R. Wright, USAF, with a 28th Weather Squadron plaque in recognition of the assistance given by the library to the USAF Air Weather Service.

THE METEOROLOGICAL MAGAZINE

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The use of anomaly maps in local forecasting

By S. J. Caughey

(Meteorological Office, Belfast/Aldergrove Airport)

Summary

Climatology provides an important input to local forecasting. This article describes the variation of mean daily values of meteorological parameters with 900 m wind direction. The spatial patterns of 'anomalies' reveal the airmass effects that usually accompany the directional changes and the local forcing by topographical and coastal effects that can occur.

1. Introduction

The greater availability of weather radar data has led to a wider appreciation of the local variability in, for example, shower activity and frontal sub-structure on the mesoscale. Some of these variations (such as orographic rainfall) may well be locally induced and detailed study of particular events can yield valuable information on the interaction of weather systems with hilly regions and coastal zones (Caughey and Partington 1983).

Other improvements in local forecasting skill, such as the prediction of fog and frost, depend on a detailed knowledge of local effects, many of which are related to topographical influences. It is in this area especially that climatological data can be used to reveal small-scale variations. Although observations from the climatological network are not available in 'real' time they contain much more detailed information than is routinely available to the forecaster.

When considered as a function of the 900 m wind direction climatological data can reveal the likely small-scale spatial variations in meteorological parameters within a region. These are due to the correlation between airmass type and wind direction, and influences from the underlying terrain. This paper describes the results of an investigation into climatic variability in Northern Ireland as a function of wind direction. The 'anomaly' maps produced enable forecasters to assess the likely ranges in meteorological variables across the Province, once the synoptic framework has been decided.

2. Available data

The distributions to be discussed were derived from data drawn from 37 climatological stations in Northern Ireland (see Fig. 1(a) and Table I). Mean daily values of the parameters considered are listed, as are the record lengths for each station. Departures (or anomalies) from the mean daily values (over the whole period of the records) were then derived as functions of the 900 m wind direction (in 30° sectors — a value of 060°, for example, includes wind directions from 045° to 075°). Maximum and minimum temperature anomalies were calculated on a seasonal basis, sunshine for the winter and summer 'half' years and rainfall for the whole year. Since topography has a major influence on anomalies the distribution of land above 1000 ft in Northern Ireland is given in Fig. 1(b).

A vector mean wind speed was derived for each day from the 00, 06, 12 and 18 GMT Long Kesh ascents. If the vector mean speed was less than 5 m s^{-1} the day was assigned to the light and variable category and is not considered further here (this resulted in rejection of from 10% to 28% of the available data, depending on the wind direction category). Otherwise the data were assigned to one of the 30° sectors. Ignoring the year-to-year variations in the quantities and the fact that different years and varying periods of records have been used for the various stations, the anomalies can be considered to reveal effects from airmass and local influences. To illustrate these the station anomalies have been drawn up in contour map form.

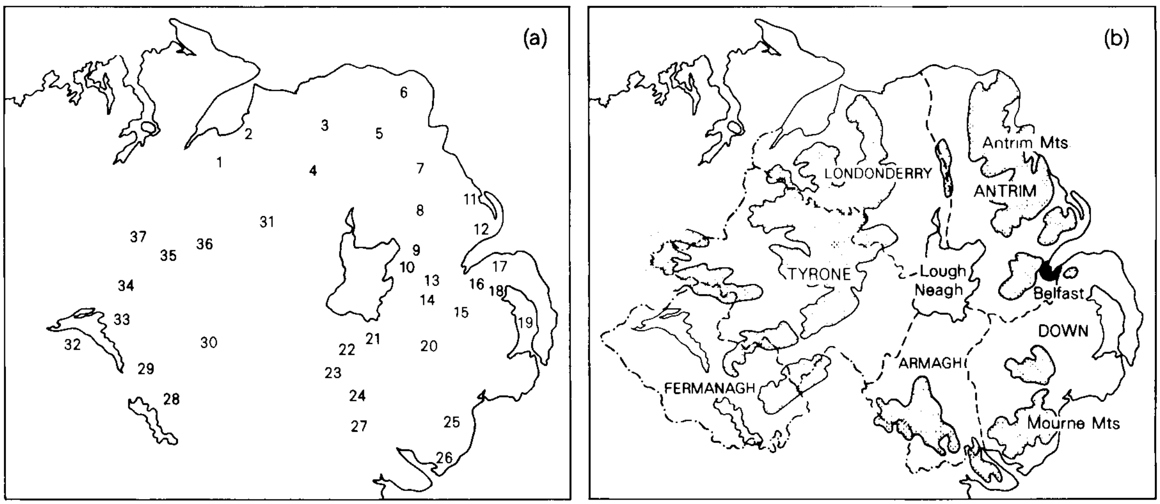

Figure 1. (a) locations of stations listed (and numbered) in Table I and (b) land above 1000 ft (shaded areas).

3. Rainfall

Rainfall distributions are strongly influenced by topography, hence only the behaviour of the annual daily averages is considered. A predominant process, which probably accounts for most of the increase of rainfall with height, is orographic enhancement. In this case hills force moist low-level air to rise forming 'cap' clouds which amplify pre-existing rain falling from higher-level frontal clouds. An important factor is the replenishment of liquid water in the cap clouds, so strong winds (>15 m s^{-1}) are required.

Table I. *Mean daily values of meteorological parameters (computed over the whole record length) for each station used in the analysis.*

Station		Length of record	Rainfall Mean daily amount Whole year averages	Minimum temperature		Maximum temperature		Sunshine Daily averages		Mean wind at 10 m as % of 900 m wind speed
Name	No.	(years)	(mm)	Autumn (°C)	Winter (°C)	Summer (°C)	Winter (°C)	Winter (hours)	Summer (hours)	
Loughermore	1	9	3.1	5.4	0.2	16.7	5.8	–		–
Ballykelly	2	13	2.2	7.0	1.6	17.7	7.4	1.9	5.0	40
Ballymoney	3	6	2.6	6.3	1.3	17.7	6.9			
Garvagh	4	9	3.2	5.8	0.8	17.3	6.3			
Altnahinch	5	6	4.2	5.7	0.9	16.0	5.3	1.2	4.9	44
Ballypatrick	6	9	3.4	6.2	1.2	15.8	6.0			43
Parkmore Forest	7	11	4.4	5.5	0.3	16.4	5.3			
Lowtown	8	5	3.8	5.3	0.4	15.9	4.9	1.4	4.9	37
Greenmount	9	7	2.3	6.4	1.1	18.1	6.8		–	
Aldergrove	10	40	2.3	6.4	0.9	17.8	6.7	1.6	4.9	46
Larne	11	9	3.0	6.7	1.8	18.0	7.1		–	
Kilroot	12	7	2.4	6.8	1.4	17.4	7.3		–	
Divis	13	8	3.2	4.9	−0.2	15.4	4.5	–	–	
Black Mountain	14	7	3.0	5.3	0.3	15.8	4.9	–	–	–
Belfast (Malone)	15	5	2.5	6.7	1.4	18.4	7.1	–	–	–
Belfast (Stormont)	16	11	2.5	6.8	1.7	17.9	6.9	1.7	5.1	35
Helen's Bay	17	10	2.4	7.4	2.3	17.7	6.7	1.9	6.4	–
Creighton's Green	18	12	2.7	6.9	1.7	16.8	6.2	–		–
Reagh Island	19	10	2.0	7.4	2.0	17.9	7.0	1.9	5.1	–
Hillsborough	20	11	2.4	6.5	1.3	17.3	6.3	1.7	5.0	25
Lurgan	21	10	2.2	6.4	1.2	18.6	7.0			–
Portadown	22	16	2.2	6.2	1.2	18.7	7.2			–
Loughgall	23	11	2.2	5.9	0.6	18.1	7.0	1.8	4.9	16
Armagh	24	22	2.2	6.5	1.4	18.7	7.2	1.8	4.8	
Tollymore	25	10	3.3	7.1	1.8	17.8	7.1			
Kilkeel	26	14	2.7	7.9	2.5	17.6	7.7	2.1	6.4	53
Bessbrook	27	10	2.8			–		1.8	5.0	
Lisnaskea	28	6	3.2	6.0	1.1	18.4	7.1	1.6	4.5	
Pubble Forest	29	9	3.1	5.6	0.1	17.5	6.5		–	
Knockmany	30	9	2.9	5.1	−0.1	17.5	6.5		–	
Derrynoyd	31	9	3.4	5.8	0.8	17.8	6.4		–	
Lough Navar	32	9	3.9	5.8	0.3	17.2	6.2	–	–	
Castle Archdale	33	8	3.1	6.0	0.8	17.5	6.5	1.6	4.6	26
Lough Bradan	34	10	3.2	5.5	0.2	16.6	5.6	1.5	4.5	39
Carrigans	35	8	3.3	5.9	1.0	17.7	6.6	–		38
Lislap	36	11	3.5	5.0	0.0	16.9	5.9	–		–
Baronscourt	37	9	3.1	5.9	0.5	17.7	6.5	–		–

Fig. 2 shows the variation of the percentage of total rainfall (in the complete period of the records) as a function of wind direction for selected stations. This illustrates the influence that wind direction exerts on rainfall amounts and the difference between areas in the south-east compared to the north-west of the Province. Thus in the south-east of Co. Down 30% of the total rainfall occurs in the quadrant 090°–180° (075°–195°), whereas in the north-west (at Ballykelly) the corresponding figure is only 16%. On the other hand, from 230°–030° the average percentage at Ballykelly is much higher than in the south-east.

The anomaly maps (Fig. 3) show the percentage of the mean daily rainfall which falls when the wind direction is 060°, 150°, 210° and 300° respectively. For 060° the rainfall is everywhere well below average, a factor well known to local forecasters as screening from the upland areas of Scotland and northern England. As expected, the anomalies are most prominent in the west where less than half the mean daily amount can be expected. At 150° the pattern has altered markedly with a prominent area in the vicinity of the Mourne Mountains in the extreme south-east; here more than twice the mean daily amount is likely. Most of the Province has above average, except for the extreme north-west. The maximum in south-east Down is doubtless due to local orographic enhancement due to forced ascent of moist onshore winds.

At 210° the maximum in the south-east is still significant and now the values are above average everywhere. A large area (140%) to the west of Lough Neagh may be related to orographic effects in the hills of Co. Tyrone and Co. Fermanagh. Finally, for 300° conditions are wetter than average in the north (up to 120%) — probably owing to onshore shower activity — but the south-east is much drier. Although these anomaly maps represent averages over all synoptic types they nevertheless provide the forecaster with useful guidance in assessing the likely variations when the synoptic framework (and hence wind direction) has been established.

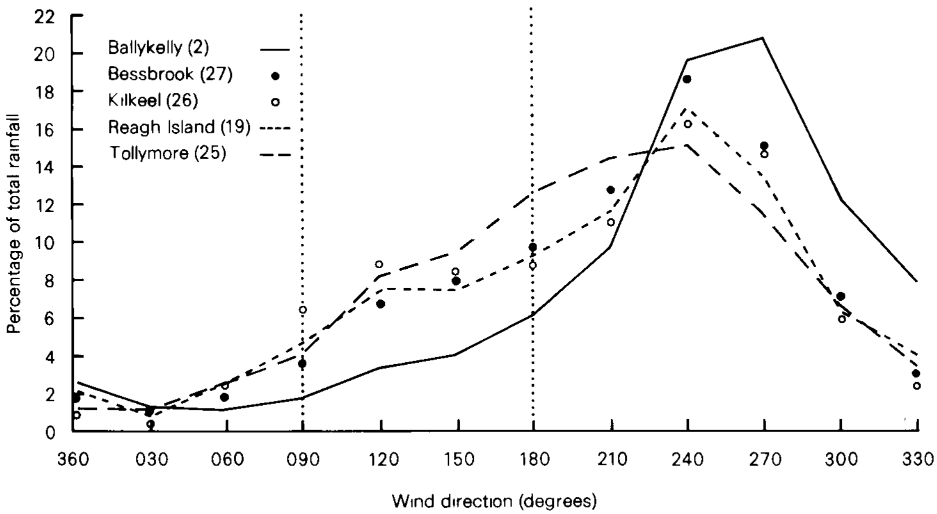

Figure 2. Percentage of total rainfall (in the complete record) as a function of 900 m wind direction for selected stations.

4. Temperature

(a) *Maximum temperature (summer)*

Because of the seasonal variations in the difference between sea surface and land temperatures it is considered more appropriate to compile the anomaly distributions on a seasonal basis. These should reveal (and quantify) the raising of night minima near coasts in winter as well as the lowering of day maxima in summer. Fig. 4(090°) does indeed demonstrate that onshore winds on the east coast reduce the day maximum by ca. 1 °C in south-east Down, whereas in the north-west continued diurnal heating over land results in increases of about the same magnitude. The highest temperatures in easterly winds are almost invariably reported from western counties of the Province. In settled sunny weather the anomalies in the north-west especially will be much greater.

Winds from 180° generally bring warmer conditions with temperatures up to 2 °C above the normal in the north-west but still a cooling of ca. 0.5 °C in the extreme south-east, where onshore winds are still

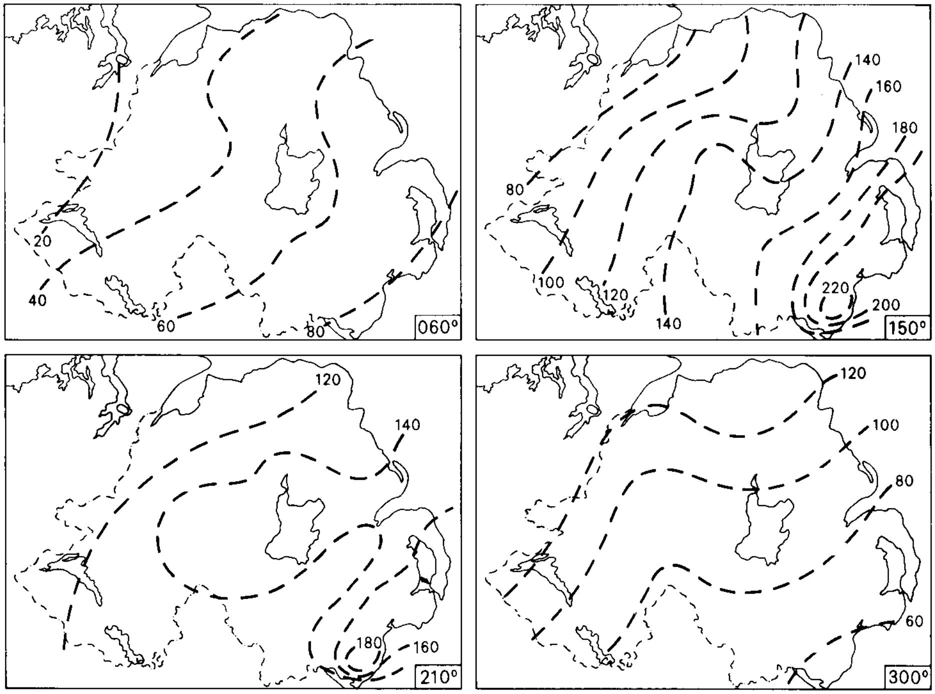

Figure 3. Anomaly maps drawn from the percentages of the mean daily rainfall at the various stations which occur for wind directions of 060°, 150°, 210° and 300°.

significant. At 270°, however, the eastern counties show a positive anomaly and the negative zone is transferred westwards to the region affected by onshore winds and probable increased cloudiness (see Fig. 9). As expected, northerly winds reduced day maxima to below average, except for a narrow coastal zone in the extreme south-east. In northern counties reductions of up to 2 °C are average and this value is doubtless markedly exceeded in cloudy polar airmasses.

(b) *Maximum temperature (winter)*

The surrounding sea in winter has an ameliorating effect on low day maxima. Easterly winds result in anomalies well below average inland, especially in the west and north-west and to the lee of the Antrim and Mourne Mountains. However, in the coastal zones of south-east Down temperatures are rather closer to average (see Fig. 5). With a 180° wind direction temperatures are everywhere above average by between 1–2 °C, but again the lower anomalies are found along the coasts, probably because sea temperatures are generally below airmass temperatures for this direction. At 270° the anomalies are again everywhere positive with the maxima as expected in inland areas. With northerly winds the pattern is entirely negative, with the greatest deviations away from the coasts. These can be as much as 2.5 °C below the winter average for all wind directions. Thus, for example, reference to Table I shows that with northerly winds at Armagh the average day maximum is reduced to 4.7 °C. In summary, therefore, the greater anomalies (positive or negative) tend to occur in inland regions with coastal regions remaining closer to the overall averages. As expected the sign of the anomaly is very sensitive to wind direction which emphasizes the correlation between this parameter and airmass type.

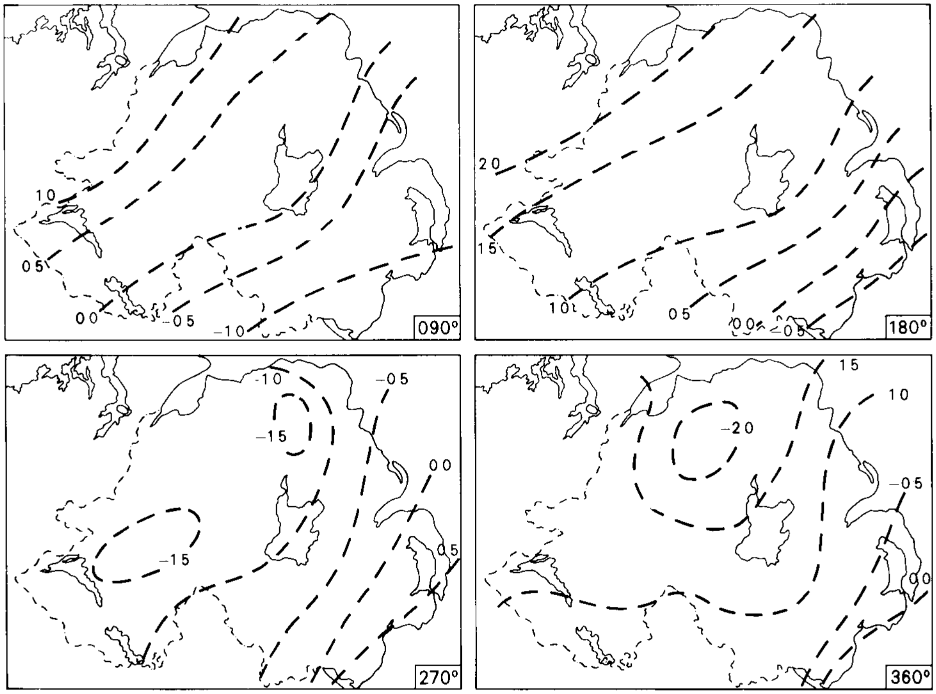

Figure 4. Anomalies of summer (June, July, August) maximum temperature (°C) for wind directions of 090 °, 180 °, 270 ° and 360 °.

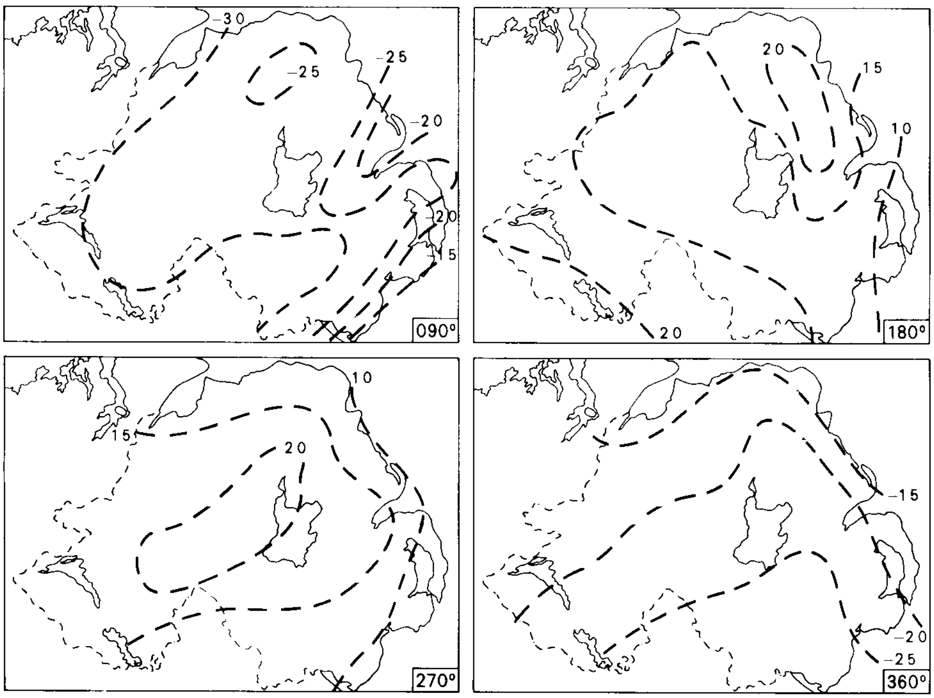

Figure 5. As Fig. 4, but for winter (December, January, February) maximum temperature.

(c) *Minimum temperature (autumn)*

Minimum temperature characteristics were felt to be most important in autumn and winter, so only these are considered here. The anomaly patterns for autumn are given in Fig. 6. For 090° a strong gradient in anomalies exists, with lowest values in the extreme west of the Province. Hence, for example, at Lisnaskea (Co. Fermanagh) the average minimum of 6.0°C becomes 3.5 °C when winds are from 090°, and clearly ground frosts may be expected in sheltered places. At Kilkeel, on the other hand, the average autumn minimum is almost 5 °C higher, at 8.4 °C. With winds from 180° the pattern is much altered, with anomalies everywhere positive. The greatest values are again in the west, up to 3°C — hence minima of around 9–10 °C may be expected. For 270° the anomalies are small. In northerly winds negative anomalies appear in all areas. As one would expect, the deviations increase in magnitude away from the north coast, to reach ca. 3.5 °C, in central and southern districts. At Aldergrove Airport, for example, the average night minimum of 6.4 °C is reduced to 2–3 °C in this wind direction, so that ground frost may again be expected.

(d) *Minimum temperature (winter)*

This is an extremely important category since Road Hazard Warnings are frequently issued in this period and a good appreciation for the location of regions particularly prone to low temperatures is vital. For 090° minimum winter temperatures (see Fig. 7) are below average, except for a narrow coastal strip in Co. Down and Co. Antrim. Thus at Lisnaskea in this wind direction the average night minimum would be -1 °C. With 180° the anomalies are everywhere positive, by up to 3 °C in the west, so air frost is much less likely with this wind direction. Similar considerations apply to 270°. However, with 360° all anomalies are again strongly negative reaching -3.5 °C in the south. The general distribution is very similar to autumn anomalies for this wind direction. The average minimum at Armagh during northerly winds is therefore expected to be -2.0 °C, and of course in 'favourable' synoptic types would be much lower.

(e) *Mean wind speed*

The main influence on near-surface wind speeds is from the reduced frictional drag over the sea compared to the land. Hence onshore winds at coastal sites are invariably a higher percentage of the 900 m wind speed than offshore winds. The values given in Fig. 8 are the percentage changes from the mean percentage that the 10 m wind speed is of the 900 m wind speed. Thus at Kilkeel, for example, the 10 m wind speed is, on average, 53% of the 900 m speed (see Table I) but for 090° (i.e. onshore winds) this increases by 140% to 75% of the 900 m wind speed. For westerly (offshore) winds, on the other hand, the percentage decreases from 53% to 45%. As expected, inland regions show much smaller variations from the average, since frictional effects vary much less with wind direction.

5. Sunshine

(a) *Winter*

With easterly winds in winter Co. Down is frequently affected by low cloud (formed by convection over the sea) which reduces sunshine amounts markedly. However, the shorter sea track to Co. Antrim results in values remaining near average. Less than 20% of the mean daily average is recorded in some places with a wind direction of 090° (see Fig. 9). In the north-west, however, the figures tend to be much

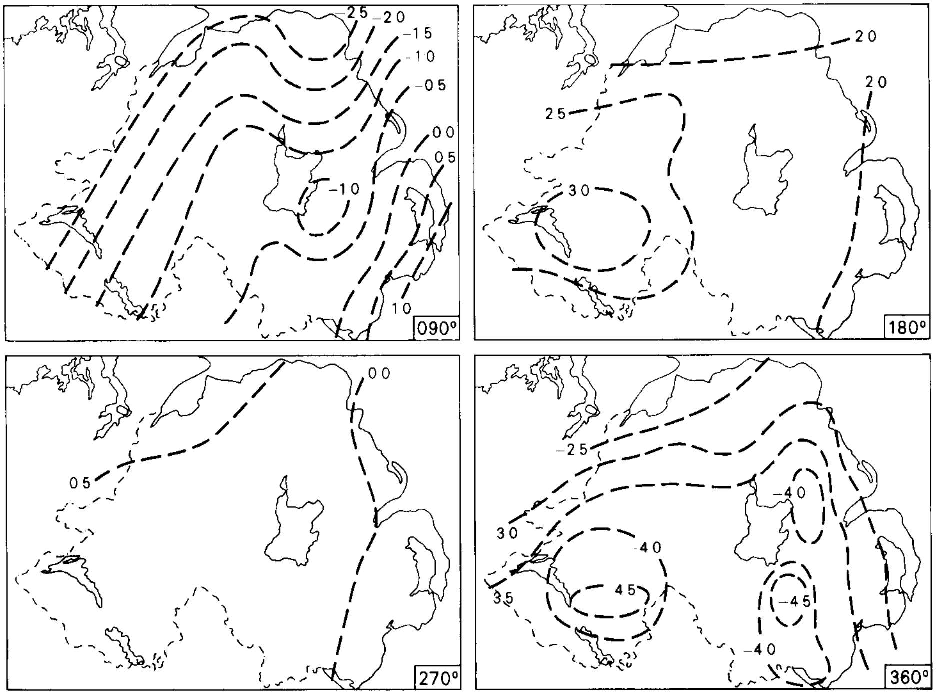

Figure 6. As Fig. 4, but for autumn (September, October, November) minimum temperature.

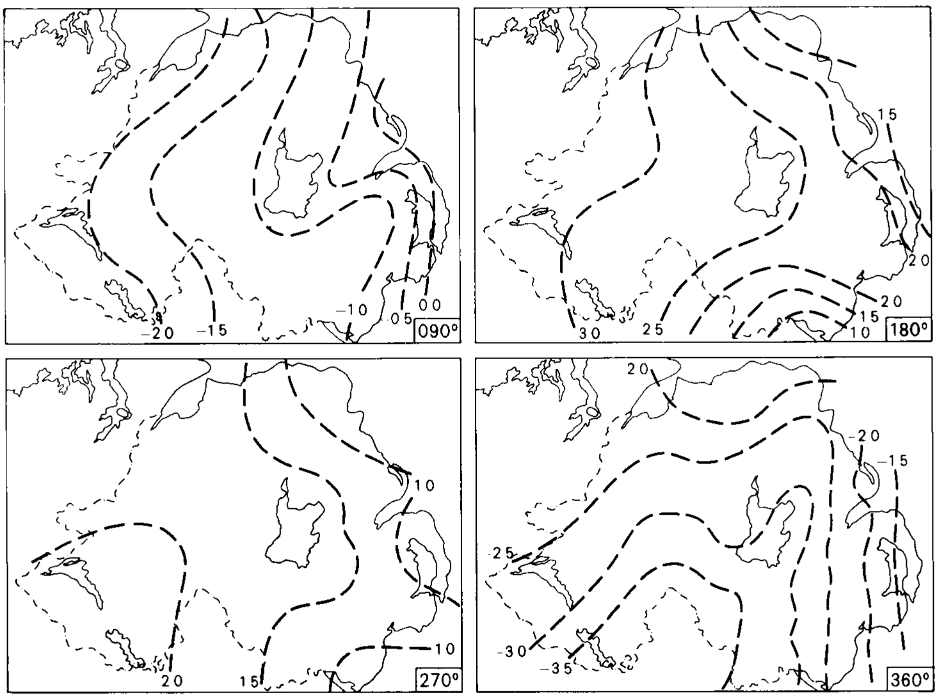

Figure 7. As Fig. 4, but for winter minimum temperature.

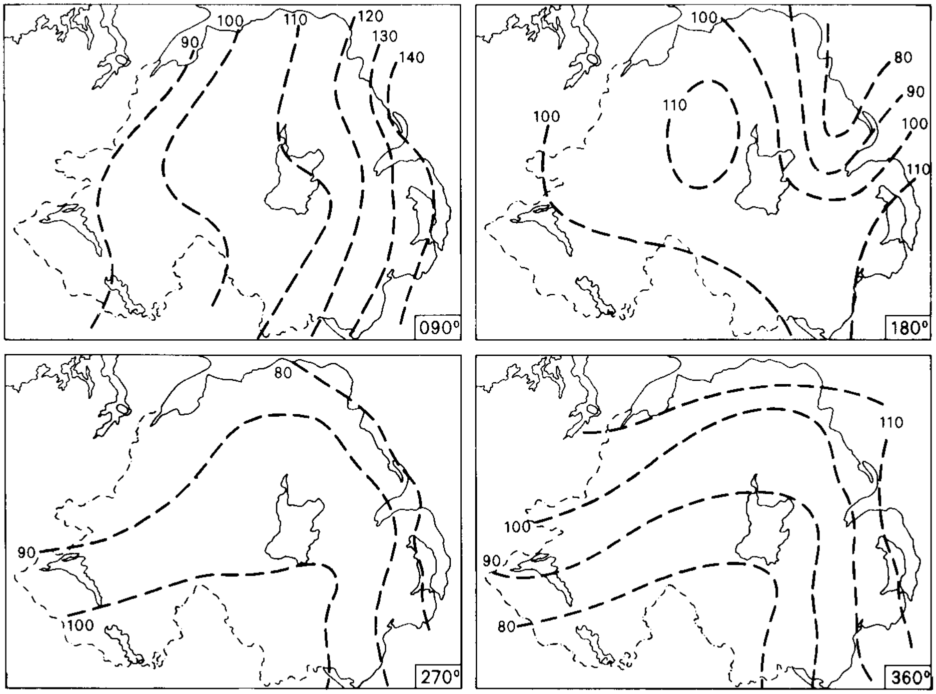

Figure 8. Percentage changes from the mean percentage that the 10 m wind speed is of the 900 m wind speed. The averages are taken over the complete record lengths without seasonal differentiation and are presented for 900 m wind directions of 090°, 180°, 270° and 360°

above average. At 180° the values are everywhere below normal so that this is a particularly cloudy direction in winter, probably because it is more frequently associated with cyclonic situations. As expected, with a wind direction of 270° the cloudier area now switches to the west of the Province, although values are also reduced in the north-east probably owing to orographic effects over the Antrim Plateau. The lowland areas of east and central Co. Down provide the only values above normal. For 360° the values range from about average on the north-west coast to 240% of average in the central and eastern regions, equivalent to about 4 hours of bright sunshine per day. This doubtless reflects greater convection over the relatively warm sea and the dissipation of cumulus or stratocumulus well inland where surface temperatures are low.

(b) *Summer*

In summer with a wind direction of 090° the coastal zones are now sunnier than inland regions, presumably owing to cumulus and stratocumulus convection over land (see Fig. 10). Values reach 140% of average, so at Reagh Island with this wind direction the mean daily amount is 7 hours. Unlike the winter period it seems that southerly winds in summer are associated with above average sunshine amounts, presumably because they are now more frequently anticyclonic. At 270° values tend to be below average, whereas for 360° they are everywhere above average especially in the Greater Belfast and north Down areas.

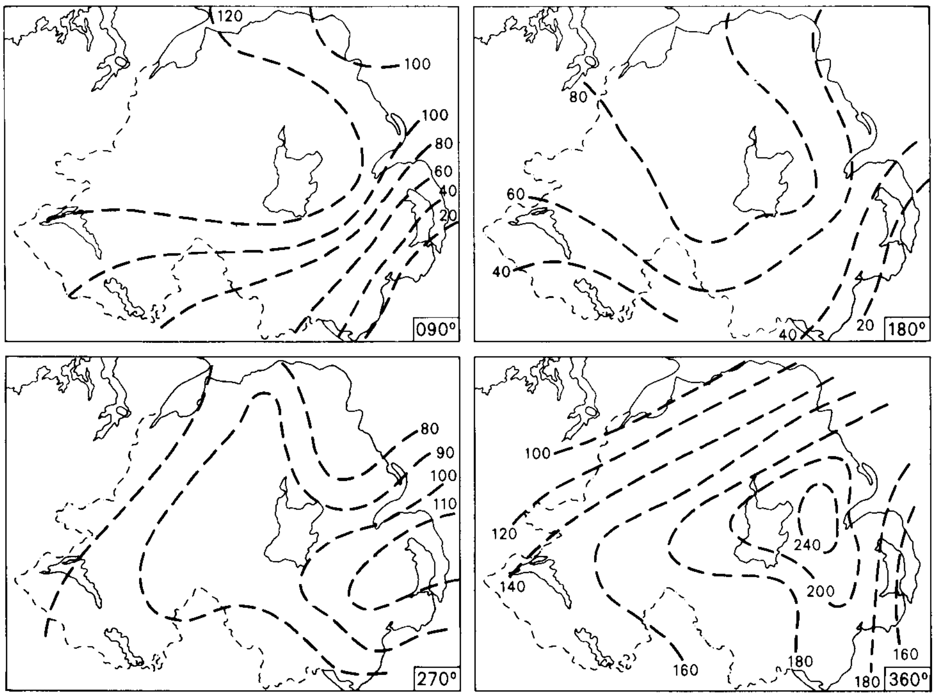

Figure 9. Percentage of the mean daily value of winter (December, January, February) sunshine for wind directions of 090°, 180°, 270° and 360°

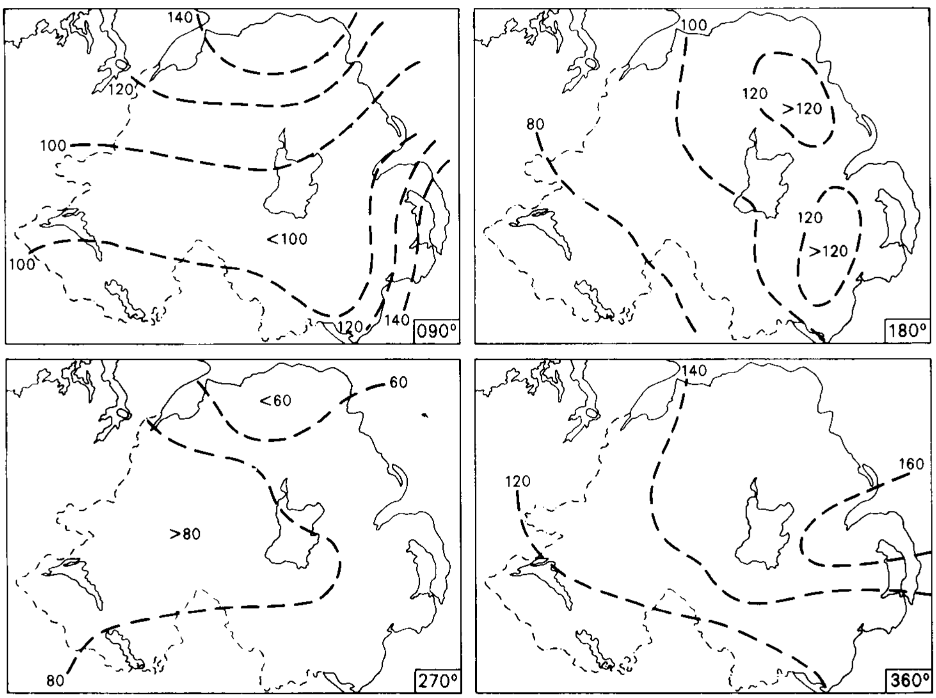

Figure 10. As Fig. 9, but for summer (June, July, August) sunshine.

Concluding remarks

This study could be further refined and extended by including, for each wind direction segment, a weather-type classification. Indeed, such an investigation has been reported for rainfall in south-east England (Stone 1983). However, in the present case further subdivisions of the number of observations in each category would not be practicable. Nevertheless, the foregoing 'anomaly' values can be exaggerated or reduced, in a subjective way, once the synoptic framework has been decided upon. The general characteristics of the patterns may be taken as giving reasonably good guidance on where, for example, the coldest or warmest regions may be expected and the 'typical' contrasts that are observed.

Acknowledgement

Thanks are due to Mr K. Grant, Met O 9 (Special Investigations Branch), for writing the computer program and processing the data from the Northern Ireland stations.

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Stone, J. 1983 Circulation type and spatial distribution of precipitation over central, eastern and southern England. Part II. *Weather*, **38**, 200–205.

551.521.11:551.521.12(41-4)

The accuracy of estimates of daily global irradiation from sunshine records for the United Kingdom

By F. Rawlins

(Meteorological Office, Bracknell)

Summary

Daily and monthly totals of global solar irradiation on a horizontal surface are estimated from records of duration of bright sunshine by Cowley's method for an independent sample of 21 stations within the United Kingdom, and the estimates compared with measured values. The accuracy of the estimate is given as a percentage and the frequency distribution of daily errors is explored. Root-mean-square (r.m.s) errors of daily and monthly estimates lie in the ranges 15–20% and 3–9% when averaged over the year but there is a marked seasonal variation.

The use of sunshine values from a location 50 km away typically increases the r.m.s. errors of daily irradiation estimates from 14% to 22% in summer.

Individual daily global irradiation is more accurately estimated from local sunshine observations than by assignment from nearby radiometric stations if these are more than about 20 km away; for monthly totals the critical distance is about 30 km.

1. Introduction

The daily total of global solar radiation received on a horizontal surface is important in a variety of meteorological applications, including the determination of evapotranspiration rates for hydrometeorological use and surface energy budget calculations for solar energy and agricultural requirements. Currently the United Kingdom solar radiation network comprises 40 stations which measure daily or hourly global irradiation of wavelength 0.3–3.0 μm using Kipp and Zonen pyranometers; a description of the network can be found in Richards (1980). The geographical distribution of stations is insufficient to give an adequate spatial resolution for all applications, and estimation of global irradiation from the much more numerous measurements of sunshine duration is widely employed. There are 370 stations in the United Kingdom which report sunshine.

A simple linear relation between global irradiation and bright sunshine duration, measured by Campbell-Stokes recorders, was established by Ångström (1925). The estimation technique for daily totals was improved by Cowley (1978) who divided days into two groups — sunless and those with some sunshine — and argued that these constitute two distinct statistical samples, giving an estimated daily global irradiation, G_E, in the form:

$$G_E/G_0 = a + bN/N_0 \quad \text{for } N>0 \qquad (1)$$

$$G_E/G_0 = a' \quad \text{for } N = 0 \qquad (2)$$

where G_0 is the extraterrestrial daily global irradiation on a horizontal surface, N is the duration of bright sunshine measured by Campbell-Stokes recorders and N_0 is the astronomical daylength. The empirical coefficients a, a', b were calculated at 10 sites from data for the period 1966–75. Maps of coefficients covering the United Kingdom were interpolated by Cowley: a and a' were assumed constant throughout the year but monthly maps of b were produced, giving 14 coefficient maps in all.

This paper examines the accuracy of Cowley's method in an independent data sample for both daily and monthly totals. Since the error in estimated irradiation is unlikely to be completely random, the frequency distribution of errors was also investigated.

An extra source of error arises when an estimate of irradiation is required for a location at which no sunshine measurement is available, and it is necessary to assign sunshine observations from a nearby site. The accompanying loss of accuracy was explored by comparing irradiation estimates obtained from sunshine recorded at neighbouring stations.

A common problem is encountered when an estimate of irradiation is required for a location at which only sunshine is recorded, but radiation measurements are available from a station at a small distance: which estimate is superior, the value given by Cowley's equations or the assigned radiation measurement? This question was examined by calculating the differences in measured irradiation within the network as a function of the separation between stations.

2. Preparation of data

Measurements within the solar radiation network are co-ordinated by the National Radiation Centre at Beaufort Park, the section of the Meteorological Office which is responsible for the calibration of radiation instruments against international reference standards. Observations of sunshine duration and irradiation are subjected to a package of quality control checks before being archived: data with major inconsistencies are labelled 'unreliable'. Daily global irradiation on a horizontal surface, G_M, taken from the controlled data is assumed to be correct for this analysis, although it should be noted that the measured values themselves have an inherent inaccuracy arising from a number of sources, with calibration and angular response errors being of particular importance. The principal causes of error have been studied by a number of workers, e.g. McGregor (1983), from which the r.m.s. (root-mean-square) error of individual hourly measurements is considered to be about 5% for the United Kingdom network, which is in agreement with results from a study of the Canadian solar radiation network (Hay and Wardle 1982). This study also quoted r.m.s. errors for daily and monthly integrated measurements, giving average figures of 3½% and 2½% respectively, but with a seasonal dependence; similar errors are expected to apply to United Kingdom network instruments.

The actual error of the estimate quoted in the present paper is $G_E - G_M$, with the percentage error being defined as $100(G_E - G_M)/G_M$, for each individual measurement. In general these calculations will underestimate the differences from the 'true' radiation field, as obtained from a hypothetical network of ideal instruments. However, since only a fraction of the measurement error can be considered to be systematic and common to the entire network, the additional error will not be as large as the figures given in the previous paragraph.

All errors given in the following sections are averages for the period 1976–82, with a minimum sample of at least 100 days for each monthly set of results. Only days with 'reliable' measurements of sunshine and radiation are used, i.e. when there is a complete record or when data are missing for only a small fraction of the day and pass the quality control checks. Similarly, each monthly total of global irradiation is required to contain at least 20 days with data. These restrictions reduce the number of stations used in this study to 21: details of each site are listed in Table I and the geographical locations are shown in Fig. 1.

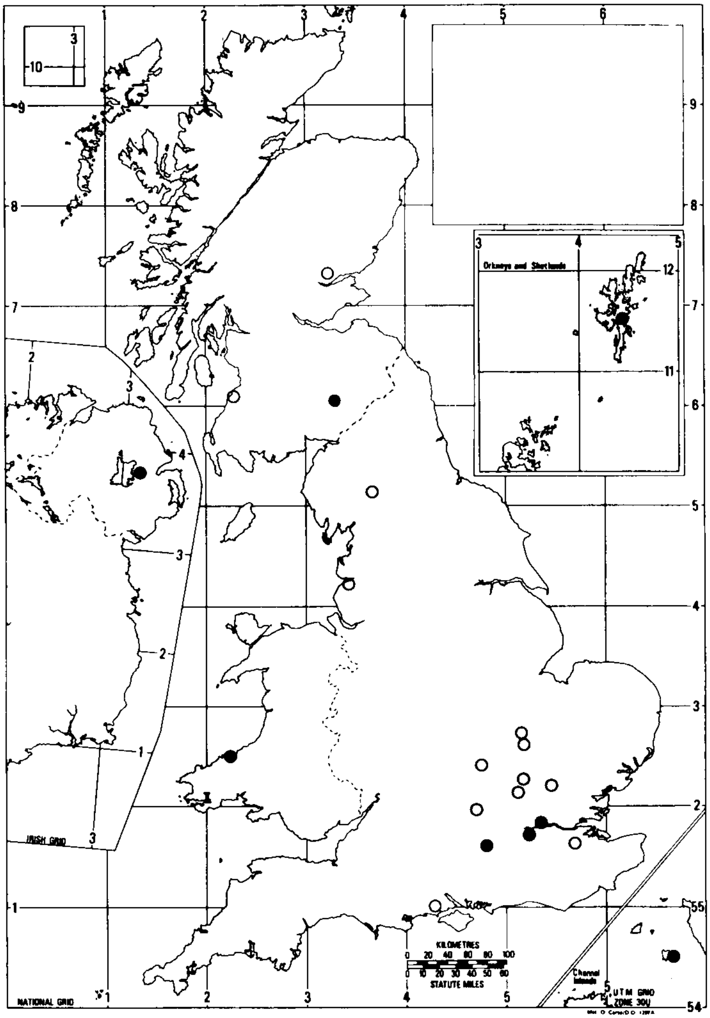

Figure 1. The geographical positions of stations used in the analysis, which measure both daily global irradiation and sunshine duration. The stations which were also included in the derivation of the empirical coefficients by Cowley (1978) are labelled by ●; other sites are labelled ○.

Table I. *Details of stations used in the analysis*

Station	Height	National grid reference		Type	Used in Cowley calculation of a, a', b 1966–75	Notes
	metres	E	N			
Silsoe	59	5.08	2.38	co-op	no	
Moor House	562	3.75	5.32	"	no	
East Malling	37	5.70	1.57	"	no	
Efford	16	4.30	0.93	"	no	(a)
Fairfield	24	3.42	4.34	"	no	(b)
Garston	77	5.11	2.01	"	no	
Lerwick	82	4.45	11.38	Met O	yes	
Eskdalemuir	242	3.24	6.03	"	yes	
Kew	5	5.17	1.76	"	yes	
Bracknell (Beaufort Park)	73	4.84	1.66	"	yes	
Aldergrove	68	1.29	5.34	"	yes	
Aberporth	133	2.25	2.51	"	yes	
Cardington	28	5.08	2.46	"	no	
London Weather Centre	77	5.30	1.81	"	yes	
Jersey	85	3.87	−0.79	co-op	yes	
Mylnefield	30	3.34	7.29	"	no	
Auchincruive	45	2.38	6.24	"	no	(b)
Grendon Underwood	70	4.67	2.23	"	no	
Rothamsted	128	5.13	2.13	"	no	(a)
Hoddesdon	47	5.38	2.11	"	no	
Wallingford	49	4.58	1.89	"	no	

Notes: (a) Radiation records are from 0900–0900 GMT.
(b) Radiation and sunshine records are from 0900–0900 GMT.
All other records refer to the period 0000–2400 GMT.
co-op : co-operating station
Met O : Meteorological Office station.
The national grid has been extrapolated to include Jersey and Aldergrove.

The maps of coefficients a, a', b were interpolated by Cowley on to a grid of resolution 40 km × 40 km covering most of the United Kingdom. The estimate of global irradiation for each day, G_E, is calculated from equations (1) and (2) using the daily duration of sunshine at each station and the coefficients found by linear interpolation from the four closest grid points. However, three sites (Lerwick, Aldergrove and Jersey) are outside the grid region and values of a, a', and b derived for the period 1966–75 at each site were used.

Those days for which the error exceeded 50% were discarded; these few outlying values constituted less than 1% of the sample, i.e. one or two days in each set of seven months' data, and were confined to the winter months. These errors mostly occurred on days of anomalously low measured irradiation, for which recording or instrument deficiencies are a likely cause. The inclusion of such days would have distorted the calculation of r.m.s. errors for the few samples in which they were present.

3. Results

(i) *Daily errors*

The mean and r.m.s. percentage errors of estimated daily global irradiation were calculated for each station in the analysis, averaged for each month of the year. The errors for Bracknell, which is considered to give typical results for the network, are listed in Table II. Average errors at each station for

Table II. *Error statistics for Bracknell, including the mean daily global irradiation*

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Units
Mean G_M		797	1270	2354	3587	4746	4826	4708	4055	3016	1727	949	613	W h m^{-2}
Daily percentage error	r.m.s.	20.0	17.8	16.3	14.4	13.9	13.2	11.2	12.8	13.0	16.7	17.7	20.5	%
	mean	–4.5	–1.1	2.5	3.3	5.0	0.7	0.7	2.8	0.1	0.3	–1.6	– 3.2	%
Daily actual error	r.m.s.	134	190	315	411	499	512	428	402	297	219	135	102	W h m^{-2}
	mean	–49	–31	56	94	148	12	–8	59	–36	–10	–33	–32	W h m^{-2}
Percentage of days with modulus (error) exceeding threshold:	100 W h m^{-2}	41	48	72	80	83	83	79	81	78	58	42	32	%
	500 W h m^{-2}	0	2	11	23	31	32	26	23	9	3	1	0	%
	1 kW h m^{-2}	0	0	0	1	4	5	2	1	0	0	0	0	%
	20%	33	22	22	14	14	12	5	10	15	19	25	30	%
Monthly percentage error	r.m.s.	7.2	3.2	4.1	3.7	4.3	2.1	1.7	2.5	2.7	2.1	4.0	5.9	%
	mean	–6.0	–2.5	2.5	2.7	3.3	0.3	–0.1	1.5	–1.2	–0.7	–3.3	–5.4	%

the entire sample of 7 years are shown in Fig. 2, where the abscissa is the northerly component of the national grid reference, with one unit denoting 100 km (national grid co-ordinates are extended to include Aldergrove and Jersey in this work). The r.m.s. percentage errors are similar at each site and mostly fall within the range 15–20%, including those stations involved in the original derivation of empirical coefficients (these are identified in the figure); there appears to be a small systematic increase in error northwards. Mean errors lie between ± 6% and seem to be randomly distributed.

The percentage error for all 21 stations combined is shown in Fig. 3 to indicate the way in which the daily error varies with each month of the year. It can be seen that there is a strong seasonal dependence, with considerably less accurate estimates (by percentage) in winter. In terms of the actual error, this seasonal dependence reverses owing simply to the large variation in solar radiation received on a horizontal surface during the year at United Kingdom latitudes. This is illustrated for Bracknell in Table II.

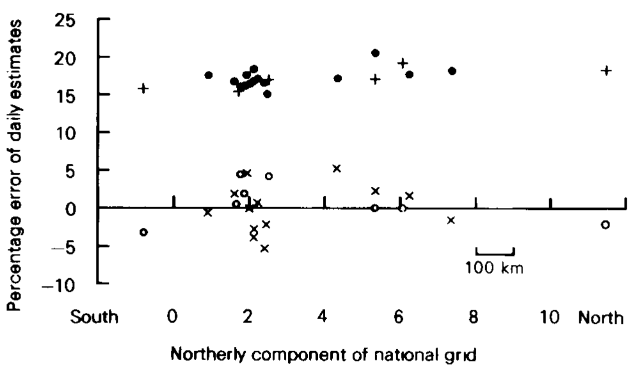

Figure 2. Mean and root-mean-square (r.m.s.) percentage errors of daily estimates of global irradiation as a function of the north component of the national grid reference for each station, averaged over the 7-year sample period. The r.m.s. and mean errors of stations included in the original derivation of empirical coefficients are labelled by + and ○ respectively; r.m.s. and mean errors of the remaining sites are labelled by ● and ×.

The accuracy of estimation is more completely determined if the frequency distribution of errors is known. A simple statistical method can be applied to test for a normal distribution. First, the null hypothesis is assumed: that percentage errors are normally distributed. Then the cumulative error distribution is subdivided into categories and the χ^2 test for significance at the 5% level is applied. The results for Bracknell data, with six categories, are shown in Table III, from which it can be seen that the hypothesis is accepted for 7 out of 12 months. Hence the error distribution approximates to a normal form for most, but not all, months.

A useful criterion of accuracy is given by the percentage of occasions on which the magnitude of the percentage error exceeds a threshold value. A threshold of 20% provides a rough guide to the usefulness of daily estimates of global irradiation: values for Bracknell are given in Table II, which indicates the relatively poor estimates obtained in winter months. These values can also be predicted from the mean and r.m.s. percentage errors, if a normal distribution is assumed. Table IV shows the observed and predicted percentage of occasions exceeding an error of 20% at East Malling. The good agreement obtained indicates that the assumption of a normal distribution is adequate for this purpose.

It may be noted that a 20% daily error corresponds to about 900–1200 W h m^{-2} in summer and to about 50–140 W h m^{-2} in winter, depending upon location. To assist the comparison of errors at different times of the year the percentage of occasions for which the actual error exceeds, 100, 500, 1000 W h m^{-2} are listed in Table II for Bracknell.

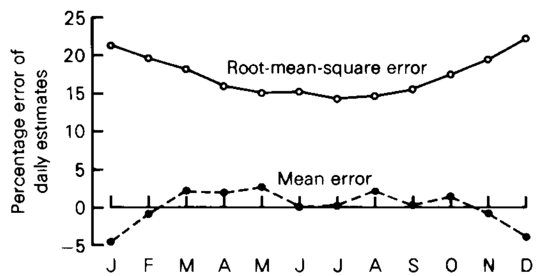

Figure 3. Mean and r.m.s. percentage errors of daily estimates averaged for all stations for each month of the year (for a 7-year sample).

(ii) *Representative sunshine measurements*

When an estimate of global irradiation is required for a location where sunshine measurements are not performed, the local sunshine duration must be obtained from neighbouring sunshine stations. An attempt to assess the importance of this source of error was made by considering the estimation of daily irradiation at a single station, with empirical coefficients appropriate for that location, but replacing the measurements of sunshine with those recorded at other sites. This gives an indication of the error introduced by the assignment of sunshine recorded at a distance. Fig. 4 shows the r.m.s. error for January and July as a function of the separation of each site from Silsoe, which is chosen as a suitable example of a 'base' station since it is located in the densest part of the network. It can be seen that there is a steady increase of error with increasing distance, particularly for July when a separation of 50 km increases the r.m.s. error from 14% to about 22%. At large distances (greater than about 400 km) the errors exhibit a wide range of values.

A similar relation between errors and the separation of sites was found for other stations and it is expected that these results are typical of lowland areas of the United Kingdom.

Table III. *Calculated χ^2 values for Bracknell with decisions of tests for a normal distribution of percentage errors. (Critical value at 5% significance for χ^2 is 7.815.)*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Calculated from error frequency distribution	19.9	6.5	4.7	4.7	32.6	5.8	7.0	15.3	35.6	15.4	2.6	1.8
Acceptance of null hypothesis	No	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	Yes

Table IV. *The percentage of days on which the modulus of the percentage error exceeds 20% at East Malling, both as observed and as predicted from the mean and r.m.s. errors assuming normal (Gaussian) statistics*

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Daily percentage error	r.m.s.	20.8	18.7	17.8	15.2	13.9	15.5	13.0	12.4	13.6	17.2	18.9	23.4
	mean	1.1	0.9	5.6	3.9	3.0	−0.2	2.3	1.8	−0.1	3.0	−0.5	3.7
Percentage of days with modulus (error) exceeding 20%	observed	32	28	22	17	12	18	11	10	12	21	29	39
	predicted	34	28	26	19	15	20	12	10	14	24	29	38

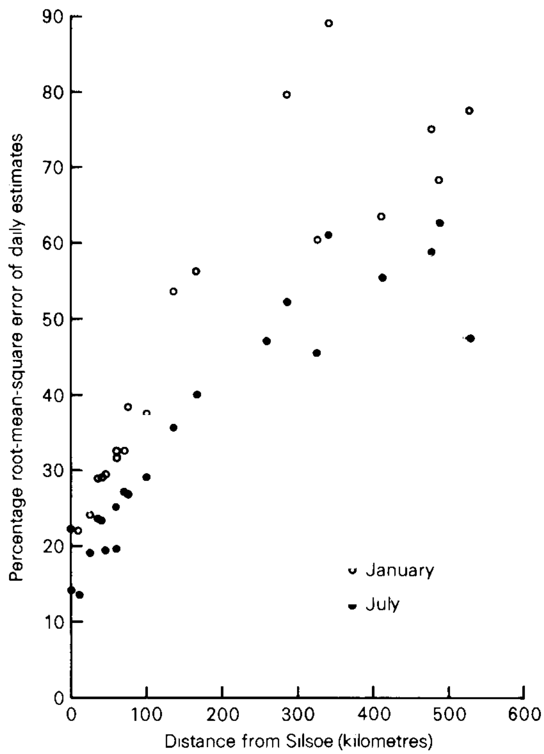

Figure 4. The r.m.s. percentage error of daily estimates for Silsoe, using sunshine recorded at other sites, for January and July, versus the distance of these sites from Silsoe.

(iii) *Monthly errors*

The preceding results apply only to daily totals of global radiation. The estimation of individual monthly totals is also of interest: Figs 5 and 6 show the dependence of mean and r.m.s. monthly errors on the geographical position and season respectively, corresponding to Figs 2 and 3 which displayed daily errors. As expected, there is a reduction in error from daily to monthly totals which is associated with the removal of part of the random error. However, the reduction is not as large as that predicted for a normal population, i.e. by dividing the square root of the number of days in a month (ca. 5.5), since the deviations of individual days making up the monthly sum are related, owing to the persistence of weather conditions for more than one day. The importance of systematic errors for monthly integrated estimates can also be seen: deficiencies in the specification of empirical coefficients are responsible for a significant proportion of the r.m.s. error.

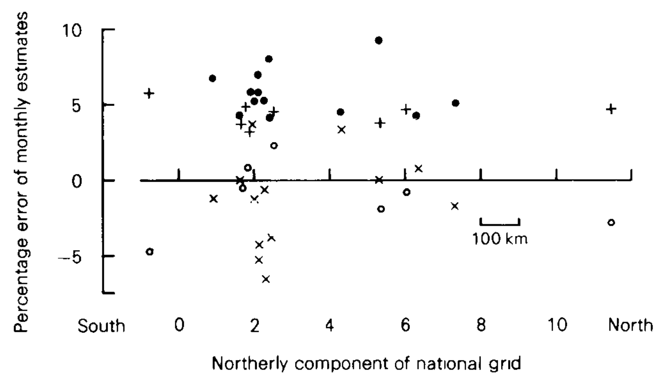

Figure 5. As Fig. 2, but for monthly estimates.

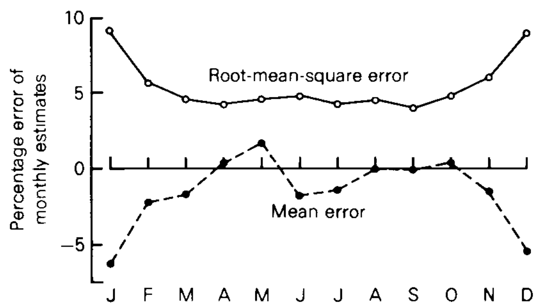

Figure 6. As Fig. 3, but for monthly estimates.

A comparison of Figs 2 and 5 indicates that mean daily and monthly errors are not identical — since errors are given in percentage terms the errors in estimated monthly totals are weighted towards days of high measured global irradiation. For example, the estimated irradiation for a day of strong sunshine may have only a small percentage error but this could amount to a significant contribution to the monthly error if other days in the month are of low irradiation. In general there is a tendency for daily mean errors to be more positive than monthly mean errors: a detailed examination of the results at several stations indicated the cause to be that high irradiation days are underestimated more often than low irradiation days. However, the data sample for monthly figures is small, with a maximum of 7 months (and a minimum of 5), and may not be characteristic of a longer period.

(iv) *Estimation: assignment of irradiation measurements or local regression from sunshine?*

A problem frequently encountered when practical estimates of global irradiation are required for a particular location is whether to assign the irradiation measured at the nearest radiometric station or to derive values from sunshine recorded locally, using the Cowley coefficients. The accuracy of the latter has already been discussed; the accuracy of estimates using assigned measurements of irradiation (i.e. equated to the nearest station) can be explored by calculating the differences between simultaneous observations within the radiation network.

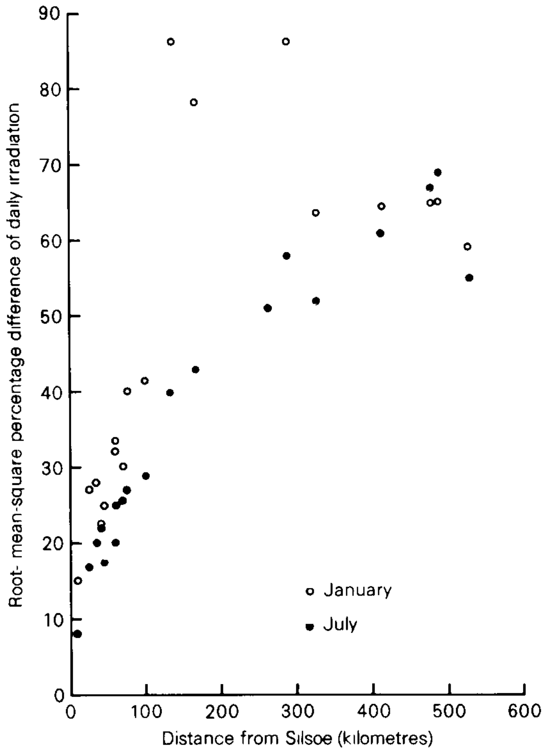

Figure 7. The r.m.s. percentage differences in daily global irradiation measured at Silsoe and at other sites as a function of their distance from Silsoe, for January and July.

Fig. 7 shows the r.m.s. percentage differences in measured daily global irradiation between station pairs, which can be regarded as errors in this context, as a function of the distance of each site from Silsoe, which is again taken to be the reference station, for January and July. These differences can be compared with the r.m.s. error of estimation from local sunshine records at Silsoe which were found to be 22% and 14% for January and July respectively (see Fig. 4). The limited number of irradiation differences and their large spread of values preclude the derivation of an explicit relation between irradiation difference and station separation. However, for both months it can be seen by inspection of the envelope of points in Fig. 7, that the r.m.s. error from assignment is larger than that from the Cowley method when the assignment distance exceeds about 20 km. Hence it can be inferred that, for the relatively homogeneous region of the United Kingdom under consideration, the estimation of individual daily global irradiation from local sunshine records is more accurate than if measured irradiation values are assigned from a single site at a distance greater than about 20 km from the desired position. Similar results are obtained for other reference stations but the scarcity of closely spaced pairs of sites allows only a very rough estimate of this limit.

The relative accuracy of the estimation methods for individual monthly totals and for the entire sample in each month of the year can be examined similarly. However, the increase in the r.m.s. percentage difference of irradiation with increased station separation, as defined above, is less pronounced for monthly sums of global radiation, partly because of the relatively small sample, but mostly because of the dominating contribution of climatological differences. In other words, r.m.s. monthly differences between measured irradiation at different stations depend mainly on the difference between the climatological average irradiation at each site, which can be fortuitously small, even when they are far apart and within quite separate radiation regimes. Fig. 8 shows the magnitude of the difference between the mean daily irradiation measured at Silsoe and at other stations for January and July, averaged over the 7-year sample period and expressed as a percentage of the Silsoe mean irradiation. Clearly there is some increase in irradiation differences with distance, but this is much less marked than in Fig. 7. For each station and for each month of the year the daily irradiation can be estimated by the Cowley method, and then averaged over the 7-year period, in a simple extension of the daily results described earlier: it is found that the errors (expressed as a percentage of the measured irradiation for the same period) vary widely from station to station. The modulus of these errors, averaged over all stations, approximates to the average error of estimating climatological mean irradiation by Cowley's method; for January and July the values are 5% and 3% respectively (for comparison with Fig. 8). Using this criterion of the error of estimating climatological irradiation, it can be seen from Fig. 8 that, on average, estimation by Cowley's method is more reliable than the assignment of mean irradiation from a single location at a distance further than a few tens of kilometres (say, roughly 30 km) from the desired position.

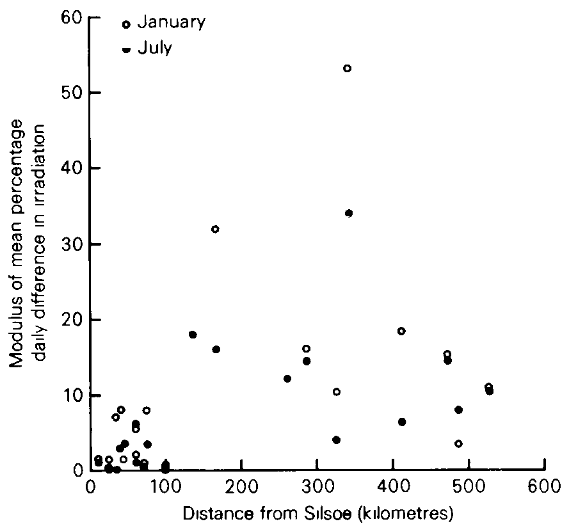

Figure 8. The modulus of the long-term mean percentage daily differences in irradiation measured at Silsoe and at other sites as a function of their distance from Silsoe, for January and July.

4. Discussion

The relation used by Ångström and Cowley ignores the detailed physical causes of variations in global irradiation at the earth's surface. These arise from changes in the composition of the atmosphere, particularly the aerosol and water vapour content; from the complex scattering and absorbing properties of water drops and ice particles within different thicknesses and configurations of clouds; and from changes in the albedo of the underlying surface. The equations only take account of a single measure of the optical characteristics of cloud, i.e. the duration of bright sunshine, and have to be derived on a climatological basis; therefore it is not surprising that large errors may be generated when they are applied to single days. Also, the measurement of bright sunshine by Campbell–Stokes recorders is known to have a number of deficiencies (Painter 1981), particularly overestimation in periods of intermittent sunshine, and these are implicitly included in the specification of the empirical coefficients.

The estimates of global irradiation are poorest for days when little or no bright sunshine is recorded — the cloud type and thickness govern a wide possible range of fractional transmission through cloudy atmospheres. There have been a number of attempts to calculate the fraction of solar radiation transmitted through various cloud species, e.g. Haurwitz (1948), Lamb (1964), and more recently Cotton (1978), and this approach may offer an improvement in accuracy when cloud information is available. In general, the daily estimate of Cowley is more reliable for sunny days than for overcast days since there is a greater variability in global irradiation due to clouds than that due to turbidity. Apart from changes in cloud cover due to variations in climate, the duration of bright sunshine is dependent on the solar altitude because of geometric effects. When the sun is low in the sky there is a greater probability that the direct beam will be intercepted by broken cloud (Davis *et al.* 1979); also the incident energy can be reduced below the burn threshold by the attenuation of a longer atmospheric path, especially when thin cloud is present or there is a large aerosol content. The average solar altitude decreases from south to north and from summer to winter, so that less accurate estimates are expected in the north compared to the south and in winter compared to in summer, quite apart from large-scale and seasonal changes in atmospheric conditions; this is consistent with the trend of errors shown in Figs 2 and 3.

Examination of the original data on which Cowley based the determination of a, a', b reveals that, strictly, a and a' as well as b should be provided as monthly rather than just constant values, since the month by month changes in a and a' are comparable to those of bN/N_0. However, this would be unwieldy to implement in practice since the coefficients are not independent, which complicates the process of obtaining consistent maps of these parameters. The inexact relationship between sunshine and irradiation does not justify an extension to a higher order polynomial for mapping throughout the UK, although some authors, e.g. Hay (1979), have used such a form for specific sites.

The importance of assigning representative measurements of sunshine duration in estimating irradiation by Cowley's method is emphasized by the results shown in Fig. 4, where the use of sunshine measurement sites away from the point of estimation leads to errors which increase roughly linearly with distance. This is most pronounced for estimates during summer (illustrated by the July results) when there is a greater variability in sunshine over small horizontal scales, which is probably due to the seasonal pattern of convective activity. Local cumuliform clouds are more prevalent over the United Kingdom mainland in summer than in winter and these can lead to considerable differences in sunshine recorded at neighbouring positions; stratiform cloud conditions seem more likely to give rise to a relatively homogeneous geographical distribution of sunshine.

The results concerning both the representativeness of sunshine measurements and the choice of estimation of irradiation presented earlier are relevant to the problem of estimation at a distance from a single measuring station. In practice it is usually possible to derive values from a number of sites, particularly for sunshine, using interpolation procedures of varying elaboration. Hence the increase in error with increasing distance from the measurement position is an overestimate of what may be achieved with a closely spaced network of stations. However, it should also be noted that these results apply only to the relatively homogeneous lowland terrain of south-east England, this being the only area with a sufficient density of radiation stations. It is expected that coastal and highland regions exhibit greater horizontal variability in the irradiation field; consequently there will be a larger increase in error with increasing distance from the measurement position. It is possible that the limiting distances quoted in previous sections are seasonally dependent but the uncertainty of the values deduced from Figs 4, 7 and 8 is too large for this to be adequately resolved.

5. Conclusions

The accuracy of estimation of daily and monthly totals of global irradiation from bright sunshine records using the method of Cowley (1978) has been investigated for 21 stations around the United Kingdom. The calculations, which are based on a sample which is independent of that used to derive the empirical coefficients, provide the following results:

The r.m.s. errors of daily estimates, averaged throughout the year, are in the range 15–20%, with mean errors within ±6%. The r.m.s. errors averaged over all stations vary from about 15% (or 600 $W\ h\ m^{-2}$) in summer to 25% (or 150 $W\ h\ m^{-2}$) in winter. The r.m.s. errors of monthly estimates are in the range 3–9% which are larger than would be inferred from assuming that each daily error is independent. The mean monthly errors are similar, but not identical, to the mean daily errors and constitute an important proportion of the total monthly error.

The number of individual days for which the error exceeds 20%, or other chosen levels, can be approximated by assuming a normal distribution of errors. The accuracy of estimation of daily global irradiation is dependent upon the representativeness of the measurement of bright sunshine duration. The use of sunshine recorded at a distance of 50 km from the location at which the irradiation estimate is required typically increases the r.m.s. error in summer from 14% to about 22%.

The estimation of global irradiation by Cowley's method, for a particular location which has sunshine but not radiation measurements available, has been compared with the assignment of measured values from a neighbouring radiometric site. For the relatively homogeneous terrain of south-east England it is found that more accurate estimates of individual daily global irradiation are obtained by regression from local sunshine records than by the assignment of irradiation measured at a station more than about 20 km distant. Similarly, long-term average global irradiation is more reliably estimated from local sunshine than by an assignment of measured irradiation more than about 30 km from the required position.

A high proportion of the day-to-day errors are due to the simplicity of the estimation scheme which ignores the detailed physical causes of changes in global irradiation at the earth's surface. However, this method provides readily obtainable estimates with sufficient accuracy for many applications and constitutes an important source of irradiation data which is supplementary to those of the solar radiation network. It is expected that a considerable amount of effort would be required to provide estimates using existing data which are significantly more accurate and can be applied throughout the UK. One obvious possible extension involves the use of observations of cloud type and cover, to improve estimation of totally overcast days.

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551.542.1:551.553.1(564.3)

Diurnal and seasonal trough-induced surface pressure gradients and winds over Cyprus

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Summary

Average values of monthly mean sea level pressure at three-hourly intervals were used, firstly, to describe purely diurnal pressure gradients and winds and, secondly, in combination with a model of the seasonal/lee pressure trough, to describe resultant pressure and flow patterns, by 'day' and 'night', and at times when no thermally induced pressure gradients exist. Results are found to agree with observed surface flow phenomena.

Data and normalization

Values of average mean sea level pressure at three-hourly intervals (00, 03, 06, etc., GMT), each month, were tabulated for five locations in Cyprus as follows: Nicosia, Paphos and Morphou, 1951–55; Cape Apostolos Andreas, 1951–54; and Akrotiri, 1957–71. The Paphos and Cape Apostolos Andreas data for 00 and 12 GMT were compared, for each month in 1951, and the simple empirical factors obtained were applied to the averages for the latter station to allow for the non-inclusion of 1955 data therein. The changes made were small. The Akrotiri data, being for a longer but non-overlapping period, were adjusted to give estimates of 1951–55 values by simple relationships of monthly average mean sea level pressures. The 1957–71 monthly averages at Akrotiri were replaced by the monthly means of the Paphos and Morphou 1951–55 averages.

Determination of sense of pressure gradients between coastal stations and Nicosia and resulting airflow

Monthly mean curves were drawn to the three-hourly average pressure data for all stations, locating maxima at or near 10 and 22 hours Zone Time (GMT + 2 h) and minima at or near 04 and 16 hours. Curves for Morphou and Paphos were superimposed on those for Nicosia by registering pressure scales. Curves for Akrotiri were superimposed on those for Nicosia by registering revised monthly averages with corresponding values on the Nicosia scales. The times when relatively falling Nicosia average pressures equalled those at the coastal stations (A) and when relatively rising Nicosia average pressures once again equalled those at the coastal stations (B) are shown in Table I. The A-value for Akrotiri in September is, presumably, a quirk of the crude normalization and should be 08 or 09. Times of sunrise and sunset on the 15th day of each month (1982) are shown for comparison.

In the absence of a synoptic-scale pressure gradient the June to September relationships imply actual pressure gradients normal to coastlines, with inflow from A to B hours, and outflow from B to A on most days. From December to March the average pressure patterns and values reflect a good deal of cloudiness and, presumably, underestimate the time-span A–B on sunny days. In other months there is, presumably, some underestimation of time-span A–B on sunny days.

B is considerably later than sunset in some months and hence sea-breezes would be expected to persist into darkness, an observed phenomenon forecasters have been reluctant to predict without physical support. Relationships between average pressures at Nicosia and Cape Apostolos Andreas were not studied because of the extreme geographical location of the latter. A- and B-times are well related to the duration of land- and sea-breezes and to the occurrence of mountain- and valley-induced (anabatic and katabatic) winds.

Table I. *Times (GMT + 2 h) when average (1951–55) mean sea level pressures for three coastal stations became* (A) *greater than and* (B) *less than average pressures at Nicosia.*

Month	Times of intersection of coastal station monthly average mean sea level pressure curves with corresponding curves for Nicosia						35°N, 33°E 15th day of month	
	Morphou		Akrotiri		Paphos		Sunrise	Sunset
	A	B	A	B	A	B		
Jan.	–				–		0656	1658
Feb.	10	16	11	18	11	17	0637	1728
Mar.	10	18	11	18	11	17	0559	1755
Apr.	08	18	09	18	09	18	0518	1819
May	07	20	07	19	08	20	0446	1844
June	07	20	07	20	07	20	0433	1904
July	09	19	08	19	07	20	0446	1902
Aug.	09	18	08	19	09	19	0508	1837
Sept.	09	17	07	19	09	18	0530	1757
Oct.	09	17	09	19	09	18	0553	1715
Nov.	11	17	12	16	11	17	0623	1642
Dec.	11	15				–	0649	1638

Determination of resultant pressure gradients when a synoptic-scale pressure system covers Cyprus

Meteorological Office (1962) gives monthly, average, mean sea level pressure maps for an area including the Mediterranean. The seasonal trough is dominant from June to August, appears weakly in May and is a fading feature in September. In summer this trough is both an extension of the Asian summer low and a result of the lee effect due to the Turkish mountains. At other times the trough is purely a lee effect. The average pressure difference over the length of Cyprus (west–east), along or near which direction the axis of the trough is usually found, is of the order of 1 mb (Meteorological Office 1962). A simple template was made (see tops of Figs 1–5) to enable the trough axis and isobars at 0.5 mb intervals to be drawn, quickly and accurately, on maps of the scale of those in Figs 1–5. The small numbers (1–28) are those of the wind sampling points used by the writer in a simple wind-tunnel study (Wales-Smith 1984) and are included here to facilitate comparisons. The five stations used here are Nicosia, slightly west of 21 (Nicosia Town), Morphou, just north of 9, Paphos 4, Cape Apostolos Andreas 16, and Akrotiri 1. Five positions (see tops of Figs 1–5) were chosen for the trough axis.

The monthly, average diurnal pressure curves for the five stations were studied and values of pressure change from afternoon minimum to evening maximum were extracted. These values, averaged over the period June to September only, were halved to give estimates of deviation from an assumed, neutral, state when pressure gradients were only those of the seasonal trough (see tops of Figs 1–5). These half-values were: Nicosia, 1.0 mb; Cape Apostolos Andreas, Akrotiri and Paphos, 0.3 mb; and Morphou, 0.5 mb. It was decided, therefore, to use the value 0.3 mb for most of the coastline.

The half-values were subtracted from and added to values in the top sections of Figs 1–5 to yield estimated afternoon and late evening patterns of pressure (centre and bottom parts of Figs 1–5, respectively). It is unfortunate that only one inland station could be included but there is no reason to doubt that summer changes inland are much larger than on the coast. The estimated isobars have been drawn so as to leave the seasonal trough pattern undisturbed except near and over land. No attempt has been made to allow for differences in pressures on north- and south-facing slopes. The study was not extended to the period including the early morning pressure minimum and the forenoon maximum as the difference can not be related, simply, to thermal changes of the sort analysed in this section.

If, following Haurwitz (1947), it is accepted that the 'day' (central) flow patterns of Figs 1–5 are not balanced over the land and if balance is also assumed to be lacking in the 'night' (lower) patterns, cross-isobar flow (or, at least, a large cross-isobar component) would be expected. If, however, the 'neutral' patterns are regarded as being associated with more or less balanced flow then, ignoring the effects of flow over and around mountains and hills, surface winds might be as shown by arrows (Vrb standing for calm or variable).

A noticeable feature of the 'night' patterns is the well-known, nocturnal north-west wind experienced at Larnaca Airport. If this wind were solely katabatic in origin it would be expected to blow from only slightly north of west. The conjectural patterns also suggest that the weakest sea-breezes on the south

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Figures 1–5

Top sections: Surface isobars at ½ mb intervals of a symmetrical trough over Cyprus with axis where shown.

Centre sections: Surface isobars obtained by subtracting the following quantities from pressures indicated in the top sections: Nicosia, 1.0 mb; Morphou, 0.5 mb; Cape Apostolos Andreas, Akrotiri and Paphos, 0.3 mb.

Bottom sections: Surface isobars obtained by adding the following quantities to pressures indicated in the top sections: Nicosia, 1.0 mb; Morphou, 0.5 mb; Cape Apostolos Andreas, Akrotiri and Paphos, 0.3 mb.

Notes: Estimated isobars in centre and bottom sections are drawn so as to leave the basic (top section) trough patterns undisturbed except near and over land. Contours are at 200 m, 500 m and 1000 m.

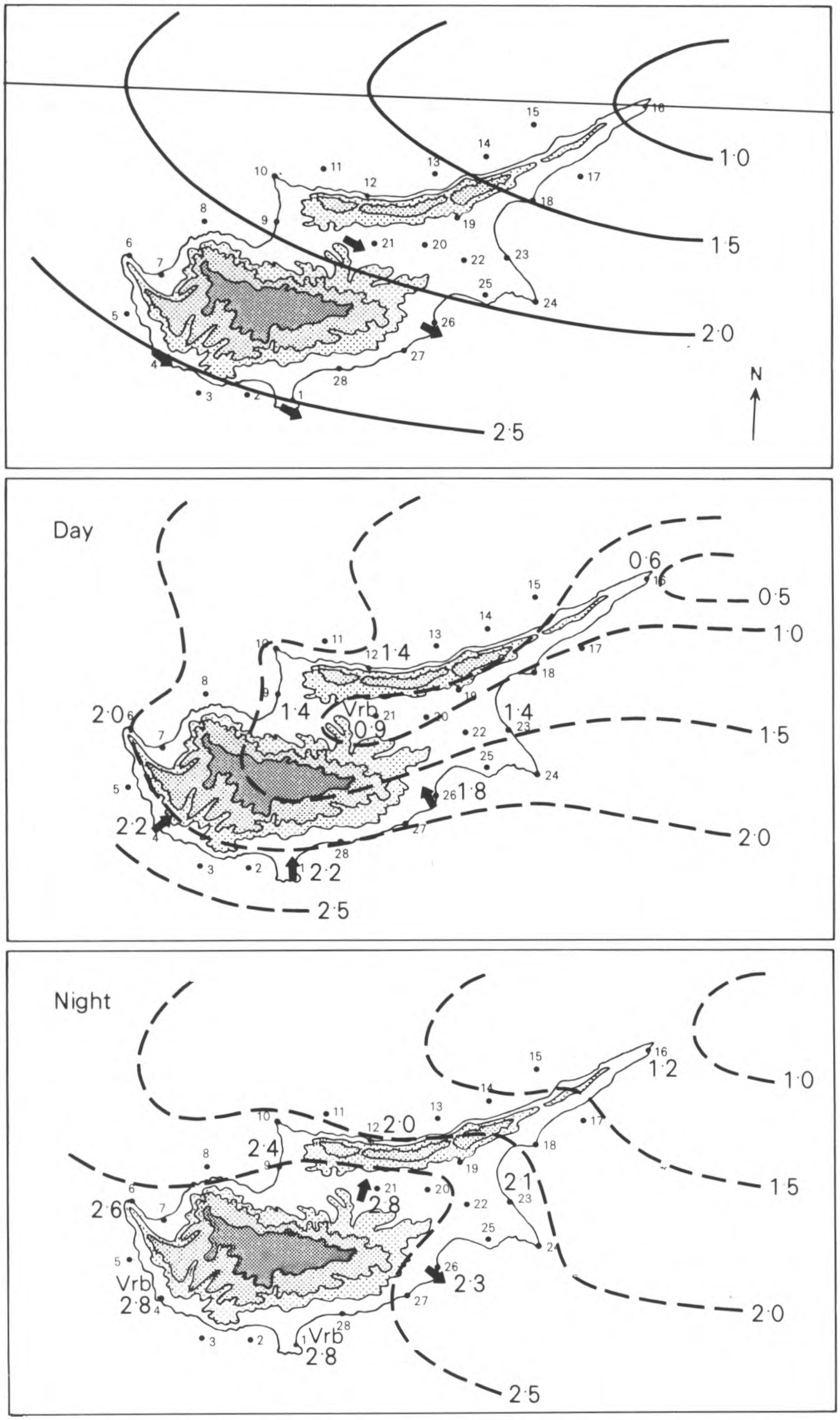

Figure 1. Local flow over Cyprus due to synoptic-scale trough. See page 201.

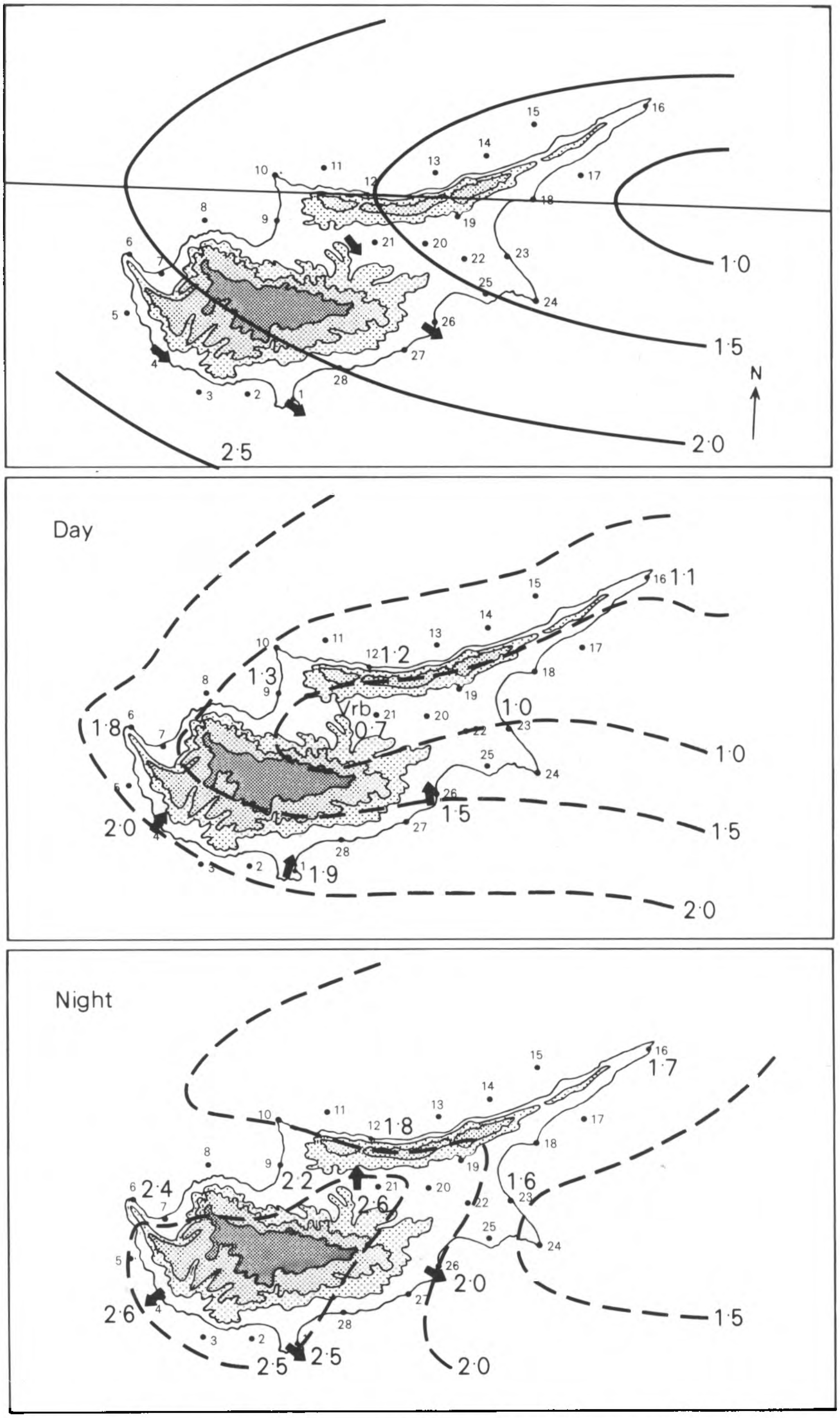

Figure 2. Local flow over Cyprus due to synoptic-scale trough. See page 201.

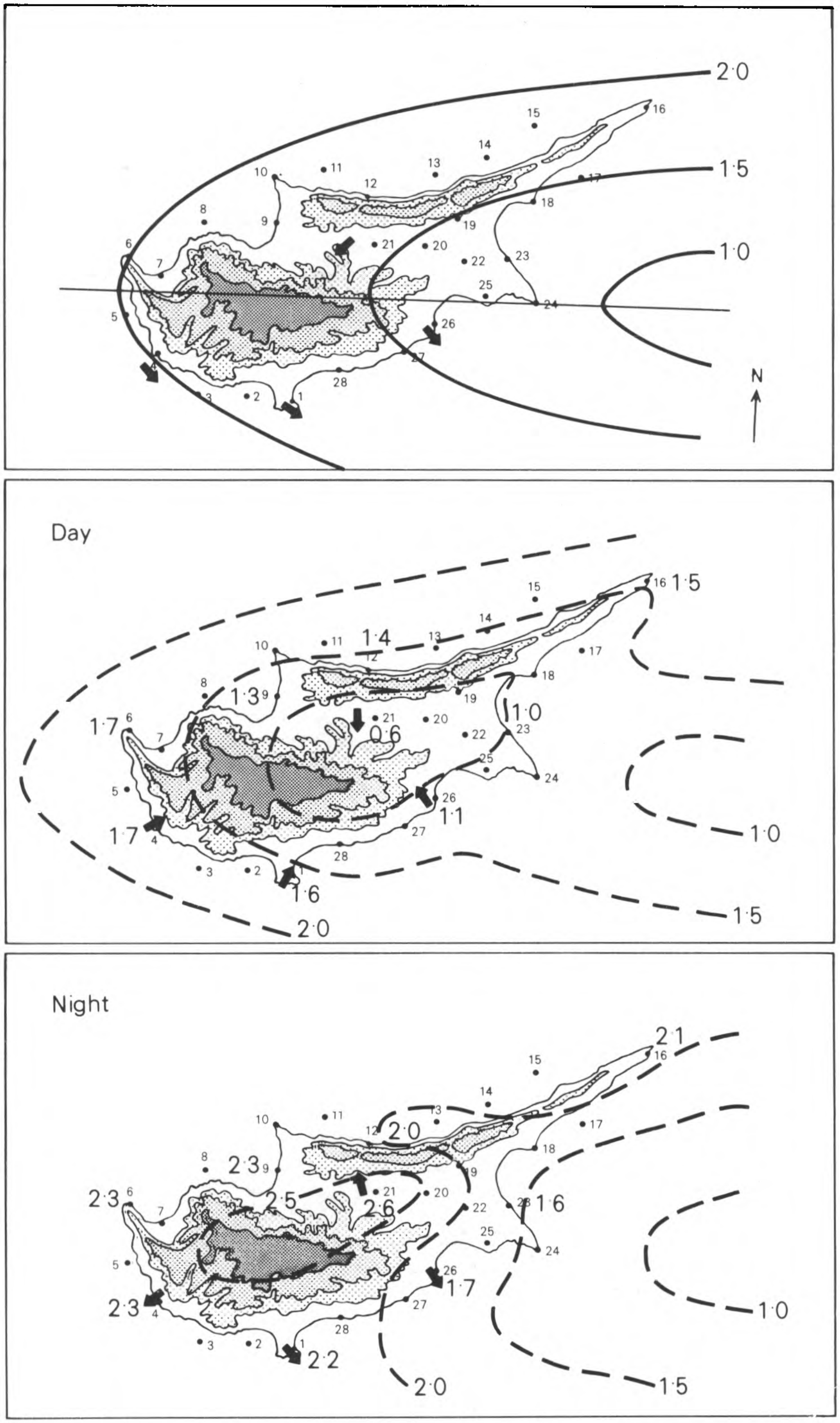

Figure 3. Local flow over Cyprus due to synoptic-scale trough. See page 201.

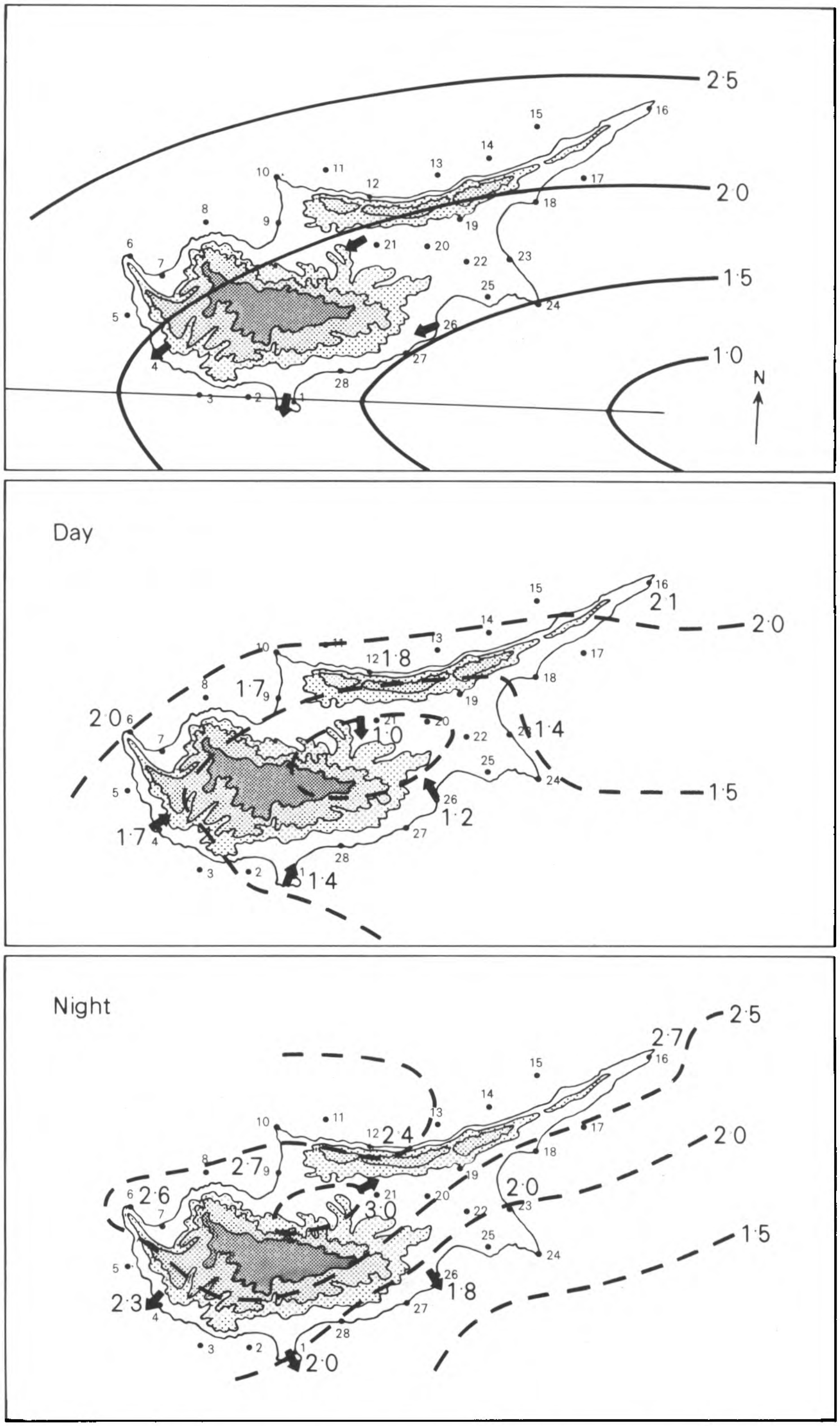

Figure 4. Local flow over Cyprus due to synoptic-scale trough. See page 201.

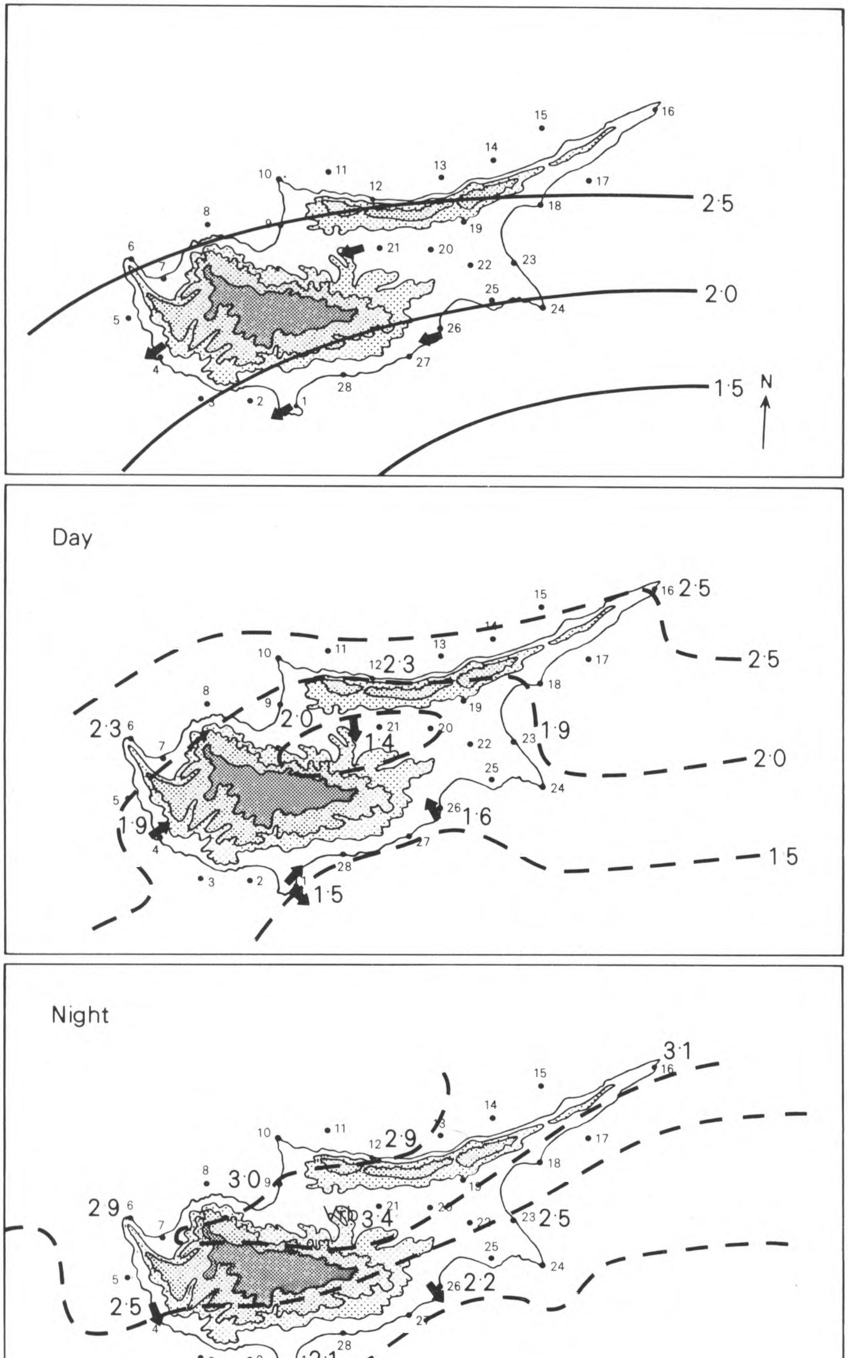

Figure 5. Local flow over Cyprus due to synoptic-scale trough. See page 201.

coast should occur when the axis of the trough is well south of the centre of the island and vice versa, modelled results which accord with experience.

No attempt has been made to study conjectural flow patterns involving other types of synoptic-scale pressure systems because of the uncertainties involved.

It is suggested that this very simple technique can be used as a contribution to understanding diurnal surface wind components wherever three-hourly average mean sea level pressure data are available from sufficient locations for the same period of years. It is probably most suited to studies of large islands and peninsulas but there seems to be no good reason why it should not be applied to areas including continental coastlines.

Acknowledgement

The writer acknowledges, with gratitude, the tedious data-extraction and arithmetic performed by his, unknown, colleagues without whose efforts this study would not have been carried out so easily.

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551.507.362.2:551.510.42:551.575.5(430.1)

Advection of fume and smog (scanned by satellite) over hundreds of kilometres

By H. Schulze-Neuhoff

(German Military Geophysical Office, Traben-Trarbach)

Poor visibility in the vicinity of emission sources is well known, for example Krames (1981). During autumn 1983 several examples have been evaluated in surface observations showing industrial haze (fume) in relatively small but long belts, similar to roads, downstream of the 'Ruhr area' (see Fig. 1) or other industrial centres. The fume is not visible in satellite pictures normally, but on 7 November 1983 a 'smog road' was shown by a low stratus cloud belt extending from Magdeburg towards Hanover (see Figs. 2 and 3). A secondary, smaller and more diffuse, belt parallel to this primary phenomenon and spreading west-north-westwards seems to be originated by the industrial area near Salzgitter.

Fig. 4 shows the synoptic chart from the Interactive Graphical System at the German Meteorological Geophysical Office (Gemein *et al.* 1982). The smog road from Magdeburg towards Hanover and the fume road from Hanover towards Emden is indicated by weather observations and visibility. One hour later the small low stratus belt had dissolved by insolation.

Smog is assumed here as being defined by visibility less than 1 km, primarily produced by industrial particles and secondarily by meteorological facts like radiative cooling and a subsidence inversion over wet ground.

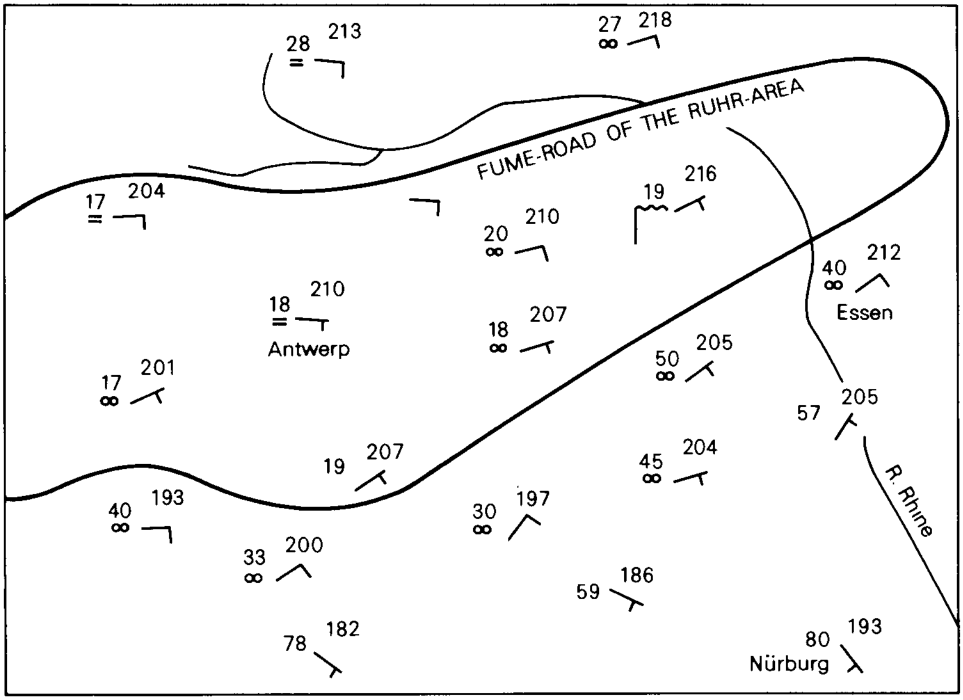
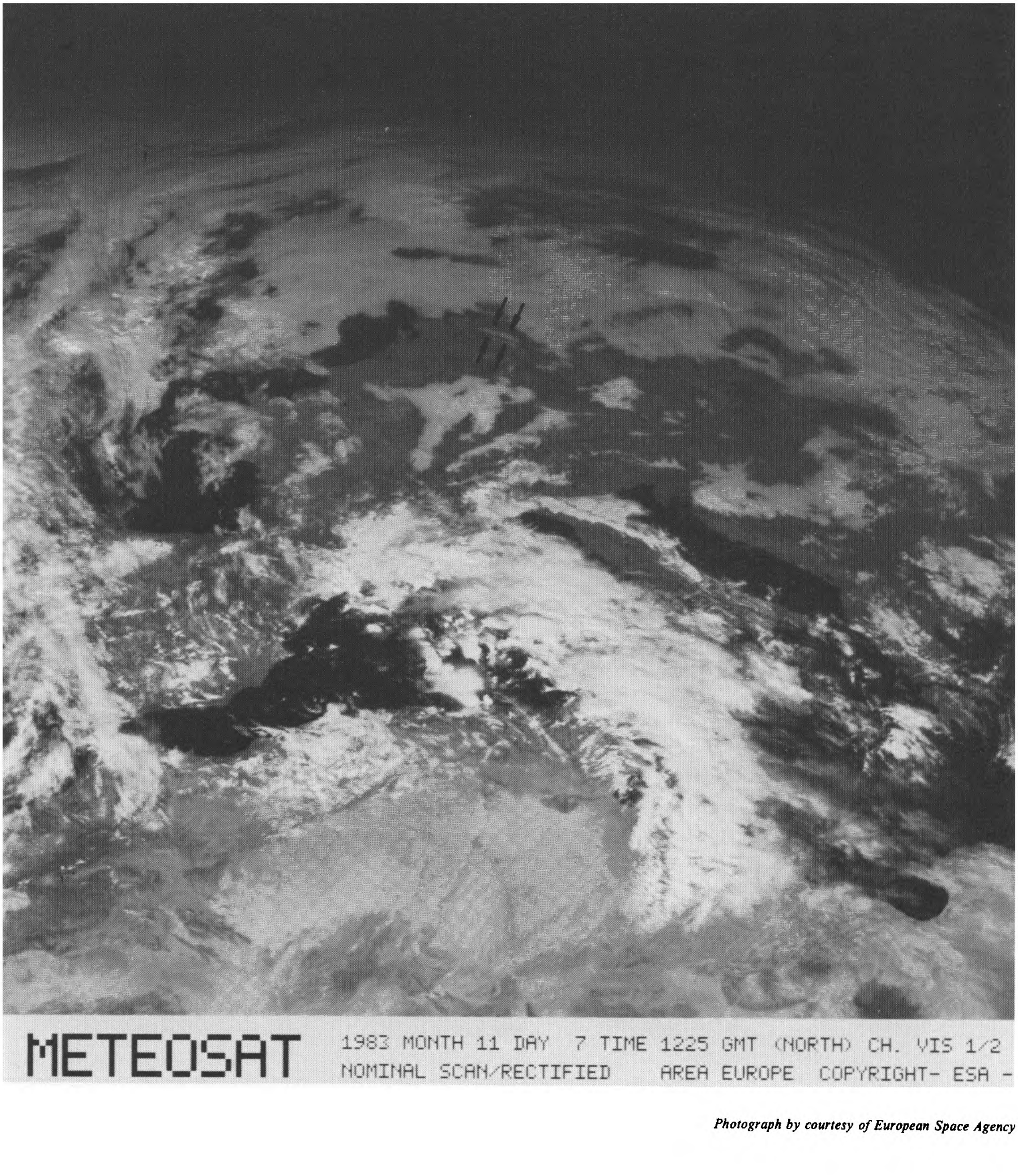


Figure 1. Surface observations (pressure, wind and visibility) for 1300 GMT 28 September 1983. The 'fume road' is shown by observations of visibility equal to or less than 2 km.

References

Gemein, H. P., Engel, M. and Schiessl, D. 1982 An operational interactive graphics system. Fachliche Mitteilungen Nr203. Herausgeber Amt fur Wehrgeophysik, Traben-Trarbach.

Krames, K. 1981 Auswirkungen von Emission auf die Flugsicht (Consequences of emissions to the flight visibility.) *Promet*, **4'81**, 16–19.



Photograph by courtesy of European Space Agency

Figure 2. Satellite (Meteosat 2) visual photograph for 1230 GMT 7 November 1983. The 'smog road' extending from Magdeburg to Hanover is marked.

Figure 3. Satellite (NOAA 7) visual photograph for 1257 GMT 7 November 1983. (The grey scale used in the picture is non-linear optimized to maximum contrasts.)

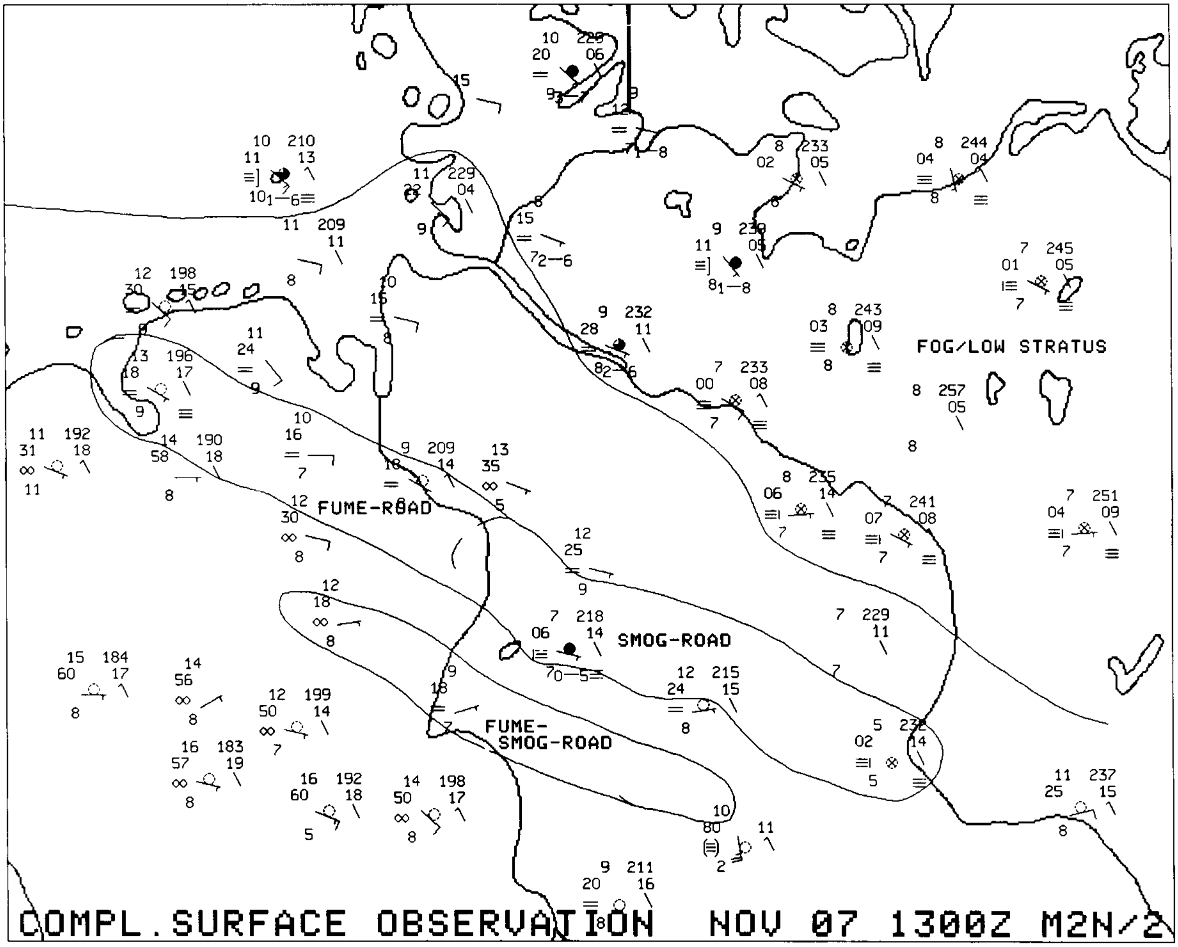


Figure 4. Plotted observations for 1300 GMT 7 November 1983 as produced by the Interactive Graphical System at the German Meteorological Geophysical Office, Traben-Trarbach.

Reviews

Introduction to environmental remote sensing (second edition), by E. C. Barrett and L. F. Curtis. 185 mm × 245 mm, pp. xiii + 352, *illus.* Chapman and Hall Ltd., London, 1982. Price £12.95.

The field of remote sensing has undergone an explosive growth in the last decade. Even in 1976, the year of the first edition, the attempt to encapsulate a wide-ranging and fast-moving subject in a book such as this must have been a bold one. By the time of the second edition, the field had grown and changed in such a way that the authors' attempt to provide 'a balanced and integrated introduction for the relative newcomer' was bound to be, at best, a partial success. There are now so many aspects to the principles, practice and application of remote sensing that it is very difficult to provide a summary of each facet which is both balanced in emphasis and up to date.

The book contains 19 chapters grouped in two main parts: 'Remote Sensing Principles' followed by 'Remote Sensing Applications'. Part I, however, deals not only with the scientific principles involved (which should require little updating) but also with the instruments and data interpretation techniques used, where continuing advances in sensor technology and data processing capability have opened up new avenues of exploration. Part II attempts to catalogue the applications grouped roughly according to scientific discipline.

After a preliminary chapter which introduces a few commonly used terms and discusses briefly the economics of remote sensing, Chapter 2 tackles the physical bases of remote sensing. It attempts to be fairly complete with discussions of the electromagnetic radiation and its spectrum and of the basic processes of emission, scattering, absorption, refraction, reflection and transmission of radiation. It is a disappointing chapter in that it contains several erroneous and misleading statements in an area of well-established theory where the fast-moving nature of remote sensing in general cannot serve as an excuse. For example, the Rayleigh–Jeans limit of the Planck function is incorrectly presented as a special case of Stefan's law. Also the discussion on the concept of emissivity neglects to mention its potential variation with wavelength and so misstates the definition of a 'grey' body. Consequently this chapter does not provide a very clear introduction to radiation theory.

Chapter 3 is considerably better and gives a brief but balanced overview of the spectral characteristics of the atmosphere, clouds and the earth's surface. The next chapter gives, again, a balanced and generally accurate introduction to the types of sensors used, including photographic and vidicon cameras, infra-red radiometers and spectrometers, active and passive microwave sensors and lidars. Chapter 5 gives a brief account of the different potential platforms for remote sensing devices, ranging from ground-based platforms, aircraft, balloons and rockets to satellites in different types of orbit. This is followed by a more detailed description of the Landsat system and of Spacelab and Shuttle.

Chapters 6 to 9 turn to the subject of data. Firstly, the collection of *in situ* data is covered, and its use in the interpretation of remote sensing data is discussed. The need for good quality 'surface truth' data is stressed. Also the use of satellite-borne data collection systems for relaying *in situ* data from remote sites is described. Turning to remotely sensed data, some important concepts are introduced: the difference between photographs and images, and between analogue and digital data. This is followed by a more detailed discussion of photographic processing and enhancement techniques and the conversion between optical and digital data. Chapter 8 covers the manual analysis and interpretation of data including methods of photo-interpretation and photogrammetry. Chapter 9 tackles the area of numerical data processing and analysis. In view of the growing importance of this field, this chapter is perhaps too brief and consequently makes some sweeping generalizations which are not valid for all satellite data types. The introductions to quantitative feature extraction and classification techniques are good in so far as they go, but one feels that the authors might have included a discussion of the concepts of information content and retrieval.

Part II starts with two chapters on 'weather analysis and forecasting' and 'global climatology' which are, perhaps, the areas to which most readers of this review would hope to look with interest. The first chapter is disappointing. Although the updating required to reflect recent satellite developments has been performed in some areas, in other places the description still refers to the status at the time of the first edition. A more important failing, however, is the discussion of applications, which does not reflect the current balance in the use of satellite data. A disproportionate amount of space is devoted to the art of manual nephanalysis, without mentioning that the growth of this practice was largely as a substitute, reflecting the past inability to provide forecasters with a good quality satellite image (or, in many cases, with any image at all). The chapter on global climatology is better balanced but suffers from a lack of infusion of recent material, the most recent reference in the section on radiation budget being 1971. This chapter also discusses briefly other aspects of global climatology under the headings atmospheric moisture (water vapour, clouds, rainfall), wind flows and air circulations, synoptic weather systems, and the middle and upper atmosphere. The emphasis is on the techniques used rather than on their role in understanding climate.

Chapter 12 provides an interesting review of 'water in the environment': radar monitoring of precipitation, ice and snow monitoring and evaporation estimation, followed by surface hydrology, hydrogeology and oceanography. The last of these covers water (surface) temperature and circulation patterns, water quality and salinity assessments, together with a description of the oceanographic satellite, SEASAT. This is quite comprehensive, although the description of sea surface temperature measurement is in need of updating.

The chapters on 'soils and landforms' and 'rocks and mineral resources' provide an interesting introduction for the non-earth scientist. Similarly, Chapters 15 and 16 on 'ecology, conservation and resource management' and 'crops and land use' are very readable. One impression which emerges from these sections is the degree to which remote sensing of these very complex land systems relies on empirical methods to a greater extent than in the disciplines of meteorology and climatology.

Chapter 17 covers the built environment and highlights some of the problems peculiar to monitoring urban areas. This is followed by a short review of 'hazards and disasters' which is mainly devoted to meteorological applications. The final chapter, 'problems and prospects', contains a plea, which will be echoed by all satellite data users, for the controlling agencies to keep the data cheap and accessible if they wish to see effective exploitation of the large investment in satellite hardware.

Throughout the book the standard of illustration is high with numerous images (both monochrome and colour) and diagrams. Indeed the problem of fitting in all the illustrations often leads to their separation from the relevant text — a minor irritation well worth bearing. Less helpful is the 'bibliography'. This is in fact a list of references cited in the text. Because this is an introductory work which often tempts the reader to inquire beyond the brief discussion possible on any particular subject, it would have been most useful to have provided a list of more detailed review papers in each area to which the reader could refer as a gateway to the relevant literature.

At the outset, the authors state as their target 'a realistic introductory survey of environmental remote sensing for students, scientists and decision makers'. With the exception of Chapter 2 and deficiences in some areas caused by lack of appropriate revision, the book largely succeeds in reaching this goal. In particular it provides a window on to the diverse range of disciplines in which remote sensing is now poised to make a significant contribution.

J. R. Eyre

Satellite microwave remote sensing, edited by T. D. Allan. 160 mm × 245 mm, pp. 526, *illus*. Ellis Horwood Limited, Chichester, 1983. Price £45.00.

This book is a collection of papers on the European contribution to the verification and use of SEASAT data. This research was co-ordinated by the SEASAT Users' Research Group of Europe (SURGE), through the European Space Agency (ESA). The flyleaf informs us that its intended readership is 'marine scientists, meteorologists, offshore operators, geodesists, military planners and those interested in all aspects of satellite technology at research, undergraduate, postgraduate and professional level... those involved in marine resources and transport'. Has anyone been left out?

SEASAT was an experimental polar orbiting satellite launched in June 1978, failing suddenly after three months. It carried five sensors, four of them operating at microwave frequencies: a scatterometer to measure wind-vectors over the ocean, an imaging radar, a radar altimeter and a microwave radiometer. The fifth instrument was a conventional visible/IR imager. SEASAT was the first satellite dedicated to oceanographic applications and its suite of microwave sensors allowed continued coverage by day or night, in cloudy or clear conditions. There was great European interest in this American venture, and under the wing of ESA, the UK tracking station at Oakhanger was modified to receive SEASAT telemetry. The SURGE members have used data from this source for their validation of SEASAT products over Europe and the Atlantic. It was a coincidence that the Joint Air–Sea Interaction (JASIN) experiment took place during the lifetime of SEASAT: the surface data measured by the ships and buoys have been used extensively to validate the wind and wave data as deduced from SEASAT.

The book is divided into six parts. These deal in turn with a review of SEASAT and the background to the European contribution, followed by papers on each of the four microwave sensors. It ends with a review of the European oceanographic satellite, ERS–1, which will carry the next generation of similar instruments. There is a total of 31 chapters, each written by an expert in their field: most of the contributors are from Europe, but some were invited from the United States and Canada. Often this approach can lead to overlapping of material or missing information which each author has assumed will be covered by another. In this case, however, the Editor has done an excellent job in ensuring that while each paper can be read as a complete entity (thereby making this work handy as a reference book), there is a minimum of repetition. Every chapter is liberally sprinkled with diagrams (and imagery where appropriate) and has individual reference lists. There are several colour plates and a comprehensive index.

By far the largest section deals with the Synthetic Aperture Radar (SAR), with several chapters devoted to various theoretical topics of SAR imaging mechanisms. Others discuss image content over sea and land, and wave spectra deduced from ocean images. The second largest topic is the Radar Altimeter and the assessment of the satellite tracking accuracy, ocean geoid and wave measurements. The remaining two instruments, the wind scatterometer (SASS) and microwave radiometer (SMMR) have only two chapters each, detailing the derived product accuracies with JASIN measurements. It is a pity that these instruments do not have a more extensive discussion of their potential use. Can it be coincidence that data from the SASS and SMMR would be of most interest to the operational meteorologist? The book is very biased towards research applications of the SEASAT payload, probably reflecting general European interest, through SURGE, in the SEASAT project. (The Meteorological Office, although greatly interested in the SASS, was not a member of SURGE.)

In conclusion, if any of the previously mentioned readership were to obtain this book, most of them would find something of interest. It is a book that can be used as a reference work, or to gain an understanding of the capabilities of the types of instrument carried by SEASAT (and by several future satellites now being planned) or just as an introduction to microwave remote sensing.

D. Offiler

Introduction to climatology for the tropics, by J. O. Ayoade. 152 mm × 230 mm, pp. xv + 258, *illus.* John Wiley & Sons, Chichester, New York, Brisbane, Toronto, Singapore, 1983. Price £6.95 paperback, £14.95 cloth.

The author's stated aim is to provide a basic text on the fundamental principles of climatology for students or teachers of geography and related environmental sciences in the tropics. It is probable that readers new to the subject would be disturbed by the numerous (over 300) errors that have unfortunately escaped the attention of the referees and proof-readers. Many of these errors are trivial and repetitive; for instance, none of the isotherms over Antarctica in the mean chart for July has a negative sign attached to its value, the wind speeds on the hodograph are misplaced by five knots, and some of the heights and saturated humidity mixing ratio values on the tephigram are wrong. Such slips may cause only a momentary hesitation in the student's reading, but a succession of them will undoubtedly cause him to lose confidence in the author. Some of the mistakes, however, are a little more fundamental and may lead to misunderstanding. Examples of these are the statement that a tropical cyclone consists of two vortices separated by a central calm area, the omission of two separate zeros leading to '50' mb being approximated to '560' m above mean sea level, and the uncritical copying of Stepanova's mistranslation of Budyko's radiation units, which are reproduced on many occasions as kg cal/cm^2 instead of $kcal/cm^2$.

A basic fault in the layout of the book is the placing of the chapter on atmospheric moisture after those on atmospheric circulation and weather-producing systems. One of the results is that the student will find himself comparing the properties of stable and unstable air masses before knowing what these words mean.

Despite the inaccuracies Dr Ayoade has covered most of the ground necessary to reach his objectives. He has included a fuller examination of the radiation budget than may be found in most books at the same level, and this is a great asset. His treatment of climatic change is slightly more extensive than usual, which is also valuable, but he seems to have been drawn by an excess of enthusiasm into a longer dissertation on the relative merits of different climatic classification schemes than is perhaps warranted in a work of this size.

The book is clearly printed and great care has been taken to ensure that the diagrams and tables are as close as possible to the portion of text which refers to them. Equations (which some geographers might be apprehensive about) are well set out and all the variables are fully defined. I think that the book does fill a somewhat awkwardly shaped slot, and I hope that there will be a second (extensively revised) edition.

B. N. Parker

From weather vanes to satellites: an introduction to meteorology, by Herbert J. Spiegel and Arnold Gruber. 210 mm × 275 mm, pp. xi + 241, *illus.* John Wiley & Sons, New York, Chichester, Brisbane, Toronto, Singapore, 1983. Price £12.20.

Any author who sets out to simplify a science, endeavouring to put a complex subject into language that a non-scientist can understand, immediately lays himself open to much criticism. He either has to oversimplify fundamental concepts and risk the scorn of his colleagues, or spend most of the text explaining technical jargon as well as the processes involved and thus obscure an overall view of the subject. Messrs Spiegel and Gruber have largely overcome these problems by steering a course between the two extremes and have produced a well thought out guide to the subject. The reader is taken on a logical progression of topics in attractively laid out chapters, each preceded by a list of objectives which a student would find quite helpful.

There are, however, several things wrong with the text and these must be weighed against the book's good points. Some are no doubt typographical errors which are mere irritations to someone who is familiar with the subject but which could be quite misleading for anyone who is learning new things. For example, on page 87, 'counterclockwise' instead of 'clockwise' for winds around a high-pressure system: page 114, Figure 10–9a, isobar 1018 should be 1008; page 175, under tropical cyclone, 'density' should read 'intensity'.

A few major errors also appear. For example, on pages 46 and 47 the explanation of stability and instability using Figure 4–10 comes out the wrong way round and this, coupled with a misleading guide to instability assessment in Exercise 9 (page 216), means that the readers' concept of instability will be very inadequate. It so happens that Exercise 9 has already come to grief owing to an error in the upper-air temperatures given in the text.

There is a real need for a book of this sort to be checked thoroughly before it is released, otherwise the people it is supposed to help are in fact misled.

It is unfortunate that a book published in 1983 should still use the old synoptic code — the new code was introduced in January 1982.

Also British readers (at least the younger among us) who have become used to SI units will be frustrated by the American predilection for 'English units'. The authors note in the preface that there is a 'national trend toward the metric system' but at present the reader is still left in a quagmire of different units.

Most of the diagrams are clear and helpful, although one or two could be misleading. For example, Figure 10–2 certainly illustrates the point that windflow in an anticyclone is divergent but it also suggests that the winds blow perpendicularly to the isobars. Also the computer-drawn charts, especially in chapters 12 and 13, leave much to be desired.

The main section of the book is followed by a series of exercises which help the reader to assimilate some of the ideas put forward in the text. This is a worthwhile item in a textbook of this sort.

There is a useful glossary that includes most of the technical words used in the text, although a few of the explanations are rather too short. However, the whole is rounded off by, what is essential in a book of this kind, a very good index.

The book has many good features. It provides a basic course in meteorology suitable for educated non-scientists. A teacher who could eliminate the errors could base a sixth form or college course upon it, although he would need to prepare his own material on air masses affecting the British Isles.

J. R. Grant

Books received

Hydrodynamic instabilities and the transition to turbulence, edited by H. L. Swinney and J. P. Gollub (Berlin, Heidelberg and New York, Springer-Verlag, 1981. DM 96) is volume 45 in Topics in applied physics and is a collaboration between physicists, mathematicians and fluid dynamicists, each of whom is a recognized leader in the field. The various chapters include: introduction to the relationship between dynamical systems theory and turbulence; a review of hydrodynamic stability and bifurcation theory; three case studies — convection, rotating fluids, and shear flows; a review of the many types of instabilities that occur in geophysics; and a discussion of instabilities and chaotic behaviour in non-hydrodynamic systems.

Mountain weather and climate, by Roger G. Barry (London and New York, Methuen, 1981) provides a comprehensive study of meteorological and climatological phenomena in the mountain areas (some 30% of the land surface of the earth) of the world. After an introductory chapter there are chapters on: geographical controls (latitude, altitude and topography) of mountain meteorological elements; circulation systems; and the climate characteristics of mountains. These are followed by case studies of selected mountain climates; a chapter on human bioclimatology, weather hazards and air pollution; and the book finishes with a chapter devoted to changes in mountain climates.

Climate from tree rings, edited by M. K. Hughes, P. M. Kelly, J. R. Pilcher and V. C. LaMarche Jr (Cambridge, London, New York, New Rochelle, Melbourne and Sydney, Cambridge University Press, 1982. £18.50) is based largely on material presented at the Second International Workshop on Global Dendroclimatology, Norwich, 1980. The detailed findings of the Workshop have been presented in the Report and recommendations (Hughes *et al.* 1980). Instrument records of climate variables are sparse before the beginning of the 20th century. Tree growth, and in particular tree rings, records responses to a wide range of climate variables, over a large part of the earth, going back several centuries.

The Guinness book of weather facts and feats, by Ingrid Holford (Guinness Superlatives Ltd, Enfield Middx, 1982. £8.95) is the second edition of this book first published in 1977. This second edition has been comprehensively updated, revised, redesigned, and almost totally reillustrated with nearly 200 black and white photographs and 16 pages in full colour. A new topic, micro-climate, has been introduced and more detail included about weather satellites and forecasting methods.

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The severe weather during 31 May and 1 June 1983 — a case study using a numerical model

By W. H. Hand

(Meteorological Office, Bracknell)

Summary

An account is given of the severe weather that occurred over England and Wales during the evening of 31 May and the morning of 1 June 1983. A forecast from the Meteorological Office numerical weather prediction model on a fine mesh, extending over this period, is presented and the results are discussed. Two experiments with the model, both of which give improved forecasts, are then described. In one of the experiments, the response of the model to an improved specification of topography over the Alps and Pyrenees is examined.

1. Introduction

The weather over the British Isles during May and early June 1983 was unsettled and often thundery. The period from 1800 GMT on 31 May to 1200 GMT on 1 June was particularly severe with thunderstorms and associated heavy rain occurring over large areas of England and Wales. This paper describes in some detail in Section 2 the synoptic evolution and weather during this period. A 36-hour forecast by the Meteorological Office numerical weather prediction model on a fine mesh (Gilchrist and White 1982), extending over this period from initial data at 0000 GMT on 31 May, is presented in Section 3. Section 4 of the paper then describes two experimental changes that were made to the model, and their effect on the forecast (particularly of rainfall) is examined.

2. Synoptic evolution

The analyses of the 500 mb constant pressure surfaces at 0000 GMT on 31 May and 1200 GMT on 1 June are shown in Fig. 1. The main features are a vortex (Fig. 1(a)) centred at 45 °N, 17 °W and a trough extending south from the centre of the vortex along longitude 15 °W. By 0000 GMT on 1 June the trough had sharpened and had moved east with the main portion lying from just west of Corunna to just west of Gibraltar. The vortex by this time had moved north and filled slightly. By 1200 GMT on 1 June (Fig. 1(b)) the trough had moved north-east and was lying west–east along the English Channel with the vortex centred at 50 °N, 10 °W. The associated mean-sea-level pressure patterns and developments are illustrated in Figs 2(a) and 2(b). The most significant feature that affected the weather over the British Isles was

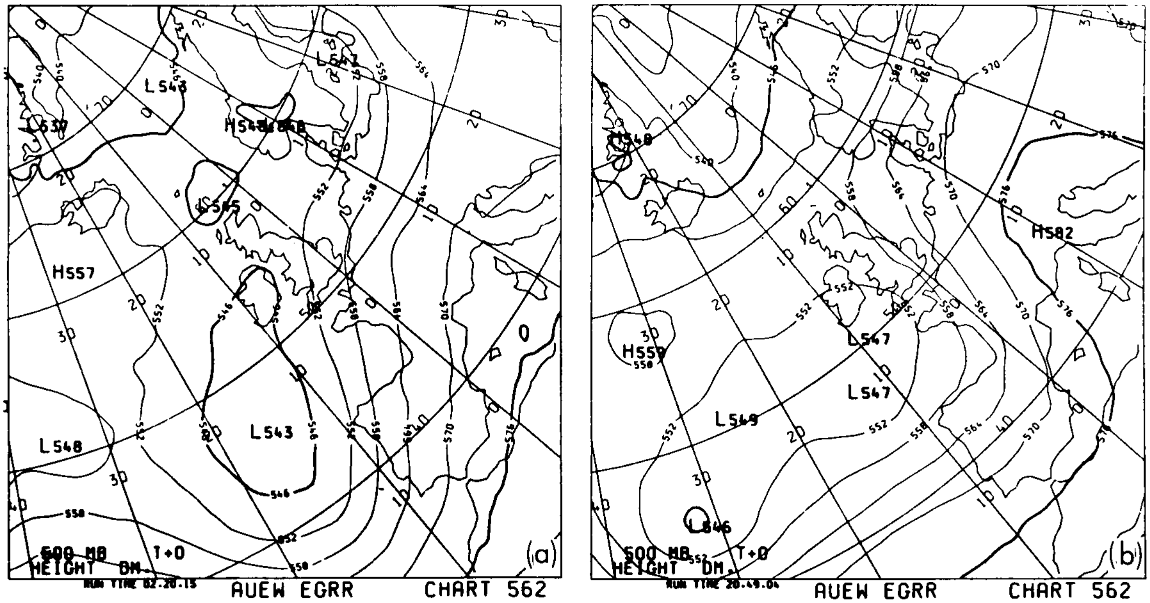

Figure 1. Analysis of the 500 mb constant pressure surface (in standard decageopotential metres) for (a) 0000 GMT on 31 May 1983 and (b) 1200 GMT on 1 June 1983.

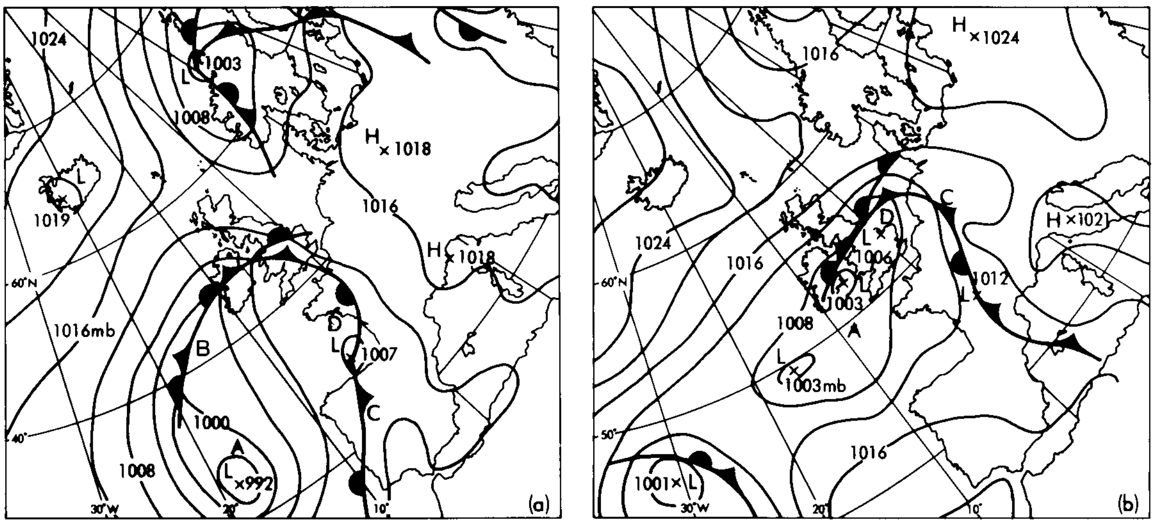

Figure 2. Hand-analysed mean-sea-level pressure pattern for (a) 0000 GMT on 31 May 1983 and (b) 1200 GMT on 1 June 1983.

depression A which moved slowly north-east from 42 °N, 18 °W at 0000 GMT on 31 May to become a complex feature to the south of Ireland by 1200 GMT on 1 June. Occlusion B moved slowly north during 31 May and became a weak decaying front over northern Scotland by 0600 GMT on 1 June. Cold front C moved steadily east over Spain and into the Mediterranean Sea during the 36 hours to 1200 GMT on 1 June. Further north, over the Bay of Biscay and north-west France, the eastward progress of the front was slow and erratic as waves developed and moved north along the front. One such wave that is shown as low D in Figs 2(a) and 2(b) and which was at 44 °N, 4 °W at 0000 GMT on 31 May, moved north into central southern England shortly after midnight on 1 June.

By dawn the wave had moved north-east to become a more pronounced feature with a much broader circulation over the eastern Midland counties. As the wave continued to move north-east into the North Sea during the morning of 1 June, very cold air at low levels was injected into the circulation of the wave by the strong easterly winds north of the warm front. Consequently a very active front was generated over northern England by midday on 1 June.

2.1 *Significant weather*

The weather associated with occlusion B at midnight on 31 May consisted of a narrow band of mainly light rain extending from northern England west into northern Ireland. By 0600 this rain area had moved north into Scotland with only scattered remnants remaining at midday. The afternoon of 31 May was dry over most of the British Isles with only slight rain in parts of Scotland and eastern England at first. Over France and Spain there were scattered showers and thunderstorms. At 1800 GMT outbreaks of thundery rain were being reported over south-west England, and by midnight over central southern England there was a large area of thunderstorms which extended south into the Channel Islands and northern France (see Fig. 3). During the early morning of 1 June, the rain and thunderstorms moved

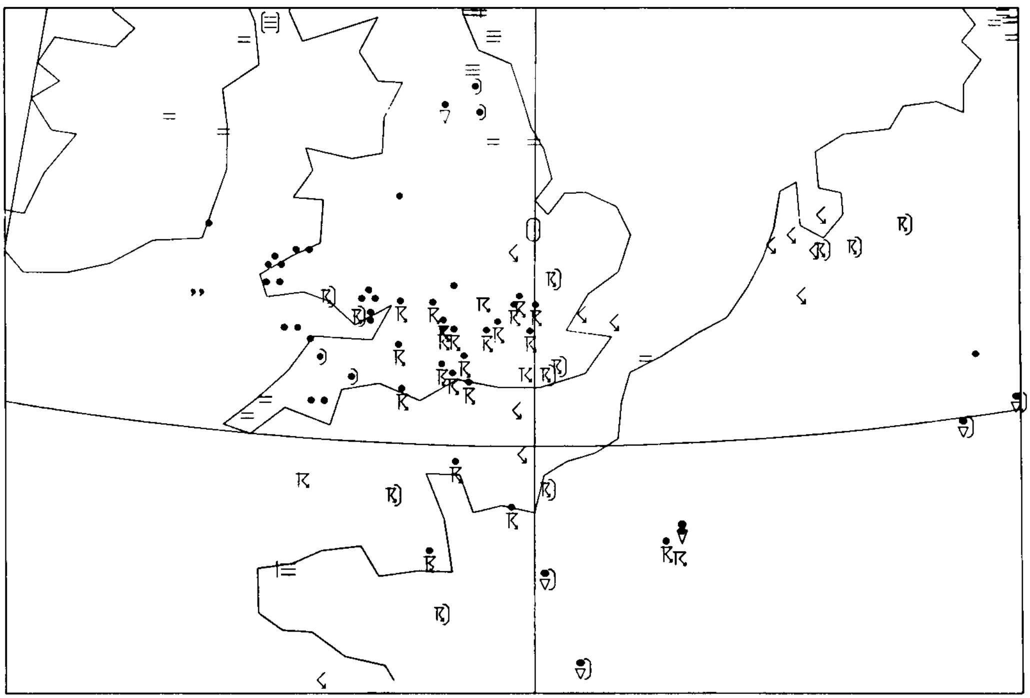

Figure 3. Significant weather at 0000 GMT on 1 June 1983.

north-east, and by 0600 GMT they were over east Yorkshire, Humberside, Lincolnshire and Norfolk, except the coast of Norfolk which was still dry. By this time, Wales, the Midland counties, central southern and south-west England had become dry. Rainfall accumulations were typically 10–15 mm over a six-hour period with a small region in the range 20–25 mm. The observed rainfall for the six hours from 0000 to 0600 GMT on 1 June is shown in Fig. 4. The map shows that the heaviest rainfall in this period occurred in a narrow band extending from the Isle of Wight in the south towards Lincolnshire further north. In contrast, the south-east part of Suffolk and the extreme east of Kent received much less rain and the coastal strip of Norfolk remained dry. By midday all the thundery activity had died out, but there remained a wide band of heavy frontal rain over northern England that extended west into Northern Ireland then south-west into Eire (see Fig. 13). The remainder of the British Isles was dry apart from some slight drizzle in Wales and a few showers on the south coast of England.

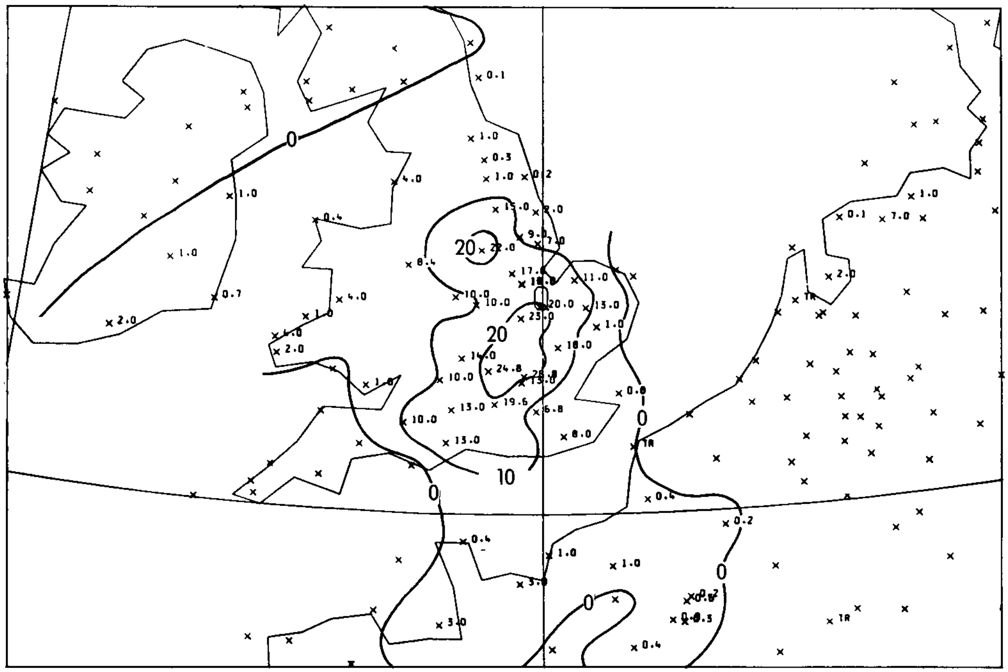

Figure 4. Observed rainfall in millimetres between 0000 GMT and 0600 GMT on 1 June 1983. Isohyets are at 10 mm intervals.

2.2 *Discussion*

The heavy rain and thunderstorms were undoubtedly associated with the frontal wave that moved north from the Bay of Biscay during the afternoon of 31 May. The air to the east of the wave was potentially unstable between 1000 mb and 650 mb. This fact is illustrated in the upper-air sounding from Trappes (Paris) made at 1200 GMT on 31 May (Fig. 5). The ascent shows a steady decrease in wet-bulb potential temperature from 16 °C at 1000 mb to 13 °C at 650 mb. The development of the thunderstorms can best be seen in Figs 6, 7 and 8 which display a sequence of infra-red satellite pictures from Meteosat taken at 1755, 2055 and 2355 GMT on 31 May over north-west Europe. The sequence shows a dramatic increase in the area of cloud just to the south of the British Isles between 1755 and 2055 GMT. This increase in cloud area can be attributed to a release of energy in the potentially unstable area to the east of the waving cold front. The mechanism for the release of energy at that time of day was partly provided by dynamical lifting associated with the frontal wave as it moved north. The situation was further complicated, however, by a trough in the wind flow at 700 mb. The 700 mb wind at Trappes at 1800 GMT was 205 °, 20 knots, but by midnight it had backed by 55 ° to 150 °, 20 knots indicating a trough approaching from the south. By 0600 GMT on 1 June the trough had passed through Trappes and had become a sharpening feature between Shoeburyness and Hemsby that extended east-south-eastwards into Holland and Belgium (see Fig. 9). The presence and subsequent development of the trough to the south of Trappes during the evening of 31 May probably provided another trigger for the release of energy in the area to the east of the cold front. After the release of energy, organized convection started. The trough then became self maintaining, developing as it moved north-east. The origin of the trough is

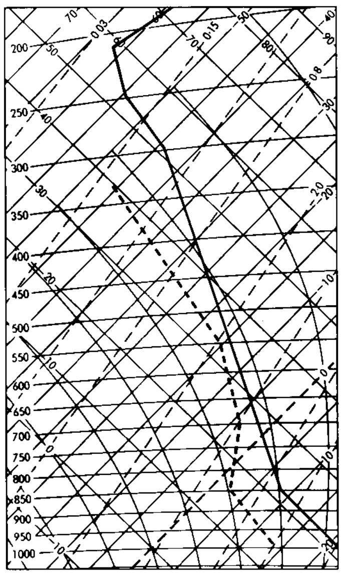

Figure 5. Upper-air sounding from Trappes (Paris) for 1200 GMT on 31 May 1983.

not entirely clear, but it seems likely that it was orographically induced by the Pyrenees. To a south-south-westerly airflow, the Pyrenees are effectively a 3000-metre-high solid barrier. Evidence of wave motion can be found in the satellite picture for1755 GMT on 31 May that is shown in Fig. 6. The strong south-south-westerly flow extends from north Africa, where a discontinuity in the cloud cover over the Atlas mountains is visible, to another discontinuity that can be seen further north in the lee of the Pyrenees. In fact this discontinuity of cloud cover in the Pyrenees and Alps region can be seen throughout the picture sequence shown in Figs 6–8. The discontinuities show up as clear areas in the satellite pictures, and are probably caused by moist air descending and drying out on the leeward sides of the mountains.

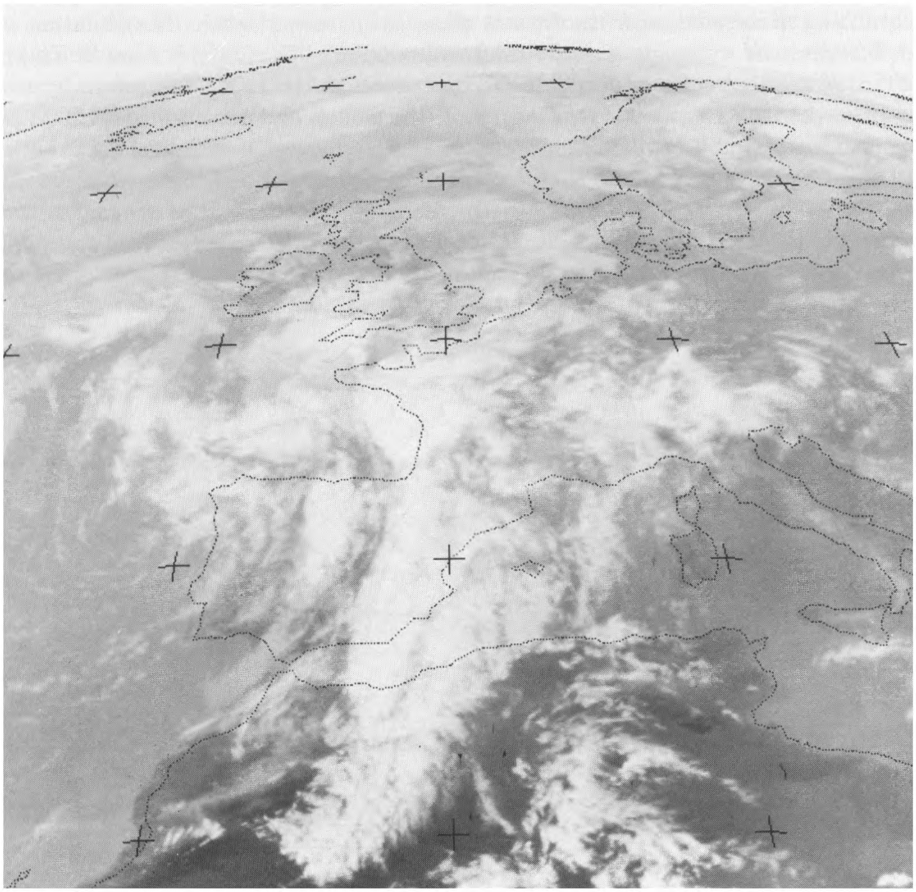

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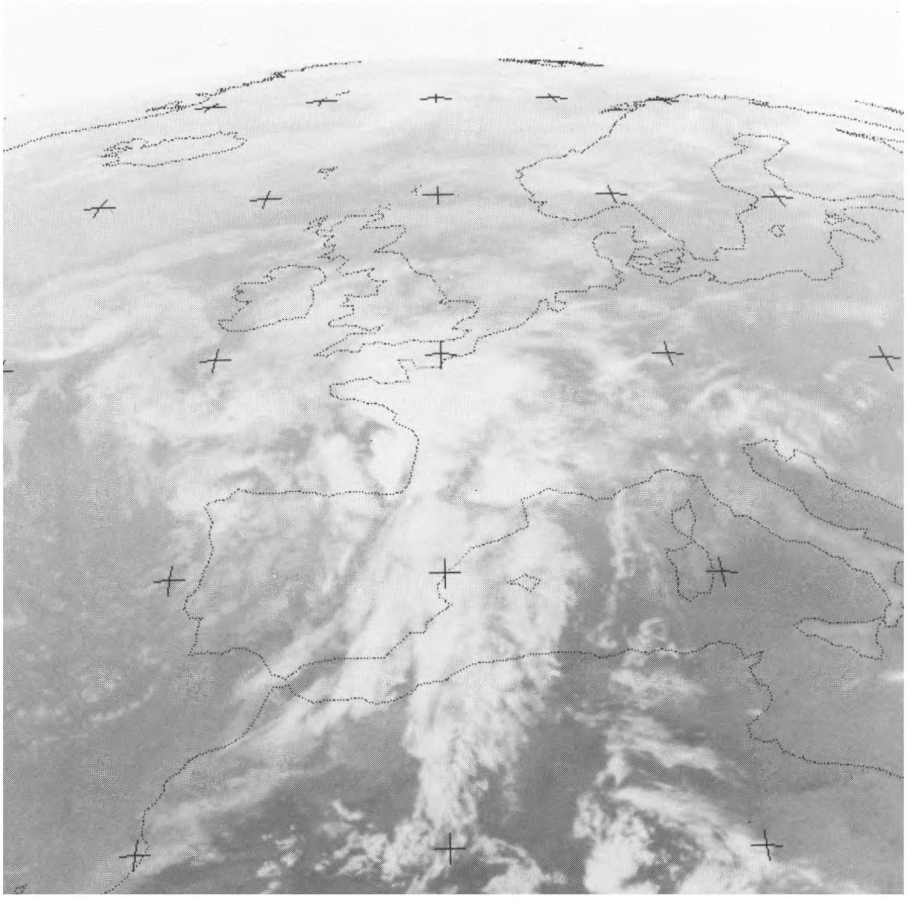
Figure 6. Meteosat infra-red picture of north-west Europe and part of north Africa at 1755 GMT on 31 May 1983.

3. The fine-mesh forecast

3.1 *Brief description of the model*

The fine-mesh version of the Meteorological Office weather prediction model uses a grid which is defined by lines of latitude and longitude and has a grid-length of 0.9375 degrees in the east–west direction and 0.75 degrees in the north–south direction. The geographical area covered by the grid extends from 79½ °N to 30 °N and from approximately 80 °W to 39 °E. This area includes most of the North Atlantic and Europe and the eastern part of America. In the vertical, the sigma co-ordinate is used which is defined as p/p_* where p = pressure and p_* = pressure at the earth's surface. The successive levels of



European Space Agency

Figure 7. Meteosat infra-red picture of north-west Europe and part of north Africa at 2055 GMT on 31 May 1983.

the model thus lie parallel to the contours of the earth's surface that are defined by the topography used in the model. The model has 15 levels in the vertical with greater concentrations in the boundary layer and near the usual jet-stream levels. Rain can be produced by the model from two processes; dynamical and convective. Dynamic rain is produced when there is mass ascent of moist air on scales larger than the grid used in the model. Convective rain, which occurs on a scale smaller than that of the model grid, is produced using a convective parametrization scheme described elsewhere (Meteorological Office 1979). In the version of the scheme that was used by the model, when a level of the model becomes supersaturated, after moist air has been lifted, the excess moisture is allowed to fall into the level below. Evaporation then occurs at this level but any remaining moisture left after evaporation has been completed is then

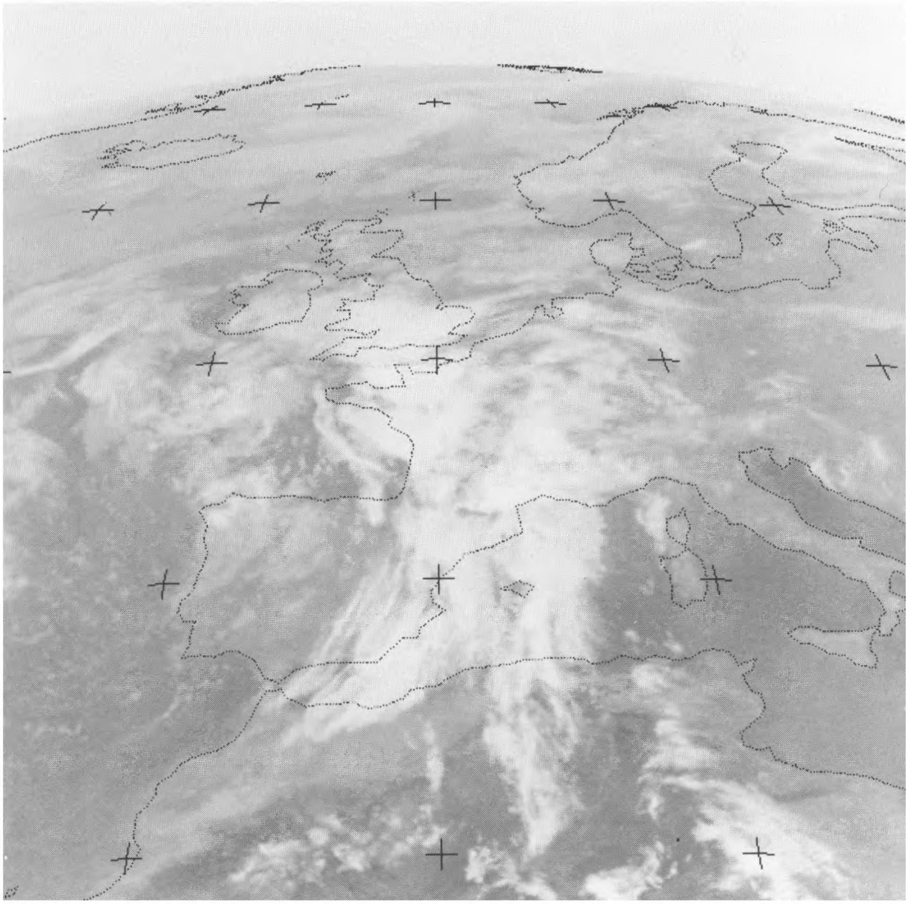


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Figure 8. Meteosat infra-red picture of north-west Europe and part of north Africa at 2355 GMT on 31 May 1983.

allowed to fall to the surface as rain. Clearly this process is not altogether realistic and can generate spurious rainfall, since in the real atmosphere moisture would be evaporated at all levels to the surface.

3.2 *The initial data*

The forecast was run to 36 hours from data valid at 0000 GMT on 31 May. The initial data fields for the forecast were in reasonable agreement with observations, except for the mean-sea-level pressure field close to the centre of depression A and near to wave D. The mean-sea-level pressure initial field is shown in Fig. 10. By comparing this field with the observed field shown in Fig. 2(a), one can see that the centre of depression A in the initial field is 5 mb too high and that the position of wave D is slightly too far south. These differences are not considered to be serious in this case since by T+6 the discrepancies

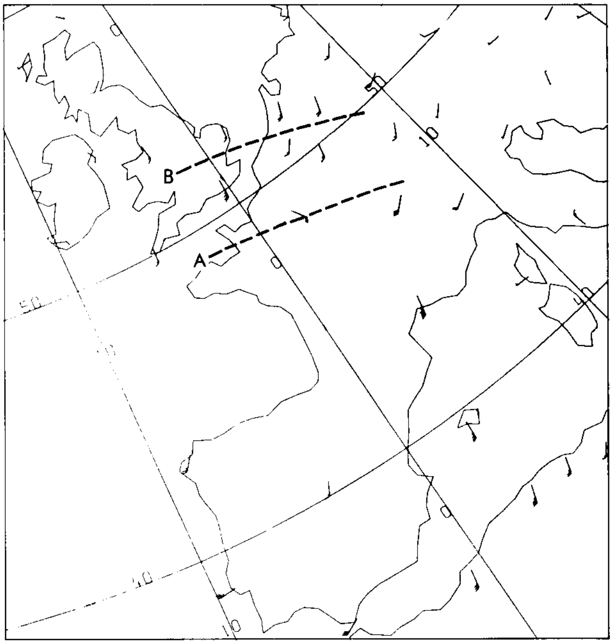

Figure 9. Observed 700 mb wind in knots at 0000 GMT on 1 June 1983. Line A indicates estimated position of trough at 0000 GMT on 1 June. Line B indicates estimated position of trough at 0600 GMT on 1 June.

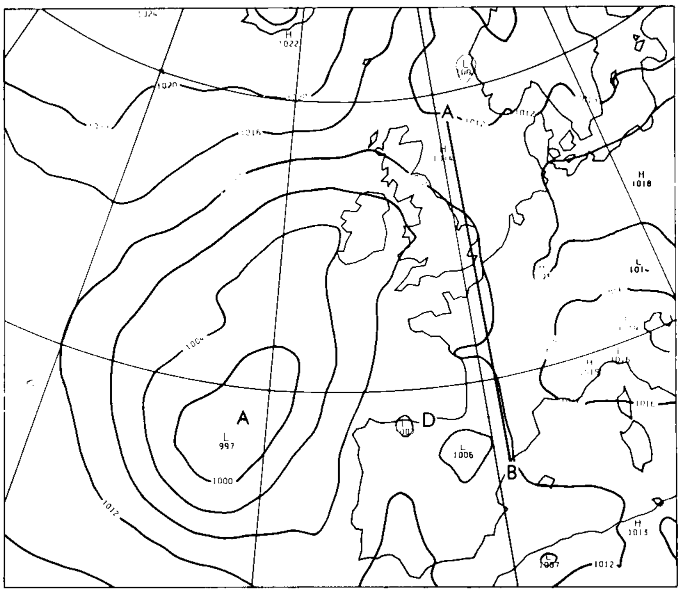

Figure 10. Mean-sea-level pressure at 0000 GMT on 31 May 1983 derived from fine-mesh initial data. The line AB denotes the cross-section shown in Figs 21 and 22.

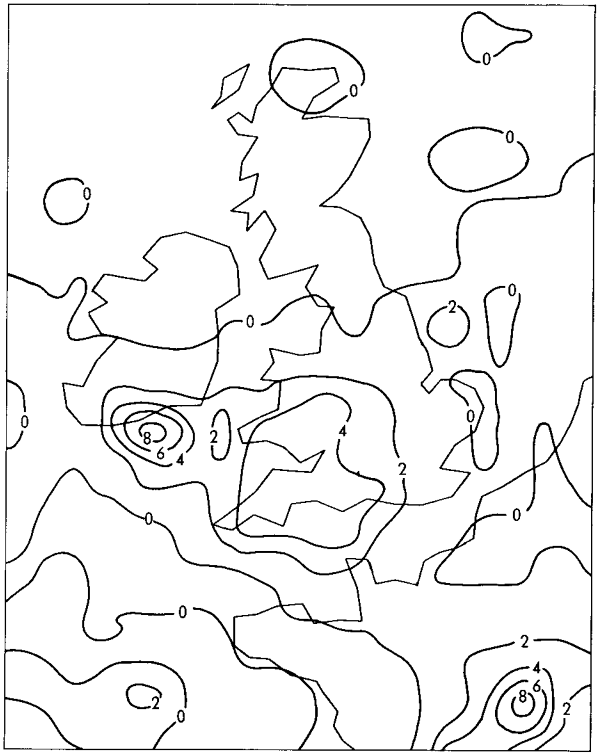

Figure 11. Total rainfall accumulations produced by forecast A for the period 0000 GMT to 0600 GMT on 1 June 1983. Isohyets are at 2 mm intervals.

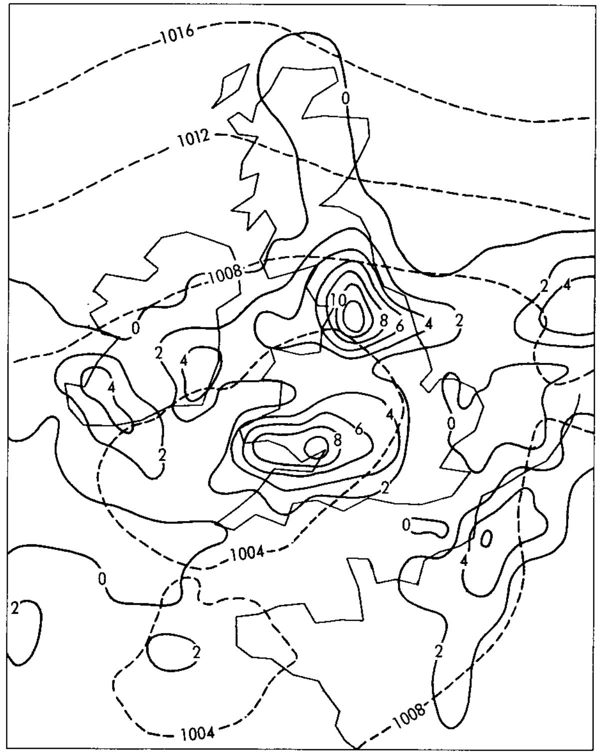

Figure 12. Total rainfall accumulations produced by forecast A for the period 0600 GMT to 1200 GMT on 1 June 1983. Isohyets are at 2 mm intervals. The forecast mean-sea-level pressure field for 1200 GMT on 1 June is shown by pecked lines with isobars at 4 mb intervals.

mostly vanish. This suggests that the differences between the mean-sea-level pressure analyses may have been due to an inconsistency between the pressure and wind analyses so that a properly initialized field would have been correct.

3.3 *The rainfall forecast*

The standard forecast will be referred to in the rest of this paper as forecast A. Although no charts are shown here, the main criticism of the rainfall forecast during the first 18 hours was that a large number of showers were predicted by the model over England and Wales in the period 1200–1800 GMT on 31 May, which was in fact a mainly dry period. There was also some spurious convective rainfall over Holland and Belgium. The onset of the thundery rain over south-west England at around 1800 GMT was quite well predicted, but the subsequent movement and development of the rain was badly forecast. Fig. 11 shows the total accumulated rainfall, that is convective and dynamic added together, produced by the model in the period 0000 to 0600 GMT on 1 June. Comparing this chart with the observed rainfall field shown in Fig. 4, one can see that the rain area in the model was too broad and that the heaviest rain did not move quickly enough north-eastwards, although the coastal strip of Norfolk was correctly predicted to remain dry. During this period south-west England was also dry, whereas in the model forecast there was still some rainfall. The total rainfall accumulations produced by the model were much too small, the largest values, 6–8 mm, covered an area over the sea just to the south of Ireland. Over England and Wales the highest totals were only 4–6 mm which does not compare favourably with the large area of rainfall in excess of 10 mm that occurred in reality. The reluctance of the model to move the thundery rain north-east shows up in the rainfall accumulations predicted for the period 0600 to 1200 GMT on 1 June which are shown in Fig. 12. The corresponding observed accumulations are shown in Fig. 13. From

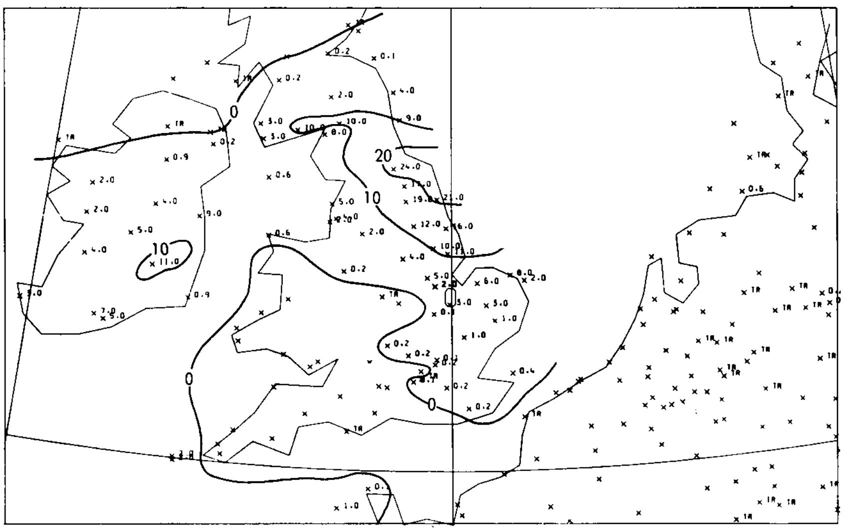

Figure 13. Observed rainfall between 0600 GMT and 1200 GMT on 1 June 1983. Isohyets are at 10 mm intervals.

these charts it can be seen that the frontal rain over northern England and Northern Ireland, with the remnants of the thundery activity over the eastern half of northern England, was not predicted accurately. The model has the area of maximum rainfall too far west and, again, the amount of rainfall was much too small in places. The highest accumulation predicted by the model was 12mm but in reality there was an area over north-east England in excess of 20 mm. The major error in the rainfall forecast at this time, however, was over South Wales, the west Midland counties and south-west England. Over these regions the model retained a separate area of quite heavy rainfall which was entirely erroneous, since the weather in this area was mostly dry throughout this period. Most of the rain predicted by the model during this forecast was convective, although the model did produce some dynamic rain after 1800 GMT on 31 May. The forecast frontal rainfall over northern England at midday on 1 June was a mixture of both dynamic and convective origin, but the erroneous area of rainfall further south was entirely convective. To summarize, we can say that the main errors of the forecast were that the model produced too much convective rainfall on the afternoon of 31 May, and that the movement and intensity of the thunderstorms and rain on 1 June were poorly forecast.

4. Experiments with the model

4.1 *Discussion*

After some investigation, it was found that the most likely cause of the spurious convective rainfall produced early in the forecast was in the formulation of the convective parametrization scheme used in the model, which was briefly described in Section 3.1. A very simple experimental change that can be made to this scheme is to change the constant that governs the rate of evaporation allowed. The change that was made in the experiment described in the next subsection was to increase the rate of evaporation substantially. By doing this it was expected that most of the spurious convective rain produced by the model early in the forecast would be removed by evaporation. This means that there would be more moisture available to the model later in the forecast and the model could then conceivably produce greater amounts of rainfall in the last twelve hours of the forecast when convection was more vigorous.

4.2 *The fine-mesh forecast with increased evaporation*

This forecast will subsequently be referred to as forecast B. Increasing the amount of evaporation did remove most of the spurious convective rain early in the forecast. This allowed the model to retain more moisture in the early stages of forecast B than it did in forecast A. This difference in moisture retention is well illustrated in Figs 14 and 15. Fig. 14 shows the forecast 700 mb relative humidity field for 1800 GMT on 31 May produced from forecast A. Fig. 15 shows the same field produced from forecast B. The area of relative humidity greater than 80% is much larger in forecast B than in forecast A, especially over the English Channel and southern England. The same effect was also seen at 850 mb and 500 mb. This added moisture retention did enable the model to produce increased rainfall amounts after T+18, particularly over England and Wales. For example, at 0000 GMT on 1 June (not shown), forecast A produced a maximum six-hour 1800 to 0000 GMT total rainfall accumulation of 10 mm over south-west England, whereas forecast B produced two maxima of 14 mm over south-west England and Brittany, which were more realistic. The differences in accumulated rainfall totals between forecasts A and B were more apparent in the period 0000–0600 GMT on 1 June. These six-hour accumulations are shown in Figs 11 and 16 respectively. The amount of rainfall over South Wales and south-west England produced by forecast B is about 4 mm higher than that produced by forecast A, although the areal extent of the rainfall is still incorrect. During the six hours between 0600 and 1200 GMT on 1 June there was an average increase of 2 mm in the frontal rainfall over northern England and the Irish Sea, and a decrease of 1 mm in the erroneous accumulated rainfall over South Wales and the west Midland counties. The differences between other forecast fields such as mean-sea-level pressure, geopotential and wind were negligible throughout the forecast.

Figure 14. Forecast A 700 mb relative humidity, with areas greater than 80% shaded, for 1800 GMT on 31 May 1983.

Figure 15. Forecast B 700 mb relative humidity, with areas greater than 80% shaded, for 1800 GMT on 31 May 1983.

Figure 16. Total rainfall accumulations produced by forecast B for the period 0000 GMT to 0600 GMT on 1 June 1983. Isohyets are at 2 mm intervals.

4.3 *Discussion*

Although changing the evaporation rate gave some improvement in rainfall amounts, the accumulations were still too small compared with observations after 0000 GMT on 1 June. Moreover, the distribution of the rainfall was still incorrect. Examination of the wind fields at 700 mb from forecasts A and B revealed that the trough, which was approaching Trappes at 0000 GMT on 1 June, was not predicted. Section 2.2 presented evidence that suggested this trough was probably an important factor in the development of the thunderstorms and heavy rain, and that it may have been initially orographically forced by the Pyrenees. The topography over Spain and part of France that was used in both forecasts A and B is shown in Fig..17. The shaded area shows actual high ground greater than 1500 metres in the region of the Pyrenees. Clearly, the Pyrenees are not correctly represented by the fine-mesh topography. Moreover, the western slopes of the Alps are too gentle, and the Massif Central and the Rhône Valley are not modelled at all. Almost certainly this lack of detail in the topography specification for these areas would cause inaccuracies and deficiences in the forecast wind and rainfall over the Alps and Pyrenees. The effect downstream, particularly upon the trajectories of the air reaching the British Isles, is not clear, although the failure to predict the trough at 700 mb correctly could be attributed to this poor representation of the Pyrenees in the model. This possibly had a detrimental effect on the rainfall forecast over the British Isles. Consequently, it was felt that the rainfall forecast might be further improved, especially later in the forecast, by giving the model a more realistic topography over the Alps and Pyrenees.

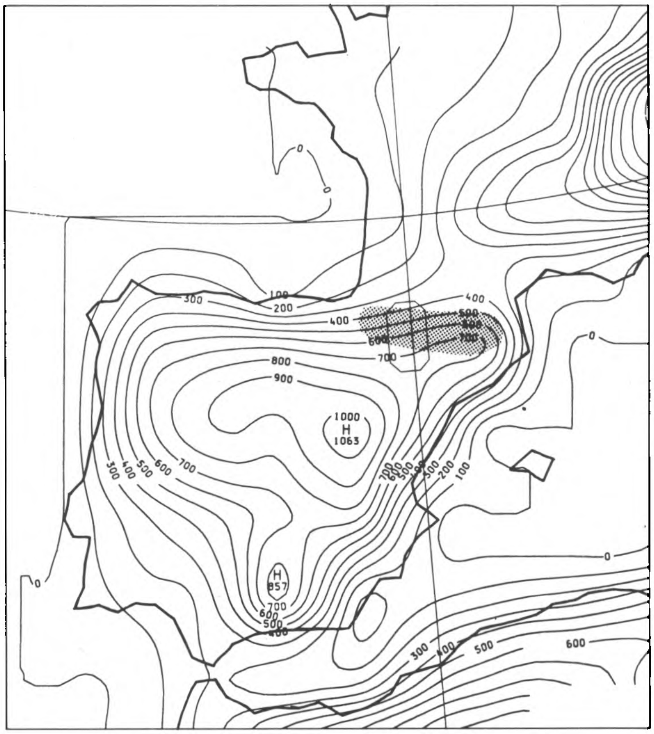

Figure 17. Topography over the Alps and Pyrenees used in forecasts A and B. Contours are at 100 m intervals. The stippled area shows actual high ground above 1500 m in the region of the Pyrenees.

4.4 *The fine-mesh forecast with an improved specification of topography over the Alps and Pyrenees*

This forecast will subsequently be referred to as forecast C. The topography over the Alps and Pyrenees that was used for this experiment is shown in Fig. 18. This new topography clearly gives an improved representation of the Alps and Pyrenees; also, the Massif and Rhône valley are now represented. Before the forecast could be re-run, the initial data had to be adjusted to correspond to the new topography. No attempt was made to balance the initial fields after adjustment; therefore, the model was given a shock at the start of the forecast. This shock generated gravity waves early in the forecast which dispersed within 6 hours. The amount of evaporation allowed in the convective parametrization scheme was set to the same value as that used in forecast A. The quantity of spurious convective rainfall over England and Wales that was produced by forecast A between 1200 and 1800 GMT on 31 May, which is not shown here, was less in forecast C. The reason for this effect was not clear but could possibly be attributed to gravity-wave propagation. Apart from increased rainfall over the Alps and Pyrenees, and the decrease of spurious convective rainfall, mainly over the British Isles, the rainfall forecast up to 0000 GMT on 1 June was similar to that in forecast A.

After midnight, however, large differences occurred between forecasts A and C. The total accumulated precipitation between 0000 and 0600 GMT on 1 June from forecast C is shown in Fig. 19. By comparing this chart with the equivalent chart from forecast A shown in Fig. 11 one can see that the forecast rainfall amounts over South Wales and the Midlands have increased by about 2 mm. More important, however, is that forecast C did extend an area of rainfall of 2–4 mm north-east from the

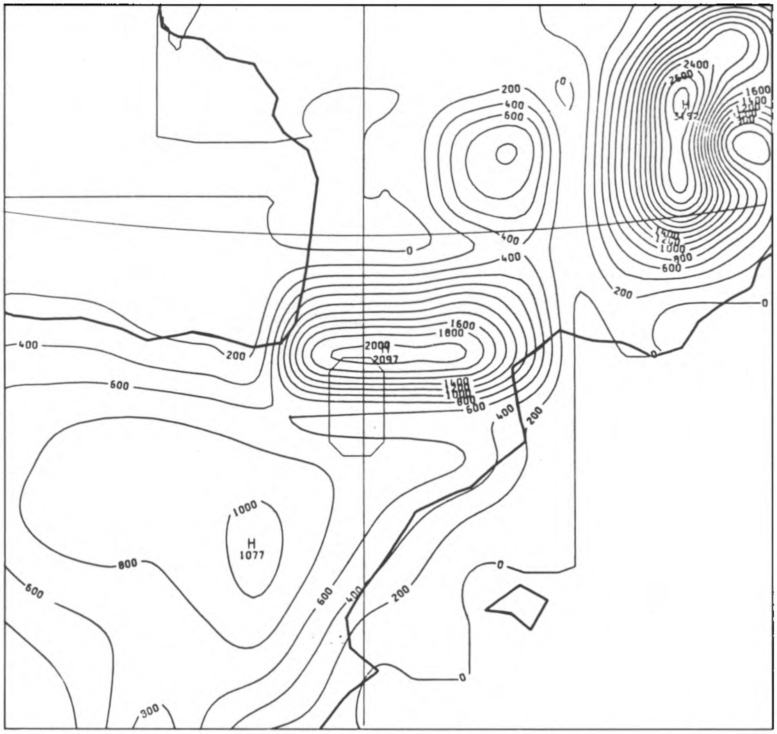

Figure 18. Topography over the Alps and Pyrenees used in forecast C. Contours are at 200 m intervals.

Midlands into Lincolnshire and East Anglia, which was a similar movement to that which actually occurred (see Fig. 4), although the rainfall totals were still much too low and the dry coastal part of Norfolk was now wet. Neither of forecasts A and B showed this movement, so in this respect forecast C was an improvement over the other two. There was a greater improvement in the rainfall forecast during the period 0600 to 1200 GMT on 1 June. The total accumulated precipitation from forecast C for this period is shown in Fig. 20; this is to be compared with the accumulated rainfall from forecast A shown in Fig. 12 and the observed rainfall shown in Fig. 13. The immediate noticeable difference is that forecast C did not produce the erroneous separate area of heavy rainfall over South Wales; also it did correctly predict a dry area over the extreme south and south-west of England. However, over northern England forecast C was worse than forecast A, since the area of heaviest rainfall in forecast C was further west, over the Irish Sea, than it was in forecast A and in reality. Also the maximum amount of rainfall in forecast C was 2 mm less than that in forecast A. However, the frontal nature of the rainfall during this period was best portrayed by forecast C, since the rainfall pattern appears to be banded rather than cellular as in the previous forecasts.

In all the forecasts a large proportion of predicted rainfall during this period was of dynamic origin within the model, and the forecast using the new topography increased dynamic rates by 1 mm per hour compared with the other two forecasts at 1200 GMT on 1 June. The highest rainfall rates obtained from forecast C were 2 mm per hour, which compares favourably with the continuous moderate rain that was reported over northern England at this time. These rainfall rates are not shown in this paper. Related to

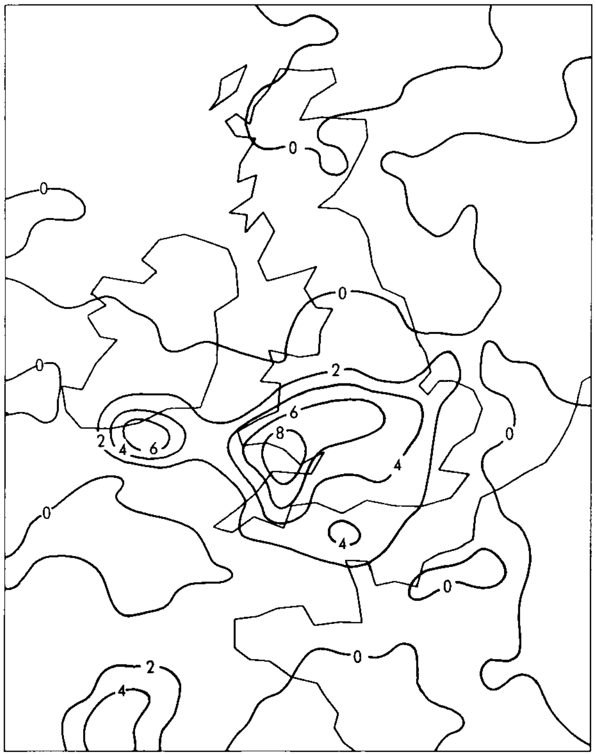

Figure 19. Total rainfall accumulations produced by forecast C for the period 0000 GMT to 0600 GMT on 1 June 1983. Isohyets are at 2 mm intervals.

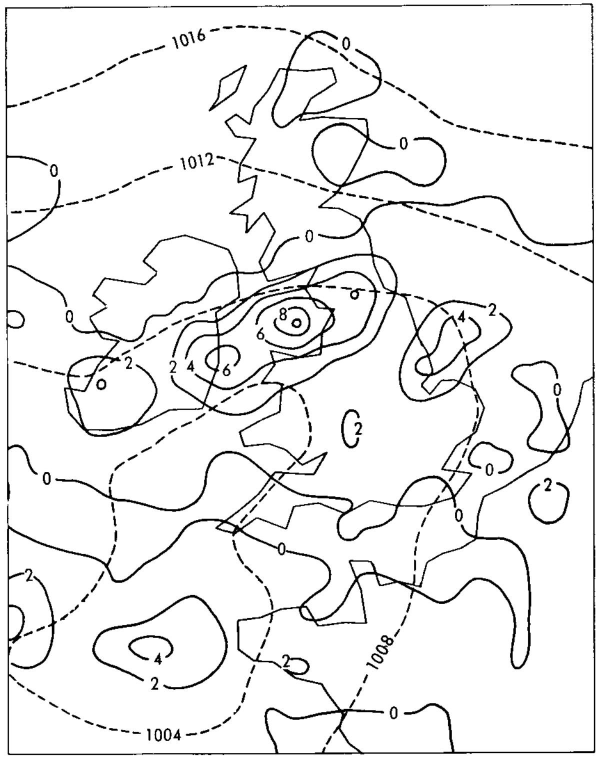

Figure 20. Total rainfall accumulations produced by forecast C for the period 0600 GMT to 1200 GMT on 1 June 1983. Isohyets are at 2 mm intervals. The forecast mean-sea-level pressure field for 1200 GMT on 1 June is shown by pecked lines with isobars at 4 mb intervals.

the improved rainfall prediction by forecast C, was an improvement in the predicted mean-sea-level pressure field at T+36. This field is shown in Fig. 20 superimposed over the forecast rainfall field. By comparing this field with the same field from forecast A which is shown in Fig. 12 and the analysed pressure field that is shown in Fig. 2(b), one can see that the pressure over the Midlands is higher in forecast C than it is in forecast A and was very close to the observed pressure shown in Fig. 2(b). Also the strong east-north-easterly pressure gradient, north of the occlusion over the Irish Sea is better predicted by forecast C than by forecast A. The trough in the 700 mb wind flow, which became evident at Trappes at 0000 GMT on 1 June, was not correctly modelled by forecast C. However, this forecast, unlike forecasts A and B, did produce to the lee of the Pyrenees a number of minor troughs which subsequently moved north-north-east into Belgium and Holland.

4.5 *Discussion*

The fact that forecast C did not correctly predict the trough near Trappes, given the improved topography over the Alps and Pyrenees, suggests either that the effect of the Alps and Pyrenees on the wind flow was still not correctly modelled, or that the trough may not have been entirely due to orographic forcing. However, the new topography did have some effect upon the wind flow. Since the trough near Trappes was not formed correctly, it is not surprising that forecast C was still incorrect; although it was an improvement over forecasts A and B, especially regarding the movement of rain after T + 18. It is not clear therefore what the reason for the improvement was.

4.6 *Investigation*

As a first step it was thought useful to compare the distribution of moisture between forecasts A and C. Figs 21 and 22 show two vertical cross-sections of relative humidity at 0600 GMT on 1 June along longitude 0.9375 °E, from 58.5 °N to 41.25 °N from forecasts A and C respectively. The line of the cross-sections is shown in Fig. 10 as line AB. The topography in each section is shown as a solid black line close to the x-axis. The difference in topography between the two sections south of 47 °N is very large. The very steep topography in forecast C causes some spurious local wave effects that can be seen in Fig. 22. Further north, the largest difference between the forecast cross-sections was found between latitudes 52.5 °N and 50.5 °N below 3000 metres (which was the height of the Pyrenees used in forecast C). In forecast A a large part of this area of the cross-section had values of relative humidity less than 80%, and in part less than 70%, whereas in forecast C, almost all this area had values greater than 80%. This effect coincides very well with the greater amount of rainfall produced by forecast C along longitude 0.9375°E between 52.5 °N and 50.5 °N in the period 0000–0600 GMT on 1 June. Although the chart is not shown here, at 51 °N, 0 °E at 0600 GMT on 1 June, forecast C had a convective rainfall rate of 0.7 mm h^{-1} which compares more favourably with the moderate rain observed at 0600 GMT than the zero dynamic and convective rates that were produced by forecast A. Above 3000 metres and north of 48 °N there are only small differences in relative humidity between forecasts A and C. The fact that there is an appreciable difference in relative humidity between forecasts A and C at heights that are greater than the topographic height over the Pyrenees used in forecast A but less than the topographic height used in forecast C, suggests that increasing the topographic height of the model over the Pyrenees had most impact on the humidity distribution below 3000 metres. This conclusion is verified by the relative humidity fields at 850 mb and 900 mb from forecasts A and C. These fields are not shown here but there were large differences in the fields between forecasts A and C, especially at 900 mb (approximately 1000 metres), throughout the forecast period. The fields derived from forecast C more closely followed the observed rainfall distributions than did those from forecast A. This seems to suggest that introducing enhanced topography over the Alps and Pyrenees enabled the model to distribute its

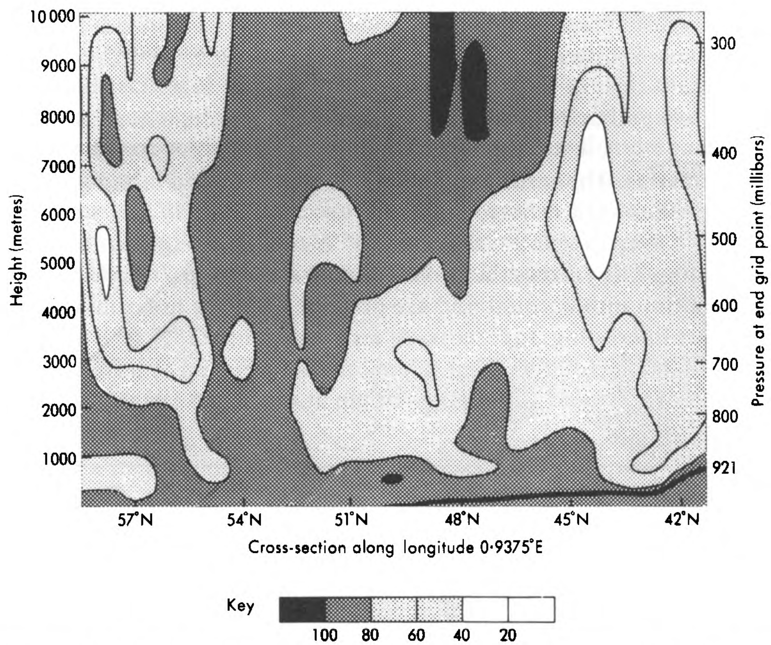

Figure 21. Cross-section of relative humidity along longitude 0.9375 °E from forecast A. Isopleths are at 20% intervals.

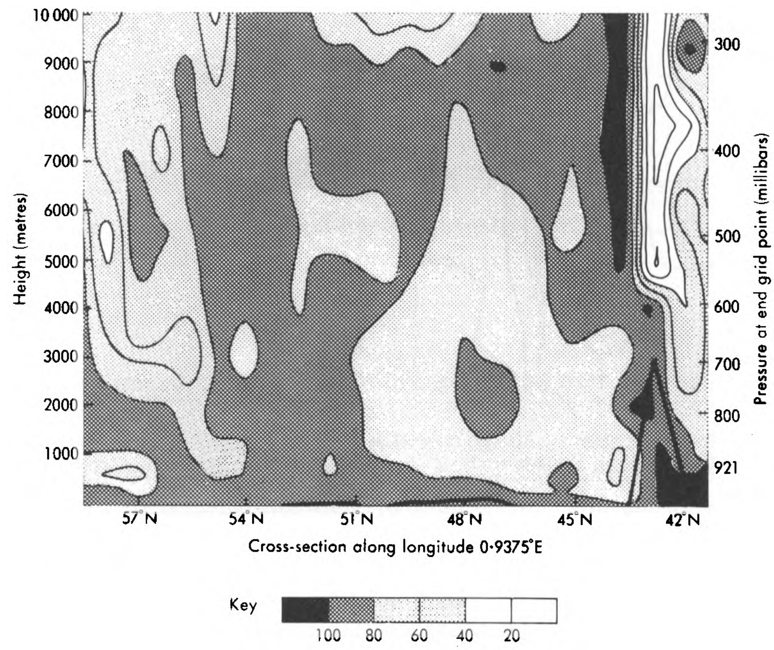

Figure 22. Cross-section of relative humidity along longitude 0.9375 °E from forecast C. Isopleths are at 20% intervals.

moisture in the lower levels in forecast C in a different manner to that in forecasts A and B, and that it was this low-level moisture redistribution that was partly responsible for the improvement in rainfall movement in the forecast.

In order to ascertain where the extra moisture, (and therefore the increased rainfall) between latitudes 52.5 °N and 50.5 °N came from, it was thought useful to calculate some trajectories backward in time of air parcels below 3000 metres. The results of these calculations at 850 mb are shown in Figs 23(a) and 23(b). Fig. 23(a) shows backward trajectories from forecast A at 850 mb, starting at 0600 GMT on 1 June, from points at 1 ° longitude intervals from 10 °W to 5 °E along latitude 52 °N, and finishing at 0000 GMT on 31 May. Fig. 23(b) shows the corresponding trajectories from forecast C. The trajectories only take horizontal motion into account and are projected on to a horizontal plane. The differences between the two maps are interesting. In forecast A, air at the point 52 °N, 0 °E at 0600 GMT would have been at 43 °N, 2 °E at 0000 GMT on 31 May if it had only been moved by horizontal advection, whereas in forecast C air at 52 °N, 0 °E would have had its origin at 45 °N, 0.5 °W at 0000 GMT on 31 May. The

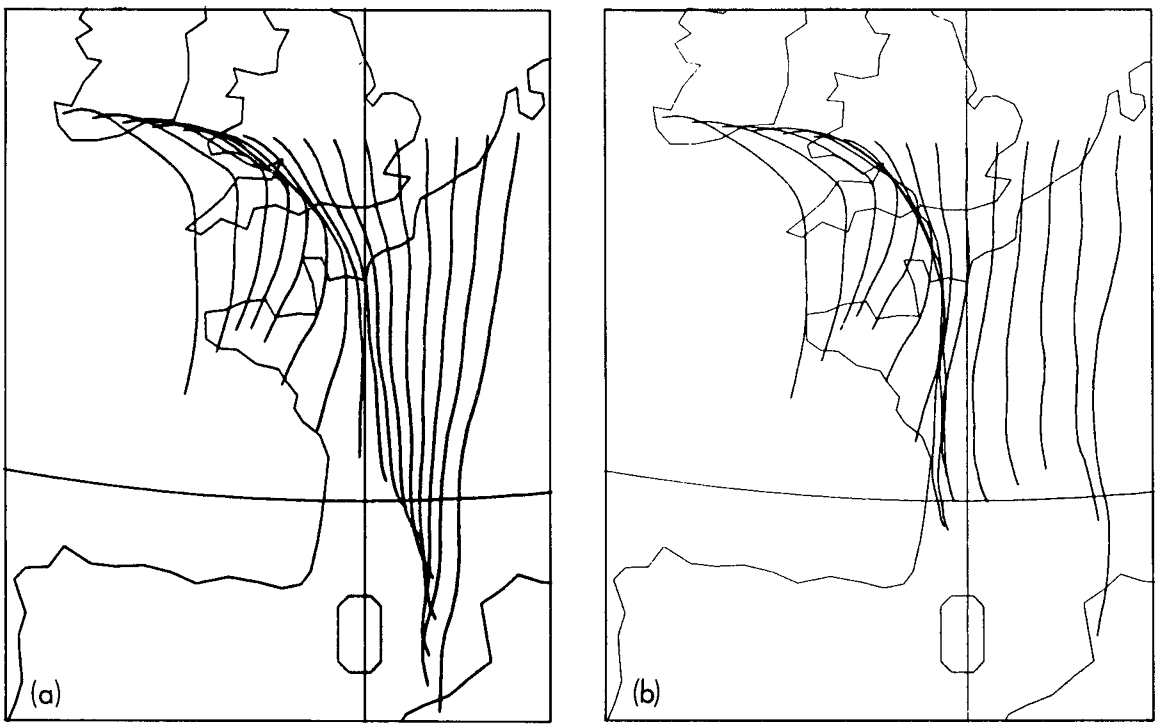

Figure 23. Thirty-hour backward trajectories at 850 mb for parcels of air initiated at 0600 GMT on 1 June 1983 from points at 1 ° longitude intervals from 10 °W to 5 °E along latitude 52 °N, (a) in forecast A, and (b) in forecast C.

two sources of the air at 52 °N, 0 °E from forecasts A and C are shown on the relative humidity initial field at 850 mb for 0000 GMT on 31 May as points A and C respectively in Fig. 24. Fig. 24 in fact shows the initial relative humidity field at 850 mb used for forecast A, but since the initial values of relative humidity at point C for forecasts A and C were identical, only one map is shown. It is clear from Fig. 24 that the origin of air that reached 52 °N, 0 °E is moister in forecast C than in forecast A. Or, alternatively, in forecast A, air that originated at point C was carried into Wales, whereas in forecast C this patch of moist air was advected towards East Anglia. The restriction of taking only horizontal motion into account when calculating the trajectories does mean that the results must be interpreted carefully since the effect of the vertical advection of humidity may be important. Nevertheless, the differences between the tracks of the air from forecasts A and C indicates the effect of the new topography on the wind fields. The introduction of the enhanced topography into forecast C had most impact on the fields at levels below 3000 metres. The main effect was to produce a number of minor troughs north of the Pyrenees and to decrease the wind speeds. Dry air to the south of the Pyrenees below 3000 metres was effectively blocked and this allowed initially moister air to the north of the Pyrenees to be advected into the eastern half of England thereby increasing the rainfall in that area.

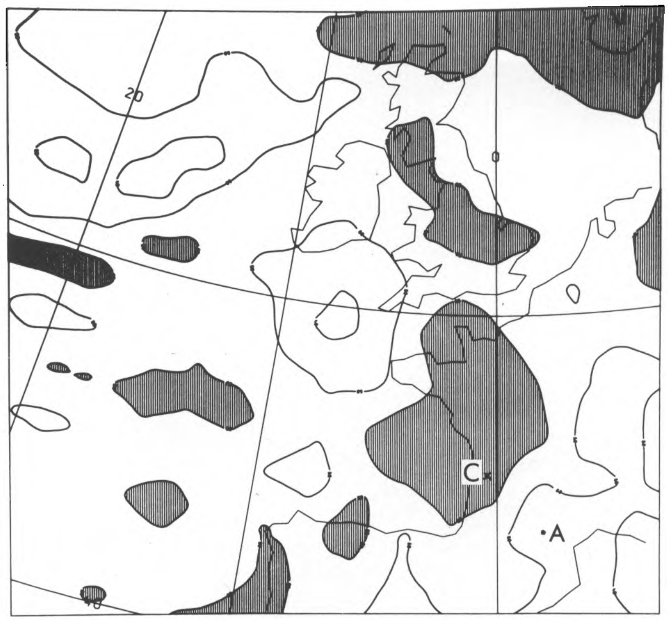

Figure 24. Initial relative humidity field at 850 mb used in forecast A. Isopleths are at 20% intervals with values greater than 80% shaded.

4.7 *Conclusions*

The introduction of an improved specification of topography over the Alps and Pyrenees into the model led to an improvement in the rainfall forecast over the British Isles. It seems that the effect of the Pyrenees upon the model was to introduce troughing in the wind fields at and below 700 mb, and to provide a barrier to the air to the south of the Pyrenees. The interaction of these effects with the moisture fields in the model have been examined and found to be important. The rainfall prediction from forecast C was the best but still incorrect, and part of the reason for this may be because the 700 mb trough near Trappes was not accurately predicted. The experiment has shown that this trough may not have been entirely orographically forced and it is likely that the initial data used for the forecast were not sufficiently accurate to develop it. Increasing the evaporation rate in the convective parametrization scheme produced some improvement in forecast rainfall amounts, but very little improvement in movement and development of the main rain areas. Probably one of the most interesting conclusions that can be made from this case study is that the effect of the Pyrenees on the wind flow may be an important factor in the development and movement of thunderstorms over England and Wales when there is a large-amplitude upper trough to the west of the British Isles. It seems that in these types of potentially thundery situations, numerical models could benefit from a realistic topography over the Alpine and Pyrenean regions.

Acknowledgements

The author would like to express his thanks to Mr M. D. Gange and Mr D. Robinson, both from the Meteorological Office at Bracknell, for their computer programming assistance in producing some of the charts shown in this paper.

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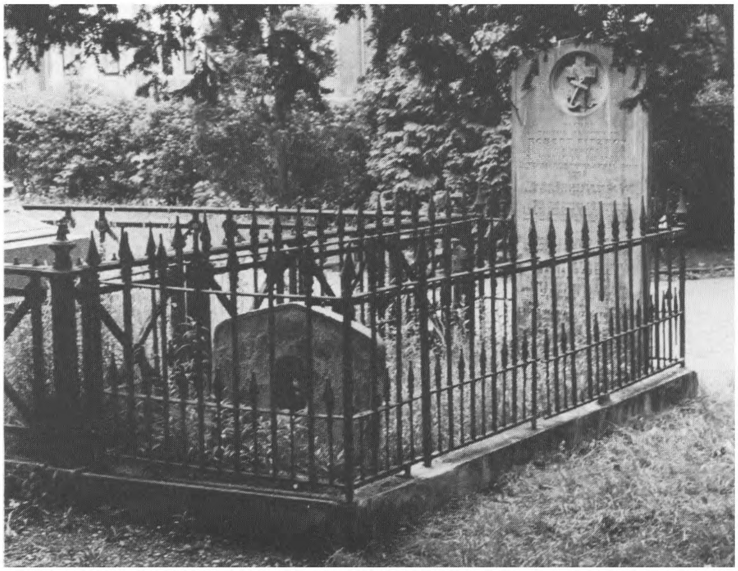
551.5:718:92

The grave of Admiral FitzRoy

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

About three years ago work was undertaken to renovate the grave of Admiral Robert FitzRoy, FRS — the first head of the Meteorological Office — including replacement of the footstone which had deteriorated very badly; see Figs 1 and 2.



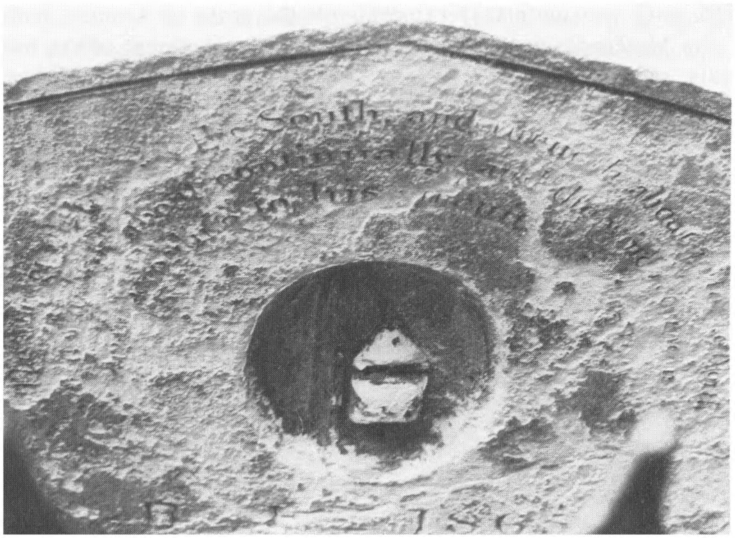
Photograph by courtesy of Mr D. Stanbury

Figure 1. Grave of Admiral FitzRoy before its renovation.

Miss R. Davis of Dulwich, a parishioner of All Saints, Upper Norwood, in the churchyard of which is the grave, reported to the Society for the Protection of Ancient Buildings in 1979 that the stones were in poor condition. On 19 February 1980 the Duke of Grafton, as the senior member of the FitzRoy family, wrote to the Director-General of the Meteorological Office asking whether the Office could have the footstone repaired.

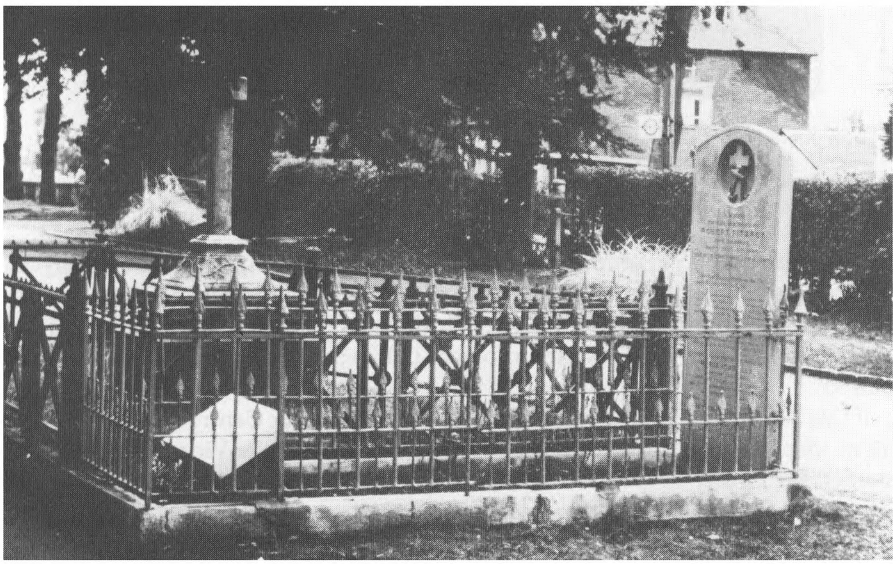
As a result of this letter, Mr G. H. Parker of the London Weather Centre visited Upper Norwood on 20 April where he inspected the grave and met both Miss Davis and the Vicar of All Saints (the Revd R. St. L. Broadberry). Mr Parker's report led to efforts by the Administrative Division of the Office to see who could execute the work and whether the necessary finance could be found from official funds. These efforts soon met with success, and it was decided that the Commonwealth War Graves Commission would design a new footstone (the old one being beyond repair) and have it made and fixed, the cost being met from Defence Votes.

The drawing up of a design and the obtaining of necessary permission from the ecclesiastical authorities both took a good deal of time — the matter had, in fact, to be referred to the Diocesan Registrar at Canterbury — and it was not until 22 October 1981 that the old footstone was removed and the new one fixed in its place. The design of the new stone differs in certain respects from the old, but all the essential components of the latter are retained, including the pictorial representation of a North Cone and Drum, part of FitzRoy's original system of storm-warnings (see Figs 3–5).



Photograph by courtesy of Mr D. Stanbury

Figure 2. The original footstone.



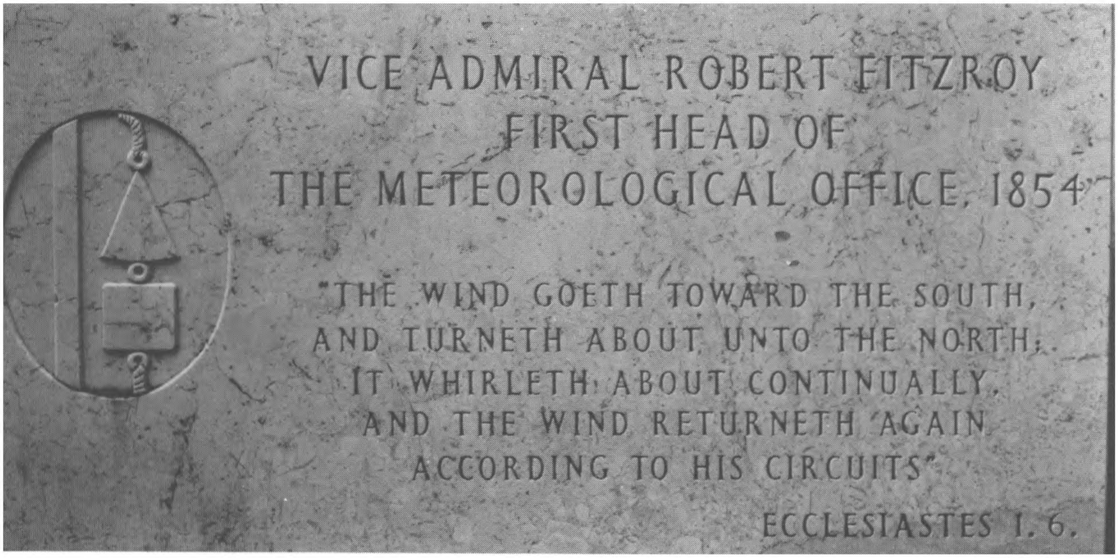
Photograph by courtesy of Mr R. P. W. Lewis

Figure 3. The grave after renovation.

Photograph by courtesy of Mr R.P.W. Lewis

Figure 4. The original headstone after renovation.

The grave of Admiral FitzRoy is now, we hope, in a state worthy of the remarkable and accomplished man who was our first Chief.



Photograph by courtesy of Mr R. P. W. Lewis

Figure 5. The new footstone.

Reviews

Lightning, auroras, nocturnal lights, and related luminous phenomena: A catalog of geophysical anomalies, **compiled by William R. Corliss. 260 mm × 180 mm, pp. v + 242, *illus*. The Sourcebook Project, Glen Arm, MD 21057, USA, 1982. Price US $11.95.**

Natural phenomena that defy explanation by established physical laws have long engaged the curiosity of both scientists and laymen, and have invited frequent speculation on the validity and mechanisms of the reported events. This book deals with anomalies associated with luminous behaviour, adding one volume to a series which attempts to identify and describe a wide range of unexplained observations in a systematic fashion. The anomalies are listed in the form of a catalogue with each entry containing a brief description, a possible explanation, and numerous references, including extracts from many of the eye-witness accounts. The author gives a subjective assessment of the quality of the data supporting the anomalies and the extent of the departure from known laws implied by their existence.

For those with a casual interest in unusual and unexplained phenomena, this book offers entertaining glimpses of the strange effects that have been reported, such as 'auroral pillars' and 'underwater lightning', and reveals a wide range of novel observations. The sets of references provide a useful, though not exhaustive, initial source for research and the copious indexing should satisfy most enquirers. However, many readers are likely to seek a deeper treatment of specific anomalies and will be disappointed with the brevity of background information, with the absence of material indicating the points of conflict with known laws and with the uncritical acceptance of unsupported evidence.

A distinction should be drawn between: those phenomena which appear to contradict established physical laws; those phenomena which are unexplained, owing to the complexity of the system (as, for example, in many aspects of weather); and those events which cannot be assigned to a specific cause, owing to the inadequacy of the data. My main complaint with this work is the inclusion of too many cases within the third category where anomalies are based on fragmentary evidence — sometimes a single report — 'hot-air blasts following lightning strokes' and 'black auroras', for instance, at the expense of better documented problems. A number of rare lightning anomalies is described, yet no mention is made of the basic difficulty in understanding the generation of lightning, which is still incompletely resolved after much research.

In brief, this book gives colourful, abbreviated accounts of a class of anomalies with luminous characteristics and offers an opportunity for an interesting browse through reports of unusual phenomena. However, the more sceptical student is poorly served by the shallow treatment of unexplained observations.

F. Rawlins

Acid deposition. Proceedings of the CEC workshop organized as part of the concerted action 'Physico-chemical behaviour of atmospheric pollutants' held in Berlin, 9 September 1982, edited by S. Beilke and A. J. Elshout. 160 mm × 235 mm, pp. X × 235, *illus.* D. Reidel Publishing Company, Dordrecht, Boston, Lancaster, 1983. Price US $32.50.

The reader attracted by the main title of this book should note that it is the result of only a one-day workshop, whose geographic remit was Europe. Nevertheless, and at the risk of mixing metaphors, one is impressed by the amount of ground covered by 'Acid deposition'.

I have a mental image of a workshop: castings ready for machining and assembly, tools ranged on the wall, cuttings on the floor, while craftsmen fashion articles of order and symmetry out of seeming chaos. How does this scientific workshop compare with such an image? First, the rough edges of a product fresh from the mould are obvious. There is no index, and apparently little editorial intervention; each paper appears in its own particular typeface, the standard of graphs is variable, and spelling errors numerous. However, such shortcomings represent the acceptable compromise between aesthetics and the prompt appearance of these proceedings on the bookshelves of scientists concerned with acid deposition.

The range of tools on the wall, in the form of scientific disciplines represented, is restricted, with only one paper concerned directly with biological aspects. Biologists and ecologists will find it a useful review of current European work on the chemistry and meteorology of acid deposition, though they may wish to take issue with the proceedings' focus on the uncertainty of trends and background levels which, somehow, manages to leave the reader with the impression that acid rain is not as serious a problem as he thought. Nevertheless, most scientists interested in the problem, even on the fringe, would be pleasantly surprised by the highly readable reviews in what could have been a very specialized and esoteric book.

The introductory review on the present situation in Europe is clear and comprehensive, and contains a list of the major questions yet to be answered. The rest of the book is a mixture of reviews and reports of individual research, and it is the former which contribute most to the book's value. Thorough resumés are presented of the acidity of background precipitation (Delmas and Gravenhorst) and on the formation of atmospheric acidity (Cox and Penkett). Delmas and Gravenhorst arrive at tentative conclusions for background precipitation pH for continental and maritime regions, and also background pH and so-called reference pH (no anthropogenic contribution) for polar regions. Showing commendable restraint in the amount of chemical notation, Cox and Penkett discuss progress in understanding oxidation occurring via homogeneous and liquid-phase reactions, and on the surface of aerosols. They draw attention to the fact that the decline of the black smoke emissions from the 1950s onwards has been accompanied by a steady increase in vehicle emissions, and call for more investigation into the role of vehicle pollutants in acid deposition. As well as reviewing and assessing existing ideas on atmospheric chemistry they introduce some new ideas on the promotion of sulphur dioxide oxidation by chlorine nitrate, or its inhibition by formaldehyde.

Trends in acidity of precipitation receive attention in three papers; all, in different ways, challenge the commonly-held view that in Europe the amount of acid precipitation has shown a steady increase with time and in geographical extent. There are two papers each on heavy metal deposition associated with acid precipitation, cloud chemistry, and surface fluxes; to express disappointment that only one paper deals with source-receptor modelling would be to expect too much from a one-day session. The editors furnish a concise 'Workshop Conclusions' to end the volume.

In my imaginary workshop I expect to see sparks fly, but this book suggests that little scientific heat was generated during discussions. To push the analogy, it seemed to be more of an assembly shop where the program ensured that various components fitted together without conflict. However, more extensive reporting of discussions would have been welcome. This lack is most evident in the section on trends: Kallend's guarded and slightly enigmatic conclusions about the changes in the geographical extent of acid rain serve to undermine existing views that accord well with 'common sense', without replacing them with an alternative theory.

Finally, what items of order and symmetry were fashioned out of the frustratingly complex mass of acid deposition data? Insofar as the perspective afforded by the reviews adds shape to the subject, then the publication of these proceedings succeeds in chipping a fresh contour from the acid rain monolith, but it is clear from the editors' conclusions that the floor of many more workshops will be littered with chippings before the final shape of acid deposition emerges.

B. A. Callander

North Sea dynamics. Proceedings of an International Symposium held in Hamburg, West Germany, 31 August - 4 September 1981, edited by J. Sündermann and W. Lenz. 170 mm × 247 mm, pp. xvii + 693 *illus.* Springer-Verlag, Berlin, Heidelberg, New York, 1983. Price DM 98.

This large volume contains no fewer than 45 papers arranged in 4 main sections: Currents and water balance; Wind waves and storm surges; Transport of momentum, energy and matter; and Ecosystems. The overlap in subject matter between the first three sections is such that in practice there are 32 papers dealing with many aspects of the modelling and measurement of dynamical processes in the sea. The subject matter is very uneven, there being just one paper on surface wave modelling, and only two directly on measurement techniques. The 12 papers in the final section reveal how the complex ecosystems in the North Sea are directly related to such dynamical processes as water exchange, mixing, etc. which affect temperature and salinity levels. The opening review article of the book successfully illustrates how the development of physical and biological oceanography, centred on the North Sea, has been led into a rewarding synthesis under the guidance of the International Council for the Exploration of the Sea.

The majority of the papers to be found in the earlier sections of the book are concerned in one form or another with mathematical modelling of either 2- or 3-dimensional systems. The equations concerned are very familiar to a meteorologist but are simplified by the incompressibility of water and the finite depth of the region of integration. Another common element in the material presented is the requirement for a good quality network of observations, preferably in real time! The problems of a synoptic meteorologist are dwarfed by the lack of data which confronts the dynamical oceanographer. The few papers that are concerned with measurement techniques are illustrative of the growing interest in remote sensing in dynamical oceanography; both radio-wave and acoustic systems are discussed.

Three papers that particularly interested the reviewer were those by I. D. James (A three dimensional model of shallow-sea fronts), G. Kullenberg (Mixing processes in the North Sea and aspects of their modelling) and J. C. J. Nihoul (Interactions between tidal residuals and 'synoptic' eddies in the North Sea). The latter two papers were more 'complete' in themselves than most of the others in the volume and gave more background and scientific justification for the solutions adopted. The paper by James was a fascinating restatement of the 'universality' of both fluid flow (air or water) phenomena and the techniques used to model them.

An interesting point to arise from many of the papers was the simplistic approach adopted when a meteorological input was required. It is to be hoped that the synthesis between dynamical and biological oceanography, highlighted in this volume, is succeeded by a similar blending with meteorology.

As is usual with this kind of book there are a greater number of misnumbered and mislabelled equations and diagrams than would be found in a conventional textbook, although this is not too much of a draw-back since the individual papers are self contained and hence the potential confusion is limited. The subject index at the end of the book is very comprehensive and adds significantly to its value as a 'state of the art' reference source. The fact of a significant delay between the ending of the symposium and the publication of the proceedings is to be regretted, but the contents of the book truly reflect the recent significant advances in dynamical oceanography.

P. E. Francis

Climate and energy systems: a review of their interactions, by Jill Jäger. 155 mm × 235 mm, pp. ix + 231, *illus.* John Wiley & Sons, Chichester, New York, Brisbane, Toronto, Singapore, 1983. Price £19.95.

This book opens with two questions: could the large-scale and widespread use of fossil fuel, and nuclear and solar energy sources cause changes in climate and, if so, might these changes constrain the future development of energy systems? As regards the first the author presents an overview by assembling the present scattered knowledge and relevant studies. Since no confident and definitive statements on the probable climatic changes can truthfully be made, we are, quite properly, spared from speculative predictions on the second question. The book is a result of the author's participation in the Energy Systems Program of the International Institute for Applied Systems Analysis (IIASA). (An unfortunate by-product is the proliferation of the jargon word 'system' throughout the text.) The author uses the projections of energy use over the next 50 years made by IIASA in 1981 as the basis for examining the impact of energy production on climate. Consideration is mainly given to two projections: in the first, the global annual energy use rises from the present 8 TW years (1 TW = 10^{12}W) to 22 TW years in 2030 and in the second it rises to 36 TW years; in both, fossil fuel is assumed to supply over 60% of the total. The world population in assumed to double to 8000 million by year 2030 with energy consumption per head per year rising from 2 kW years to 3 or 5 kW years.

After an introductory chapter summarizing the main findings of the Energy Systems Program relevant to the aim of the book there is a concise and readable account of the physical basis of climate intended for non-climatologists. Methods of assessing the influence of human activities are described including past analogues and the use of numerical models; the shortcomings of atmospheric general circulation models such as absence of an interactive ocean model, poor treatment of clouds and hydrological processes and sub-grid-scale processes are noted here and are usually recalled later when describing the results of particular studies that have used such models. The chapter concludes with a brief review of observational and model investigations of the effect of sea surface temperature anomalies on climate to illustrate the nature of the interactions between major components of the climate system; I found this rather out of place here.

The next four chapters form the core of the book and examine respectively the CO_2 question, the effect of waste heat, other pollutants besides carbon dioxide, and the potential climatic consequences of large-scale use of renewable energy sources. Given the large consumption of fossil fuels assumed in the projections (above) of energy use, the increase in atmospheric CO_2 is taken to be the most serious climate issue and is the one treated most fully. The observed increase of atmospheric concentration, the carbon cycle and the box models of it are covered briefly whilst more attention is given to speculations on future atmospheric concentrations of CO_2. Given the evident difficulties of economic forecasting, it is not surprising that divergent projections result from different workers. Indeed the assumptions of the IIASA study are all questionable and neglect unforseeable events such as wars, sudden oil price increases or technological advances in transport. The treatment of the effect on climate of increased CO_2 is largely confined to equilibrium surface temperature increases given by radiative convective models and atmospheric general circulation models in studies up to 1981, though the role of oceans, the transient response and the feasibility of detecting a CO_2 signal above the natural 'noise' are all briefly mentioned. The uncertainties about response of the biosphere and possible control strategies are also examined.

I found the chapter on waste heat and the effects of solar energy systems interesting and informative. The local increase in summer cloudiness in a mesoscale model of southern Spain, which included a large array of solar reflectors, causes doubt whether the exploitation of benign energy sources is relatively straightforward. The interesting question of possible climatic perturbations caused by other gaseous pollutants and particles is only briefly treated and I found my appetite whetted and requiring further information.

The penultimate chapter reverses the standpoint and considers the effect of climate on energy supply and demand (a familiar exercise to temperature forecasters for gas and electricity industries!). This is mostly serious and sensible stuff but one hopes that the proposed intentional climate modification schemes such as damming the Gulf Stream remain forever science fiction.

The concluding chapter summarizes the topics covered and the conclusions reached on present knowledge. In general the review is well balanced and fairly presents many viewpoints and results. The diagrams are well reproduced and clearly labelled and abundant references are provided at the end of each chapter. Inevitably the treatment of complicated and controversial questions has been shortened to keep the book a manageable size. The book might have benefited, however, if the author had more often stated her own judgement on conflicting results.

C. A. Wilson

Books received

The urban climate, by Helmut E. Lansberg (New York and London, Academic Press Inc., 1981. £29.50) is volume 28 in the *International geophysics series* and it is hoped that it will be found useful by city planners and developers, and human ecologists as well as boundary layer meteorologists. The book attempts to summarize knowledge of the physical relations that create the climate differences of urbanized areas gained from studies made over the last quarter of a century since the last monographic review about urban climates was published.

Dynamic meteorology: data assimilation methods, edited by L. Bengtsson, M. Ghil and E. Kallen (New York, Heidelberg and Berlin, Springer-Verlag, 1981. DM 44) is volume 36 in the series *Applied mathematical sciences.* The book contains selected lectures from the 1980 seminar devoted to data assimilation methods held at the European Centre for Medium Range Weather Forecasts. It attempts to give a review of the fundamental progress made in defining atmospheric states and of issuing forecasts from the states so defined using new observing systems, in particular polar-orbiting and geostationary satellites.

Food – climate interactions, edited by Wilfred Bach, Jurgen Pankrath and Stephen H. Schneider (Dordrecht, Boston and London, D. Reidel Publishing Co., 1981. Dfl 135 cloth, Dfl 65 paper) is an account of the *Proceedings of an International Workshop* held in Berlin in December 1980 which was the third in a series of international conferences carried out under the project 'Impacts of air pollution on climate'. The problems of supplying the increasing world population with food while the production of agricultural products is decreasing are difficult enough even without the climatic changes caused by man's activities. This book contains Working Groups' reports and recommendations, 'Climate as a hazard' and 'Climate as a resource'.

The earth's problem climates, by Glenn T. Trewartha (Madison and London, The University of Wisconsin Press, 1981) is the second edition of this book first published in 1961. This new edition is extensively revised and updated from the former edition which received a favourable review in this magazine. The revisions affect particularly the sections on Pacific Colombia, the Chilean-Peruvian desert, the drought region of north-east Brazil, the dry region of the southern Caribbean, the dry-subhumid belt of the eastern and central parts of the equatorial Pacific, equatorial East Africa, the Indian subcontinent, East Asia and western Anglo-America.

The weather of Britain, by Robin Stirling (London, Faber and Faber Ltd, 1982. £12.50) sets out to analyse and describe systematically the patterns and the aberrations, to be discerned through the haze of statistics over the past 100 years. The book contains information about every conceivable aspect of the weather over Britain with fully documented sources of information. It is suggested that we may easily be lulled into thinking that because our climate is temperate, the weather will be mostly benign, if variable.

Correction

Meteorological Magazine, April 1984, p. 91, tenth line from bottom of page. For 50 m read 500 m.

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CONTENTS

NOTICES

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Large hail over north-west England, 7 June 1983

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Summary

An account is given of a series of severe thunderstorms which produced large hail and developed 'severe-right' supercell characteristics. The Malvern network radar display was used operationally for forecasting the movement of the storms, and the Hameldon Hill radar data to identify individual storm cells in retrospect.

Synoptic developments

The period May–June 1983 has been declared one of 'outstanding meteorological interest' over England following a long spell of unsettled weather which culminated in widespread thunderstorms and severe hailstorms. In May, Manchester experienced seven consecutive days of thunder (compared with a long-term average of 2.5 for the month) and on 18 May 55.6 mm of rain fell in two hours at Finningley, South Yorkshire during a thunderstorm. On 5 June hailstones up to 70 mm in diameter were reported along the south coast from Dorset to Kent (Royal Meteorological Society 1983).

Two days later exceptionally severe storms swept north-east from Cornwall across Wales, north-west England and eventually north-east England, producing a swath of large hail of up to 70 mm in diameter over Greater Manchester and adjacent areas.

On 6 and 7 June an anticyclone intensified to 1032 mb as it moved across Scotland towards Denmark and eastern Europe. As it moved away eastwards a south-easterly airflow developed over England on 7 June bringing warm unstable air northwards ahead of a cold front which crossed the country from west to east during the morning of 8 June.

Computer predictions from the Meteorological Office 15-level coarse-mesh operational model for 1200 GMT on 7 June, based on data for 0000 GMT on 7 June, indicated warm advection of moist air ahead of an advancing upper trough implying marked mass ascent (Figs 1(a) and 1(b)). The model predictions showed wet-bulb potential temperatures (θ_w) at 850 mb of 16 °C extending over much of England and Wales. Of particular interest is the area of strong horizontal wind shear on the warm exit side of the forecast upper-level jet stream (Fig. 1(b)). The actual upper winds reported at Camborne, compared with other stations, at 1200 GMT on 7 June confirm strong vertical wind shear between the 900 and 300 mb levels as shown in Table I.

Table I. *Upper winds reported at 1200 GMT on 7 June 1983*

	Camborne		Crawley		Aberporth		Aughton	
	(degrees)	(knots)	(degrees)	(knots)	(degrees)	(knots)	(degrees)	(knots)
900 mb	200	10	155	19	200	22	160	29
300 mb	190	68	210	40	185	53	195	46
Vector wind diff.		58		33		34		28

Ludlam (1963) found a striking relationship between severe storms over England and the neighbouring Continent and the presence of strong vertical wind shear, with the hail or tornado located on the warm side of the jet. The Meteosat infra-red satellite photograph at 1400 GMT on 7 June (Plate I, page 264) shows the presence of an area of deep convective cloud in exactly the same area as the strong wind shear.

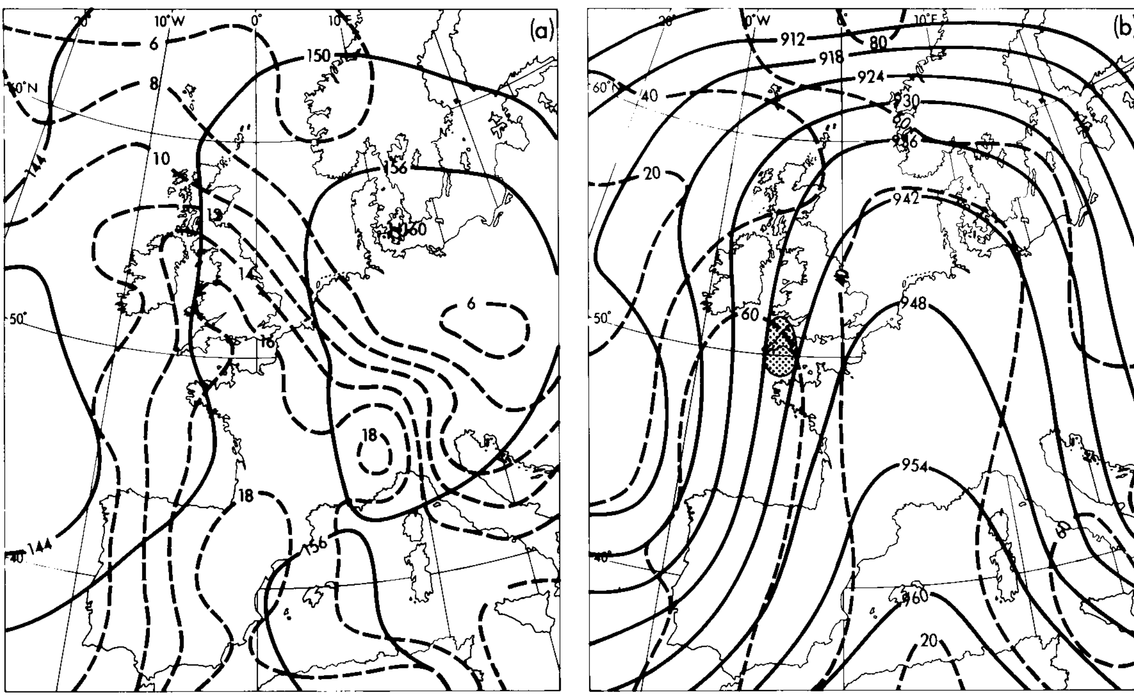


Figure 1. 15-level model forecast charts for 1200 GMT on 7 June 1983 showing (a) 850 mb wet-bulb potential temperatures (pecked lines) and 850 mb contours (solid lines), and (b) 300 mb isotachs (pecked lines) and 300 mb contours (solid lines). The stippled area over Cornwall (Fig. 1(b)) represents an area of strong horizontal wind shear.

The Aughton sounding for 1200 GMT on 7 June (Fig. 2) suggested deep convection of air from the 900 mb level to around 11 km (36 000–37 000 ft), with the possibility of some cumulonimbus tops bursting through the tropopause to around 13.5 km (45 000 ft) given sufficiently undiluted updraughts. Surface temperatures over north-west England increased from 9 °C at dawn to 23 °C in mid-afternoon, but the maximum updraughts were probably associated with air that had crossed south-east England and the Midlands where temperatures reached 25 °C in places. This air probably became the warm layer at the 900 mb level on the Aughton sounding. Another feature of this sounding was the temperature inversion between 750 and 700 mb and the dry layer above, which, combined with the low-level south-easterly inflow and the south-westerly upper flow on the right flank of the storm area, is a characteristic of severe tornadic storms often giving large hail. Fawbush and Miller (1953) found that, although hail exists to some extent in all thunderstorms, great convective or potential instability is necessary for the production of large hail. This is provided in this case by the dry air overlying the moist air below 750 mb on the Aughton sounding. Palmen and Newton (1969) also refer to this instability and the similarity of temperature soundings for both tornado and hail situations. Thunderstorm warnings had in fact been issued soon after 0800 GMT for civil airfields over northern England and the Midlands, and public forecasts mentioned the possibility of spectacular storms overnight.

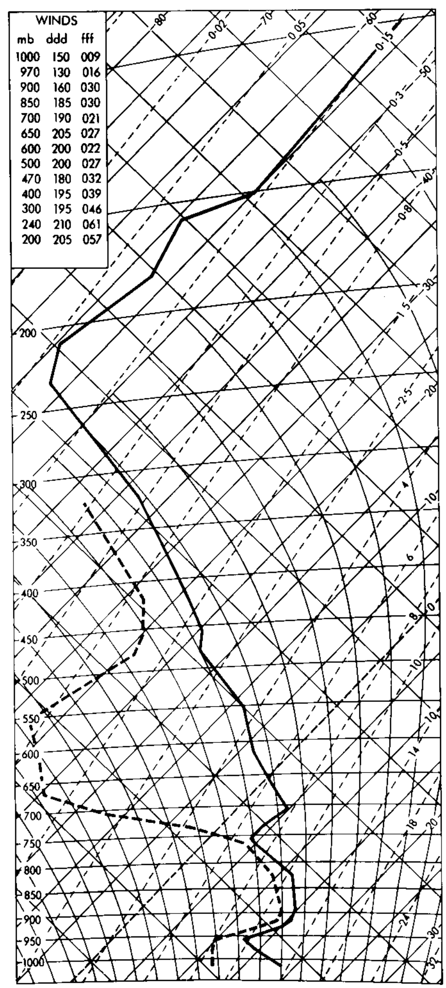


Figure 2. Upper-air sounding for Aughton at 1200 GMT on 7 June 1983. Winds are in degrees and knots.

The extent of the thunderstorm development at 1600 GMT on 7 June is shown on the SFLOC chart, Fig. 3. The reports, made by the Cathode Ray Direction Finding (CRDF) system are only made to an accuracy of half a degree of latitude and longitude, but it is clear from the plotted reports that a large area of thunderstorms extended from Cornwall to mid-Wales and subsequently moved north-eastwards across North Wales, Cheshire and Greater Manchester between 1800 and 2000 GMT. It was from within these latter areas that the reports of large hail were received. Only two reports of hail were received from the routine meteorological network of observing stations. These were from St Harmon in mid-Wales at 1800 GMT and Manchester Weather Centre at 1955 GMT and are included in Table II as items numbered 1 and 41. All the remaining sixty or so hail reports were gleaned retrospectively from local newspapers, individual members of the public and meteorological staff off duty at the time. A number of interesting photographs of hailstones and hail damage were received and a selection of these has been included in this account (Figs 4(a), (b) and (c), 5 and 6). The complete collection —30 in all — has been deposited in the National Meteorological Library at Bracknell. The selected photographs are discussed in a later section of this report.

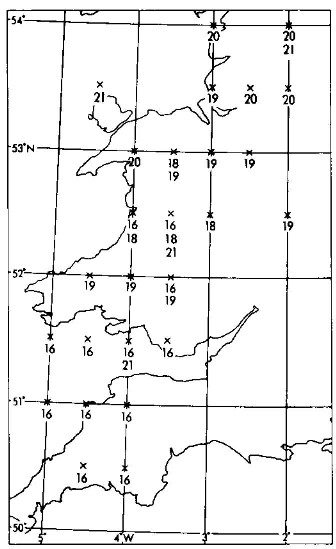
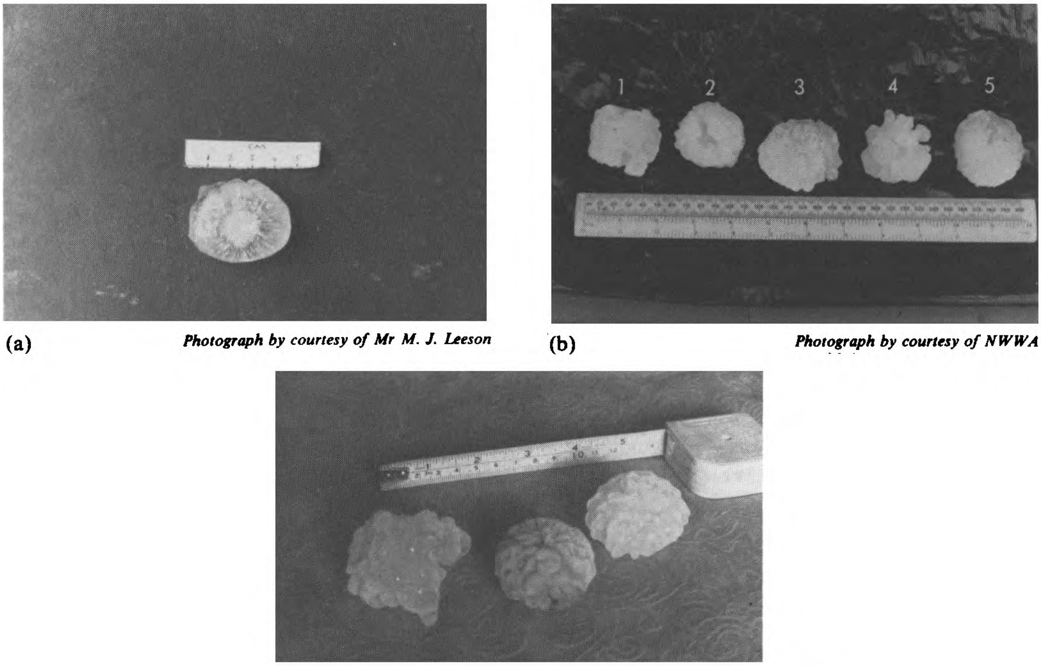


Figure 3. SFLOC chart for 7 June 1983. Figures are times in GMT.

Hail reports

Table II has been compiled from all the reports of hail received, and also those where only rain fell near the swath. Accounts of hail from individuals or newspapers have, so far as possible, been checked and were only included where a specified location was named. Some newspapers carried headlines of hail damage, but not all referred to the actual site where hail occurred. The times are less certain in some cases but seem to fall into the 1600–1800 GMT period over North Wales and 1800–2000 GMT over Greater Manchester. Table II lists the reports from south to north. This investigation only extends as far south as mid-Wales but in view of the distribution of SFLOC activity at 1600 GMT it is considered more than likely that some hail fell over South Wales.

The first hail recorded in Table II was from St Martin near Ruabon (item 5) at 1615 GMT in a severe thunderstorm: more fell at 1705 GMT in another separate storm. These storms produced hailstones of 10–30 mm in diameter. Further south-west the Meteorological Office auxiliary station at St Harmon reported a severe thunderstorm with hail while another Meteorological Office station at Cynwyd reported a severe thunderstorm with rain at the the same time.



(a) *Photograph by courtesy of Mr M. J. Leeson*

(b) *Photograph by courtesy of NWWA*

(c) *Photograph by courtesy of NWWA*

Figure 4. Selection of photographs of hailstones taken on 7 June 1983, (a) at Urmston, Greater Manchester, (b) at Kelsall, Cheshire and (c) at Weaverham, Cheshire.

Photograph by courtesy of Northwich Guardian

Figure 5. Largest hailstone found in Antrobus on 7 June 1983.

Table II. *Reports of hail (△) and no hail (○) near swath listed south–north*

Abbreviations: MO — Meteorological Office; Stn — Station; A/P — Airport; P — Photograph; WC — Weather Centre; ☈ — Thunderstorm; ☈̲ — Severe thunderstorm; ☈• — Severe thunderstorm with rain; ☈△ — Severe thunderstorm with hail

Item no.	Place	Grid reference		Source	Time (GMT)	Size (mm)	△/○	P	Remarks
1	St Harmon	2990	2730	MO Stn 505	1700–1800	50–75	△		☈△ Hail damage, two bursts
2	Shawbury	3560	3200	MO Stn 414	1700		○		No hail, trace rain
3	Cynwyd	3070	3400	MO Stn 408	1800		○		☈• No hail
4	Overton	3375	3418	*Shropshire Star*			△		Huge hail
5	Ruabon	3300	3440	J. M. Thompson	1600–1800	10–30	△	P	Two ☈△ 1615 and 1705 GMT
6	Lower Eyton	3342	3442	Mrs D. Moreton	1740		△		Letter, > golf ball hail
7	Cefendre	3340	3490	*Shropshire Star*			△		Golf ball hail
8	Wrexham	3360	3500	Mr Watkiss-Thomas	1745		△		Letter, giant hail
9	Kelsall	3520	3680	NWWA	1815	60	△	P	Knobbly hail, lobes
10	Cuddington	3595	3720	Airline pilot		70	△		Sketch, jagged ice, tail
11	Weaverham	3611	3743	NWWA	1830–1900	50	△	P	Knobbly hail, lobes
12	Knutsford	3760	3760	MO staff			○		No hail
13	Antrobus	3650	3810	*Northwich Guardian*		73	△	P	65 grams, £5 prize
14	Wilmslow	3840	3810	*Wilmslow World*			○		No hail
15	Runcorn	3530	3820	Manchester WC call	1925	25	△		
16	Liverpool A/P	3437	3825	Weather reports			○		No hail
17	High Legh	3700	3835	Nurseryman		10–20	△		No large hail, little damage
18	Appleton	3640	3840	V. Molloy			△		Hail Appleton but none, only heavy rain, M6 from Carnforth
19	Manchester A/P	3824	3847	MO Stn 334			○		No hail, 0.1 mm rain
20	Bramhall	3880	3860	C. Combe, MO			○		No hail
21	M56, junction 7	3744	3852	P. Josty, MO	1920	25	△		Ice cubes 1½ mins, then mod/heavy rain for 30 miles west
22	Grappenhall	3640	3860	*Warrington Guardian*			△		Kennels and nurseries damaged, runaway horse killed on M6
23	Lymm	3680	3870	Capt. C. Cruickshank	1800	63	△		Sketches, two storms 4 mins and 2 mins
24	Lymm	3680	3870	Janet Sheehan	1800–1900	30–50	△		
25	Thelwall	3650	3874	NWWA	1800–1815 (1850?)	20–45	△	P	Hailstones mixed, some smooth, some knobbly
26	Altrincham	3770	3880	Altrincham			△		Bus windows smashed
27	Rixton	3685	3895	DHAO MAFF			△		} Mainly crop damage outdoors
28	Woolston	3660	3905	DHAO MAFF			△		}
29	Carrington Moss	3750	3915	*Altrincham Guardian*			△		Golf ball hail, two farmers hurt
30	Partington	3720	3917	*Manchester Evening News*			△	P	Greenhouses damaged, youth died in car avoiding floods
31	Locking Stumps	3646	3917	Mr Sinuks	1800–1900	26	△		Hail 20 mins, average 15 mm, max 26 mm
32	Heaton Moor	3880	3920	G. Marshall, MO			○		No hail
33	Ashton-on-Mersey	3780	3920	R. King, acquaintance	1830–1900	50	△	P	Golf/tennis ball hail
34	Glazebrook	3695	3925	Nurseryman					Large hail, much damage
35	Glazebrook	3695	3925	DHAO MAFF			△		} Mainly crop damage outdoors
36	Irlam	3720	3940	DHAO MAFF			△		}

Item no.	Place	Grid reference		Source	Time (GMT)	Size (mm)	%	P	Remarks
37	Urmston	3750	3950	*Manchester Evening News*, E. Graham	1900		Δ	P	Newspaper cutting
38	Urmston	3750	3950	M. J. Leeson, MO	1930–2000	40–50	Δ	P	Lobed hailstones, radial bubble structure
39	Stretford	3795	3950	G. Butler, MO	1830, 1930	50	Δ		Golf ball hail, two distinct bursts one hour apart, marked wind increase each time
40	Barton A/P	3745	3972	Mr Young, SATCO	1900		Δ		Golf ball hail
41	Manchester WC	3840	3986	MO Stn 335	1955	25–50	Δ		Hail 5 mins, gust 37 kn, $\overset{\Delta}{\text{K}}$ 4.3 mm rain
42	Eccles	3780	3987	*Manchester Evening News*			Δ	P	Newspaper cutting, golf ball hail
43	Crosby	3300	4000	MO Stn 316			O		No hail 6 mm rain
44	Prestwich	3810	4030	*Manchester Evening News*			Δ		Roof collapsed on elderly couple
45	Clifton	3770	4035	G. Wood, local weather observer	1845	35	Δ		K 1700 GMT, 25 mm rain, jagged ice
46	Middleton	3870	4050	Mrs D. Berry			Δ		Also *Rochdale Observer*
47	Simster	3840	4055	*Bury Times*, Sue Campbell		25	Δ		2 × 5 min bursts
48	Formby	3300	4070	M. J. Robinson, MO	2325		Δ		K 1800–2325 GMT, hail 3 mins, broken window, storm ended suddenly
49	Little Lever	3750	4075	Manchester WC call	1910	25–50	Δ		
50	Radcliffe	3780	4080	*Bolton Evening News*, Mr Greenhalgh		25–50	Δ		
51	Parbold	3500	4110	G. Monk, MO	2140		Δ		Tiny hail, 15.9 mm rain
52	Tottington	3775	4125	Manchester WC call	1920	25–50	Δ		
53	Bamford	3860	4130	W. Malley	1900–2000		Δ		Large hail, pulled off road for safety, worst hail ever seen
54	Walmersley	3810	4140	Mrs M Berry	1930	50	Δ		Golf ball hail
55	Greenmount	3770	4140	*Bury Times*	1910	> 25	Δ		
56	Rochdale	3890	4140	*Rochdale Observer*		35	Δ	P	Newspaper photo, greenhouses smashed
57	Southport	3340	4170	A. Cook, MO	2330	30	Δ		Hail, 30-second burst
58	Blackpool	3320	4310	MO Stn 318			O		No hail, 16.8 mm rain
59	Warton	3410	4290	DHAO MAFF	After 2300	50–75	Δ		At least 11 greenhouse holdings damaged, most greenhouse roofs devastated in parish, 2.2 hectares of glass on 9 holdings damaged, losses to standing crops estimated at £30 000 for 1.2 hectares
69	Kirkham	3430	4320				Δ		
70	Kirkham	3430	4320	*Lancashire Evening Post*			Δ	P	G. Book, golf ball hail
71	Burnley	3845	4325	*Burnley Express*			O		No hail
72	Foulridge	3890	4423	*Burnley Express*, Ann Knowles		40–50	Δ		Golf ball hail
73	Kelbrook	3900	4450	*Craven Herald*	2000		Δ		Widespread damage to cars and greenhouses, one factory had 450 panes of reinforced glass (1m × 0.5 m) broken; cost £7000 to repair
74	Barnoldswick	3875	4465	*Craven Herald*	2000		Δ		
75	Earby	3905	4465	*Craven Herald*	2000		Δ		
76	Thornton in Craven	3905	4485	*Craven Herald*	2000		Δ		
77	Elslack	3930	4493	*Craven Herald*	2000		Δ		

Item no.	Place	Grid reference		Source	Time (GMT)	Size (mm)	△/○	P	Remarks
78	Skipton	3990	4510	*Craven Herald*			O		No hail
79	Leeming	4290	4900	MO Stn 257			O		No hail
80	Richmond	4170	5020	*Darlington*			O		No hail
81	Darlington	4290	5150	*Evening*			O		No hail
82	Bishop Auckland	4220	5300	*Despatch*			O		No hail
83	Newcastle A/P	4200	5720	Weather reports			O		No hail, ⛈ 2020–2320 GMT

The lines of the reference grid used in this paper coincide with those of the National Grid, but for ease in locating points across the whole extent of the storm the references are given not in National Grid form, but in a completely numerical form with point of origin at the south-west corner of National Grid square SV.

There were clearly several severe storm cells over Wales at this time: the *Shropshire Star* subsequently described the fall of huge hail of golf ball size at Overton and Cefendre near Wrexham. The storm damage in the Wrexham area was considerable; there were raging floods and a bridge was swept away. The devastation was vividly described in a letter from Mrs Dorothy Moreton of Lower Eyton (item 6 Table II): her cottage had ten windows and the front door smashed, and the ensuing floods brought in three tons of silage from the farm opposite. The garage was split in two, paving stones were ripped out and the car was filled with water.

At Kelsall and Weaverham in Cheshire the North West Water Authority (NWWA) staff kindly supplied photographs of hail 50–60 mm in diameter. Captain C. Cruickshank of Britannia Airways, while at home in Lymm, collected a variety of interesting hailstones and kept them in a freezer, as did Janet Sheehan, also of Lymm. Captain Cruickshank later assisted in producing some sketches which

Photograph by courtesy of Manchester Evening News

Figure 6. Greenhouses at Partington wrecked by hail on 7 June 1983.

included hailstones of 25 mm diameter with smooth egg shapes, some of 35–40 mm diameter resembling chestnuts with spikes, and others 60 mm in diameter of flat disc shapes with central indentations. The storm was so severe that Captain Cruickshank phoned to advise Air Traffic Control at Manchester Airport to warn controllers not to route aircraft over Lymm. The hail fell in two separate bursts lasting four and two minutes respectively and damaging his car and greenhouse. The largest hailstone brought to our attention was reported in the *Northwich Guardian*, measured 73 mm across and weighed 65 grams. It was collected by Lorraine and Bernice Riley and taken to Mr Colin Campbell, a local business man who offered a £5 reward for the largest hailstone in Antrobus (Fig. 5). Two farmers at Carrington Moss were hurt when hit by hail of golf ball size, and bus windows were smashed in Altrincham. A market gardener at Partington had several greenhouses wrecked by hail (Fig. 6) over a width of 70 metres, although a polythene structure survived intact and nearby houses escaped unscathed. Several other nurseries in this area suffered similar damage. The Divisional Horticultural Advisory Officer (DHAO) for the Ministry of Agriculture, Fisheries and Food (MAFF) assessed damage ranging from 20 to 100 per cent for 776 hectares of outdoor crops in the parishes of Rixton, Woolston, Glazebrook and Irlam (Table II items 27, 28, 35 and 36).

The hail swath continued to move north-north-east over Thelwall, Urmston and Eccles where photographs were taken of hailstones 25–50 mm across. It missed Manchester Airport by some 5 km where only 0.1 mm of rain was recorded in a thunderstorm. However, Peter Josty, one of the day shift forecasters, having observed the passage of thunderstorms northwards over Wales and the Irish Sea on radar, set off home soon after 1900 GMT. He travelled about six miles west along the M56 motorway to near junction 7 in intermittent light rain and then quite suddenly encountered irregular-shaped ice cubes about 25 mm in size which just 'plonked down' unlike normal driven hail. This lasted for about one-and-a-half minutes and forced motorists to pull off the road onto the hard shoulder. The hail then turned suddenly to torrential rain and after another minute or two Mr Josty continued his 30-mile homeward journey to near Southport in moderate to heavy rain with thunder. At Manchester Weather Centre, in the city centre, thunder was heard at 1844 GMT and rain commenced at 1905 GMT continuing until 2115 GMT. A burst of hail at 1955 GMT lasted about five minutes with hailstones estimated to be 25–50 mm in diameter. The total rainfall recorded was only 4.3 mm of which 3.6 mm fell in three minutes, an average rate of 72 mm per hour. Gust fronts reached both Manchester Airport and the Weather Centre during this time and are clearly shown on the anemograph trace for Manchester Weather Centre (Fig. 7) and for comparison in Table III.

Table III. *Gust speeds recorded at Manchester Airport and Manchester Weather Centre, 14 km apart*

Time (GMT)	Airport (knots)	Weather Centre (knots)
1942	17	
1955		37
2015	25	
2025		20

Hailstones of golf ball size were observed at Prestwich, Bolton, Bury, Rochdale and a number of other places north and north-west of Manchester. A local weather observer at Clifton near Bolton recorded 25 mm of rain and for a few minutes saw 'lumps of jagged ice' falling. The main hail swath was later observed over the Craven area and a number of reports in the *Craven Herald* mentioned widespread damage to cars and greenhouses. Earby and Barnoldswick were badly hit but there was no hail in Skipton. So far as can be judged the hail swath then dispersed over the Pennines; in North Yorkshire, Durham and Tyneside only rain accompanied the vivid thunderstorms. A final but separate burst of hail was reported at several places along the Lancashire coast sufficient to damage

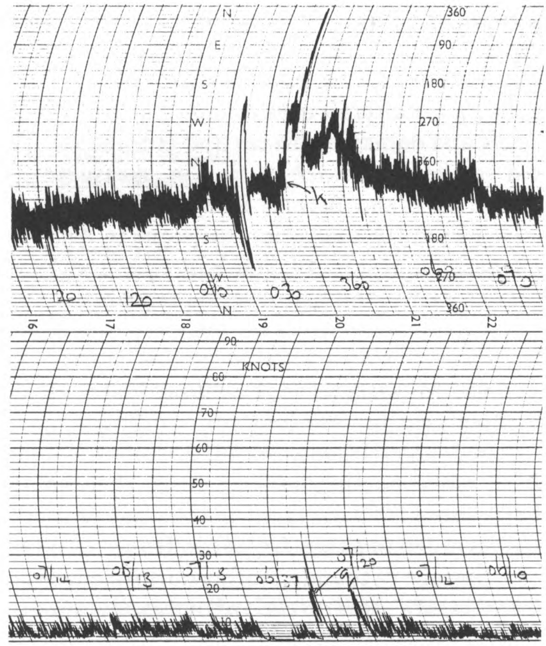


Figure 7. Part of anemograph trace for Manchester Weather Centre, 7 June 1983.

greenhouses badly and to break the window of a house occupied by an off-duty meteorological assistant at Formby. The 2315 GMT launch of the radiosonde ascent from Aughton near Ormskirk was curtailed at 500 mb because of thunderstorm activity — the plotted ascent showed some very moist layers with superadiabatic lapse rates indicative of the chaotic vertical ascent likely to be found in a thunderstorm. However, a second sounding was made at 0100 GMT and this reached a level of 10 mb. Although no change in airmass had occurred the still-unstable atmosphere was much drier with more normal lapse rates.

The full extent of the hailstorms from mid-Wales to Elslack-in-Craven covered 200 km although we cannot be sure it was an unbroken swath. Fire brigades within the Greater Manchester region received 189 emergency calls for assistance between 8.00 p.m. and midnight on 7 June and the Clwyd fire services received 150 calls. A comprehensive estimate of the cost in terms of damage and compensation is very difficult to make for a number of reasons, and we can only quote figures available from individual sources as a partial estimate. These amount to £1.1 million, but could well be an underestimate by a factor of three. One insurance company alone paid out claims of more than £650 000.

Radar and rainfall analysis

Earlier expectations of spectacular storm activity were realized in late afternoon when the senior forecaster at Manchester Airport identified intense precipitation echoes, inferred to be thunderstorms, advancing northwards over Wales. Warnings of heavy rainfall were issued at 1620 GMT to the NWWA for the Mersey–Weaver, Lancashire and South Cumbria catchment areas for falls of around 20 mm. The radar display was used later in the evening by the forecaster in drafting the aviation TREND* forecasts, giving warning of thunder and hail, although in the event the hail narrowly missed the airport.

*A TREND is a 2-hour landing forecast which is routinely added to hourly observations at some airfields.

Rain-gauge and radar data from Hameldon Hill (inset Fig. 8) were used in retrospect to examine the distribution of precipitation, primarily to identify and track individual storm cells. A number of intense cells were located, mostly of short duration, but six separate long-lasting cells were also found. The cells labelled 1 to 5 in Fig. 8 were the only cells from which hail was reported. The lifetimes, velocities and number of hail reports definitely attributable to each cell are shown in Table IV. Cell 6 may have

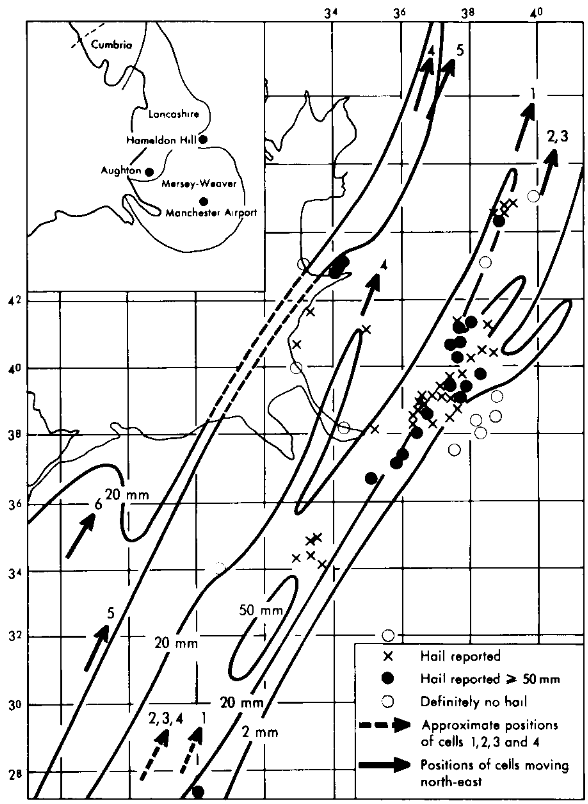


Figure 8. Distribution of hail and rainfall reports. Rainfall analysis is for 24 hours commencing 0900 GMT on 7 June 1983. Isohyets shown by solid lines.

Table IV. *Characteristics of the six hail cells*

Cell no.	Average velocity (degrees)	(knots)	Estimated deviation to right of the average velocity during severe-right phase (degrees)	Duration of severe-right phase (hours)	Lifetime of cell after entry into Hameldon Hill radar coverage (hours)	No. of reports of hail attributable to each cell
1	200*	28	20	1	5½	25
2	200*	32	25	2	6 †	5
3	200*	31	25	1¾	5	1
4	200	30			6¼ †	1
5	200	30	25	½	4¾	14
6	200	28			3	0

*Does not include period when cells deviated to right
† Passed out of Hameldon Hill coverage without decay

produced hail but crossed Cardigan Bay and sparsely-populated Snowdonia before decaying. It also remained at long range from Hameldon Hill radar and its behaviour is excluded from subsequent discussion.

The radar wind sounding for Aughton at 1800 GMT (Fig. 9) shows a shallow surface layer of south-easterly winds, less than 1 km deep, above which winds generally veer and increase with height. The surface flow backed north-easterly prior to the onset of thunderstorms thus increasing the vertical shear. Between 3 km and 6 km there is little shear suggesting a well mixed convective layer with a velocity of 200° 30 kn, close to that of cells 1 to 6. However, cells 1, 2, 3 and 5 show an anomaly in that they all deviated temporarily to the right whilst maintaining similar speeds. The path of each cell is shown in Fig. 10 — cells 1, 2 and 3 all turned right on entry to the Cheshire Plain immediately after leaving the hilly terrain of north-east Wales. Each cell returned to its original direction of movement over or north of Greater Manchester. We believe these cells became severe-right supercells during this period with the shallow north-easterly inflow providing the necessary updraught into the storm (Browning 1964).

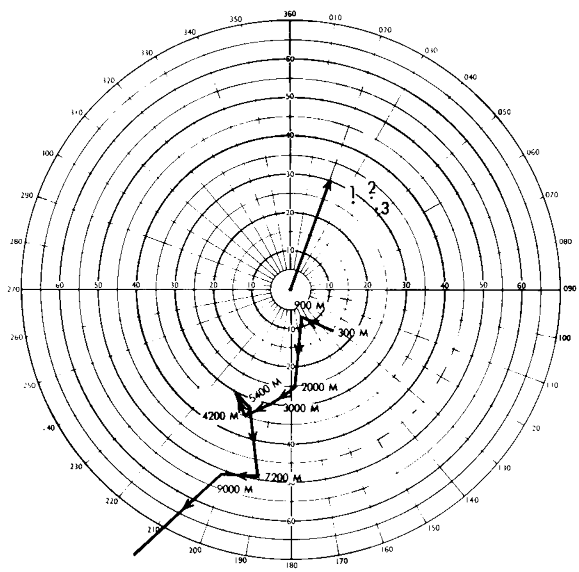


Figure 9. Radar wind sounding for Aughton at 1800 GMT on 7 June 1983. Arrow at top of diagram depicts the mean motion of cells 1 to 6. Numbered points refer to the velocities of cells 1, 2 and 3 during anomalous movement to the right.

Flash flooding occurred in the Wrexham area where the passage of cells 1 to 4 on similar tracks resulted in total accumulations of nearly 50 mm (47 mm fell in Wrexham). Gauge totals in excess of 40 mm probably extended along a narrow band, less than 10 km wide, from Wrexham as far as Warrington, north-east of which the diverging paths of the four cells (see Fig. 10) resulted in smaller spot totals. Cells 1 to 4 were positioned at the extreme right edge of a large cluster of storms visible on radar (Plates II and III, page 264), but individual storm tops were indistinguishable in enhanced infra-red imagery at 1630 GMT (Plate IV). Analysis of cloud-top temperatures (not shown) indicated a uniform temperature within the red area of cloud, with tops near the tropopause, at the eastern limit of the cloud mass. Successive thunderstorm cells taking similar tracks have been noted on a number of previous occasions, for example the south coast hailstorms two days earlier (Wells 1983), and a flash flood at Darwin, Lancashire on 5 June 1980 (Carpenter and Owens 1981).

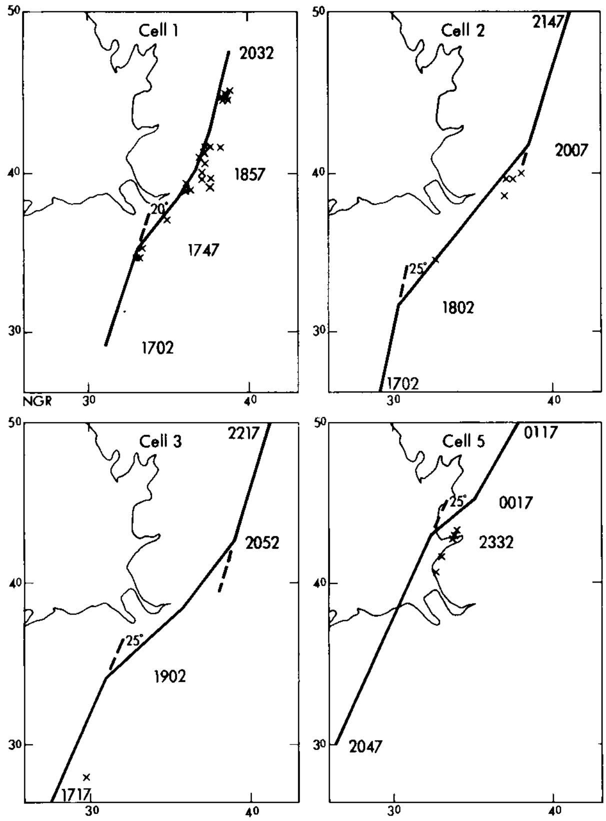


Figure 10. Radar tracks of centroids of hail cells 1, 2, 3 and 5 together with locations of hail (XXX) associated with each cell. Times in GMT.

Cell 5 was observed later in the evening at the south-eastern limit of a completely separate cluster of cells and turned right briefly as it crossed the Fylde near Blackpool. This storm occurred near midnight with a stable layer at the surface, and convection took place owing to the ascent of air of high θ_w located just above the 900 mb level. All hail reports, with only one exception, were located close to or east of the centroid of each cell. The exception was an unsubstantiated report from Runcorn (Table II item 15), made by telephone to Manchester Weather Centre, of hail 25 mm in diameter. Damaging hail fell from cells 1, 2, 3 and 5, but only one report could definitely be attributed to cell 3, St Harmon (Table II item 1), although subsequently we learned of others in the area that are not listed in Table II. Since cells 1, 2 and 3 were on similar paths, at least over Cheshire and south of Greater Manchester, some of the hail reports, not accompanied by a specific time, may have been associated with cell 3. All damage, with the exception of that in the St Harmon and Craven areas, corresponded with the severe-right phase of the appropriate cell, although that at Formby and Southport was immediately prior to the severe-right phase of cell 5 (Fig. 10). Hail was reported as far as 15 km to the right of the centroid of each echo, many reports being at the extreme right flank. Perhaps this is typified by Mr Josty's experience (Table II item 21) of encountering large hail immediately on entering what has been identified as cell 2 from the east, and later driving through rain, heavy at times, beneath and to the west of the cell centre. According to Browning (1964) it is common for large hail to occur on the right flank of severe hailstorms. This is a size-sorting effect such that, when a variety of particles descends through a wind field relative to the moving storm, the largest particles descend on the right flank close to the axis of the updraught, whilst the smaller particles get carried further towards the left flank. There is also some suggestion in Mr Josty's observation of a rather lower vertical velocity to the hail despite its size. Perhaps at this point on the extreme right of the storm the vigorous updraught was initiated very close to the ground.

Hailstone structure

The lobe structure of giant hailstones has been discussed by Browning (1966) and the selection of photographs (Figs 4(a), (b) and (c) from these storms make interesting comparisons with Browning's findings.

The photograph in Fig. 4(a) was taken by Mr M. J. Leeson, an off-duty meteorologist from Manchester Airport, at Urmston (Table II item 38). This shows the central opaque embryo surrounded by alternate layers of transparent and relatively opaque ice with a radial array of air bubbles visible between the external lobes. Differential melting at the surface could have produced the asymmetric arrangement of knobbles.

The photographs in Figs 4(b) and (c) were taken by NWWA staff from Kelsall and Weaverham respectively (items 9 and 11 in Table II). They illustrate very clearly the knobbly, lobed structure discussed by Browning. In the Kelsall photograph (Fig. 4(b)) the hailstones numbered left to right as 2, 3 and 5 exhibit radial symmetry indicative of random tumbling motion during descent. Numbers 1 and 4 on the other hand have become more convoluted possibly owing to preferential growth into the airstream during a period of more or less constant orientation, although some of the asymmetry (especially on hailstone 4) may be due to differential melting.

Browning points out that practically all hailstones are built up of successive layers of ice of different opacity and crystal structure. The opacity depends upon the number and size of entrapped air bubbles. For the growth of large hailstones the pronounced surface knobs are the rule rather than the exception.

Comparisons and conclusions

Large or giant hail is uncommon in Great Britain, but it has been reported and documented on numerous occasions. The south coast storms of 5 June 1983 have already been mentioned in this discussion. Owens (1980) described hail of 30 mm diameter in the south Devon winter hailstorm of 13 December 1978, and the Wiltshire storm of 13 July 1967 was discussed by Hardman (1968) with hail of 50-75 mm diameter. Browning and Ludlam (1962) reported hail of 25 mm diameter or more in the Wokingham storm of 9 July 1959. However, the heaviest hailstone observed in Britain fell at Horsham in Sussex on 5 September 1958 (Ludlam and Macklin 1960) and was reported to weigh 190 grams. The present authors understand that there are an average of about 5 damaging storms per year in Britain.

Mason (1975) reproduces a table (Table V) for the size distribution of the largest hailstones in Denver, Colorado 1949-55 (631 cases).

Table V. *Size distribution of the largest hailstones in Denver, Colorado (1949–55)*

Diameter of largest hailstones		No. of cases	
Grain	< 6 mm	10	
Currant	6 mm	122	
Pea	13 mm	282	
Grape	19 mm	149	
Walnut	25-30 mm	38	Fell at least twice a year
Golf ball	45-50 mm	26	
Tennis ball	60-75 mm	4	

The largest hailstone reported in the United States fell in Nebraska, was 138 mm in diameter and weighed 670 grams (Mason 1975).

Although such storms are much less frequent in Great Britain than in the United States those of 7 June were clearly unusual. They developed as the culmination of a period of unsettled weather which in fact continued for another week before a changeable westerly type gave way to anticyclonic conditions on 15 June. It is our view that the storms were forced dynamically by a combination of favourable factors — the advancing upper trough, strong vertical windshear and warm advection into the trough. The developing storms then encountered suitably cold dry air above an inversion which, together with the strong low-level windshear in the updraught regions, enabled the storms to develop the self-perpetuating characteristics of severe-right supercells.

Acknowledgements

The authors wish to thank all those members of the public and Meteorological Office staff who contributed information used in this report. We would especially mention the following newspapers: *Altrincham Guardian*, *Bolton Evening News*, *Burnley Evening Star*, *Burnley Express*, *Bury Times*, *Craven Herald*, *Darlington Evening Despatch*, *Lancashire Evening Post*, *Manchester Evening News*, *Northwich Guardian*, *Rochdale Observer*, *Shropshire Star*, *Warrington Guardian*, *Wilmslow World* and *Wrexham Evening Leader.*

We gratefully acknowledge the helpful comments and advice given by Dr Keith Browning, Chief Meteorological Officer, Radar Research Laboratory, Royal Signals and Radar Establishment, Malvern. We are also indebted to the Divisional Horticultural Advisory Officer of the Ministry of Agriculture, Fisheries and Food for the reports on damage to crops and greenhouses and to a number of insurance companies for estimates of claims.

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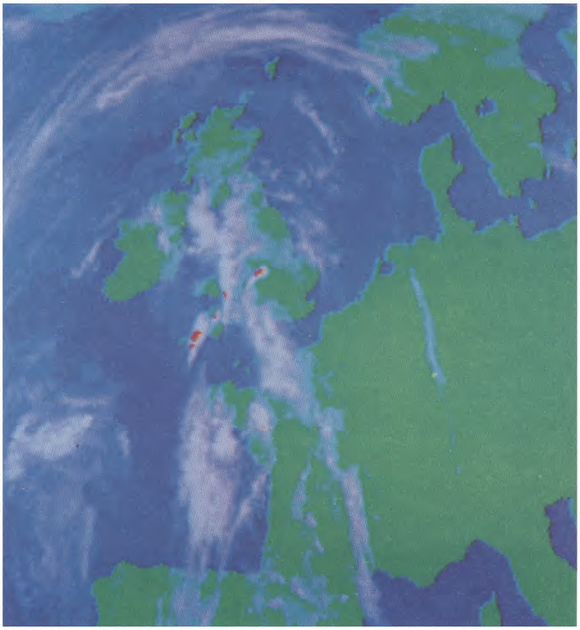

Plate I. Meteosat infra-red image at 1400 GMT on 7 June 1983.

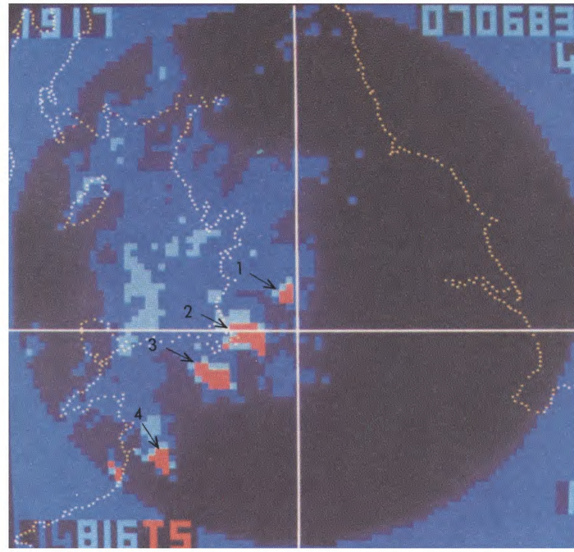

Plate II. Hameldon Hill radar display for 1917 GMT on 7 June 1983 with cross wires intersecting on Manchester Airport. Numbers indicate cells 1 to 4. Rainfall intensities (mm h^{-1}) are represented as follows: dark blue 8 (and also area outside radar range), light blue 8–32, red >32. The dark blue area south-west of Manchester is anomalous propagation.

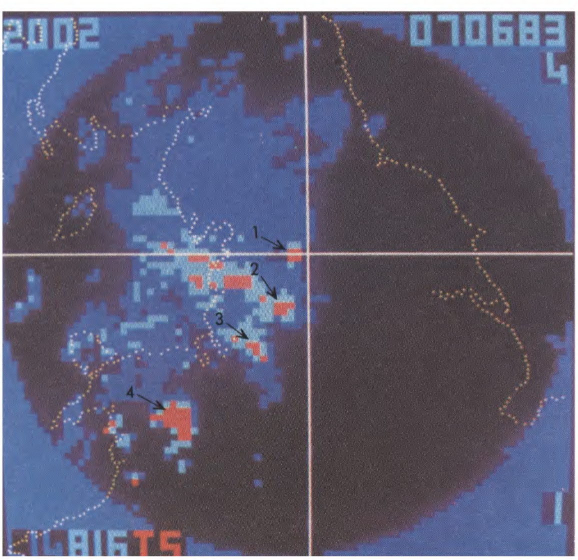

Plate III. Hameldon Hill radar display for 2002 GMT on 7 June 1983 with cross wires intersecting on Skipton. Cell 1 west of Skipton was producing large hail but none fell on the town. See Plate II for details of the colour key.

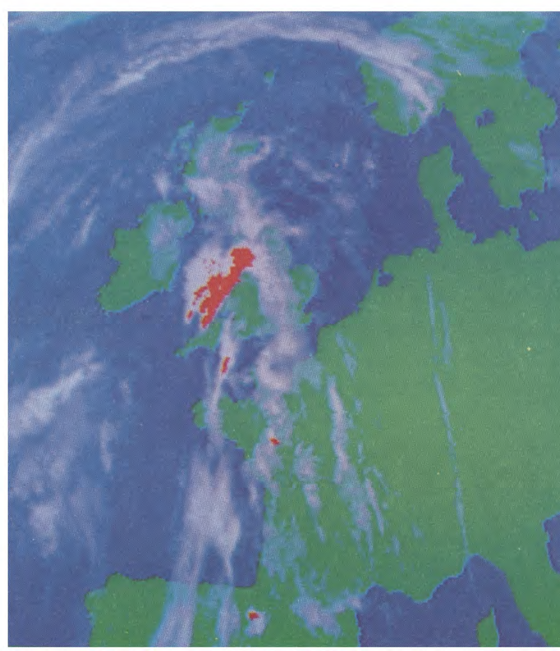

Plate IV. Meteosat infra-red image at 1630 GMT on 7 June 1983.

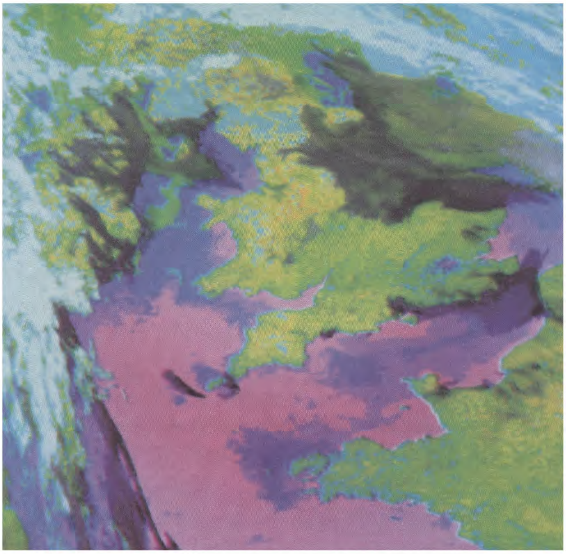

Plate I. Bispectral image from AVHRR channels 3 and 4 of 1024 × 1024 pixels at 0330 GMT on 28 August 1981. Areas of fog appear as shades of grey. (For other colour coding see text.)

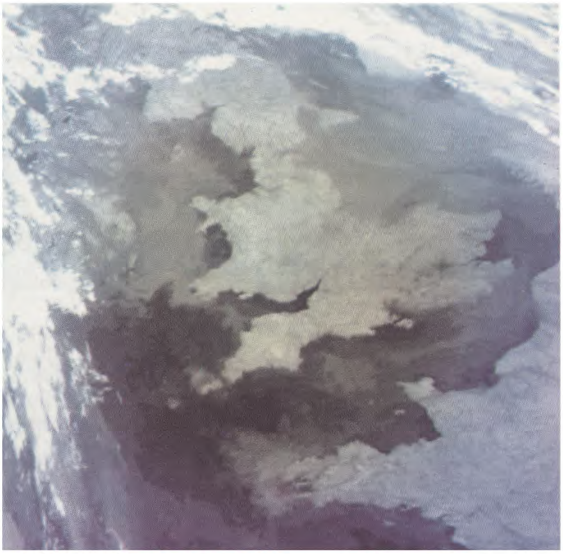

Plate II. Monochrome image from AVHRR channel 4 equivalent to Plate I.

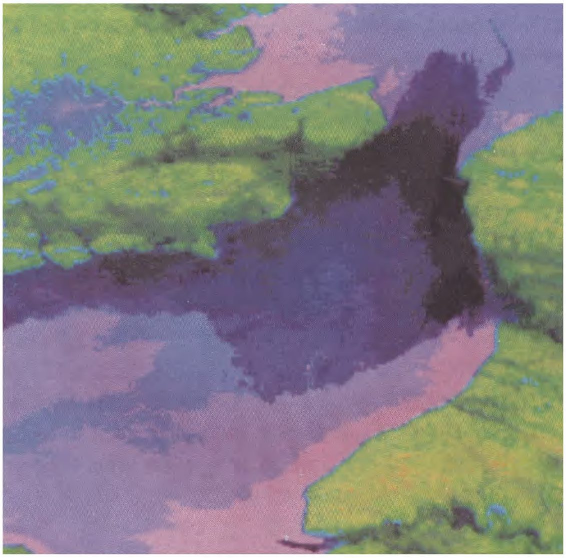

Plate III. Section of Plate I (enlarged four times) centred on eastern end of English Channel.

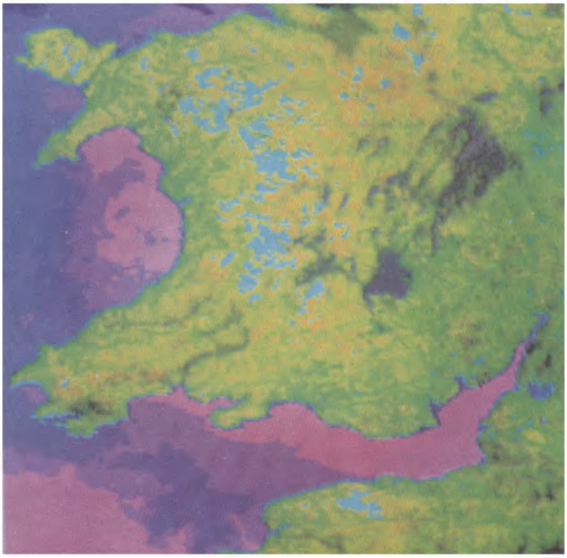

Plate IV. Section of Plate I (enlarged four times) centred on Wales.

551.507.362.2:551.521.325:551.575.2

Detection of fog at night using Advanced Very High Resolution Radiometer (AVHRR) imagery

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Summary

A method of detecting fog at night using a combination of infra-red images at different wavelengths is presented as an example of a meteorological application of remote sensing. The variation of emissivity with infra-red wavelength exhibited by fog is used to distinguish it from land or sea surfaces at similar temperatures. An interactive image display system has been used to provide a false-colour representation of a combination of AVHRR images at 11 and 3.7 micrometres (μm) in such a way as to highlight areas of fog and low stratus cloud.

1. Introduction

For some years satellite images have been used routinely in operational weather forecasting as a means of detecting the positions and development of cloud systems and for analysing their characteristics. Such applications have mainly been limited to interpretations which can be made using conventional visible and infra-red images displayed in varying shades of grey by facsimile recorder. The usual quality of images obtainable with such a system and the inflexibility of the display place a severe limitation on the amount of useful information which can be extracted, and recent developments have therefore sought to improve display techniques. Systems have been developed which present the image on a display screen and which have sufficient interactive capability to allow enhancement of each image through changes to the grey-scale contrast, magnification, etc. Also, increasing use is envisaged for colour display systems further to extend the amount of information which can be conveyed with a single image. This paper presents an example of such an application: an interactive image display system has been used to provide a false-colour representation of a combination of two infra-red images of the same scene but at different wavelengths, in such a way as to highlight areas of fog and low stratus cloud.

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

In this study the variation of fog emissivity with infra-red wavelength has been used to distinguish it from land or sea surfaces using infra-red images only. This allows fog and low stratus to be detected effectively at night, when fog usually develops and when it is most important to have a good description of its horizontal extent for forecasting purposes.

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2. Basis of technique

The AVHRR on the National Oceanic and Atmospheric Administration (NOAA) series of polar-orbiting satellites produces images in five spectral bands or 'channels' with a horizontal resolution of about 1 km. Three of these channels are located in the thermal infra-red region of the spectrum. In this spectral range most of the radiation measured at the satellite has been emitted by the underlying surface (land, sea or cloud top). All three channels are situated in infra-red 'windows' — spectral regions in which the atmospheric absorption is relatively low and in which we are able to 'see' down to the surface in the absence of cloud. Channel 3 is centred in a window region at about 3.7 μm, and channels 4 and 5 (centred at about 11 μm and 12 μm respectively) are in another window, in the spectral region conventionally used for thermal infra-red imaging.

A property of fog (and other water cloud), which can be used to characterize it in the absence of visible channel data, is the variation of its emissivity with wavelength. At around 11 μm opaque water clouds emit radiation as though they were almost perfect black bodies (i.e. they have an emissivity of almost one). Therefore, if the radiance measured at the satellite is converted to an equivalent black-body temperature (or 'brightness temperature') this will be almost equal to the physical temperature of the cloud top (assuming that the effects of the intervening atmosphere are small). At 3.7 μm opaque water clouds have an emissivity significantly less than one: calculations from the present study based on the brightness temperatures measured over fog suggest that it is around 0.8–0.9, which is in broad agreement with theoretical calculation (Hunt 1973). Therefore the measured brightness temperatures will be significantly lower than the physical temperature. This property is not exhibited by land or sea surfaces to the same degree, and so the difference in measured brightness temperature between channels in the two spectral regions can be used to distinguish fog or low stratus from other surfaces (land or sea). In this study we have used channels 3 and 4 of AVHRR. Although the effects of atmospheric absorption are different in the two channels, the difference is sufficiently small for the emissivity effect to dominate the difference in brightness temperature between them.

3. Details of image processing

The difference in brightness temperature between channels 3 and 4 is the principal quantity on which we have based the discrimination of fog and low stratus, and the details of the AVHRR data processing required are as follows. The raw image data in channels 3 and 4 are calibrated into radiance units and then expressed as brightness temperatures. For each pixel (picture element), the difference in brightness temperature between the two channels is then calculated. From here on it would be possible to use a number of different methods for converting the data into a colour display which highlights the areas of fog. We have chosen to construct a combined image in which each pixel is represented by 8 bits (i.e. an integer in the range 0 to 255). The 6 most significant bits (an integer in the range 0 to 63) represent the brightness temperature (K) in channel 4 minus 240K, and the 2 least significant bits (an integer in the range 0 to 3) represent the brightness temperature difference between channels 4 and 3, ΔT, defined as follows:

$$0 : \Delta T < 0.5,$$
$$1 : 0.5 \leqslant \Delta T < 1.5,$$
$$2 : 1.5 \leqslant \Delta T < 2.5,$$
$$3 : 2.5 \leqslant \Delta T.$$

These intervals were chosen empirically following a study of the ΔT values for different scenes.

By assigning an appropriate colour to every pixel value between 0 and 255 the image can be displayed in false colour. The technique is illustrated in Plate V, page 265 using AVHRR data from 28 August 1981 at 0330 GMT for an occasion of widespread fog in parts of England, Wales, northern France and adjacent sea areas.

In this example the transformation table used to convert a pixel value in the digital image to a colour on the display has been derived as follows:

(a) For $\Delta T < 0.5$, a range of colours is used depending on the brightness temperature in channel 4:

white	: $T < 273$ K
white – cyan	: 273 K $\leqslant T <$ 281 K
yellow – green	: 281 K $\leqslant T <$ 286 K
blue – violet	: 286 K $\leqslant T <$ 289 K
violet	: $T \geqslant 289$ K

These ranges were chosen interactively for this particular image to give the best discrimination between land and sea, and to provide a good representation of the temperature field for sea and land.

(b) For $\Delta T \geqslant 2.5$, the colour transformation gives shades of grey depending on the temperature in channel 4:

white	: $T < 273$ K
white – black	: 273 K $\leqslant T <$ 289 K
black	: $T \geqslant 289$ K

This corresponds to areas of opaque water cloud, with the level of grey representing the temperature. Fog and low stratus therefore appear as areas of grey, with the darker areas being warmer.

(c) For intermediate values of ΔT, a colour intermediate between the values given by (a) and (b) is used. Such values occur if opaque water cloud fills only part of a pixel or if semi-transparent fog or cloud covers a whole pixel. Other physical reasons for this state may also exist but they do not appear to affect the detection of fog.

The overall effect of this scheme, as illustrated in Plate V, is to show cloud-free and fog-free areas in bright colours, depending on temperature, and areas of fog and stratus in shades of grey.

The display technique chosen has the following advantages:

(i) It compresses the information required to represent the features of interest into only 8 bits — an important consideration if such images are to be transmitted and displayed routinely.

(ii) It provides a 'natural' colour representation (land—green, sea—blue, cloud—grey) and so is easily interpreted.

(iii) It retains good discrimination between bodies at different temperatures and even resolves sea surface temperature features, with only a moderate amount of interactive manipulation.

This particular display method has been developed empirically; similar methods may convey the same information equally well, and other schemes would be required to optimize the discrimination of different phenomena. An important aspect of the system used in this case is its interactive capability which allows a colour transformation suitable for the image in question to be derived very quickly.

For comparison, Plate VI, page 265 shows the same scene displayed as a monochrome image (AVHRR channel 4). A contrast higher than that usually used on conventional images has been obtained by stretching the grey-scale linearly from white to black over the brightness temperature range 270–295 K. It can be seen that, even with this degree of enhancement, the presence of either fog or stratus in many areas cannot be detected unambiguously.

Plate VII, page 265 shows an enlargement of an area centred on the eastern end of the English Channel. Again, this scene was obtained interactively using facilities of the display system. It illustrates the vast amount of detail available from suitably enhanced AVHRR imagery at its highest spatial resolution. Over the English Channel we can see an area of fog depicted in dark grey and shades of dark blue. The gradations of colour within this area are probably related to the thickness of the fog; as the transparency of a vertical path through the fog increases, the contrast between channels 3 and 4 is reduced. The contrast in temperature between London and the surrounding area is clearly shown, as are variations in sea surface temperature. The detailed structure of the fog over Kent, Sussex and northern France is also portrayed.

Plate VIII, page 265 shows a similar enlargement of an area centred on Wales. Again, the presence of fog in some valleys is detected and is shown in shades of grey. The land-surface temperature features in fog-free areas are also depicted at high resolution by a range of colours.

4. Comparison with conventional observations

Fig. 1 shows a synoptic analysis for 0300 GMT on 28 August 1981 constructed by an experienced forecaster. It was drawn using all the data which might have been available to an operational forecaster. These data included both synoptic information from the stations indicated in Fig. 1 and conventional satellite imagery as received on a facsimile recorder. Aspects of continuity have therefore been taken into account, and the positions of some areas of low cloud have been estimated using visible images from the preceding day.

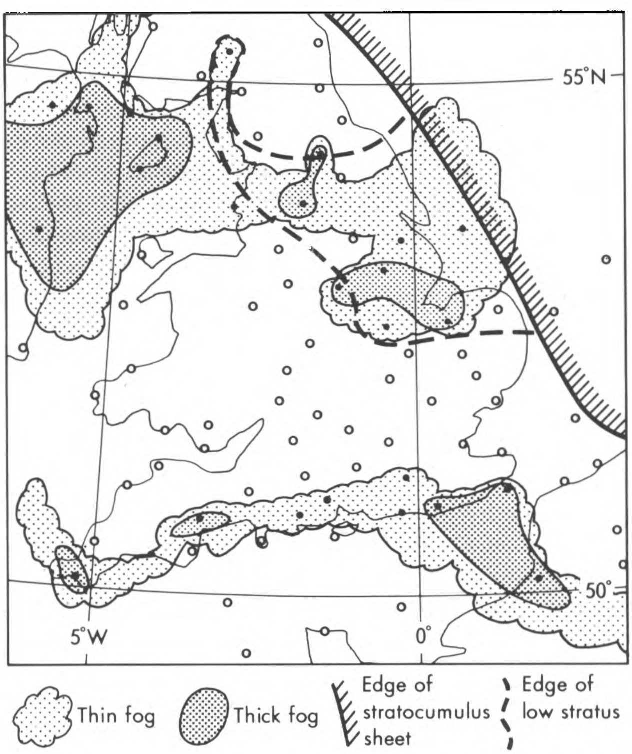

Figure 1. Analysis of areas of fog and low cloud at 0300 GMT on 28 August 1981 constructed from conventionally-available data. Closed dots correspond to reports of fog and open dots to any other reports. 'Thick fog' represents an area in which 'sky obscured' was reported.

A ridge of high pressure lay over the country giving rise to light winds. A sheet of stratocumulus thick enough to give light rain or drizzle in places lay close to the east coast of England and Scotland. A number of areas of fog and low stratus cloud are evident from the analysis.

A continuous area of fog has been inferred along the south coast of England, across the eastern end of the English channel and into northern France. The enhanced image shows that the fog in this area was quite localized inland and that the inferred continuity of the fog is an artefact caused by the sparsity of observations. The density of the observations used in this analysis can be seen in Fig. 1. The image also shows that extensive banks of fog lay off Cornwall, further west than analysed.

The analysis shows an area of fog and very low stratus which covered parts of eastern England and linked up with a further large area over the Irish Sea and parts of Ireland. The image shows the fog and low cloud over eastern England clearly, with a distinct edge to its southernmost limit. The fog over the Irish Sea is also evident. However, the image indicates that the fog near the north-west coast of England was very patchy. The analysed link between the fog in the east and that over the Irish Sea is therefore also an artefact caused by the sparsity of conventional observations.

Other areas of interest include Wales, where radiation fog formed in the valleys but was not analysed because of a lack of observations. A similar feature is evident over Essex and Suffolk where, despite the comparatively high density of observations a large area of fog lay between synoptic stations. Only later in the night (analysis not shown) was widespread fog inferred from the impingement of the expanding area of fog on the synoptic stations.

5. Discussion

Repeated reference has been made to fog and low stratus. Both of these are weather phenomena with important forecasting considerations, particularly in the aviation field. We might ask, then, whether it is possible to distinguish between fog and stratus using the technique described here. The relationship between the features and the orography will provide a useful guide, since fog will often tend to form in valleys. Also, the temperature difference between the feature and surrounding sea or land will indicate the probability of stratus, which will often have a lower temperature than that of the surface. However, this will not always be the case. Nor is the brightness temperature difference between channels 3 and 4 likely to be a good guide since it is more closely related to optical depth for both fog and stratus. The most reliable method may well be to use whatever surface observations are available to determine whether the cloud base is at the surface, and to use the imagery to define the horizontal extent of a feature and to indicate its depth.

Further work is required to examine the detailed relationship between the horizontal visibility estimated at a particular station and the difference in brightness temperature between channels 3 and 4, which is used in the enhancement process and is related to a difference in emissivity. However, it is expected that the intensity of the fog-related feature in the images will be closely correlated with the transparency of the fog as seen from above. This aspect may be as interesting to an aviation forecaster as the conventionally-measured visibility at the surface.

A potential complication in the interpretation of the imagery concerns the size of the 'atmospheric correction' (the difference between the measured brightness temperature and that which would be measured if the atmosphere above the fog were completely transparent). More precisely, we are concerned with the variation in atmospheric correction between channels 3 and 4. The magnitude of the atmospheric correction depends on the amount of water vapour in the lower layers of the atmosphere, which in turn is limited by the temperature. The fact that atmospheric correction effects do not seem seriously to complicate the interpretation for this case in August, when the temperatures of the surface and lower atmospheric layers are fairly high, suggests that differences in atmospheric correction between channels will not prejudice the detection of fog in the UK region in any season.

The application of this technique to the detection of fog at night has been demonstrated but during the day it would not be so successful. Because the fog has an emissivity at 3.7 μm significantly different from unity, it also has a sufficiently high reflectivity for reflected sunlight to contribute significantly to the measured radiance. This complicates the interpretation of the channel 3 radiances during the day-time. However, this situation arises at times when the visible channel images are also available, allowing a visible/infra-red image pair to be used for identification of fog. Alternatively, an extension to the technique presented here involving a careful interpretation of the reflected sunlight contribution to channel 3 day-time images may be useful.

6. Conclusions

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

Acknowledgements

The images presented in this paper were produced on the HERMES (High-resolution Evaluation of Radiances from Meteorological Satellites) system at the Meteorological Office using an ARGS 7000 series interactive image display system. However, much of the preliminary work for this study was performed on the GEMS image-processing and display system of the National Remote Sensing Centre at the Royal Aircraft Establishment (RAE), Farnborough. The assistance and co-operation of Mr M. R. Boswell of RAE is gratefully acknowledged.

We also wish to acknowledge the assistance of Mr J. Findlater (Meteorological Office) in the analysis of conventionally available data.

Reference

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551.593.653(4)

Noctilucent clouds over western Europe during 1983

By D. M. Gavine
(Leith Nautical College, Edinburgh)

Table I summarizes the noctilucent cloud (NLC) reports received by the Aurora Section of the British Astronomical Association (BAA) during 1983, from Great Britain, Finland and Denmark.

Times (UT) in the second column of the Table are of reported sightings, not necessarily the duration of a display. Maximum elevations of the upper border are given, with limiting azimuths where possible. Co-ordinates of the observing stations are given to the nearest half-degree.

Only two meteorological stations continued to send routine hourly sky reports so a full assessment of 'negative' nights (i.e. clear with no visible NLC) was not possible. Such negative reports are indicated (B) Belgium, (F) Finland and (G) Great Britain. However, thanks to the efforts of observers in 11 UK stations, some 15 amateur astronomers, the active 8-man NLC network in Finland co-ordinated by Mr Mäkelä, and Mr Olesen and Mr Andersen in Denmark, a reasonable coverage was obtained for positive sightings between latitudes 50.5° N and 62.5° N and longitudes 29° E to 4.5° W.

Again tropospheric cloud and haze interfered, especially over Scotland, only 6 nights averaging 3 oktas or less at Eskdalemuir from mid-June to mid-July; and Iceland's summer was so bad that no NLC could be observed. Mr van Loo, a very experienced observer (Itigem, Belgium) reported 12 clear nights over the season, all negative.

Of a total of 34 positive sightings, 23 were visible in Finland, 15 in Britain and 8 in Denmark. The NLC of 30 June/1 July was well observed throughout Britain south of Fife (Crane 1983, Gavine 1984) and on 22/23 July a brilliant display, overhead at Aberdeen, was described at Alrö by Mr Olesen as the greatest amount of NLC covering the sky in his 24 years of observing.

Time-lapse cine and photometric work was continued at Aberdeen University by Dr M. Gadsden, who is organizing an amateur program of parallactic photography using fixed-bracket 35 mm cameras, with identical exposures exactly on the quarter-hours. Successful results were obtained on 30 June/1 July by Dr Simmons (Milngavie) and Dr Gavine (Joppa). Mr J. Shepherd (Edinburgh) took time-lapse and all-sky photographs.

Grateful thanks are due to all the voluntary observers, to Dr. D. H. McIntosh for his advice and for passing on data received at his Department, to Dr Gadsden for his enthusiastic encouragement, and to Mr N. M. Bone, Director of the Junior Astronomical Society Aurora Section, for helpful collaboration.
As stated before (Gavine 1984), NLC data are no longer handled by the University of Edinburgh but in the interests of continuity the survey has been taken over by an amateur group, the Aurora Section of the British Astronomical Association (Director of Section: Mr R. J. Livesey, 46 Paidmyre Crescent, Newton Mearns, Glasgow G77 5AQ). Immediate NLC news will also be announced in the monthly magazine, *The Astronomer*.

NLC data up to 1980 are now stored at Aberdeen University and 1981–83 data are at present held by the BAA Aurora Section. Instructions and report sheets may be obtained from Dr D. M. Gavine at 29 Coillesdene Crescent, Joppa, Edinburgh EH15 2JJ. The Section would also greatly appreciate any aurora sightings, especially below geomagnetic latitude 63°. Reports of these should be sent to Mr Livesey.

Table I. *Displays of noctilucent clouds over western Europe during 1983*

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev. (degrees)	Limiting azimuths (degrees)
15/16 May		No NLC (B)				
18/19	1930–2000	Faint bands 2° wide at Imatra.	61°N 29°E		10	340–345
22/23		No NLC (G)				
26/27		No NLC (G)				
1/2 June		No NLC (B)				
3/4		No NLC (B)				
5/6		No NLC (G)				
6/7		No NLC (B, G)				
9/10		No NLC (B)				
10/11		No NLC (B)				
11/12	0200–0250	Veil, bands, billows into southern sky, bluish patch at 180° at Newcastle. No NLC visible at Prestwick or Edinburgh.	55°N 01.5°W	0200	90+	
				0230	50	220–280
12/13	2240–0230	Faint bands first seen at Edinburgh, brightening, rising and spreading further east, developing whirls. Visible from RGO Herstmonceux at 0145 as low band in east. Met. Station Church Fenton describes cirriform structure with bright spots. All-sky aurora over N.Y. State, dawn to dusk.	55.5°N 03°W	2240	8	060–075
				2255	10	050–070
				2315	10	050–070
				2330	10	045–055
				2342	10	050–070
			55°N 01.5°W (Morpeth)	2330	4	015–035
				2345	6	015–045
				0000	7	015–030
				0015	8	015–055
				0030	4	020–060
				0045	4	020–060
				0100	4	020–060
				0115	18	015–080
				0130	18	015–090
				0145	18	015–090
				0200	18	
			55°N 01.5°W (Newcastle)	0040	12	045
				0120	12	
				0150	25	045–068
			54°N 01°W	0045	low	030
				0145	13	060
				0215	NLC present	
			53°N 00.5°W	0145–0230	11	016–057
			51°N 00.5°E	0145–0212	7	085
14/15	2045–2100	Medium bright bands 15° wide at Imatra, no NLC (G).	61°N 29°E		35	345–025
15/16		No NLC (B, G)				
17/18		No NLC (G)				
18/19	2045–2100	Faint bans 1° wide at Joutseno. No NLC (G).	61°N 28.5°E		16	355–000
23/24	2235–0030	Faint wisps invisible to naked eye at Aberdeen, visible NLC at Vildbjerg.	57°N 02°W	2235–2335	No NLC	
				0010	5	022
				0030	No NLC	
			56°N 09°E	2310 0000	NLC present	
25/26	2030	Faint band 2° wide, Joutseno.	61°N 28.5°E	2030	17	355–005
26/27		No NLC (B)				
27/28	0045–0315	Small NLC patches at Marham, a large faint area with a bright core showing wave structure at Plymouth, the waves in a linear formation with an intense patch at lower end in north near dawn at Exeter.	52.5°N 00.5°E	0045	4	
				0125	7	358–030
				0200	15	
				0230	30	
			50.5°N 03.5°W	0250–0315	10	357–010
			50.5°N 04°W	0247	12	340–020
				0305	12	350–020
28/29		NLC in cloud breaks at Ränne.	55°N 14.5°E			–

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev.	Limiting azimuths
					degrees	
30 June/ 1 July	2130–0300	Display of medium to bright irregular and twisted bands and whirls. Faint patches near Polaris in central Scotland, visible from Wirral, bright silvery or bluish curved bands described from Bedford, Ketteringham, Cambridge, Blackpool, Marham and RAF Wittering. Little wave structure reported except at Edinburgh from 0120. No NLC (F).	56°N 03°W	2245	55	280–020
				2300	35	260–060
				2315	30	280–040
				2330	22	290–040
				2345	20	320–050
				0000	20	330–030
				0015	15	cloud
				0030	15	cloud
				0045	–	330–060
				0100	16	320–060
				0115	20	330–060
			56°N 04.5°N	2230	80	
				2250	50	
				2300	30	
				2315	24	
				2330	20	
				2345	17	
				0000	14	
				0015	13	
				0030	14	
				0045	14	
				0100	15	
			55.5°N 04.5°W	2200	No NLC	
				2300	NLC in cloud	
				0015	NLC in cloud	
			54°N 03°W	2245	12	340–355
				2350	12	015
				0015	10	010
				0025	No NLC	
			53.5°N 03°W	2215	25	270–000
				2230	8	270–010
				2245	7	275–015
				2300	6	280–020
				2315	6	285–025
				2330	5	300–020
			53°N 00.5°W	0045–0220	13	332–012
			52.5°N 00.5°E	2245	5	
				0100	12	330–350
				0200	15	
				0300	25	
			52.5°N 0°	2215	NLC present	
				2250	5	330–350
				0050	5	330–030
				0152	6	330–030
			52.5°N 01°E	2245–2315	10	330–350
			52.5°N 0°	2140–2215	15	000
			51.5°N 01.5°E	0200	5	345
1/2 July		No NLC (F)				
2/3		No NLC (F)				
3/4	0100–0230	Bluish structureless veil observed at Morpeth, brightest 0130–0145. No NLC (F).	55°N 01.5°W	0100	7	010–035
				0130	7	015–038
				0145	7	035–050
				0200	7	045–058
				0215	7	045–058
				0230	7	045–058
4/5	2240–2305	Waves visible at Wirral, faint NLC at Vildbjerg. No NLC (F).	56°N 09°E	–	NLC present	
			53.5°N 03°W	2305	10	310–030
5/6	2130–0200	Low bands visible at Joutseno, no NLC at other Finnish stations. High faint NLC detected at St Andrews then parallel bands appeared low in north at Edinburgh. From 0130 these developed into large curved structures and patches of waves which rapidly moved south and disappeared into dawn.	61°N 28.5°E	2130–2150	13	340–350
			56.5°N 03°W	2215	50	330–000
				2241	No NLC	
			56°N 03°W	2345	6	350–030
				0000	10	320–050
				0015	11	325–040
				0030	11	325–050
				0045	11	330–055
				0100	10	335–060
				0115	13	330–070
				0130	30	320–070
				0145	45	315–090
				0200	55?	–

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev.	Limiting azimuths
					degrees	
6/7	2215-2230	Faint veil at Turku, no NLC at other Finnish stations, or Britain.	60.5°N 21°E	2150	No NLC	
				2215	25	305-085
				2230	25	310-090
7/8		No NLC (F)				
8/9		No NLC (F, G)				
9/10		No NLC (F, G)				
10/11	2118-2335	All forms visible in bright display from N horizon into southern sky at Joutseno. No NLC at other Finnish or British stations. Faint NLC at Vildbjerg.	61°N 28.5°E	2118-2225	106	322-020
			56°N 09°E	2243-2335	NLC present	
11/12	2120-0205	Bright extensive display well beyond zenith at Rautalampi, all forms. At Turku bands developed into whirls as display moved south. NLC traces at Prestwick.	62.5°N 26.5°E	2140-2305	125	220-030
			61°N 28.5°E	2120-2200	45	293-016
			60.5°N 21°E	2155	25	345-050
				2215	40	300-045
				2230	55	300-035
				2245	70	310-040
			60°N 25°E	2120-2130	15	60° extent
				2200	30	
			55.5°N 04.5°W	0150-0205	40	
12/13		No NLC (F)				
13/14	2135-2209	Faint veil and bands at Kuopio in poor observing conditions.	63°N 28°E		5	290-010
14/15	2215-	Faint wisps and patches over most of sky at St Andrews, possibly all or part tropospheric cloud. No NLC (F).	56.5°N 03°W			
15/16	2200-0230	Low parallel bands observed at Edinburgh, Aberdeen and Milngavie, increasing in altitude from 0100, rapidly near dawn.	57°N 02°W	2200-2245	No NLC	
				2305	NLC	000-045
			56°N 03°W	2300	6	335-cloud
				2315	5	330-020
				2330	8	330-045
				2345	8	320-050
				0000	8	320-040
				0015	6	320-045
				0030	8	320-040
				0045	11	320-cloud
			56°N 04.5°W	2257	7	
				0017	7	
				0030	8	
				0045	9	
				0100	10	
				0115	13	
				0130	16	
				0145	20	
				0200	24	
				0230	38	
16/17	2200-0210	Veil, bands and waves, medium bright, beyond zenith at Turku, bands passed overhead at Aberdeen 2205 and 0210. Faint veils at Ränne, NLC in cloud breaks at Vildbjerg.	60.5°N 21°E	2200	110	
				2215	100	260-100
				2230	100	260-100
				2245	100	260-020
				2300	75	270-020
			57°N 02°W	2205	90+	
				2220	50	
				0200	70	
				0210	90+	
			56°N 08°E		NLC in cloud	
			55°N 14.5°E		NLC present	
17/18	2126-2315	All forms covering most of sky at Rautalampi. At Turku bright veil, bands and waves slowly receded north. Faint veils at Ränne. NLC seen at Kemnay near Aberdeen — no details.	62.5°N 27°E	2126-2220	156	320-080
			61°N 28.5°E	2130	No NLC	
			60.5°N 21°E	2145	80	260-060
				2215	60	270-090
				2230	50	270-080
				2245	40	275-075
				2300	40	285-115
				2315	30	295-090
			55°N 14.5°E		NLC present	
18/19		No NLC (F)				

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev. (degrees)	Limiting azimuths (degrees)
19/20		No NLC (F)				
20/21	2140-2235	Waves and whirls over most of sky at Rautalampi. NLC suspected in cloud breaks at St Andrews. No NLC (B).	62.5°N 27°E	2140-2235	134	240-090
			56.5°N 03°W	2215	NLC?	
21/22		No NLC (G)				
22/23	2145-0300	Mr Kaye's pictures from Sumburgh show bright twisted bands against a faint silvery veil, waves visible briefly. Curved bands and patches at Edinburgh extended past zenith at Aberdeen. At Vildbjerg at 0043 Mr Andersen photographed a panorama of intense bands and waves, as did Mr Olesen (Alrö) with faint patches near Polaris and Vega later.	60.5°N 21°E	2145	No NLC	
			60°N 01.5°W	0000	28	338-065
				0030	30	325-050
				0100	60	303-048
				0115	60	313-040
				0130	70	325-070
				0200	60	308-090
			57°N 02°W	2200	No NLC	
				2230	15	000
				0228	100	
			56°N 03°W	0230	50	320-090
				0245	45	320-130
				0300	NLC present	
			56°N 10°E	2220	NLC present	
				0105	20	
				0145	56	
				0200	NLC present	
			56°N 09°E	0043	10	
23/24		No NLC (F)				
24/25	2130-2255	Faint bands and whirls at Rautalampi, no NLC at Turku.	62.5°N 27°E		30	300-090
25/26	2200-2208	Low, faint veil at Rautalampi, no NLC at other Finnish stations.	62.5°N 27°E		10	290-040
26/27	2130-2300	All forms visible at Imatra and Joutseno; very bright, overhead at Rautalampi. Medium bright bands against fading veil at Turku.	62.5°N 27°E	2130-2255	90	260-090
			61°N 29°E	2300	28	320-050
			60.5°N 21°E	2140	24	315-050
				2215	22	305-040
				2230	10	335-045
				2245	10	340-045
				2300	14	350-050
27/28	2215-2300	Bands and veil at Rautalampi, no NLC at Turku.	62.5 27°E		15	000-036
29/30		Faint NLC in cloud breaks at Alrö. No NLC (F, G).	56°N 10°E			
30/31	0215-0250	Faint band photographed at Edinburgh. No NLC (F).	56°N 03°W	0230	6	045
31 July/ 1 Aug	2100-2330	Bright waves and whirls against extensive veil at Rautalampi, fairly bright bands and small waves low in sky at Helsinki. Bright bands on veil described as greenish at Turku by Mr Parviainen. Bands and whirls at Imatra.	62.5°N 27°E	2100-2320	100	270-080
			61°N 29°E	2100	40	310-050
			60.5°N 22°E	2100	No NLC	
				2130	20	355-045
				2145	18	350-050
				2200	16	350-035
				2215	13	350-035
				2230	12	350-035
				2245	10	350-040
				2300	12	345-045
			60°N 25°E	2100	–	330-
				2115	12	328-
				2130	12	337-
				2145	13	339-
				2200	11	340-
				2215	13	348-
				2230	12	352-
				2245	13	347-
				2300	14	353-
				2308	12	328-070
				2315		328-065
				2330	17	329-
1/2 Aug	2015-2045, 2100-2140	Medium bright waves against veil at Imatra and Rautalampi. No NLC at Turku.	62.5°N 26.5°E	2125-2140	21	270-080
			61°N 29°E	2015-2045	45	340-045
2/3	1947-2015	Bands and whirls high in sky at Pertteli, no NLC at other Finnish stations.	60°N 23°E	1947	85	
				1953	75	
				2000	70	
				2006	60	
				2015	60	

Date — night of	Times UT	Notes	Station position (to nearest 0.5 degree)	Time UT	Max elev.	Limiting azimuths
					degrees	
3/4		No NLC (F)				
4/5		No NLC (F)				
5/6		No NLC (F)				
6/7		No NLC (F)				
7/8		No NLC (F)			Aurora at Helsinki	
8/9	2045–2055	Faint veil at Turku	60.5°N 21.5°E		3	357–003
9/10		No NLC (F)				
10/11		No NLC (F)				
13/14		No NLC (F)				
14/15	2330	Faint band at Turku	60.5°N 22°E		3	352–007
17/18		No NLC (F)				
18/19	1900–2300	Faint waves in zenith at Pertteli, no NLC at Imatra.	60°N 23°E		90	315–090
19/20		No NLC (F)				
20/21		No NLC (F)				
21/22		No NLC (F)				

Photographs

30 June/1 July	2340–0246	Edinburgh (Corstorphine)	J. Shepherd
	2249–0018	Edinburgh (Blackford)	N. Bone
	2330–0100	Edinburgh (Joppa)	D. Gavine
	2230–2330	Edinburgh (Cammo)	J. D. Waldron
	0225–0308	Edinburgh (Braids)	J. Bartholemew
	2250–0100	Milngavie	D. A. R. Simmons
4/5 July	2305	Heswall, Wirral	P. Irons
5/6	0020–0145	Edinburgh (Joppa)	D. Gavine
15/16	2330–0000	Edinburgh (Joppa)	D. Gavine
	2330–0000	Edinburgh (Blackford)	N. Bone
	2330–0130	Aberdeen	M. Gadsden
	2257–0230	Milngavie	D. A. R. Simmons
16/17	2315–0201	Aberdeen	M. Gadsden
22/23	2300–0245	Aberdeen	M. Gadsden
	0000–0200	Sumburgh	R. A. Kaye
	0105–0200	Alrö	J. O. Olesen
	0143	Vildbjerg	H. Andersen
	0230	Edinburgh (Joppa)	D. Gavine
30/31	0230	Edinburgh (Calton Hill)	J. D. Waldron
31 July/1 Aug	2138	Helsinki	D. Frydman

References

Crane, A. J. 1983 Noctilucent clouds 30 June/1 July 1983. *Weather* **38**, 323.

Gavine, D. M. 1984 Noctilucent clouds. *Weather*, **39**, 46.

Reviews

The new solar system (2nd edition), edited by J. Kelly Beatty, Brian O'Leary and Andrew Chaikin. 220 mm × 290 mm, pp. viii + 240, *illus. Cambridge University Press, 1982. Price £12.50.*

The awakening of public interest in astronomy during the past two decades, stimulated in part by the data and remarkable images of the planets from the recent American and Soviet spacecraft, has resulted in a considerable crop of popular and semi-technical books on the solar system. Few, however, have achieved the authority and breadth of coverage found in *The new solar system.* In contrast to many previous books aimed at a similar market, the editors have chosen to adopt the (more logical) modern approach of 'comparative planetology', introducing each aspect of solar system research (e.g. planetary surfaces, atmospheres, magnetospheres, etc.) topic by topic, rather than planet by planet. Each chapter is written by a leading US specialist on the particular discipline described, thereby ensuring an up-to-date and authoritative (though necessarily personal) review from an active researcher. The book is lavishly illustrated and is clearly aimed at a level familiar to readers of *Scientific American* or *New Scientist*, intermediate between the glossy popular astronomy text and the serious research review.

Most currently important areas of research are covered, ranging from the traditional studies of planetary surfaces and atmospheres, comets and meteorites, to the newer disciplines made possible specifically by space technology, such as planetary magnetospheres, lunar geology and the *in situ* search for living material on Mars. Of particular interest to atmospheric scientists are articles by James Pollack and Andrew Ingersoll. Pollack reviews the atmospheres of the terrestrial planets in one chapter, providing a personal view of his own areas of interest (the composition and origin of planetary atmospheres, and climatic variations on Mars and the Earth), together with a succinct, though remarkably comprehensive, summary of the meteorology of the inner planets. In a second short article he presents some of the latest findings from the Voyager spacecraft fly-by of Saturn's moon Titan, including the intriguing speculations concerning Titan's meteorology and surface ('does it rain methane into an ocean of hydrocarbons?'). Ingersoll's review of Jupiter and Saturn highlights many of the important questions concerning their atmospheres, especially those raised by the recent Voyager spacecraft data. The interpretations of Jovian meteorology discussed are not, however, comprehensive and clearly reflect the author's own viewpoint which is not universally accepted. Also of interest are articles by David Morrison and Dale Cruikshank on the outer planets (Uranus, Neptune and Pluto), including a discussion of the recent ground-based data on their atmospheres, and by Jack Eddy on the latest views of the Sun (including recent spacecraft measurements of secular variations in the solar 'constant'!).

The new solar system is already into its second edition, published only one year after its first edition, mainly in order to include some more up-to-date results from the Voyager 2 encounter with Saturn. Despite the potential pitfalls in attempting to combine the efforts of so diverse a team of authors, the editors are to be congratulated on achieving a remarkably uniform and cohesive production of a consistently high standard, and for so reasonable a price.

P. L. Read

Man-made carbon dioxide and climatic change: a review of scientific problems, by P. S. Liss and A. J. Crane. 147 mm × 230 mm, pp. vii + 127, *illus.* Geo Books, Norwich, 1983. Price £3.95, US \$7.90 (paperback), £8.50, US \$17.00 (hardback).

Originally produced as an internal report within the Central Electricity Generating Board, this short book is a very readable introduction to man's impact on the atmospheric carbon dioxide concentration and the possible climatic consequences of this concentration increasing. A background in mathematics or physics at university level is probably necessary fully to appreciate this book.

The book is divided into two main parts. In Part I the authors deal with the global behaviour of man-made carbon dioxide. Starting with an outline of the observational evidence for the increase of atmospheric carbon dioxide they go on to give a fairly detailed description of the carbon cycle. The authors correctly stress the large uncertainties in man's knowledge of the carbon cycle and the consequent difficulties in estimating future trends.

Part II deals with the 'climatic consequences of increased carbon dioxide concentrations'. This starts with a description of the 'greenhouse effect'. One-dimensional climate models are discussed as a method of estimating the global mean warming due to a doubling of the atmospheric carbon dioxide concentration. The theory behind global climate models is presented next; two areas of difficulty are identified, the modelling of cloud and the necessity of including the feedback between the ocean and the atmosphere. Finally, in this section, a broad survey is given of the results of doubling carbon dioxide as predicted by various global climate models in the United States and the United Kingdom.

There is a short section at the end of the book on the 'implications of increased carbon dioxide for the use of energy in the future'.

Overall this is a very readable introduction to, and survey of, this very difficult area of climate research. For someone entering this field of research this review would give a good introduction to the relevant literature. For the scientist not specializing in this area most of this book would be rewarding. One possible exception to this is the chapter on the 'uptake of carbon dioxide by the oceans' which would be heavy-going for the reader with little knowledge of chemistry. The diagrams are generally clear and well labelled without too much information being presented at once. I would recommend this book to any scientist, non-specialist or specialist, interested in this topic. It would also be a welcome addition to any scientific library.

J. F. Dyson

Books received

The stratospheric aerosol layer, edited by R. C. Whitten (Berlin, Heidelberg and New York, Springer-Verlag, 1982. DM 54 (approx), US $25.20) is a comprehensive treatment of the structure of the stratospheric sulphate aerosol layer and its physical, chemical, optical, and morphological characteristics. Included are chapters on observations of precursor sulphur-bearing gases, *in situ* aerosol particle sampling, lidar and satellite measurements, pertinent laboratory experiments, models and model applications, and climate effects. Much of the work is very new, some of it being published for the first time.

The theory of homogeneous turbulence, by G. K. Batchelor (Cambridge, Cambridge University Press, 1982. £6.95) is a reissue of Professor Batchelor's text on the theory of turbulent motion, first published in 1953. This classic account includes an introduction to the study of homogeneous turbulence, including its mathematical representation and kinematics. Linear problems, such as the randomly-perturbed harmonic oscillator and turbulent flow through a wire gauze are then treated. The author also presents the general dynamics of decay, universal equilibrium theory, and the decay of energy-containing eddies. There is a renewed interest in turbulent motion, which finds applications in atmospheric physics, fluid mechanics, astrophysics, and planetary science.

Intense atmospheric vortices, edited by L. Bengtsson and J. Lighthill (Berlin, Heidelberg and New York, Springer-Verlag, 1982. DM 56, US $23.40) examines the different mechanisms for vorticity intensification that operate in two different kinds of meteorological phenomena of great importance, namely the tropical cyclone and the tornado. The understanding of these phenomena has grown in recent years owing to increased and improved surveillance by satellites and aircraft, as well as to numerical modelling and simulation, theoretical studies and laboratory experiments. The book summarizes these recent works with contributions from observational studies (from radiosonde data, aircraft, satellites and radar) and from studies concerning the physical mechanism of these vortices by means of theoretical, numerical or laboratory models. The book contains articles by the leading world experts on the meteorological processes and on the fundamental fluid-dynamic mechanisms for vorticity intensification.

Environmental isotopes in the hydrosphere, by V. I. Ferronsky and V. A. Polyakov, translated by S. V. Ferronsky (Chichester, John Wiley and Sons, 1982. £31.00) presents a discussion of the distribution and geochemistry of the naturally-occurring stable isotopes of hydrogen, oxygen and radioactive tritium, and also of radiocarbon and other cosmogenic isotopes and radiogenic isotopes of the thorium–uranium series, in the ocean and in atmospheric, surface and ground waters. The use of environmental isotopes in three main areas of investigation in the study of natural waters is discussed. These are their genesis, dynamics and residence time in natural reservoirs. The origin of the hydrosphere is examined in the light of isotopic, new cosmochemical and recent theoretical results. This is a revised and supplemented edition of a work first published in Russian in 1975.

Cloud dynamics, edited by E. M. Agee and T. Asai (Tokyo, Terra Scientific Publishing Co., Dordrecht, Boston and London, D. Reidel Publishing Co. 1981. Dfl 115, US $49.50) serves as a brief introduction to the study of cloud dynamics, with primary emphasis on current international research efforts. The book contains papers presented at the Cloud Dynamics Symposium held at the Third General Assembly of the International Association of Meteorology and Atmospheric Physics, held in Hamburg, 17–28 August, 1981, as well as introductory and summary material provided by the co-editors. Convective phenomena are addressed in terms of shallow versus deep convective systems, with the emphasis on the comparison of theoretical model results and field observations. Cloud phenomena considered range from cumulus and cloud streets to organized mesoscale cellular convection, and wintertime lake-induced snow squalls. Deeper convective systems are also considered, including thunderstorms, hailstorms and tornadoes. Comparisons are made between Doppler radar observations and thunderstorm model results.

Turbulent shear flows 3, edited by L. J. S. Bradbury, F. Durst, B. E. Launder, F. W. Schmidt and J. H. Whitelaw (Berlin, Heidelberg and New York, Springer-Verlag, 1982. DM 140 (approx), US $56.00) is a collection of papers from the Third International Symposium on Turbulent Shear Flows held at the University of California, Davis, September 1981. The papers are divided into four sections: wall flows, scalar transport, recirculating flows and fundamentals. As with previous volumes, each section is preceded by a brief introductory article whose purpose is to make some general observations about the various sections and to fit the individual papers into the context of the general topic.

Air pollution: Assessment methodology and modeling, edited by Erich Weber (New York, Plenum Press, 1982. US $39.50) explores the fundamental steps in developing a worldwide coherent pollution control policy on air quality management systems, air quality modelling and assessment methodology. Experts from eight industrialized countries have contributed, drawing on their practical experience. Methods of management, modelling and assessment discussed in this volume have been selected because they were successfully applied in specific cases. The Gaussian method for pollution modelling, now almost universally employed, is described, and calculations for its practical application are included. The volume also provides a glossary explaining in detail about three hundred terms used in air quality management.

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THE METEOROLOGICAL MAGAZINE

No. 1347, October 1984, Vol. 113

This issue of the Meteorological Magazine is dedicated to three papers on the topic of mesoscale weather forecasting. The first two describe the current status of two research programs which, if successful, would lead to a large amount of additional guidance being available for local forecasting.

The third paper examines in more general terms some of the opportunities and challenges in making use of such guidance. It presents one view of how forecasting geared to periods of 12 hours ahead or less might develop, particularly at outstations. It is not a blueprint for the future and depends upon forecasts from the FRONTIERS* system and from the mesoscale numerical model achieving an accuracy and precision which have not yet been demonstrated, and which will require at the very least a further period of intensive research effort. The real developments are likely to be different from those envisaged in the paper, but the general trend towards the kinds of equipment and techniques which the authors describe is almost certainly correct. It must be expected that they will have a substantial influence at meteorological stations within the next few years.

*FRONTIERS: Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite

551.501.81:551.507.362.2:551.509.324.2

FRONTIERS five years on

By K. A. Browning and K. M. Carpenter
(Meteorological Office Radar Research Laboratory, Royal Signals and Radar Establishment, Malvern)

Summary

Five years have elapsed since FRONTIERS was first written about in the *Meteorological Magazine*. The FRONTIERS program is a strategy for using a radar network together with Meteosat to provide meteorological offices and other users with precipitation nowcasts, i.e. detailed descriptions of the current distribution of precipitation plus forecasts up to several hours ahead obtained by extrapolation. An important part of this program is the involvement, within an otherwise highly automated system, of a forecaster who can exercise judgement by means of a centrally-located interactive display system, or work station. The purpose of this paper is to describe the current status of the FRONTIERS program.

1. Introduction

The Meteorological Office has been using an integrated network of radars with remote colour displays of composited data as a forecasting aid for some years. It is also developing ways of processing and displaying Meteosat cloud imagery in the same format as the radar pictures. The background to these programs was reviewed by Browning (1980) and some recent examples of the operational utility of these products have been presented by Booth (1984).

Quite early in the development program it became apparent that the usefulness of the radar network pictures is often impaired by errors, many of which are meteorological in origin and difficult to correct objectively. The need was felt for a means of exercising effective quality control and analysis in real time. Moreover, although the radar and satellite products were found to be very useful separately, it was considered that the limited coverage of the radar data was a major restriction that could be largely removed if ways were developed of combining radar and satellite data to provide analyses of precipitation over an area rather larger than the radar network. Given rainfall analyses of such a kind it would then be natural to derive ways of producing, on a regular basis, detailed forecasts for several hours ahead, by extrapolation of successive patterns of precipitation. It was with these aims in mind that the FRONTIERS program was conceived (Browning 1979).

The radar data used in this program are summarized in section 2. The satellite data used to extend the radar coverage, and the generation of forecasts, are outlined in section 3. Of the new techniques being used, the key element is the development of interactive methods whereby a forecaster can analyse and combine the radar and satellite pictures and generate forecasts directly on the screen of a colour monitor. The FRONTIERS interactive display system (Browning and Collier 1982), described in section 4, is intended to be operated as a central facility. The idea is that a forecaster in the Central Forecasting Office could exercise judgement in the processing of the radar and satellite imagery so that improved products could be sent to meteorological outstations and other customers using the same means as are currently being established to distribute the ordinary radar network pictures.

Two features distinguish the FRONTIERS interactive display system from other interactive systems in use by the meteorological community. The first is that FRONTIERS is designed to solve a single specific problem, the derivation of actual fields and forecasts of precipitation. This has enabled us to design the system in detail at an early stage. The second is that the system is genuinely interactive and not merely a very modern display device. Using the FRONTIERS display the operator actually changes the data directly, just as if he were rubbing out data on a piece of paper and sketching in fresh information.

The FRONTIERS interactive display is, at the time of writing (March 1984), still undergoing pre-operational trials and development. The network of radars on which it depends, however, is close to being fully operational, and we shall review the current status of this next, before going on to consider the actual FRONTIERS system in more detail.

2. The weather radar network

Fig. 1 shows the network of radars available to the Meteorological Office as it is expected to be by autumn 1984. The network is a mixture of C-band (5.6 cm) and S-band (10 cm) radars with beam widths of one or two degrees. The first four radars to be installed (numbers 1 to 4 in the diagram) have all been in regular operation since 1980 or earlier. The data processing required to achieve the composite radar display is described by Collier (1980). Each radar in the network has its own on-site minicomputer which accepts the raw radar data, applies various corrections, and sends the data over dedicated telephone lines to a number of locations, including Malvern where another minicomputer automatically generates an overall radar composite picture. The networking computer used for this purpose, now referred to as Radarnet, is expected to be moved to Bracknell and backed up as a fully operational system during 1985. At present the composite picture is derived on a 256 × 256 grid of 5 km squares, and a 128 × 128 array of 5 km squares is extracted covering the dashed square in Fig. 1. The pictures are disseminated for presentation on special-purpose (Jasmin) displays with limited action-replay facilities. These are currently being made available to an increasing number of forecasting offices.

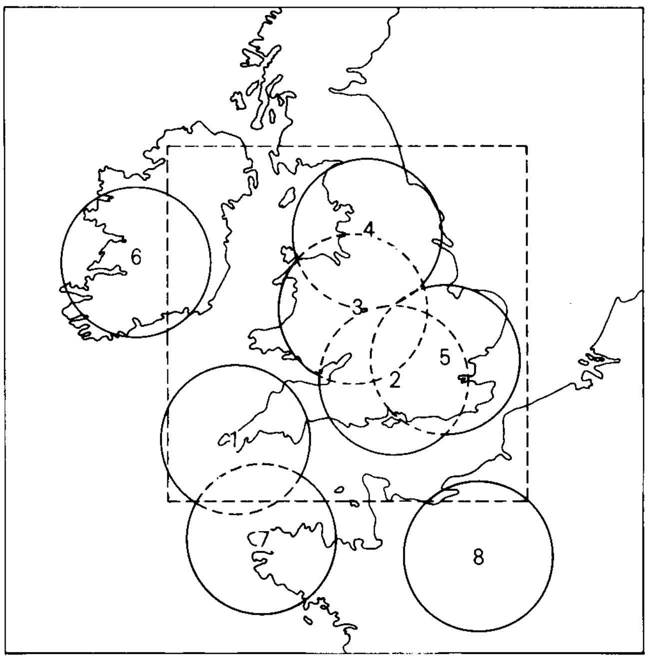

Figure 1. Coverage of weather radars and radar-compatible Meteosat data to be used in FRONTIERS as from autumn 1984. Radars are at (1) Camborne (Cornwall), (2) Upavon (Wiltshire), (3) Clee Hill (Shropshire), (4) Hameldon Hill (Lancashire), (5) Chenies (Buckinghamshire), (6) Shannon (Republic of Ireland), (7) Brest (France), and (8) Dammartin en Goelle (France). The circles show the range of generally useful coverage for each radar — 150 km (i.e. between the so-called quantitative limit of 75 km and the maximum range of 210 km). The solid outer frame is the boundary of Meteosat imagery normally used in the FRONTIERS display and the dashed inner frame the area of the radar network routinely available on Jasmin displays.

During summer 1984 several more radars were being added to the network as part of collaborative projects. Radar 5, covering the London area, is a new unmanned radar. It resembles radar 4 which was established as part of the successful North West Weather Radar Project (Collier *et al.* 1980). Data from radars 6 to 8 are available as part of the European Weather Radar Network Project (COST 72 1982) or through bilateral agreements with neighbouring countries. Further extension of the network is under active consideration both as part of national plans involving the Meteorological Office in collaboration with other parties, especially the water industry, and also as an extension of the international exchanges already mentioned.

In order to display data from the extended radar network shown in Fig. 1 without degrading resolution, a new user display will be required to succeed the existing display. A replacement display system has been specified and two prototypes are expected to be available for evaluation by 1985. In addition to being able to display products available directly from the network computer, the new display will be able to replay long sequences, zoomed or unzoomed, of several kinds of pictures which may be generated centrally using the FRONTIERS display. The maximum area of coverage of these pictures would be a 256 × 256 array of 5 km squares, approximately as shown by the outer frame.

3. Products from FRONTIERS

The new forms of data that could be generated using a centrally-located FRONTIERS interactive display include:

Product I:	quality-controlled radar rainfall analyses,
Product II:	rainfall actuals over a large area derived from a combination of radar network and Meteosat imagery,
Product III:	rainfall forecasts for a period of say one to six hours ahead,
By-product IIa:	registered (i.e. accurately located) Meteosat imagery in the same format.

Such products, given an operational system, would probably be generated at 30-minute intervals and distributed with a delay of 20 to 40 minutes. This is to be compared with pictures every 15 minutes distributed with a delay of about 5 minutes for radar composite pictures obtained as at present from the Radarnet computer. Clearly the added value in the FRONTIERS products can only be obtained with some sacrifice of speed. Indeed we suspect that, when FRONTIERS becomes operational, some users would wish to continue to make use of the automated Radarnet product, with all its defects, because it is available so quickly, in addition to using the slightly delayed FRONTIERS products. We shall now consider the FRONTIERS products in more detail.

The cycle of operations carried out by the forecaster at the FRONTIERS interactive display is constrained by the 30-minute cycle for the reception of B-format digital Meteosat data. At present the processed cloud imagery is available in the FRONTIERS display within 20 minutes or so of the nominal observation time, i.e. 15 minutes after the corresponding radar pictures. There are three main stages in the cycle of operation corresponding to the generation of Products I, II and III, and the present approach is to allow the operator about 10 minutes for each. In round figures this means that the first stage starts at $T+10$ minutes, with Product I available for dissemination at $T+20$ minutes. The second stage starts at $T+20$ minutes, with Product II available at $T+30$ minutes. The third stage starts at $T+30$ minutes, with Product III available at $T+40$ minutes.

In more detail, the FRONTIERS operator carries out a selection of the following steps during the generation of Product I: deletion of unreliable radars from the composite picture; deletion of spurious echoes unrelated to precipitation; monitoring and modification of bright-band (melting level) corrections derived at radar sites; designation of rainfall types to allow appropriate calibrations and range-dependent corrections to be applied; adjustment of calibration of any suspect radars in the light of available ground truth and space/time continuity; incorporation of likely orographic rainfall enhancement by specifying the nature of the low-level airflow.

The generation of Product II involves three main steps using the Meteosat cloud imagery. The first step is to register the imagery. The Meteosat pictures used in FRONTIERS have the distortions due to the viewpoint in space removed objectively and they are displayed in the same National Grid format as the radar pictures. However, they are not always positioned accurately and so it is necessary to check the registration by comparison with a coastline overlay. The second step is to transform the imagery objectively to a first-guess rainfall pattern using algorithms that relate surface rainfall to infra-red radiance and, when available, visible brightness (Lovejoy and Austin 1979). The FRONTIERS operator can select either universal relationships derived for different cloud types, or current relationships based on contemporary co-located radar data. The third step is to apply the rainfall pattern estimated objectively from Meteosat to extend the rainfall analysis beyond the area covered by the radars, intervening subjectively to delete or extend areas of rain inferred from the satellite so as to obtain consistency with the radar-derived patterns and any ground truth available from other sources. There are times, especially on occasions of widespread cirrus, when the satellite guidance is positively misleading as a first guess of the rainfall pattern. The operator then has to disregard much of the detail of the satellite imagery and build up his own analysis in an almost entirely free-hand manner. The extension of coverage of estimated rainfall using Meteosat data, although clearly qualitative, is nevertheless valuable in that it sets the more accurate radar data in a broader synoptic context and gives advance warning of possible rain clouds approaching from data-sparse areas over the sea.

In the derivation of Product III, the rainfall forecasts, the first step is for the computer to divide the analysed fields of rain into a number of clusters of contiguous rain areas. It then compares the position of each cluster with that obtained 30 minutes earlier and derives an extrapolation forecast on the basis of the resulting set of displacement vectors. This can be done entirely automatically but it has been found (Browning *et al.* 1982) that subjective forecasts based upon the same principles are more accurate and reliable. This is partly because a forecaster can recognize and allow for deficiencies in the initial data, as in the generation of Product I. It is also because the objective extrapolation algorithms now being used do not perform well in other than simple situations. Thus at present the best results are usually obtained by determining the velocity of rainfall clusters subjectively, e.g. by using the Lagrangian replay facility described in section 4. In essence the FRONTIERS computer takes the burden of calculation away from the operator but allows him to make a variety of logical choices or to modify forecasts that have been calculated.

4. Technical aspects of the FRONTIERS interactive display system

The FRONTIERS interactive display system is being developed jointly by the Meteorological Office and Logica Ltd as a central node within a distributed computer network. The FRONTIERS computer is a DEC VAX 11/750 supported by two RM80 discs and a TGU 77 tape drive. Other centrally-located minicomputers processing the radar network and Meteosat imagery pass data to it via high-speed (56 000 bits per second) DMR 11 interfaces. The FRONTIERS computer provides images to two Ramtek 2455 display systems which support two colour monitors and a joystick. As shown in Plate I, (page 298) the operator interacts with the imagery via one of the monitors which is fitted with a touch screen; this is sensitive to touch and is able to transmit coordinate information to the FRONTIERS computer. The facility shown in Plate I is referred to as a work station. A data tablet is also available

(Houston Instruments Hipad digitizer) which can be used interchangeably with the touch screen. The second monitor is there to provide supporting information and is not used interactively. Images on both monitors can be replayed at six frames per second. The response time for calling up an image is about two seconds.

A design constraint placed on the FRONTIERS display is that it should be easy for a forecaster to use without special training or aptitude in computer operation. The operator has to be allowed to concern himself solely with the meteorology. Accordingly keyboards, codes and complicated instruction sets are avoided. This has been achieved by basing the system on menus that are displayed as required, and from which the operator can choose the appropriate action by touching the screen. The FRONTIERS computer supports two VDUs (Visual 100s) fitted with touch screens for this purpose. A typical task is one in which an area of radar echo needs to be deleted. The echo in question is defined by touching the appropriate menu item and drawing a line round the echo on the colour monitor. Similarly, the displacement needed to position a satellite image accurately can be achieved by touching the menu and then using the joystick to bring the image into correspondence with a coastline overlay. Where the operator has a choice of device, e.g. between the colour monitor touch screen and the data tablet, he makes the choice simply by using the preferred device.

Another example of the sort of operation possible using the FRONTIERS interactive display is provided by the Lagrangian replay facility, referred to earlier. As part of the forecasting sequence the computer identifies areas or 'clusters' of rainfall and automatically calculates their velocity. The operator can modify the clusters by amalgamating or subdividing them and can also modify the velocities that have been calculated. There are several ways in which the operator can determine velocity and one of these is by means of the Lagrangian replay. When the operator requests this facility he touches a feature of the rainfall pattern at the beginning and end of the sequence he wishes to replay. Touching the same feature twice defines its velocity. The system then replays the full sequence in a Lagrangian frame of reference, i.e. with the velocity of the feature subtracted. If the feature still moves a little, the operator can use the joystick to modify the velocity until he is satisfied that the image is truly stationary in the Lagrangian frame. Once this has been achieved, the velocity of the feature of interest is accurately defined.

5. An example of the use of the FRONTIERS interactive display system

Plates II to VIII, (pages 298 and 299) depict the FRONTIERS display at different stages during the interactive processing of the data for 10 GMT on 9 December 1983 when a low-pressure system was centred over Wales.

Plate II shows the radar network display derived automatically from radars 1 to 4 (Fig. 1). The circles show the maximum range of each radar. By replaying a time sequence of pictures the FRONTIERS operator was able to ascertain that the echoes in the eastern parts of the coverage of radar 2 were spurious, and Plate II shows the line he has drawn to demarcate them. The operator then deleted all the spurious echoes and the resulting cleaned-up display is shown in Plate III.

Plate IV shows Meteosat infra-red imagery over the whole area corresponding to Plate III. This immediately enables the forecaster to make more sense of the radar rainfall pattern in Plate III. The relationship of the rain to the swirl of cloud and the low-pressure centre is obvious. The irregular western boundary of the radar echo over the Irish Sea, for example, is due to the range limitations of the individual radars.

Plate V shows a combined image in which the operator has displayed Meteosat data everywhere except within the area of good radar coverage. Because the visible imagery was poor at this hour the operator has had to make the best use he could of the infra-red imagery alone. On this occasion he has subjectively selected essentially a single threshold to obtain reasonable continuity between the radar and satellite data. Above this threshold he has displayed most of the satellite data as light blue, corresponding to light-to-moderate rain. However, he knew from surface reports in Ireland and Scotland that any precipitation falling from the deck of high cloud was evaporating before reaching the ground in some of those areas, and Plate V shows the line he has drawn on the display to mark the probable boundary of surface rain (the analysis over the North Sea and France is uncertain). The operator then deleted the non-raining cloud and allowed the computer to reduce the resolution from 5 to 20 km, as shown in Plate VI, in readiness for the computation of objective forecasts.

Plate VII shows the computer-generated analysis of the rainfall pattern in terms of clusters and cluster velocities: different rainfall clusters are identified by different colours and each cluster is assigned a displacement vector. Replay of the previous series of actuals showed the operator that, although most of the clusters were indeed travelling in a southerly direction as indicated by the vectors, the blue cluster over the Midlands was travelling towards the east. Accordingly he redefined its velocity subjectively using the Lagrangian replay facility. In fact this blue cluster is seen to be contiguous with the yellow cluster and the operator had first to intervene subjectively to override the computer analysis which initially had portrayed it simply as part of the large yellow area. Given the modified rainfall clusters and vectors, the final stage was for the computer to derive a set of forecast rainfall patterns by extrapolation of the 10 GMT analysis. One of these forecasts, for $T + 2$ hours (i.e. 12 GMT), is shown in Plate VIII.

6. Concluding remarks

The FRONTIERS interactive display system was designed to solve a very specific problem, the analysis and very-short-range forecasting of precipitation. This has enabled us to anticipate the questions the forecaster would face and the manner in which he would seek to answer them. Each half-hour the forecaster operating the system has to consider three broad problems, i.e. the use of the radar data to estimate surface rainfall, the use of Meteosat data to extend the coverage, and the generation of extrapolation forecasts. This imposes a stringent timetable and it is this fact as much as the general need for efficiency and 'user-friendliness' that has led to the facilities described.

An important aspect of the mode of operation of the FRONTIERS display is that it is menu-based. In normal real-time operation the forecaster using the system is taken through a (more or less) fixed sequence of menus in a (more or less) predetermined order. However, the architecture is so designed that as part of the development of the system it is easy to alter the menus and the logical relationships between them. The FRONTIERS interactive display system is to be moved from Malvern to Bracknell along with the Radarnet and Meteosat computers during 1985. This will not mark the end of the development stage, however. As in the case of the existing forecasting system based upon numerical–dynamical methods, we can expect the development of the FRONTIERS nowcasting system to be a continuing process over a period of many years. It is to be hoped that regular use, backed up by an active research and development program, will help us to achieve a steady improvement in the quality of mesoscale precipitation guidance over the coming decade.

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The Meteorological Office mesoscale model: its current status

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Summary

A numerical forecast model with very fine resolution is being developed as a short-period forecast tool to give detailed guidance on local weather up to a day ahead. The processes represented in the model have been specially developed to take account of the scales represented. Surface synoptic reports are incorporated into the initial data to give mesoscale detail on boundary layer and cloud variables. A weekly trial of the complete system has started and is giving encouraging results.

1. Introduction

Numerical models in current operational use give valuable guidance to forecasters on the broad-scale atmospheric structure. A grid length of about 150 km is used for global predictions and half that for the regional model covering the North Atlantic and Europe. However, even this latter model cannot represent the topographic differences between parts of the United Kingdom which are important for short-period forecasting. A mesoscale numerical forecast model with very fine resolution is being developed to tackle this problem with the aim of providing guidance to forecasters on the local variations of weather in the period up to a day ahead. This model will be closely tied to the regional model through its boundary conditions so it must be seen as a sophisticated tool for adding detail to the predictions of the coarser models. In particular it will not be able to correct timing errors in systems that are passed through the boundaries. On the other hand, in slow-moving situations the topographically-induced effects should be well forecast and should be of considerable help to the outstation forecaster. It is widely recognized that model predictions of mesoscale systems that are not forced by topography will be difficult. However, the errors will often be in timing or location in the same way that regional scale models predict realistic development of secondary depressions but often at the wrong time or place. It may also be that much of the mesoscale variation in weather from larger-scale systems is actually induced by topographic variations, perhaps through the surface temperature or moisture. In these cases the added detail will be of considerable value provided that the regional model has correctly predicted the large-scale evolution. In these situations an important task to be performed after the forecast will be to apply gross timing or development corrections which have become apparent through consideration of other observations and forecasts. This will involve the sort of techniques discussed by Browning and Golding (1984). In the present paper, the remaining sections will describe the model formulation, the methods currently used for preparing the initial data, and some recent results.

2. The forecast model

The model is planned to cover the British Isles with a grid length of 10 km but currently uses a 15 km grid length (see Fig. 1). With this resolution a reasonably faithful representation of the orography can be given, and the coastline, indicated by the zero contour in Fig. 1, has a realistic shape. The mountain ranges are still somewhat lower than reality, e.g. the Cairngorms reach 750 m rather than the observed 1200 m. Also the valleys which dissect them are not represented and so their local effects on the weather of cities like Sheffield, for instance, cannot be accounted for. A grid length of under 5 km would be needed to represent such features and is not feasible on a national basis with current computers. Their effects will therefore have to be added to the model guidance by the forecaster.

The basic dynamical equations used by the model have been described in Tapp and White (1976) and Carpenter (1979). In most respects they are the same as those used in the lower-resolution operational models. Important differences are that hydrostatic balance is not imposed and that the vertical co-ordinate is height above land surface rather than a pressure-based coordinate. Non-hydrostatic effects are important for small-scale thermally-driven circulations while the height coordinate is advantageous for prediction of near-surface effects. The vertical structure of the model is shown in Fig. 2 for the current version with 16 levels. The lowest level is at 10 m and the spacing increases linearly from 100 m to 1500 m at the top. The highest level at 12 010 m is in the stratosphere. This arrangement gives 5 levels in the lowest kilometre, and, when expressed in terms of the standard atmosphere, an almost constant spacing of 60 mb from there up to the tropopause.

In large-scale models, many of the weather-producing processes occur at scales much smaller than the model's resolution. They are parametrized in terms of scales that are resolved by assuming that they can be represented by the effects of a statistically homogeneous and stationary ensemble covering a grid square. These models ignore the presence of processes at intermediate scales. It is these intermediate scales that are explicitly forecast by the mesoscale model. Smaller-scale processes must still be parametrized and in many cases the same techniques can be applied as in larger-scale models. However, deep convection occurs on scales close to the model resolution so the statistical assumptions are not tenable in this case. In the following sections descriptions of these parametrizations are given under the headings of boundary layer, layer cloud, and convective cloud processes.

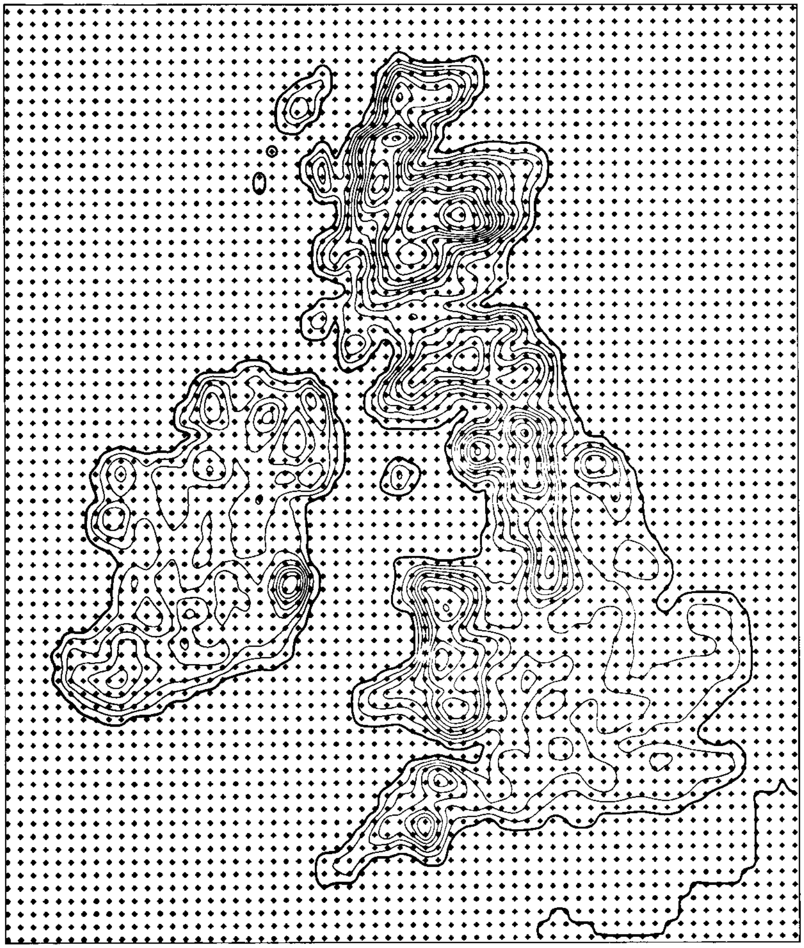

Figure 1. Model domain and orography. The grid points have a 15 km spacing and the contour interval is 50 m. The bold contour is at zero metres and indicates the model coastline.

(a) *Boundary layer processes*

The processes involved are illustrated schematically in Fig. 3. They may be divided into three groups: radiation, turbulent transport in the atmosphere and conduction in the ground. All three are controlled by the characteristics of the ground, e.g. its wetness, reflectivity, conductivity and porosity, and the vegetation present. At present two characteristics, the albedo and soil conductivity are specified as fixed over all land areas. However two others, the roughness length (Z_0) and the surface resistance to evaporation, can be varied. Over the sea the latter is zero and roughness is related to wind speed through Charnock's formula (Charnock 1955):

$$Z_0 = \mathrm{k} g^{-1} u_*^2$$

where g = acceleration of gravity, k = 0.035 and u_* is calculated from the 10-metre wind, using the

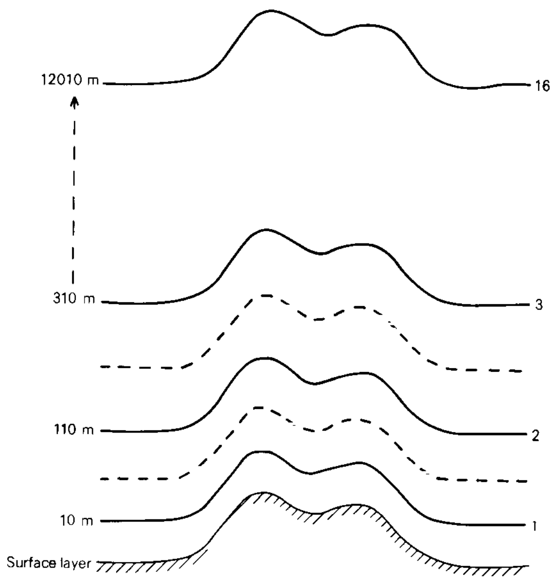

Figure 2. Vertical structure of the model. The vertical co-ordinate is height above ground and there are 16 levels from 10 m to 12 010 m. Wind, pressure, temperature, relative humidity and cloud are carried at the main levels indicated by solid lines. Vertical velocity and turbulent kinetic energy are carried at intermediate levels.

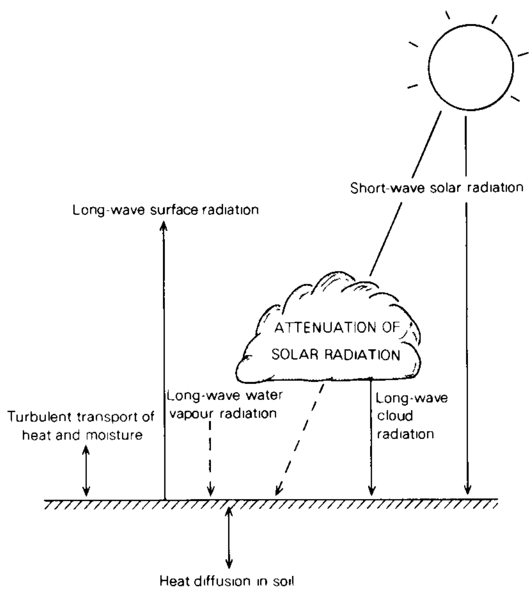

Figure 3. Schematic diagram of processes involved in the surface heat balance of the model.

previous timestep's drag coefficient. Over land, roughness length is at present fixed at 0.1 m but variations for urban and forest areas will be included soon. The resistance to evaporation is allowed to vary with time over land. The value at night is much greater than during the day to model the effects of darkness on the transpiration of plants, and it is zero when rain is falling or dew is forming. Clearly a desirable improvement will be for this parameter to remain zero after rain has fallen until it has evaporated, percolated into the ground, or run off into rivers.

Most of the heat gain at the surface comes from solar radiation. This is strongly affected by the presence of clouds in the atmosphere and is modelled by applying a transmission function (T) which depends on the integrated density of forecast cloud through a column of the atmosphere. The function has been fitted to data obtained from the radiation scheme of Slingo and Schrecker (1982) and has the form

$$T = \exp \{ -7.9 \, W^{0.5} \, / \, (1.84 + \cos^2 \alpha) \}$$

where W is the total liquid water path in kg m^{-2} and α is the solar zenith angle. The variation of T with W, for $\cos \alpha = 0.4$, is shown in Fig. 4. Clouds also emit long-wave radiation and it is the balance between

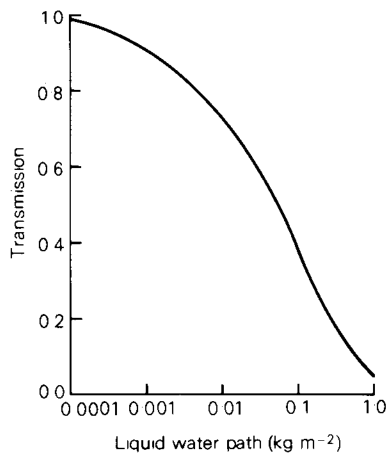

Figure 4. Transmission of solar radiation by cloud as a function of total liquid water path.

this and the radiation emitted by the ground which determines the surface temperature in overcast conditions. The cloud emission (L) is again dependent on the total liquid water path (W) and is based on a scheme of Lind and Katsaros (1982) giving

$$L = \sigma \{ 1 - \exp(-70 \, W) \} \, T_c^{\,4}$$

where σ is the Stefan–Boltzmann constant and T_c is the cloud-base temperature.

Heat conduction in the ground is crudely modelled by predicting the temperature of a single level in the ground. This varies slowly depending on its difference from the surface temperature.

The final component of heat balance at the surface is turbulent diffusion through the lowest layers of the atmosphere. In the model, transport between the surface and the first level at 10 m is modelled using the Monin–Obukhov similarity theory to calculate the mixing coefficient. A full description of the formulation is given in Carpenter (1979). The surface resistance to evaporation, defined above, is important here in determining the relative transports of sensible heat and of moisture. Above the 10 m level the mixing coefficients are determined from a forecast parameter, the turbulent kinetic energy (TKE), and a diagnosed one, the mixing length. The latter increases above the ground until it reaches an empirically-defined fraction of the boundary layer depth. The TKE is generated by shear and buoyancy and can also be transported. In particular, it can be diffused upwards from where it is generated near the ground to the boundary layer top, where the resultant entrainment of air from above is an important factor in the boundary layer evolution. The present formulation of these processes does not account for the reduced stability when saturation occurs. However, a revised formulation including its effects is under test and in particular should improve the prediction of stratus and stratocumulus cloud.

(b) *Layer cloud processes*

The processes involved in the layer cloud parametrization are depicted in Fig. 5 for a region of orographically-induced cloud. When moist air is cooled to saturation point in the model, condensate is

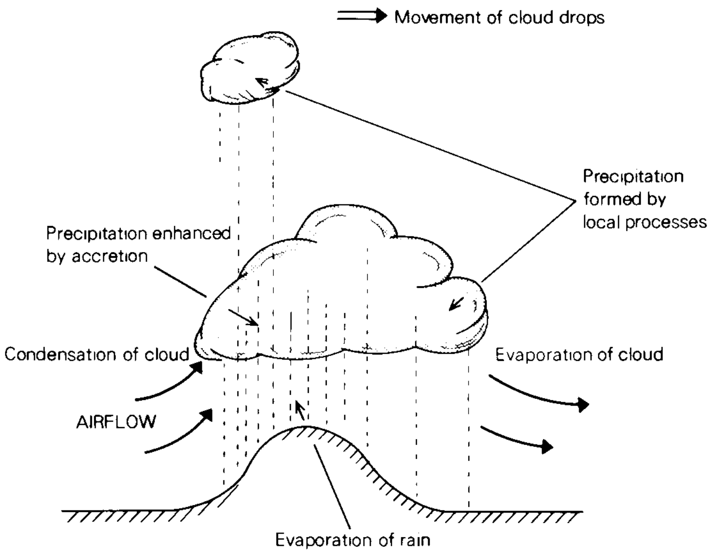

Figure 5. Schematic diagram of processes involved in the layer cloud parametrization. The wind is assumed to be blowing from left to right at all levels.

not immediately rained out as in most large-scale models, but is stored as cloud water. When enough has accumulated, it will precipitate. Meanwhile, it is transported by the wind and, if warmed, may re-evaporate. The precipitation process itself is based on a simplified version of a scheme by Sundqvist (1978). It has two components, a local production term and an accretion term.

$$\frac{dP}{dz} = \left(C_L + C_A P(z)\right) \left[1 - \exp\{-(m/C_M)^2\}\right] m$$

where m is the cloud water mixing ratio, $P(z)$ is the precipitation rate at height z and C_L, C_A and C_M are empirical constants. The exponential term merely ensures that for very low cloud water densities, no rainfall is produced. Above a threshold determined by C_M, the local production depends linearly on m and the accretion term depends on the product of m and P, the precipitation rate from higher cloud. The effect of the accretion term in enhancing the precipitation from 'seeder' clouds can be seen in Fig. 5. The combined effect of the two terms for clouds of increasing depth but fixed cloud water mixing ratio is shown in Fig. 6. Below cloud base, precipitation is evaporated as it falls to the ground. No specific allowance is made for the physics of solid precipitation in the model. However, the cooling effect due to melting snow is included because of its importance in modifying the low-level temperature structure when surface temperatures are near freezing.

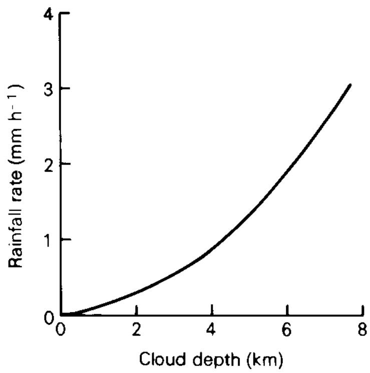

Figure 6. Rainfall rate as a function of total cloud depth for a fixed cloud water mixing ratio (0.6 g kg^{-1} in this example).

(c) *Convective cloud processes*

In large-scale models, cumulonimbus clouds are modelled by parametrizing the mean effect of a large number scattered throughout a general area of instability. This approach is inappropriate for a model with a grid length of the same order as the largest clouds and much smaller than a typical spacing between clouds in an area of instability. It is therefore necessary to model the processes in an individual cloud rather more carefully. The scheme used in the model attempts to do this but is still capable of considerable improvement. It is based on that described by Fritsch and Chappell (1980). Fig. 7 shows a schematic of the 'typical' cumulonimbus cloud used in the parametrization. An important departure from schemes used in large-scale models is that the cloud has a specified lifetime, much larger than the model timestep. Indeed a version currently being tested allows the cloud to move during its life. The details of the cloud's life cycle are not, however, modelled. Its growth, maturity and dissipation are all averaged out over its lifetime. A major problem for all cumulonimbus parametrizations is to determine the amount of cloud or, more specifically, the mass flux of air through the cloud(s). In the present case this is determined by the maximum deviation of the pseudo-adiabat of a parcel lifted from cloud base from the environmental temperature sounding. For a given depth of cloud, a standard mass flux is defined taking account of the observation that the aspect ratio of depth to area is of limited variability. If the temperature criterion would give a very tall, thin cloud, the aspect ratio criterion overrides this. Another difficulty in formulating a parametrization is to determine under what conditions a cloud will form. These are sensitive to the formulation of the boundary layer scheme and in the present model are determined by testing the stability to lifting of layers that have already been saturated, normally by upward turbulent transport of moisture.

Other details of the scheme are illustrated in Fig. 7. The updraught is modelled as an entraining plume with inflow below cloud base and outflow where the upward momentum created by buoyancy is reduced to zero. The downdraught is forced by precipitation drag and cools by evaporation below cloud base before spreading out in the lowest three layers, i.e. 460 m, of the model. The net mass flux from the updraught and downdraught is balanced by subsidence in the environment. Finally, air from the

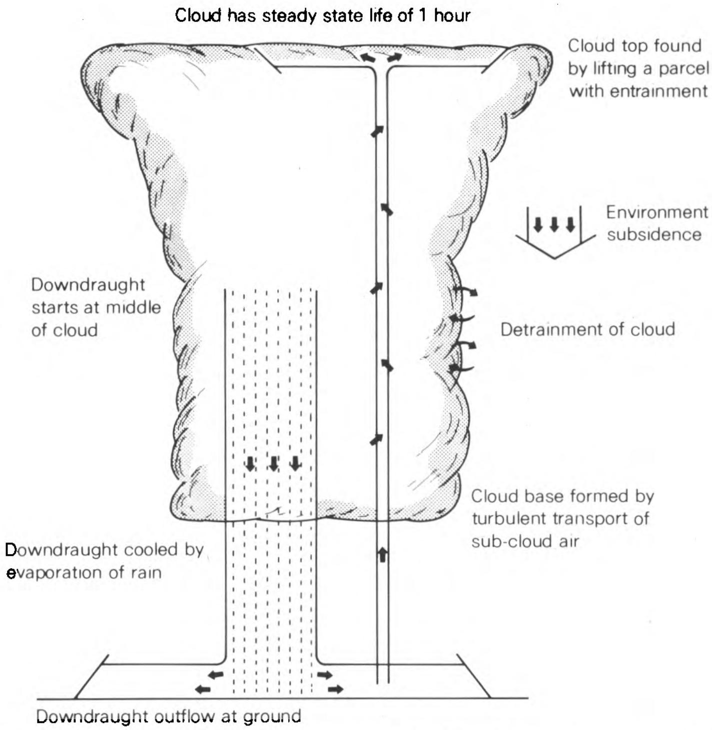

Figure 7. Schematic diagram of the cloud model used in the convection parametrization.

updraught and downdraught is mixed into the environment to simulate the dissipation process. Rainfall is determined as a proportion of the total moisture condensed in the updraught, the proportion having an empirical dependence on mean vertical shear and humidity. The remaining condensate is mixed into the environment with 60% from the 'anvil' and 40% from the lower layers of the cloud. An empirical formula is also used to relate the rain area to the mass flux and mean shear of the cloud so that local rainfall intensity can be diagnosed. Despite this sophistication, the scheme inherits many of the limitations of those in larger-scale models. Most important is the assumption that there is no net vertical mass flux in a grid column. This is reasonable for grid lengths of several hundred kilometres but incorrect for 10 km grid lengths. At present the scheme also lacks parametrizations of momentum transport and ice phase effects.

3. Initialization

The representation of the initial state of the atmosphere is of critical importance to the quality of forecast that can be expected from the model. As with large-scale models, the constraints of near-geostrophy must be satisfied if a stable forecast evolution is to be obtained. However, a short-range forecast model must also be correctly initialized with cloud if the temperature and precipitation are to be realistically forecast. Indeed, the atmosphere 'remembers' much of its initial state over a 12-hour period on many occasions and this contributes to the accuracy of subjective forecasts based on modified extrapolation procedures.

In the mesoscale model, the basic specification of initial conditions is obtained by interpolation of a short forecast (usually six hours) from the operational regional model. The regional model analysis is not used since that is at present an interpolation from the global model analysis with a grid length of 150 km and having a very crude topography specification. The interpolation to the mesoscale model grid is a complex process since the models are based on different map projections, they have different vertical coordinates and different orography, and the mesoscale model has finer resolution. These initial conditions are then enhanced by the use of surface synoptic observations. At present the techniques used are purely objective but interactive facilities are being developed and it is intended that the human analyst will be able to influence the process at all stages (Browning and Golding 1984). The modifications are made in two stages. First, surface variables and then cloud variables are analysed and incorporated.

The use of surface variables is illustrated in Fig. 8. Temperature, relative humidity and wind observations are first used to correct the interpolated 10 m values of these variables. When a well mixed

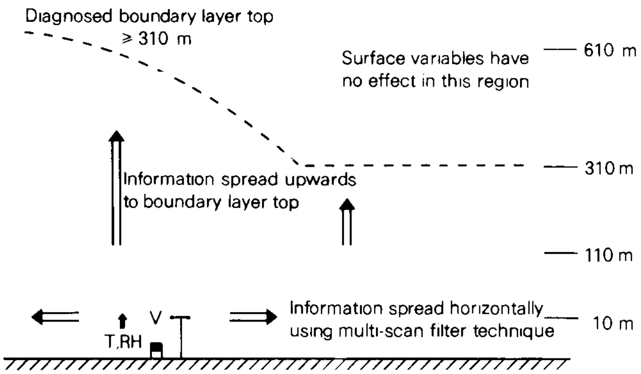

Figure 8. Schematic diagram of the method of incorporating surface observations into the model initialization. T—Temperature, RH—relative humidity and V—wind velocity.

boundary layer is present in the atmosphere, it can be assumed that information about the surface quickly reaches the boundary layer top. The corrections at 10 m are therefore applied with decreasing weight at higher levels up to a diagnosed boundary layer top. This is defined as the level at which parcels from 10 m, rising with a slightly positive lapse of potential temperature, will cease to be buoyant, provided it is at or above the third model level.

The use of cloud observations is illustrated in Fig. 9 and has been described in Higgins and Wardle (1983). Surface observations are used to correct the values of cloud base, cloud top and precipitation rate which are all diagnosed from the regional model. The model's precipitation scheme is then used to define the cloud water mixing ratio which, with the analysed cloud depth, will give the analysed rainfall rate. At the 10 m level, fog observations are also used to correct the cloud water values.

Some comparison runs have indicated that the forecast is quite sensitive to the enhancement of initial conditions described above and, in particular, to the cloud data.

4. Examples

A version of the model containing all the processes described here was first produced in October 1983. During late 1983 a number of case studies were run which indicated where further work was needed but also showed sufficient skill to justify starting a weekly trial of the model from the start of 1984. Since then several good forecasts have been obtained although weaknesses remain at present.

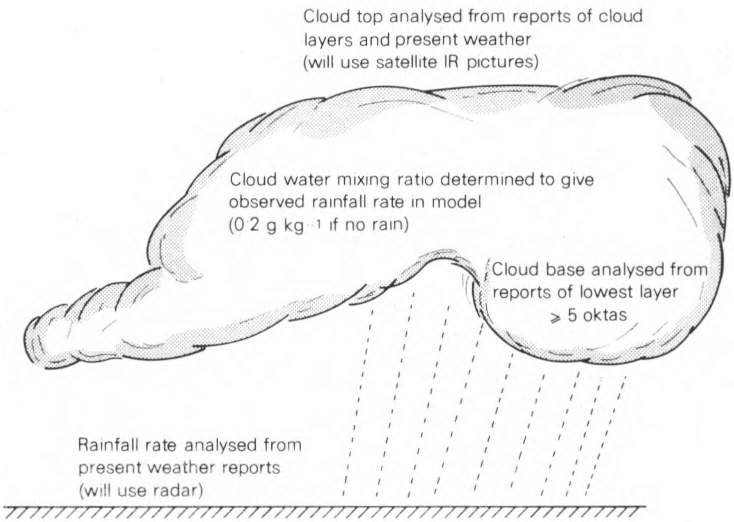

Figure 9. Schematic diagram of the method of incorporating cloud observations into the model initialization.

An example of a forecast from the model is shown in Fig. 10 with a verification chart in Fig. 11. The information displayed was extracted from charts of several model variables but could, in principle, be obtained automatically. It shows a 6-hour forecast from a data time of 06 GMT on 12 December 1983. An occlusion was moving slowly eastwards with a belt of associated rain and snow and was followed by a cold airstream with showers, especially on coasts. In the observations (Fig. 11) the 1 °C surface isotherm was a good indicator of the boundary between rain and snow. Although somewhat larger in area in Fig. 10, the prediction of snow using this indicator would have given excellent guidance to a forecaster. The timing is not quite correct with the frontal rain belt a little slow and too small a gap behind it before the showers start. However, it is encouraging to see the model prediction of a cluster of showers in the Midlands, close to the reported snow. It should be noted here that the model will naturally appear to have a greater density of showers than observed because its resolution is finer than the reporting network. Nevertheless, the predicted showers on the north-east coast are clearly erroneous. In the north-west the model has predicted a lot of convective cloud but mainly light rain from stratiform cloud rather than showers. This is because the convection scheme did not account for the effect of the freezing level on shower precipitation and finds insufficient water in the clouds to produce rain. The result is a thick deck of stratocumulus cloud giving drizzle. A simple change to the convection scheme has been made to correct this behaviour.

During February and March 1984 an extended period of anticyclonic weather affected England with spells of cold north-easterly winds and overcast skies. A number of forecasts were run in this period and they demonstrate the skill of the model in forecasting surface temperature when air mass changes are not occurring. Fig. 12 shows the surface temperature curve for Heathrow from the model compared with that observed on 27 February 1984. A thick layer of low stratus persisted throughout the day and although the model cloud was not quite thick enough, the temperatures show very good agreement. In contrast to this case, Fig. 13 shows a comparison for the same location on the following Saturday when the cloud was well broken. The agreement is again quite good, the main error being the excessive fall of temperature in the first hour. These cases show that the model can correctly represent the effects of the presence or absence of low cloud on the surface temperature.

Plate I. The FRONTIERS work station with an operator at work.

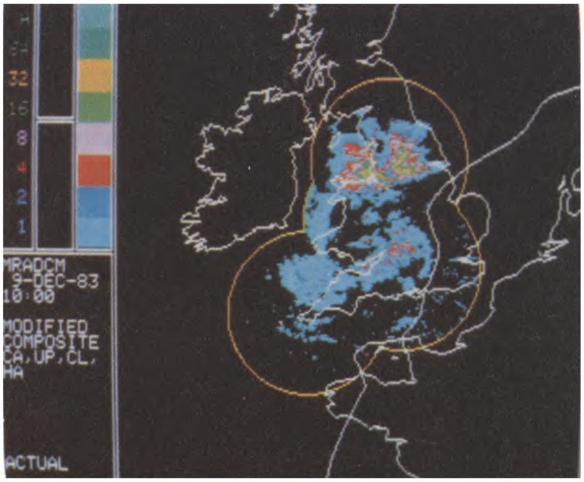

Plate II. Radar network picture derived automatically from radars 1–4 in Fig. 1. Colours represent equivalent rainfall intensity at intervals of a factor of two starting with light blue for rates up to 1 mm h^{-1}. Yellow circles represent maximum radar ranges of 210 km. The white line has been drawn by the operator to demarcate areas of spurious echoes due to interference.

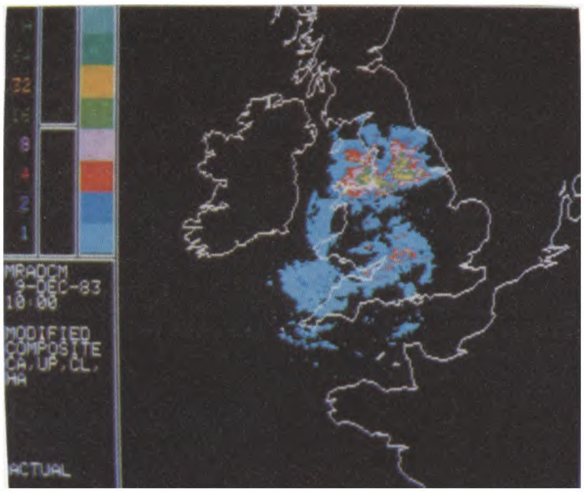

Plate III. Cleaned-up radar network picture with spurious echoes deleted. Colour key same as Plate II.

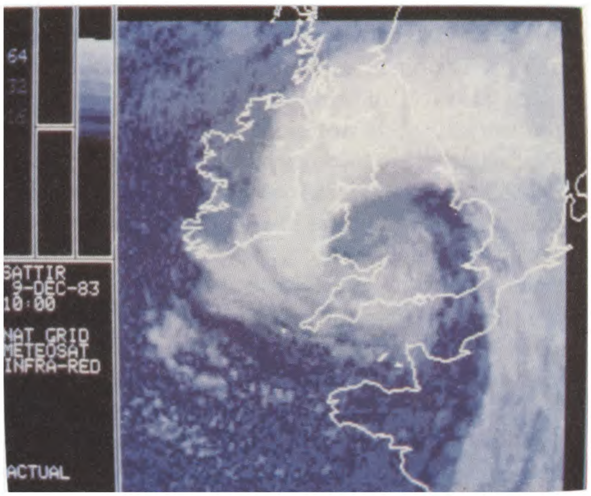

Plate IV. Infra-red Meteosat cloud picture. The brightest areas represent the coldest cloud tops.

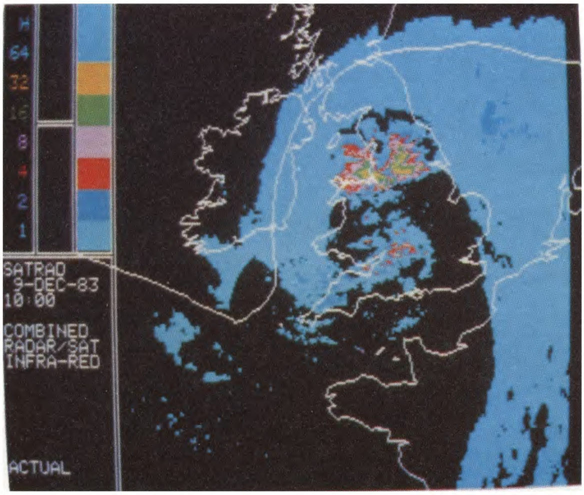

Plate V. Combined radar and Meteosat picture. Meteosat data above a certain threshold are used outside the area of good radar coverage and show as mainly light blue. The white line has been drawn by the operator to demarcate areas where rain was probably not reaching the ground.

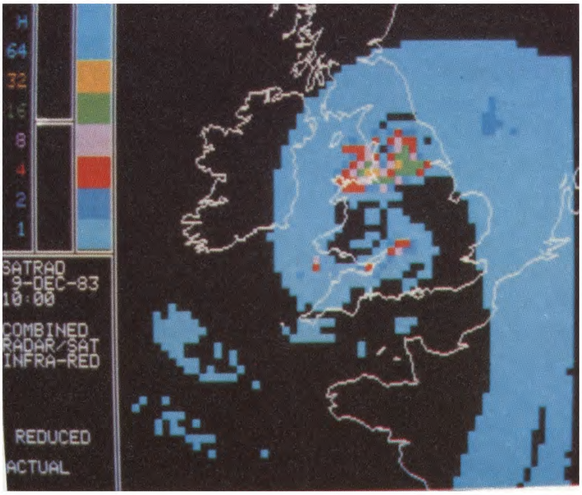

Plate VI. Same as Plate V but with resolution reduced from 5 to 20 km and the light blue area beyond the white line deleted.

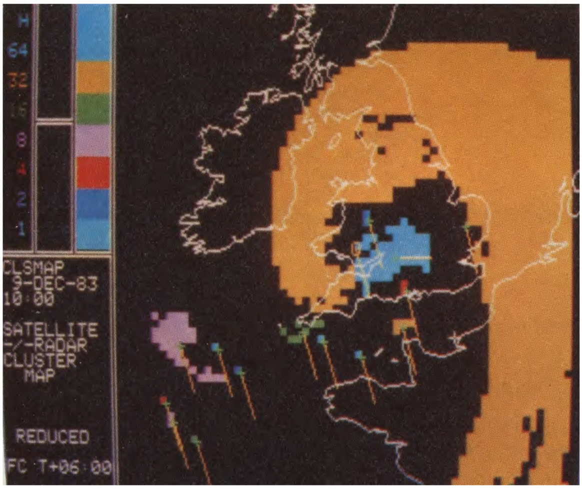

Plate VII. Same pattern as Plate VI but with the colours now denoting different rainfall clusters. The velocities of the clusters are shown by yellow vectors.

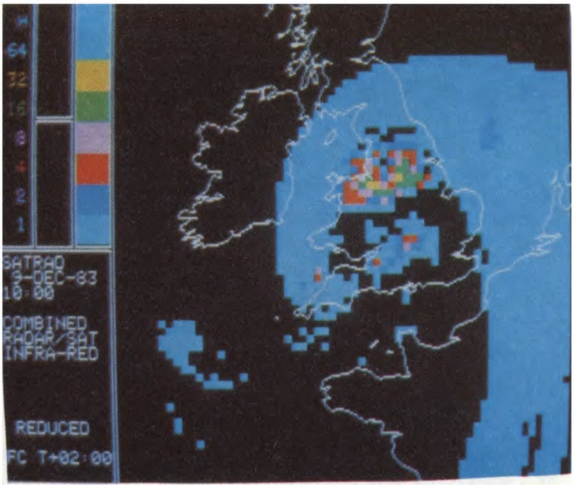

Plate VIII. Extrapolation rainfall forecast for $T + 2$ hours, in the same format as Plate VI.

Figure 10. Six-hour model prediction of the weather for 12 GMT on 12 December 1983. Triangles indicate showers, and dots are very light layer cloud precipitation. The shaded area in the south-east is the main layer cloud precipitation belt and the dashed lines enclose areas below 1°C where snow is predicted.

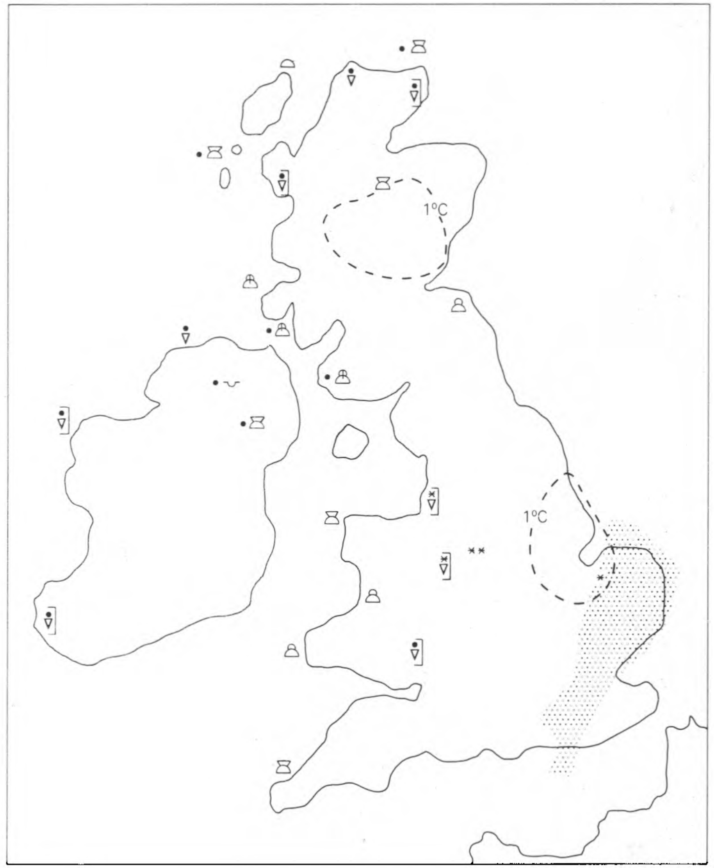

Figure 11. Observations at 12 GMT on 12 December 1983. Cloud and weather symbols indicate the extent of showery activity (for meanings see World Meteorological Organization 1974 and 1977). The shaded area in the south-east is the main frontal precipitation belt and the dashed lines enclose areas below 1°C where snow was reported.

During the tests some faults in the model have been identified. These are mainly associated with the boundaries which are of particular importance because of their proximity to the forecast area. Work is in hand to correct these faults. A more difficult challenge is posed by the sensitivity of the model to its initial conditions, especially cloud. A great deal of work remains to be done to incorporate all the available information from radar, satellite pictures and radiosonde ascents as well as from the surface reports. As the use of these data increases, the model forecasts can be expected to improve further.

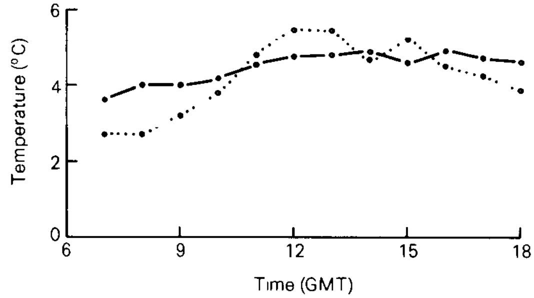

Figure 12. Comparison of 12-hour model-predicted (dotted line) and observed (solid line) temperatures for Heathrow starting at 06 GMT on 27 February 1984.

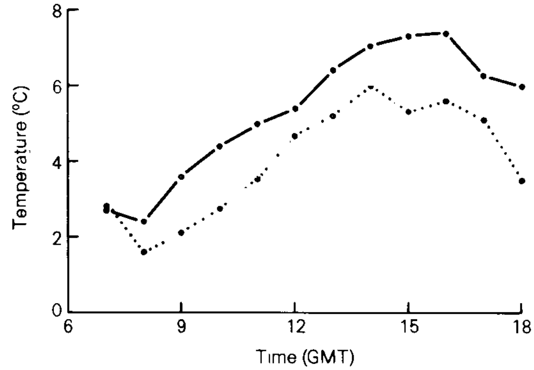

Figure 13. Comparison of 12-hour model-predicted (dotted line) and observed (solid line) temperatures for Heathrow starting at 06 GMT on 3 March 1984.

5. Conclusions

A short-range, fine-scale forecast model has been developed for forecasting for the British Isles. Many of the physical parametrizations have been specially written to take account of the scales represented by the model. A sophisticated scheme for analysis of surface synoptic reports has been developed for preparing fine-scale initial data of the boundary layer and cloud fields. The complete system has been under regular test since the beginning of 1984 and has produced some encouraging results. However, further development and testing are required before it can be used for operational guidance. In particular the format in which the output will be presented to forecasters must be determined. This is a much more complicated task for a model that predicts variables such as cloud, rain and visibility than for one whose main prediction is a pressure pattern. In addition, facilities must be developed for checking the forecast and making any necessary modifications. On the broad scale this may be done centrally but detailed processing for specific requirements will have to be done at the outstation where the guidance is used. The techniques which might be used in these processes form the subject of a paper by Browning and Golding (1984).

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Mesoscale forecasting in the Meteorological Office: the way ahead?

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Summary

Two companion papers in this issue have discussed the sort of mesoscale products that will become available if FRONTIERS and the mesoscale model are implemented operationally in the Meteorological Office Central Forecasting Office. This paper considers some of the challenges that will be encountered in exploiting the new forms of guidance and an attempt is made to deal with them from the viewpoint of an outstation forecaster. The paper looks ahead to the early 1990s when advanced interactive display systems are likely to be sufficiently inexpensive to be used at major outstations.

1. Introduction

Meteorologists are justifiably proud of the improvements in forecasting skill for periods of more than 24 hours ahead that have been achieved by advances in numerical weather prediction. These advances have, however, had little influence on forecasts for shorter periods. It has to be said that guidance issued centrally is still lacking in local detail, whilst at the outstations, where most of the short-period forecasts are issued, the mode of working is still, in many respects, much as it was 30 years ago. There is, moreover, little prospect of improvement by conventional means. Although there have been some small advances, brought about by recent research, in conceptual understanding of the behaviour of the atmosphere on the mesoscale, the scarcity of data from existing, conventional observing networks does not allow these to be used effectively for local forecasting.

As suggested in a recent review (Browning 1980), however, we believe we are at the threshold of a new era in local forecasting. Two important ingredients for improvement lie in the advances in the use of satellite and radar for observing on the mesoscale (e.g. Browning and Carpenter 1984) and in the development of mesoscale numerical weather prediction methods (Golding 1984). A further ingredient is the revolution in information technology and telecommunications; this not only forms the basis of the first two ingredients but will also enable the resulting forecast products to be disseminated to users in a rapid and cost-effective way. The challenge will be to blend these ingredients into a working system — one that can cope with the generation, quality control and rapid distribution of the large variety of tailor-made forecast products that the new forecast methods will be capable of delivering. The manner in which the new local forecasting methods might be implemented within the context of the Meteorological Office and the role of the forecaster are the subjects of this paper.

The implementation of a total system depends to a great extent upon the design of the telecommunications network. To this end a strategy for the Meteorological Office has recently been agreed whereby all forms of data and forecast guidance will be sent in digital form via fast links (64 kilobits per second) to outstations. Local storage and processing power will enable separate data streams to be manipulated and displayed according to local requirements. Initially, at the outstations, alpha-numeric data will be presented on displays known as ROASTs (Remote Outstation Automation System Terminals), imagery on colour monitors known as Jasmin displays, and numerical model products on digital facsimile outlets. These are all separate displays and, whilst the outstation forecasters will doubtless wish to retain the facility of continuously available separate displays, we shall be stressing in this paper the need to evolve towards a system in which he will, in addition, be able to combine and compare different products on a common display. The interactive display and manipulation of the combined data sets at an outstation are discussed in section 4. Similar interactive methods are important also for the centralized generation of the new mesoscale products, as discussed in section 3 (see Browning and Carpenter 1984). First, however, in section 2, we make some more general points.

2. General considerations

2.1 *Analysing on the mesoscale*

A primary requirement in local forecasting is to identify mesoscale features of the weather having significant variability on scales of tens of kilometres and over periods of an hour or so. The network of conventional (*in situ*) observations by itself is not capable of resolving this variability. On the other hand, imagery from the geostationary satellite Meteosat and from the growing network of weather radars provides fields, with the necessary resolution in both space and time, of several important weather elements: precipitation intensity, cloud extent and cloud-top temperature, and, in cloud-free areas, land and sea surface temperatures. These fields can help the forecaster make more sense of the relatively sparse network of conventional observations, and thus aid him in the preparation of finer-scale analyses of more elusive elements such as visibility. We have already caught a glimpse of the operational value of satellites and radar but at most outstations the only experience of these data is as pieces of paper separate from the main charts. In one or two forecast offices the same data have begun to be presented as moving images on a television screen. This is certainly helpful but it represents only the tip of the iceberg of opportunity.

2.2 *Forecasting on the mesoscale*

Two basic approaches are being developed in the Meteorological Office to enable centralized generation of mesoscale forecast guidance:

(i) Extrapolation or advection of detailed observed weather patterns — the nowcasting approach.

(ii) Prediction using a mesoscale numerical model — the dynamical approach.

The Meteorological Office effort in nowcasting, which goes under the name of FRONTIERS (Browning and Carpenter 1984), is at present focusing on the use of radar and satellite data for monitoring and forecasting precipitation. Another system being developed, known as HERMES (High-resolution Evaluation of Radiances from Meteorological Satellites), is providing soundings of high spatial resolution using the TIROS-N Operational Vertical Sounder (TOVS) data from the NOAA satellites (Eyre and Jerrett 1982). The HERMES system is also being used to develop techniques for deriving high-resolution products from AVHRR (Advanced Very High Resolution Radiometer) imagery, such as fog and cloud-type analyses as well as surface temperatures. The dynamical approach, which is under development in the Meteorological Office Forecasting Research Branch (Golding 1984), lends itself to forecasting a wider range of elements. The output of both forecasting methods can be refined for particular applications either by subjective interpretation or the use of statistical methods (e.g. model output statistics).

The basis of the nowcasting approach is for the evolution of meteorological fields to be monitored closely and for the future state to be derived by assuming the current patterns will continue to move in the same way essentially without development or decay. Very detailed site-specific forecasts can be derived using this approach but their accuracy falls off rapidly with forecast period. The use of the term nowcasting underlines the heavy dependence on the description of the current situation.

The dynamical method uses a primitive equation model with a horizontal grid length of about 10 km which is initialized using a combination of forecast fields from a model of lower resolution and recent observational detail from a variety of sources. These inputs are reconciled by means of a process of near-continuous assimilation. The resulting mesoscale forecasts have the great advantage that they take into account development and decay. Compared with the nowcasts, however, they suffer from being based on less recent data and also from a degradation in spatial resolution. The smallest scale that can be properly represented is about 40 km except perhaps when topography exerts a strong influence.

The products generated by the nowcasting approach can be expected to be superior for forecast periods of, for example, zero to four hours, because they are better able to represent the actual fine-scale variability (which in the case of precipitation can be very great). For longer periods development and decay become important and the products of the dynamical approach should then become superior. Thus it is not a question of either the dynamical or the nowcasting method being superior to the other — they are complementary. The break-even point of four hours, mentioned above, is not well defined: we might expect it to be as much as six hours in some frontal situations, for example, but less than two hours in situations of rapidly evolving thunderstorms especially where topography has an important effect. Thus one of the tasks when generating a local forecast for a few hours ahead will be to choose between or reconcile the guidance produced by these two methods. It is important, therefore, for the forecaster to be provided with the necessary facilities to be able to display, compare and combine these two sets of central guidance.

2.3 *The work station concept*

The need for the forecaster to combine or compare multiple data sets, including their evolution, arises in a number of contexts. One will arise centrally where conventional, satellite and radar data need to be analysed together (i) to produce the nowcasts and (ii) to initialize the mesoscale model. The other, just discussed, is where a forecaster needs to reconcile the two sets of central guidance that have been derived in different ways in order to prepare user-specific forecasts.

There is thus a general need to combine diverse data sets. Large sets of data have to be manipulated and this has to be done very rapidly under the control of forecasters. It is our view that this should be achieved using digital data sets displayed on interactive video displays — so-called work stations. The common element in the design of all meteorological work stations is that they should enable the data streams to be combined, action replayed and amended on a common scale and map projection. By means of modern man–machine interface techniques the forecaster can analyse the merged products, operating directly on the data base, using a light-pen or his finger on a touch-sensitive television screen much as he would a pencil or rubber on a plotted chart.

It will be possible, given an appropriate local processor, to implement various automatic procedures for the more routine tasks, e.g. objective analysis and extrapolation. However, the incomplete nature of the data sets is such that the forecaster is almost always likely to be in the position of needing to refine the products subjectively in important areas. In doing so he might be aided by computer-archived climatological statistics or diagnostic packages, but his selection of the appropriate supporting information will depend on his understanding of the physical/dynamical mechanisms at work in the atmosphere as well as on the particular demand he has to satisfy.

The idea behind the work station, in a nutshell, is to simplify the routine chores of basic data manipulation so that the forecaster is given maximum opportunity to exercise his judgement within the context of what is otherwise a highly automated system. It provides the forecaster with the tools so that he can respond to the customer's requirements with the maximum effectiveness which the science and technology will allow.

2.4 *Machine-assisted tailoring*

A weakness of the present outstation forecasting system is that the forecaster has to spend too much time carrying out the routine aspects of the work needed to tailor the products to the formats required by the customer. An advantage of the work station approach is that, by having all the working data in digital form, the analyses and forecasts that the forecaster generates on the monitor screen are ready to be tailored and disseminated automatically. Part of the continuing role of the forecaster will be to provide the appropriate emphasis for the user and an indication of confidence in the product. In some circumstances products can be provided direct to the user in predetermined formats. Given sets of hourly forecast fields derived using the work station, it would, for example, be possible for 'point' forecast sequences to be generated and disseminated automatically for an array of small sub-areas within the whole forecast domain. It would also be possible for forecasts for non-standard locations, or along flight tracks, to be generated automatically in response to the forecaster pointing to the appropriate locations on the monitor screen.

2.5 *Modern dissemination methods*

Very-short-range forecasts are by their very nature highly perishable: they must be disseminated promptly if they are not to lose their value. Advances in information technology and particularly in telecommunications now offer the means for rapid dissemination and also new methods for presenting the material conveniently to the user. In some cases dissemination may be by direct computer-to-computer link to the data user's control system. In many cases, however, the user will find it convenient to have a visual presentation of the information. One approach is to use high-speed dedicated lines to colour-monitors and other displays at outstations as mentioned in the Introduction. Another approach, appropriate to customers requiring only intermittent access to specific information, would be to use a viewdata system. The British Telecom viewdata system, Prestel, suffers in its basic form from poor resolution and the requirement for a specially modified television set. However, with one of the telesoftware schemes now available, a user may, by making a local telephone call to the Prestel data base, receive and display on an unmodified domestic television set both textual and pictorial data having good resolution. To do this, all he needs is a low cost modem and a personal microcomputer of a kind now commonplace in homes and offices.

It is clear that information technology is opening up all sorts of creative marketing opportunities — opportunities for adding value and for aiming the product at different market sectors. Access to different parts of the data base would be controlled through a system of 'closed user groups'. Each time a page of information is accessed a charge would be automatically levied by the information provider. The automatic tally of the usage of different pages could be stored in the management and accounting information system and would be readily available for market research. Market research will become more important with the availability of increasingly flexible methods of deriving and delivering tailored products.

3. New mesoscale facilities within the context of the Meteorological Office Central Forecasting Office (CFO)

3.1 *Overview*

In CFO at present two numerical models provide guidance to the forecaster — the fine-mesh and coarse-mesh models. Neither of these is capable of representing mesoscale phenomena, although the fine-mesh model is an improvement over earlier models in its ability to predict synoptic-scale features. During the next few years mesoscale products may become available from the mesoscale model, FRONTIERS, and HERMES-type facilities so as to extend the central guidance on the mesoscale. The central forecasting facilities would then be as shown in Fig. 1. When these new facilities are fully

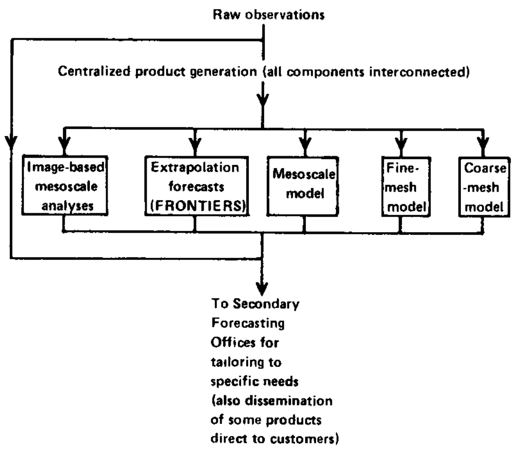

Figure 1. Central Forecasting Office facilities.

operational CFO will be capable of generating an impressive range of guidance, covering a variety of weather elements over a wide range of scales as summarized in Table I. The main preoccupation of CFO will, however, continue to be with large-scale phenomena and, although a limited number of mesoscale products may be disseminated directly to end-users, the mesoscale guidance is likely to be used mostly by

Table I. *List of products capable of being generated centrally*

		Nowcast products			Dynamical products		
		HERMES-type analyses		FRONTIERS analyses and extrapolation forecasts using Meteosat and radars†	Mesoscale model†	Fine-mesh model	Coarse-mesh model
		from NOAA TOVS†	from NOAA AVHRR†				
Parameters		temperature humidity	cloud fog surface temperature	precipitation cloud	temperature wind cloud precipitation	pressure wind temperature precipitation	pressure wind temperature
Spatial resolution (km)	analyses	75 or better	1	5	10	75	150
	forecasts			20	30	75	150
Area of coverage		N Atlantic and Europe	British Isles	British Isles	British Isles	N Atlantic and Europe	global
Period of forecasts (hours)				1–6	3–18	6–36	12–144
Interval of forecasts (hours)‡				1	1	6	12
Availability after data time (hours)	analyses	$T+1$	$T+1$?	$T+\frac{1}{3}$*	$T+1$		
	forecasts			$T+\frac{2}{3}$	$T+2\frac{1}{2}$	$T+3\frac{1}{2}$	$T+6$
Interval (hours) between issue of new products	analyses	6	6	$\frac{1}{2}$*	1		–
	forecasts			$\frac{1}{2}$	6	12	12

*Less for raw radar composite data
† The mesoscale components of the forecasting system
‡ i.e. interval between validity times of successive members of a series of forecasts made from the same data

the network of Secondary Forecast Offices (SFOs) to which it is distributed. The SFOs may have regional responsibilities, as at Weather Centres, or they may serve specialized interests such as at RAF airfields; however, in this paper we shall use the term SFO for generality. The main role of the SFOs is to refine and tailor the central guidance for specific customers.

Internally, within CFO, the various components shown in Fig. 1 will need to interact with one another. Thus the coarse-mesh model supplies boundary conditions for the fine-mesh model, and the fine-mesh model for the mesoscale model. The mesoscale model in turn will help in the derivation of extrapolation forecasts obtained by FRONTIERS, whilst products from FRONTIERS and HERMES will help in the initialization and updating of the mesoscale model. Sounding products from HERMES will probably be used both to initialize the fine-mesh model and to help in the interactive analysis for the mesoscale model as discussed later. All this calls for an advanced local communications network at Bracknell and multiple facilities for man–computer interaction within CFO so that forecasters can exercise judgement concerning the manner and extent to which each of these products is permitted to influence the other. The nature of the forecaster's interaction varies from the limited subjective quality control and 'bogusing' of observations currently practised for the coarse- and fine-mesh models to a very high degree of interactive analysis as required for FRONTIERS and for the mesoscale model.

3.2 *FRONTIERS nowcasting facilities within CFO*

Details of the FRONTIERS system are given by Browning and Carpenter (1984). In brief it is an interactive system by means of which a forecaster can blend data from a network of weather radars and Meteosat, in the light of other information, so as to generate frequent analyses and forecasts of the precipitation distribution. FRONTIERS is being developed for use as a central facility so that forecasters expert in radar and satellite meteorology can come to grips with the unusual error characteristics of radar and satellite data. The intention is that a forecaster at a SFO using guidance produced by FRONTIERS would not have to worry unduly about the peculiarities of the observing techniques but would instead receive quality-controlled analyses and forecasts of precipitation.

The main characteristics of the FRONTIERS guidance are summarized as part of Table I. A precipitation actual plus a set of forecasts could be generated every half-hour and distributed as images for display on a colour monitor according to the schedule given in Table II.

Table II. *Half-hourly interactive cycle for FRONTIERS*

Minutes past each half-hour	
0	Data time
<10	Precipitation data received from network of radars
10–20	Analysis and quality control of radar data
20	Possible dissemination of quality-controlled precipitation actual
20	Meteosat imagery received
20–30	Meteosat imagery interpreted in terms of precipitation by a combination of objective and subjective analyses and then combined with radar data to extend coverage
30–40	Extrapolation forecasts generated by a combination of objective and subjective methods
40	Dissemination of precipitation (and cloud) forecasts

In addition to this half-hour cycle, radar composites may continue to be available at 15-minute intervals, within about 5 minutes of data time but without the benefit of FRONTIERS quality control.

The data from radar and Meteosat are particularly well suited to very-short-range forecasting because of their frequency: every half-hour or better. Data from polar-orbiting NOAA satellites are available at only six-hour intervals (assuming two satellites) but nevertheless they are useful for mesoscale forecasting because of their ability to produce very high spatial resolution imagery for identification of cloud type and fog (from AVHRR imagery) and mesoscale resolution soundings (from TOVS).

3.3 *The mesoscale model within CFO*

Details of the structure of the model are given in Golding (1984). It is planned that the model shall cover mainland Britain and Ireland using a grid length of 10 km. With the model covering such a small area, the effects of boundary conditions will quickly become important. The forecasts will, therefore, be restricted to periods of up to about 18 hours and will have to be repeated at frequent intervals. A satisfactory arrangement may be four model runs per day. The timing of such runs will depend partly on the user requirements. It is also necessary to devise a cycle which fits into the cycle of other operational forecasts and at the same time benefits from up-to-date inputs from the fine-mesh model. A possible schedule is shown in Table III, according to which, mesoscale model guidance would reach SFOs at about 0230 GMT, and again at 0830, 1430, and 2030 GMT.

An essential part of the mesoscale model operational cycle in Table III is the hourly interactive analysis, each analysis being followed by a one-hour model forecast to provide a first guess for the next hourly interactive analysis etc. A forecaster working with the computer through a graphics display will produce analyses for the whole of the British Isles for a wide range of variables using mainly surface observations together with radar and satellite images from FRONTIERS and the HERMES soundings.

Table III. *Six-hour operational schedule for mesoscale model*

Time (GMT)	
0000	
0030	Interactive analysis of 0000 data
0100	Run forecast from 0000 to 1800
0130	Interactive analysis of 0100 data
0200	Check forecast results, 0000 to 1800, and start dissemination
0230	Interactive analysis of 0200 data
0300	
0330	Interactive analysis of 0300 data
0400	
0430	Interactive analysis of 0400 data
0500	
0530	Interactive analysis of 0500 data

The analysed variables will include surface pressure, temperature, humidity and wind; precipitation intensity; layer and convective cloud amounts, bases and tops; and visibility. In short, the end product of each interactive analysis will be a detailed picture of the weather over the whole country. Objective analysis schemes will be employed but the forecaster should be able to exploit his judgement, e.g. to incorporate discontinuities in mesoscale fields inferred from radar and satellite imagery. Although carried out for the purpose of initializing the mesoscale model, these interactive analyses will be a valuable input in their own right to the work of the Senior Forecaster in CFO and will be a natural development of the advice currently given to him by the British Isles Forecaster in CFO.

In the hourly schedule in Table III only half an hour has been allocated to the task of interactive analysis. Clearly, therefore, the interactive dialogue will have to be developed carefully so that the forecaster can contribute as much as possible in that time. This development will be undertaken on a powerful interactive graphics system which is being acquired in 1985. One can expect that the steps involved in the interactive procedure will resemble those in Table IV. For each step the computer will highlight the areas that need attention, e.g. by comparing observations with first-guess fields to show up suspect reports, or comparing analyses against observations to show where the analysis has failed to fit the observations.

The interactive analyses, in addition to providing the initialization for the forecasts, would provide a check on the last forecast issued. If substantial deviations are noted, the fields might be updated and the resulting revised forecasts disseminated again. In such circumstances, the forecaster would have little time to make detailed amendments and might simply have to blank out parts of a field. At some times of the day it might be possible to rerun the numerical forecast if the error became sufficiently serious.

The mesoscale model output will initially be used in CFO as additional guidance in the preparation of regional forecasts for the Synoptic Review*. The full usefulness of this guidance will not be realized,

*A review of the expected weather for the United Kingdom, and the associated synoptic development

Table IV. *Hourly interactive analysis cycle for mesoscale model*

Minutes past each hour		
00–20	Observations received; computer forecasts first guess for analysis using analysis for previous hour	
20–50	Interactive analysis:	(a) Quality control observations
		(b) Objective analysis
		(c) Modify objective analyses by comparison with station observations, imagery and other analyses
		(d) Objective transformation to model variables
		(e) Selective checking of model fields near key observations especially where imagery implies discontinuities or soundings give vertical structure
50–60	Dissemination of analyses, warnings, etc.	

however, until it is available at SFOs where the information can be refined and tailored to the needs of the customers. In principle, the model is capable of forecasting a wide range of variables including, as already noted, visibility, wind, temperature, rain, height and type of cloud layers, and also turbulence. The vertical resolution is such that information on temperature, wind and moisture could, for example, be presented at five levels below 1 km. This amounts to a lot of data and it will be important, therefore, to consider the form in which these products might be made available to the SFOs. The quantity of data distributed may be reduced by degrading the resolution. Although the full resolution of the analyses will be useful, much of the detail at individual grid points of a forecast will be spurious. Thus the forecast resolution can probably be degraded to about 30 km without loss of significant detail.

4. New mesoscale facilities required within Secondary Forecasting Offices

4.1 *Nature of the requirement*

The task of the outstation forecaster at a SFO is to take the centrally-generated guidance and use it selectively to provide forecast products for specific areas, variables and applications. This involves him in three categories of activity:

(i) *Selecting* the products appropriate to his needs (thus, for example, for some applications he may choose to use the FRONTIERS rainfall forecast for 2 hours ahead without modification, whilst for another application he may use the mesoscale model forecast of temperature 12 hours ahead without further analysis).

(ii) *Modifying* aspects of the central guidance to provide an improved product for a specific requirement (thus, for example, if he requires a forecast of cloud base for two hours ahead, he may need to carry out a combined analysis reconciling the FRONTIERS product, mesoscale model products and certain surface station observations in the light of information about the local climatology).

(iii) *Tailoring* the wanted information in a format to suit the needs of the customers.

In order to facilitate performance of these tasks, new kinds of facilities are needed in the SFO. They are best regarded as a development of the Outstation Automation System (OASYS) already implemented in three offices. Both hard copy and soft copy outputs are provided by OASYS; what we believe is needed is an extension of the soft copy component. In the present OASYS system the VDU is essentially an efficient filing system enabling easy selection, display, and also action replay. The required system, in our view, will need to be a fully interactive work station of the kind discussed in section 2.3, supported by a local host computer and capable of providing facilities for combining different forms of data and for analysing them on the screen. Some experience in work station design has already been gained within the Meteorological Office with the FRONTIERS interactive display (Browning and Carpenter 1984); however, that system is narrowly focused on the nowcasting of precipitation, and so it depends mainly on radar and satellite data and only marginally on other kinds of data. The required work station system for the SFO has to be suited to a wider range of forecasting responsibilities. Similar weight has to be given to station observations, to computer-derived fields from fine-mesh and mesoscale models, and to radar and satellite data.

4.2 *A work station configuration for use at a Secondary Forecasting Office*

A possible work station configuration is shown in Fig. 2. It consists of (a) a data display panel, with three intelligent displays, and (b) an interactive analysis display. The data display panel is just a filing system with rapid access and easy viewing facilities. It enables the forecaster to have simultaneous full-size displays of selected FRONTIERS or HERMES-type products, the mesoscale or fine-mesh model

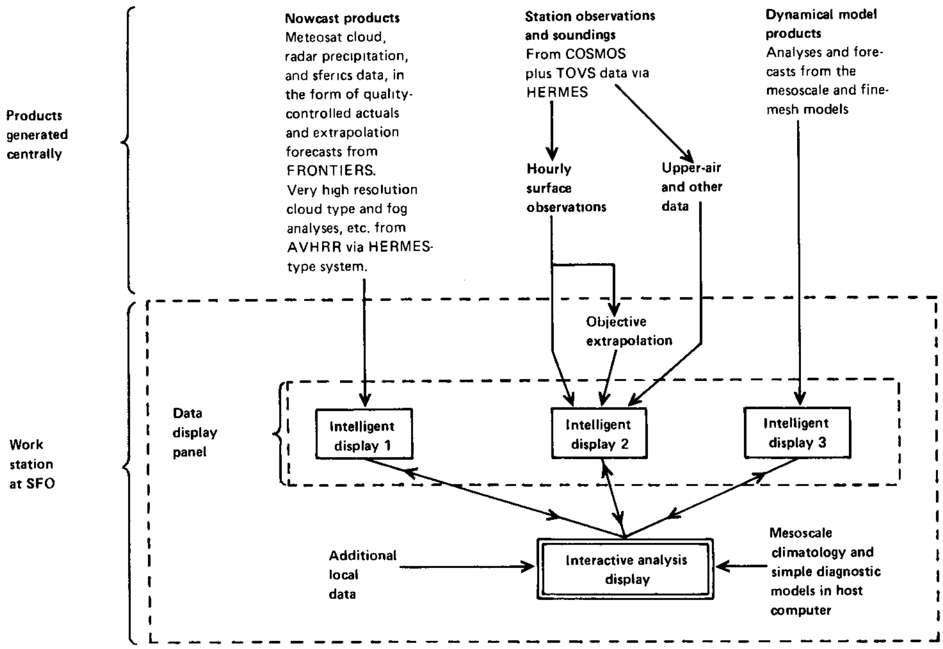

Figure 2. Secondary Forecasting Office (SFO) facilities.

products, and basic station observations, thereby enabling him to achieve a time-lapse replay of any of these whilst continuing to view the others undisturbed on the adjacent displays. The interactive analysis display enables the forecaster to combine products from the other three displays and to amend them for his purposes (whilst retaining the capability of referring to other products on the data display panel without disturbing his working display). Although the work station shown in Fig. 2 is essentially a soft copy system designed for easy manipulation of the data, limited facilities for providing hard copy will also be needed for some briefing purposes.

(a) *The data display panel*

The FRONTIERS and conventional products on displays 1 and 2 (in Fig. 2) would be available promptly within half an hour or so of data time. The mesoscale and other model products on display 3, however, would be based on older observations. Thus the outstation forecaster interested in the period about two hours ahead, say, would often be concerned to reconcile the nowcast and observational data on displays 1 and 2 with the information on display 3 which, though less up-to-date and detailed, nevertheless would have benefited from a dynamical treatment.

Each of the three displays in the data display panel would, according to our scenario, hold a sequence of charts including several actuals and hourly forecasts. In the case of displays 1 and 3 the forecasts would be based on those generated at CFO; however, for display 2 it is possible that the forecasts for certain surface variables might be derived at the outstation itself for the particular area of interest using simple objective analysis and extrapolation algorithms, and supplementing the observations from CFO with more frequent (15-minute) observations received direct from local stations. It would thus be possible to show, on display 2, sequences of actuals plus simple extrapolation forecasts for such variables as temperature, dew-point temperature, dew-point depression, pressure, gradient wind, pressure tendency, wind speed and direction, divergence, cloud base and amount, and visibility. These elements could be displayed one at a time if desired. The station observations (alpha-numerics) and fields (colours or lines) of a given element could be viewed either separately or together.

(b) *The interactive analysis display*

The set of three intelligent displays constituting the data display panel would be for monitoring purposes only and, although the outstation forecaster could interact with the system in the limited sense of selecting different frames and replays, he could not intervene directly to modify any of the fields being displayed there. To do this he would instead use the large interactive analysis display (Fig. 2). This single monitor would need to have a large number of image planes, preferably with separate brightness controls, so that any required combination of the actuals and/or extrapolation forecasts could be superimposed at any brightness level — rather like stacking charts on a light table. To select images for display and manipulation on the interactive analysis display the forecaster could simply transfer whatever frame he had called up for display on the data display panel.

Having transferred products from the data display panel to the interactive analysis display, the outstation forecaster would first compare them to establish their consistency. He might then modify the automatically-derived fields (i.e. redraw isopleths) so as to carry out the following kinds of tasks:

(i) Removing any obvious errors in the objective analysis (such as those sometimes associated with closed contours around single station reports).

(ii) Refining computer-derived fields, interactively where necessary (e.g. detailed rain and cloud patterns from radar and satellite imagery will enable the analyses of other parameters to be refined near fronts and other mesoscale features).

(iii) Adjusting for expected errors in the extrapolation forecast products as indicated by numerical model guidance or as inferred from the nowcast data themselves (e.g. the predicted arrival of a wind shift will alter the influence of local topography on cloud base etc.).

In carrying out these tasks the forecaster could be aided by mesoscale climatological information, topography overlays, etc., stored in the host computer. He could also use this computer to insert local data and to run simple diagnostic models and evaluate empirical formulae corresponding to local forecasting rules of thumb. In addition it would be helpful for him to be able to access a variety of derived products from the synoptic data base such as cross-section analyses along arbitrary sections. Finally, having carried out an interactive analysis of the kind just described, the forecaster could transfer his re-analysed chart back to the appropriate monitor on the data display panel where it would be ready for automated tailoring and dissemination according to predetermined procedures. Although the forecaster in a SFO would be concentrating his attention on refining the forecasts for specific areas and purposes, many of the tools enumerated above are similar to those needed by a mesoscale analyst in CFO; obviously these procedures must be developed in harmony.

5. Concluding remarks

What are the main problems in establishing and exploiting a system of the kind outlined in this paper? One problem is that of clarifying user needs and developing new markets. This takes on added significance with the new opportunities for greater specificity in the forecasts. Another, which will be with us into the next century, is that of obtaining better mesoscale observational inputs to the system. The challenge of extending numerical modelling down to smaller scales and to periods less than 12 hours ahead is being tackled by the current efforts with the mesoscale model. A telecommunications strategy has been agreed that will enable the required amounts of digital information to reach the outstations rapidly; however, an important bottleneck, highlighted in this paper, is the forecaster's difficult task, both centrally and in the outstations, of integrating and analysing the large data sets that already exist and which are likely to become more widely available and more extensive soon. Programs therefore should be set up in which forecasters, research meteorologists and systems designers can work together to develop and test work station practices for mesoscale analysis and very-short-range forecasting. An aspect of such programs will be to investigate the division of effort between CFO and outstations. Some tasks requiring a high degree of precision and specificity will require close customer contact and a high level of subjective interpretation to get the most out of the available guidance. Such tasks may be more appropriately undertaken at outstations. On the other hand, checking the consistency of the synoptic-scale development in different forecast products may be better done centrally.

Although an early task has to be the establishment of prototype work station facilities, a more challenging task will be that of learning how best to use them: only practical experience with using the merged data sets will tell us how to optimize the forecasting procedures. There will be a continuing need for the outstation forecaster in particular to interpret the guidance subjectively in the light of conceptual models of atmospheric behaviour. However, conceptual models now in use still owe too much to the early frontal models of the Norwegian School. Thus there is a continuing requirement to learn more about the structure, evolution and mechanism of mesoscale and synoptic-scale weather systems and their interdependence. In the long run, improvements in mesoscale forecasting are likely to be limited by meteorological understanding and our ability to interpret new forms of observational data.

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Reviews

Mesoscale meteorology — Theories, observations and models, edited by Douglas K. Lilly and Tzvi Gal-Chen. 160 mm × 245 mm, pp. x + 781, *illus.* D. Reidel Publishing Company, Dordrecht, Boston, Lancaster, 1983. Price Dfl. 220, US $88.00.

This substantial book on mesoscale meteorology forms the Proceedings of the NATO Advanced Study Institute on Mesoscale Meteorology — Theories, Observations and Models, held at Bonas, France in 1982. It comes at a time when several new books on mesoscale meteorology are appearing. In many ways it is a compromise between a conference proceedings consisting of separate papers, and an advanced textbook. The order of the original lectures has been modified by the editors in an attempt to impose a structure to the volume. Unfortunately this has not been very successful and in some places has destroyed the coherence that papers on different subjects by the same author have. As a textbook, one feels that it would have benefited if about half the papers had been left out. On the other hand some of the reviews are excessively long for the proceedings of a conference.

There are eight sections, the first of which is an introduction on scales of motion, the next six are ordered by decreasing scale, and the last is on observational technology. The attempts to 'define' mesoscale in section 1 seem to be judged by their lack of use in the rest of the book. The second section on cyclonic scale motions and prediction models is a collection of almost unrelated papers. The main one is by Buzzi and Speranza on lee cyclogenesis and contains much interesting material. Unfortunately a few of the diagrams have not reproduced well. There is no summary or conclusion so the reader has to go through all 88 pages. Two papers on initializing mesoscale models only touch the surface of the problem and could have been omitted without much loss. The third section is on fronts and has a valuable historical introduction by Sanders. However, I was disappointed to find no references in this section to the work on frontal rainbands. In section 4 a pair of papers by Emanuel gives a good theoretical introduction to symmetric instability. I would like to have seen a comparable treatment of the rest of frontal theory. The survey of cold air mass disturbances by Rasmussen is comprehensive and well illustrated. The next section on gravity waves is given a good theoretical introduction by Lilly and is followed up with some useful papers by Egger, although the first of these duplicates some of Lilly's material. It is unfortunate that Egger's paper on observations of flow in valleys which naturally follows his paper on topographic forcing was removed to the boundary layer section. The next section on buoyant convection is 250 pages in length and much the largest. A sequence of well written papers by Simpson traces the development of understanding, principally from the observational viewpoint. This is complemented in the next paper by Miller and Moncrieff who present the modeller's viewpoint. Several of the other papers in this section present valuable material but there is much duplication and little coherence. The boundary layer section also starts with two authors whose papers complement each other. Wyngaard takes an observational viewpoint while André concentrates on turbulence closure modelling. The remaining papers here are again rather disconnected and duplicate these first two. The final section on observational technology seems quite out of place. For instance, one feels that a discussion of the theory of wind retrieval from a Doppler radar is hardly relevant without some indications of how the results may be used.

To summarize: there is much valuable material in this book for both newcomer and established researcher in the field of mesoscale meteorology. However, the opportunity has not been taken to produce a textbook from the material and so, as with any conference proceedings, the reader will have to search for what he wants.

B. W. Golding

Hydrology in practice, by Elizabeth M. Shaw. 150 mm × 215 mm, pp. vii + 569, *illus.* Van Nostrand Reinhold Company Ltd, Wokingham, 1983. Price £18.50 (cloth), £9.75 (paper).

This book represents the culmination of the author's long career as a lecturer and researcher in hydrology. It has been primarily written as an introduction to the subject for undergraduate students of civil engineering and environmental sciences. Its scope is very widespread and, whilst presented from a British viewpoint, is set in a global context.

The book opens with an introductory chapter on the hydrological cycle and basic hydrometeorology. The remaining chapters are then grouped into three sections under the general headings: 'Hydrological measurements', 'Hydrological analyses' and 'Engineering applications'. The first section begins with the design of hydrometric networks and then goes on to describe the various methods available for measuring precipitation, evaporation, soil moisture, river and ground water flow, and water quality. The final chapter in the section deals with the processing of hydrological data; in particular that of rainfall and river flow. It is unfortuate, however, that the description given in this chapter of the Meteorological Office rainfall quality-control program actually refers to the version used prior to 1976. Readers who are interested in knowing about the methods currently being used by the Meteorological Office should refer to *Meteorological Magazine*, **104**, 102–108 (Computer quality control of daily and monthly rainfall data, by R. J. Shearman, 1975).

The second section covers the analytical treatment of hydrological data and includes chapters on precipitation and river flow analyses dealing with the fitting of frequency distributions and the calculation of exceedance probabilities from extreme-value statistics. This section also includes rainfall run-off relationships, catchment modelling and the use of time-series analyses. In addition there is a chapter on calculations of evaporation and soil moisture deficit which includes an explanation of the Meteorological Office Rainfall and Evaporation Calculation System (MORECS). Whilst the current operational model of MORECS is described in principle the model did undergo a few modifications whilst the book was in its final stages of preparation. For specific details readers should see *Hydrological Memorandum No. 45*, Meteorological Office, Bracknell (The Meteorological Office rainfall and evaporation calculation system: MORECS (July 1981), by N. Thompson, I. A. Barrie and M. Ayles, 1981).

The final section describes the application of hydrological analyses in the field of civil engineering. This includes chapters on flood routeing, design floods, urban hydrology and the management of river basins and water resources.

In order to cover a large portion of what is a vast subject the author has in general restricted herself to giving an overview of the various facets of hydrology rather than detailed discussions. However, for the reader who wishes to follow up particular aspects in greater depth references are provided at the end of each chapter, although in some cases these are rather too few in number.

This book should nevertheless prove a useful aid to anyone whose work requires a knowledge of hydrology and provides a useful introductory guide to the subject.

A. P. Butler

Books received

Energy at the surface of the earth: an introduction to the energetics of ecosystems, by D. H. Miller (New York, London, Toronto, Sydney and San Francisco, Academic Press, 1981. £14) is volume 27 in the International Geophysics series and presents one way of looking at the manner in which the biological, physical and cultural systems enable the land masses of our planet to receive, transform and give off energy. The first part of the book deals with the radiant energy absorbed by ecosystems; the fulcrum chapter deals with the raising of surface temperature from the increase of such absorption and is followed by chapters on temperature-dependent fluxes of energy. The final chapters are concerned with vertical stratification and areal contrasts in energy budgets, the augmented energy budgets of the city, and the responses that serve to keep the budget balanced.

Chemistry of the unpolluted and polluted troposphere, edited by H. W. Georgii and W. Jaeschke (Dordrecht, Boston and London, D. Reidel Publishing Company, 1982. Dfl 145) is the Proceedings of the NATO Advanced Study Institute held on the island of Corfu, 28 September - 10 October 1981. The introductory Part I presents the problems and methods of measuring trace gases and aerosols; this is followed in Part II by the influence of the thermodynamic structure of the atmosphere on the transport and distribution of trace compounds and the interactions between trace compounds and climate. Part III deals with atmospheric cycles of some trace elements and compounds, Part IV with the fact that the troposphere is not a homogeneous gas phase, and Part V is concerned with the problems of pollution.

General hydrogeology, edited by E. V. Pinneker (Cambridge, London, New York, New Rochelle, Melbourne and Sydney, Cambridge University Press, 1983. £22.50) is from the Cambridge earth science series and is a translation by D. E. Howard and J. C. Harvey of a book originally published in Russian in 1980. The introductory section consists of the subject matter of hydrogeology, its definition as a science, an historical review and a discussion of terminology. The circulation of water in the earth and a description of ground water-bearing systems, distinguished according to the manner in which they are deposited, is then given. The book ends with chapters dealing with the features of hydrogeothermics and regional hydrogeological laws.

Severe and unusual weather, by Joe R. Eagleman (New York, Cincinnati, Toronto, London and Melbourne, Van Nostrand Reinhold Company, 1983. £22.50) is divided into three parts. The first includes, amongst others, frontal cyclones, blizzards and thunderstorms, and acquaints the reader with the nature of such events. The second part considers floods and droughts, in the main, and the final part weather simulation and management.

Sunsets, twilights and evening skies, by Aden and Marjorie Meinel (Cambridge, Cambridge University Press, 1983. £17.50, US $29.95) is a lavishly illustrated book describing twilight effects in the atmosphere for the general reader. It is the fruit of the authors' many years of personal experience and unites science and aesthetics in describing and explaining a subject of intrinsic beauty. Among the many topics covered are the earth's shadow and sunset phenomena, volcanic eruptions and twilights, zodiacal light and the aurora.

Award

We are pleased to record that Emeritus Professor H. H. Lamb of the University of East Anglia has been awarded the 58th Vega Medal of the Swedish Geographical Society. Professor Lamb was presented with the medal by Princess Christina of Sweden in Stockholm in April.

The Vega Medal, for significant contributions to geographical science, was first awarded in 1881 to Nordenskiöld, leader of an expedition with the SS *Vega* in 1878–79 through the North East Passage to the Pacific. Previous recipients include Nansen, Amundsen, Scott and Shackleton among explorers, and L. Dudley Stamp, Jacob Bjerknes and T. Bergeron among geographers and meteorologists. The citation recognizes Professor Lamb's 'pioneering contributions to the history of climate variations and their dependence on changes in the general atmospheric circulation'.

After more than 30 years' service in the Meteorological Office Professor Lamb left Bracknell at the end of 1971 for Norwich to direct the new Climate Research Unit that had been set up at the University. His many friends and ex-colleagues in the Office will wish to add their congratulations to the many others he has doubtless received.

THE METEOROLOGICAL MAGAZINE

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NOTICE

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A long time-series verification of hindcasts from the Meteorological Office wave model archive

By I. Houghton

(Coventry (Lanchester) Polytechnic)

Summary

Wave height data from the Meteorological Office fine-mesh wave model hindcast archive are compared with measured wave data at three stations in the west of Great Britain. The results are discussed with time series and graphs of error statistics.

1. Introduction

The purpose of this study was to compare some products of the Meteorological Office wave forecasting model (Golding 1983) with instrumentally measured wave data. The archived model data are available for a period of nearly five years, 1 January 1978 to 26 September 1982. During this time the model was being continually improved and the principal dates in its development are given in Table I. Since 26 September 1982 the model has been transferred from the IBM 360/195 computer to run operationally on the Cyber 205 machine. At the same time the computation grid length was decreased from 50 km to 25 km and the atmospheric forecast model which provides the basic forecast winds was also improved.

Insufficient real-time measured wave data are available, hence a hindcast technique is used in place of a wave analysis in the operational cycle. It is these hindcasts of sea state that comprise the archive. A hindcast is started from a wave field generated at *T*-12, using winds from an atmospheric forecast made 12 hours earlier. These winds are adjusted using pressure analyses every 6 hours and wind analyses every 3 hours. This process gives the best available estimate of the actual wind conditions during the past 12 hours. The accuracy of the archived hindcasts depends on the accuracy of the hindcast winds and on the predicting skill of the wave model itself. For the purpose of this study the winds are assumed to be adequately represented, and therefore any errors identified will be attributed to the wave model prediction processes.

All data sources used are in the west of Great Britain and thus consist of wind-sea and Atlantic swell components. The swell contribution may have, in reality, been generated outside the fine-mesh grid area and would be specified as boundary conditions derived from a forecast run of the coarser-mesh Atlantic wave model. For this reason the model swell contribution may be of poorer quality than the wind-sea.

Table I. *Principal dates in the development of the wave model*

Date	Development	Effect
18/07/78	Surface wind analysis introduced	Better hindcast winds
26/09/78	Shallow-water friction term introduced	Lower wave heights in shallow water
23/10/79	Wave growth includes JONSWAP spectrum	More realistic wave growth
	11 frequencies	Higher-resolution wave spectrum
18/03/80	Dissipation coefficient increased	Greater attenuation of swell and slower wave growth
14/04/81	Modification of archived spectrum representation	More accurate storage of high-frequency wave energy components

2. The measured data sources

Instrumentally measured data were supplied by the Marine Information and Advisory Service (MIAS) of the Institute of Oceanographic Sciences (IOS). Three sites were used: Isles of Scilly waverider buoy, South Uist waverider buoy and St. Gowan light-vessel shipborne wave recorder. Locations are as shown in Fig. 1. A fourth site at Channel light-vessel was rejected because of possible errors in the data caused by marine fouling of the recording instrument. The periods of data availability are shown in Table II.

Archived model data are available only at 00 and 12 GMT; measured data are available every three hours on average although not always on the hour.

The IOS data are considered reliable, as quality control is exercised on all data that enter the MIAS data banks.

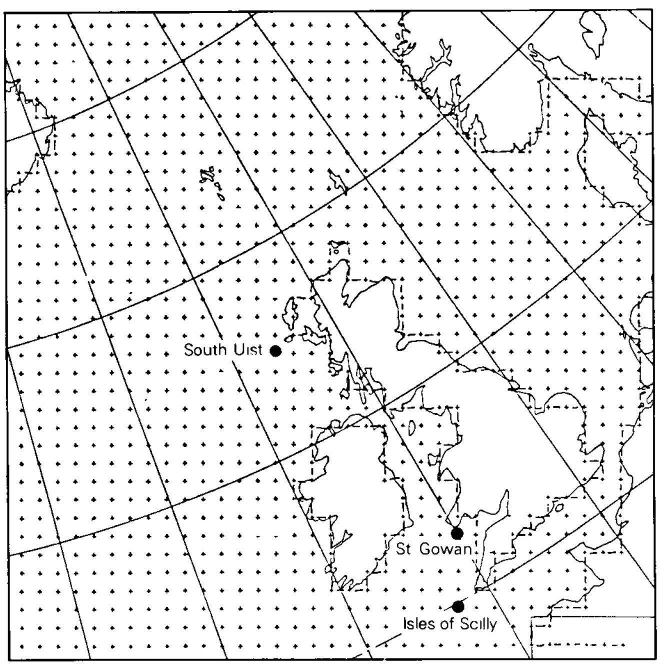

Figure 1. Grid points of the fine-mesh wave area and sites used in this study.

The wave forecast model is based on a polar stereographic grid and data are available only at these grid points. The positions of the instrument sites and corresponding model grid points are given in Table III.

As noted above, two sites used waverider buoys (WRB) to measure wave height while the third used a shipborne wave recorder (SBWR). The WRB contains an accelerometer which measures the vertical displacement of the buoy and records the variability of the surface elevation about the mean sea level. The SBWR uses two pairs of accelerometer and pressure units which are situated one on each side of the ship approximately on the pitch axis. For wavelengths longer than the length of the ship the SBWR measures vertical displacement like the WRB. For wavelengths shorter than the length of the ship the pressure units record variations in pressure as the waves pass.

Work has shown that there are differences in the results of these devices (Graham *et al.* 1979). On average the SBWR measures wave heights as 8% higher than the WRB. The percentage is greater for low waves and smaller for high waves; indeed heights measured by SBWR can be as much as 14% greater than heights measured by WRB for 1 m waves.

Table II. *Dates of available data and periods used at each site*

Site	Period of available data	Period used
Isles of Scilly	11/02/80 - 31/12/81	02/80 - 12/81
South Uist	15/08/80 - 31/12/82	08/80 - 01/82
St. Gowan	01/01/77 - 31/12/81	01/78 - 12/81

Table III. *Positions of sites and of corresponding model grid points*

Site	Site position	Grid-point position
Isles of Scilly	49°51.8′N 06°41.0′W	49°54′N 06°18′W
South Uist	57°17.8′N 07°53.6′W	57°24′N 08°06′W
St. Gowan	51°30.5′N 04°59.8′W	51°24′N 05°00′W

3. Analysis of data

At each site time-series plots of wave height for each month were drawn by computer, each plot comparing model and instrumentally measured data. Before input into the graph-drawing program the record times of the measured data were converted to the nearest hour. Initially all data were used to produce the time-series plots and these showed considerable fluctuations in the measured time series between data points on the model time series (see Fig. 2). These fluctuations can be masked if only measured data with record times within an hour of model data points are used; this can be seen in Fig. 3.

The model archive does not purport to represent wave heights at times other than 00 and 12 GMT, so the latter time series offers a better comparison; however, as the first time series shows, the wave field is changing on a much smaller time scale so it will be of use to consider both representations of the measured time series.

Various statistics were also produced at each site; for these only data with coincident record times were used. As the statistics were compiled on a monthly basis this procedure reduced the number of observations to a maximum of 62 and any month with fewer than 20 observations was rejected. The main outcome of these statistics is shown as plots of mean and root-mean-square (r.m.s.) error for each month and graphs of mean and r.m.s. error against mean observed height.

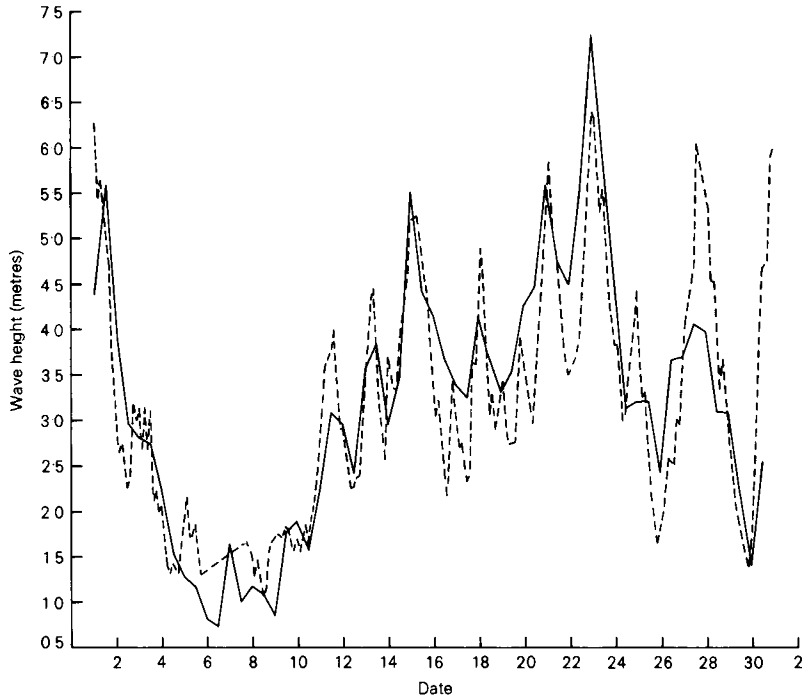

Figure 2. Time series of wave heights at South Uist for November 1980, using all data. ——— model data – – – – measured data

4. Results

Considering first the plots of r.m.s. and mean error (Figs 4(a), (b) and (c)), it can be seen that for the periods shown all sites have a monthly mean error of less than 1 m while for South Uist and the Isles of Scilly it is less than 0.4 m.

An interesting feature to note at the St. Gowan site is that the sign of the mean error changes from being mainly positive to mainly negative after October 1979. The exact time of the change cannot be found because instrumental data are not available for the whole of the period in question. There were, however, a number of major wave-model changes implemented around that time.

These changes were designed to modify the wave-growth curve and the effect was to lower wave heights for high wind speeds and short fetches. The fetch at St. Gowan in a westerly direction is approximately 200 km and for low wind speeds (e.g. 10 m s^{-1}) the modelled waves from this direction become fully developed both before and after the change in formulation, so there was little effect on low waves because of this change.

From Fig. 5, which depicts dimensionless growth rate as a function of dimensionless fetch, it can be shown that significant wave height, H_s, = 6.9 m for a 20 m s^{-1} wind over 200 km in the pre-October 1979 model. Also from Fig. 5 it can be shown that H_s = 4.9 m for a 20 m s^{-1} wind over 200 km in the post-October 1979 model. So at high winds (high waves) the change in the model should be manifested by a drop in modelled wave heights of about 1 or 2 metres. This fact explains an anomalous previous verification exercise for data from Kinsale Head (51° 30′N, 7° 55′W) and suggests that short-fetch wave growth is too low in the post-October 1979 model, even though it now agrees well with results from the

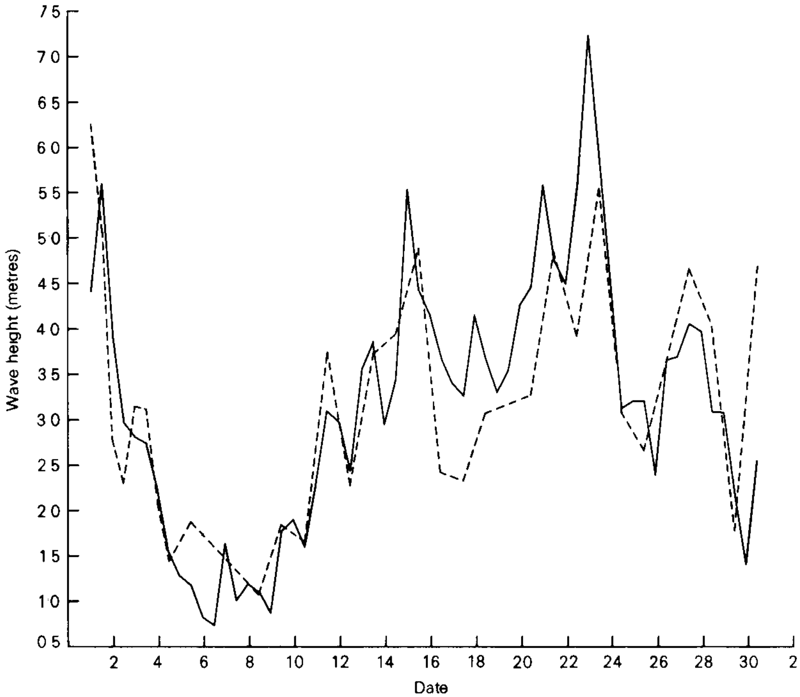

Figure 3. Time series of wave heights at South Uist for November 1980, using only data for 00 and 12 GMT. ——— model data – – – measured data

Joint North Sea Wave Project (JONSWAP), which measured wave growth in the North Sea (Hasselmann *et al.* 1973).

There seems to be some seasonal variation in mean error at St. Gowan but not at the Isles of Scilly and South Uist (Fig. 4(c)). This variation takes the form of smaller errors in 'summer' and larger errors in 'winter'. An associated relationship is found in the plots of mean error against mean observed wave height for St. Gowan (Fig. 6(c)). These show a roughly linear relationship before the change in October 1979, with large wave heights associated with high positive mean errors and a similar linear relationship after October 1979 but with large wave heights associated with large negative mean errors. These relationships are explained by the representation of low waves not being affected by the modelling change while the modelled high waves were greatly reduced in short-fetch situations.

This diagnosis can be further confirmed by considering two months (June and October 1981) at St. Gowan. June has a small mean error while October has a large negative mean error. Analysis of the wind direction for these months reveals the distribution shown in Table IV. When the wind direction is between north and west, St. Gowan is sheltered by Ireland and waves have only a short fetch, and are mostly high-frequency wind waves. For wind directions between south and west, waves have a long fetch and are mainly low-frequency Atlantic swell. In winter the wind is mainly from the sector from north to west, giving shorter fetches.

This wind distribution therefore explains the seasonal variation, with the mean error more negative in winter than in summer after October 1979 owing to under-forecasting in short-fetch conditions and the reverse applying before October 1979. Also the absence of a seasonal variation in mean error at the other

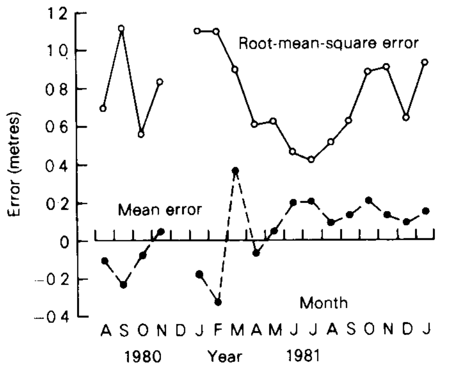

Figure 4(a). Root-mean-square and mean errors of model against observed wave height for each month at South Uist.

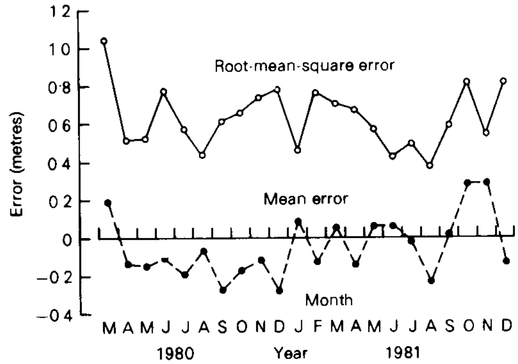

Figure 4(b). Root-mean-square and mean errors of model against observed wave height for each month at Isles of Scilly.

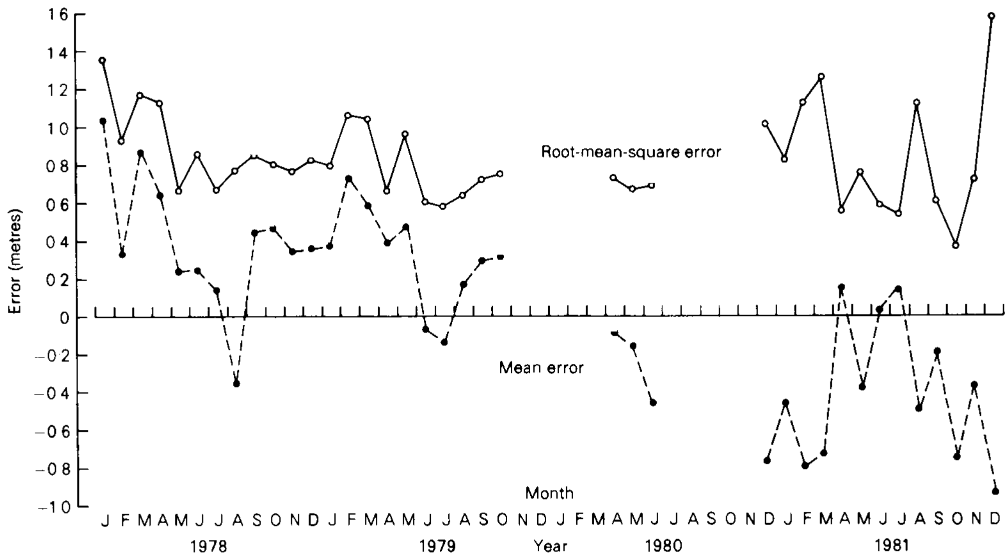

Figure 4(c). Root-mean-square and mean errors of model against observed wave height for each month at St. Gowan.

Table IV. *Number of occasions during two months when the wind was blowing from each sector at St. Gowan*

Month	Sector north-west	Sector south-west
June 1981	17	27
October 1981	27	20

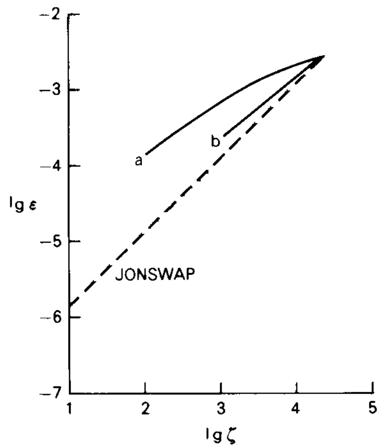

Figure 5. Dimensionless wave-growth rate (ϵ) as a function of dimensionless fetch (ζ) for before October 1979 (a), after October 1979 (b) and in the Joint North Sea Wave Project (JONSWAP).

$\epsilon = \frac{g^2}{u^4} E$, $\zeta = \frac{g}{u^2} x$ and $H_s = \sqrt[4]{E}$,

where g = 9.81 m s^{-2}, u = wind speed (m s^{-2}), E = wave energy (m^2), x = fetch (m) and H_s = significant wave height (m).

two sites (Figs 6(a), (b) and (c)) would be explained by the fact that they both enjoy a long fetch for prevailing wind directions and hence were not affected by the modelling change.

The r.m.s. errors for the Isles of Scilly and South Uist are again fairly good (Fig. 4), with those at the Isles of Scilly being mainly less than 0.8 m and those at South Uist being less than 1.2 m. St. Gowan's largest error is less than 1.6 m but in the main this site also has an r.m.s. error of less than 1.2 m.

There also seems to be some slight seasonal variation in r.m.s. error, again with smaller errors in the 'summer' and larger errors in the 'winter'. The idea that this is associated with waves in summer being generally smaller than in winter is strengthened by the plots of r.m.s. error against mean observed wave height (Figs 7(a), (b) and (c)). These seem to show an approximate linear relationship with higher mean observed waves giving higher r.m.s. errors.

Table V gives the mean and r.m.s. errors for the whole period of the verification exercise at each site.

The measured data at St. Gowan seem very variable, for example December 1978 (Figs 8(a) and (b)) compared to the other sites (e.g., Fig. 2). The period of these oscillations was checked in months with little model variability and was found to be about 12 hours. This is also the approximate time between high tides and between times of maximum current flow. Table VI gives values of current range and tidal range at each of the three sites (Hydrographer of the Navy 1961, 1969, 1978).

It is possible to estimate the effect of tidal current on wave height using Fig. 9 and an estimation of its parameters. Using the deep-water approximation for wave velocity,

$$C_0 = \frac{gT}{2\pi},$$

where $C_0 \approx 10$ m s^{-1} for typical-period waves and if $\upsilon \approx \pm$ 1 m s^{-1} from the mean tidal current velocity range at St. Gowan (Table VI), then $\upsilon / C_0 \approx \pm$ 0.1 and $0.9 \leqslant H/H_0 \leqslant 1.25$ for a typical situation at St. Gowan. The amplitude of the tidal modulation of wave height is about $0.35 H_0$ which is about 1 m when the undisturbed wave height (H_0) is about 3 m. This calculation is in reasonable agreement with the oscillations shown in Fig. 8(a) which have a period of 12 hours and an amplitude of approximately 1 m.

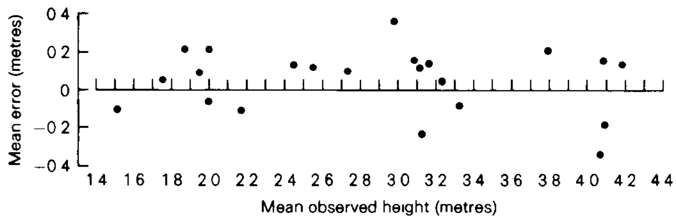

Figure 6(a). Mean error against mean observed wave height at South Uist.

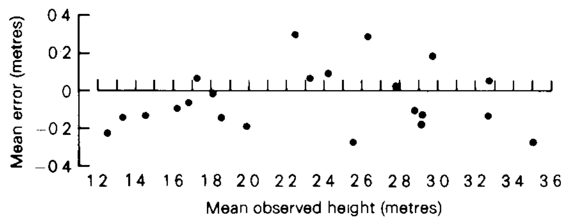

Figure 6(b). Mean error against mean observed wave height at Isles of Scilly.

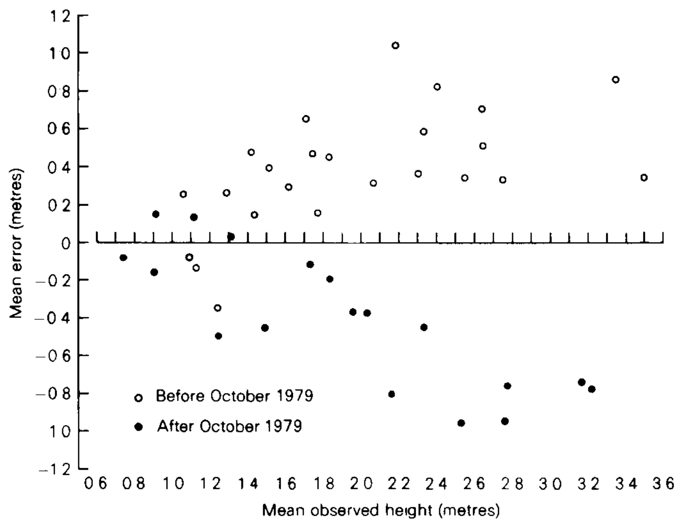

Figure 6(c). Mean error against mean observed wave height at St. Gowan.

Table V. *Mean and root-mean-square errors for each site for the stated periods*

Site	Period	Mean error (m)	R.m.s. error (m)
South Uist	02/80 – 12/81	0.05	0.73
Isles of Scilly	08/80 – 01/82	−0.05	0.63
St. Gowan	01/78 – 12/81	0.03	0.89
St. Gowan	01/78 – 10/79	0.36	0.86
St. Gowan	10/79 – 12/81	−0.38	0.93

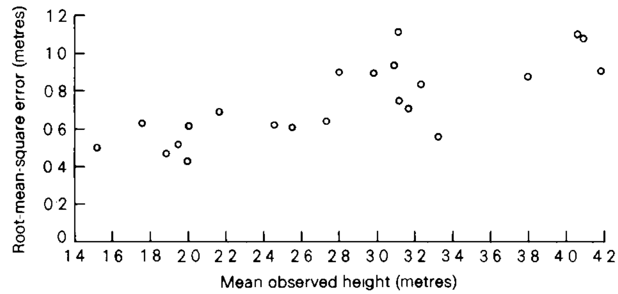

Figure 7(a). Root-mean-square error against mean observed wave height at South Uist.

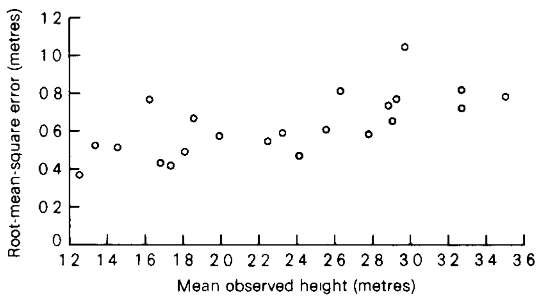

Figure 7(b). Root-mean-square error against mean observed wave height at Isles of Scilly.

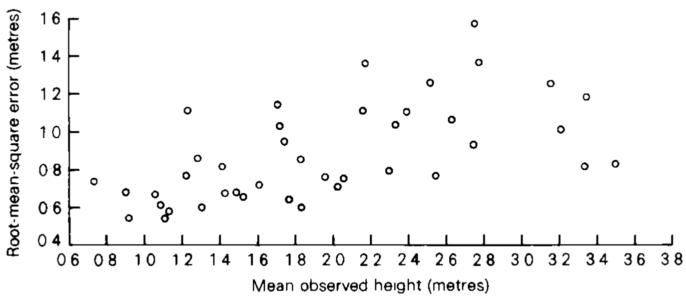

Figure 7(c). Root-mean square error against mean observed wave height at St. Gowan.

Table VI. *Values of current and tidal range for each site*

Site	Spring/ Neap	Tidal range (m)	Current in (kn)	Current out (kn)	Current range (kn)
South Uist	S	3.8	0.4	0.4	0.8
	N	1.7	0.2	0.2	0.4
St. Gowan	S	6.3	2.5	2.2	4.7
	N	2.7	1.4	1.2	2.6
Isles of Scilly	S	5.0	1.5	1.5	3.0
	N	2.3	0.8	0.8	1.6

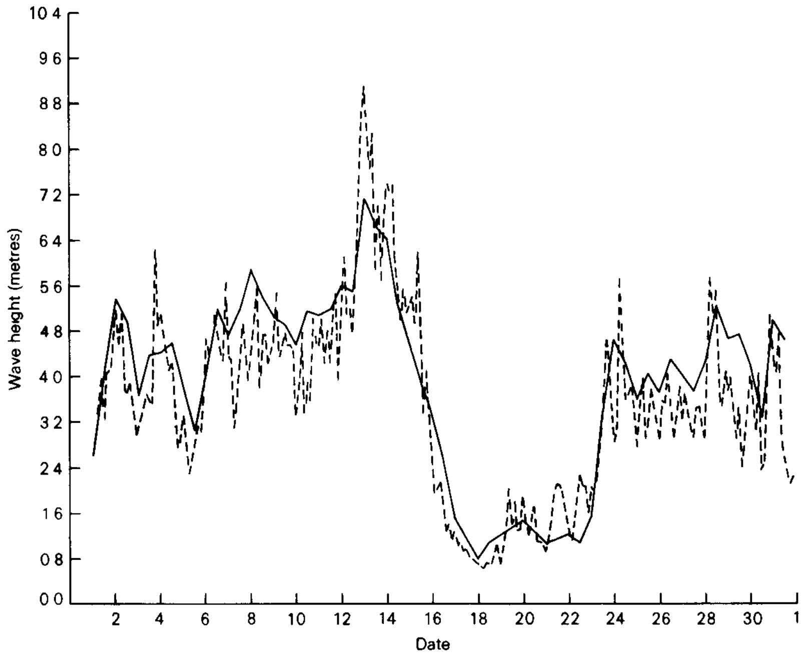

Figure 8(a). Time series of wave heights at St. Gowan for December 1978, showing great variability in the measured data.
——— model data – – – measured data

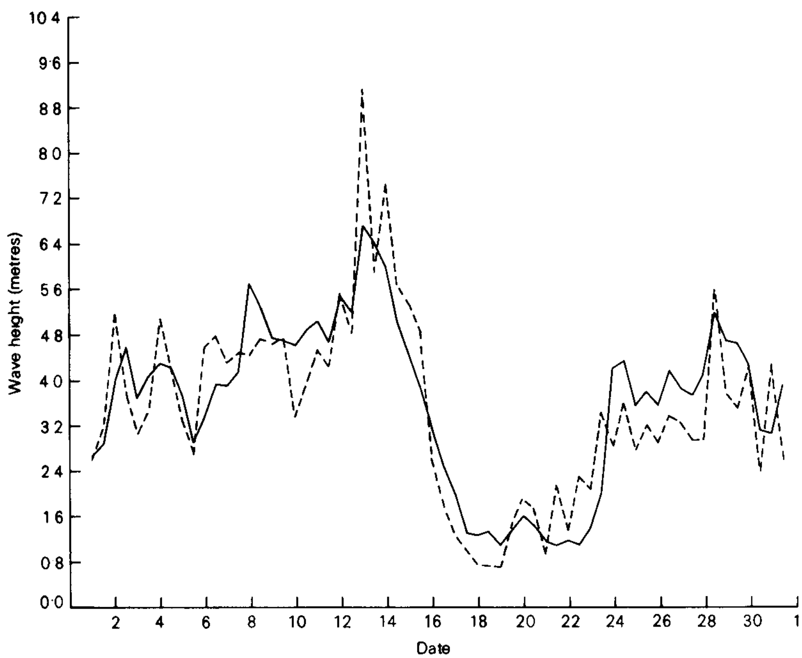

Figure 8(b). Time series of wave heights at St. Gowan for December 1978, using only data for 00 and 12 GMT.
——— model data – – – measured data

This analysis seems to support the idea that the small-scale oscillations in the measured data at St. Gowan are due to tidal currents. The current at St. Gowan is much stronger than at the other sites and this may be why there are no marked fluctuations in the measured data at the Isles of Scilly and South Uist. As the wave model does not include the effects of current this may be one reason why the verification statistics at St. Gowan are worse than those of the other sites. There should be some change in the amplitude of the oscillations due to spring and neap tides but it is not possible to identify this, usually because it is hidden by the natural variability of the measured wave height.

It should be remembered that the measuring instrument at St. Gowan site is a shipborne wave recorder (SBWR) whereas at the other sites there are waverider buoys (WRB) which tend to be viewed as the more accurate instrument. As mentioned earlier, SBWRs measure wave heights higher than WRBs by as much as 14% for 1 m waves and 8% for 4 m waves, and if we were to accept the WRB as an absolute standard for wave measurements it would be possible to correct the SBWR data at St. Gowan by these factors. The result would be to add between 0.1 and 0.2 m to the mean error distribution at this station shown in Fig. 6(c), which would improve the results from the post-October 1979 model but not remove the bias completely. It is possible that some of the errors apparent at St. Gowan can be attributed to the measuring device employed there, but given the complex nature of the true and the modelled wave climate at this location it is clear that there are many contributing sources of error which cannot be individually identified and isolated.

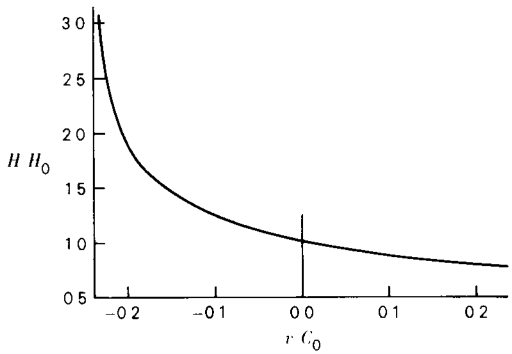

Figure 9. Change in wave height in an opposing or following current (Scripps Institution of Oceanography 1944). H_0 = wave height in still water, H = wave height in current, C_0 = wave velocity in still water and v = velocity of current — positive for following, negative for opposing.

5. Conclusions

The aim of this study was to compare the Meteorological Office IBM wave model archive with instrumentally measured wave data. Three sites were chosen at which reliable measured data were available.

The Isles of Scilly and South Uist sites were very similar in that they were both exposed stations in deep water (100 m and 96 m respectively) with small tidal effects, and data were collected by waverider buoy. Data were available for 17 months at South Uist and 21 months at the Isles of Scilly. The verification results were fairly similar, with mean errors for these periods being 0.05 m and −0.05 m and r.m.s. errors being 0.73 m and 0.63 m, for South Uist and the Isles of Scilly respectively.

The model thus appears to agree well with measurements in deep water and exposed locations, and displays no bias of mean wave-height error over any of the height ranges compared. The r.m.s. error, however, is found to increase with height.

St. Gowan was a station with a varying fetch (depending on the wind direction) in shallow (49 m) tidal water, and data were collected by shipborne wave recorder. Three years of data were available and gave results for the period of mean error 0.03 m and r.m.s. error 0.89 m. The mean errors at St. Gowan change greatly after October 1979, from 0.36 m to −0.38 m. The St. Gowan data do not agree as well as those from the Isles of Scilly or South Uist sites and this is probably due in part to the stronger currents and larger tidal range at St. Gowan. The analysis of the results at St. Gowan is complicated owing to the presence of several simultaneous effects which modify the local wave climate. However, the effects of tidal variations on the accuracy of the model results seem to be limited to time-scales of less than a day. In general the model still successfully simulates the wave climate despite a degradation of small-scale detail.

There also seems to be no time error in the model; i.e. it follows the measured wave field well with respect to time.

For verification of the wave archive containing values for once every 12 hours, intermediate measured wave activity is not important. Peaks on the measured wave-height time series occur randomly and most take approximately 12 hours to build up and decay, so model data every 12 hours will not represent all the peaks. If it is important for the model to predict these peaks, for example if the archive is used for climatological purposes where no measured data are available, then the provision of model data every 6 hours would be required to overcome this deficiency. Obviously the shorter the interval is between model data points the better, but unfortunately there are other constraints which restrict this, such as the physical problems of producing and handling such large amounts of data.

Owing to the differences between shipborne wave recorders and waverider buoys (and between different SBWRs), especially at low wave heights, it would be an advantage if only one type of recording device is selected for future verification exercises.

Model results are very sensitive to fetch regime. Verification data exposed to short and long fetches are needed to assess the model performance fully.

6. Summary of conclusions

(1) The model cannot be expected to agree with observations as well in coastal areas with strong currents as it does at less tidal locations.

(2) The model is very sensitive to fetch, and long and short fetches are needed for checking purposes.

(3) Modelled wave heights follow measured values well with respect to time.

(4) If the model is to be used for climatological purposes then model data are needed at least every six hours to capture high-wave event maxima.

(5) For verification, measured data should be standardized on one type of recording instrument, preferably the waverider buoy.

Acknowledgement

My thanks go to Mr J. J. Ephraums for his invaluable help in this work.

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551.524.36

The estimation of mean temperature from daily maxima and minima

By P. Collison and R. C. Tabony

(Meteorological Office, Bracknell)

Summary

Departures from the true mean temperature of the average of daily maxima and minima are shown to depend on the combined effects of radiation and advection. In Britain, systematic errors are generally less than 0.3 °C, but pronounced seasonal and geographical variations are caused by changes in radiation and in the relative importance of advection. Differences between 12-hour maxima and minima read at 09 and 21 GMT and 24-hour values read at 09 GMT are also investigated, and are found to vary seasonally but not geographically.

1. Introduction

Mean temperatures are often calculated from the average of daily maxima and minima. This is clearly convenient, since at many stations more frequent observations, from which more reliable estimates could be made, are not available. It is clearly important, however, to have some knowledge of the errors introduced by such a procedure.

Synoptic automatic weather stations currently being introduced by the Meteorological Office record 24 hourly observations of temperature, but not maxima or minima. Since the true mean temperature is very closely approximated by the mean of 24 hourly observations, there will be no difficulties in obtaining mean temperatures for such stations. It will be important to know, however, how these compare with values derived from the averages of maxima and minima.

The problem of estimating the true mean temperature has been investigated many times before. Brooks (1921) undertook a global appraisal, but rather than quoting errors associated with the use of maximum and minimum, concentrated on finding a combination of hourly observations which gave better estimates of the true mean temperature. For the United Kingdom, he suggested a weighted mean of temperatures observed at 07, 13, and 21 GMT, these being the times at which observations were commonly made in those days. Baker (1975) has shown that the errors in using daily maxima and minima depend upon the time at which the observations are made. If this is close to the time of the minimum, then an underestimate of the mean is made, while if it is close to the time of the maximum, then an overestimate is obtained.

The World Meteorological Organization recommends taking the mean of the day maximum in the period 09–21 GMT and the night minimum in the period 21–09 GMT, and, in the United Kingdom, this practice is followed at stations manned by Meteorological Office staff. At the 480 or so voluntary climatological stations observations are made only once per day at 09 GMT. An investigation of the differences between 12-hour (09–21 and 21–09 GMT) and 24-hour (09–09 GMT) maxima and minima based on 38 stations in the period 1957–70 was reported by the Meteorological Office (1976). It was found that differences in the summer were small, but that in the winter the 24-hour values were more extreme, with a difference of 0.4 °C for the maxima and 0.7 °C for the minima. Unpublished work in the Meteorological Office based on 14 stations in the period 1957–70 also investigated errors in the estimates of the mean of 24 hourly observations obtained by averaging the daily maxima and minima. In summer, both 12-hour and 24-hour maxima and minima were found to overestimate the mean by 0.2 °C. In winter, the 12-hour maxima and minima gave good estimates of the mean, while the 24-hour values gave means which were 0.2 °C too low. The results were stated to be similar for all the stations examined.

The present investigation essentially repeats the earlier Meteorological Office work using data from 15 stations for 1961–80. The broad results are confirmed, but the factors responsible for producing the departures from the true mean temperatures are discussed, and these are used to explain a substantial geographical variation which was not revealed in the previous analysis.

2. Differences between the mean of 24 hourly temperatures and the average of daily maxima and minima

The departure of the mean of maximum and minimum from the true mean will depend upon the distribution of temperature in a 24-hour period. If the temperature spends more time near the minimum than the maximum, i.e. the distribution is positively skewed, then an overestimate of the mean is made. If the skewness is reversed, then an underestimate is obtained. On any given day, the sequence of hourly temperatures will depend upon the combined effects of radiation and advection. It is changes in radiation and in the relative importance of advection which are responsible for the seasonal variations in the errors of mean temperature, and for the differences obtained from the use of either 12-hour or 24-hour values of the maximum and minimum. The relative importance of advection, however, will also be greater on coasts than inland, and in the north-west of Britain than in the south-east. This leads to the expectation that there may be geographical variations in the errors of the estimates of mean temperature. These expectations are confirmed by the analysis.

The distribution of the 15 stations used is shown in Fig. 1, and results are presented for two groups of stations. The first group — Ringway, Elmdon, Heathrow, Waddington, and Boscombe Down — represents inland stations in England, while the second group — Lerwick, Wick, Stornoway, Tiree and Valley — represents coastal sites in the north-west of Britain. Let Δ_9 denote the departure from the true mean of the mean of the 24-hour maxima and minima recorded at 09 GMT, and Δ_{DN} the departure from the true mean of the day maxima and night minima recorded at 21 and 09 GMT respectively. The true mean is obtained from the average of 24 hourly observations of temperature. Monthly values of Δ_9 and Δ_{DN} are presented for the two groups of stations in Fig. 2, and their distributions are seen to be quite different. At inland stations a bimodal pattern emerges, with values exceeding 0.2 °C in spring and autumn, and falling to near zero in winter. At the coastal sites, a simpler distribution, with a summer maximum and winter minimum emerges. For both groups of stations, Δ_9 is similar to Δ_{DN} in summer, but lower in winter.

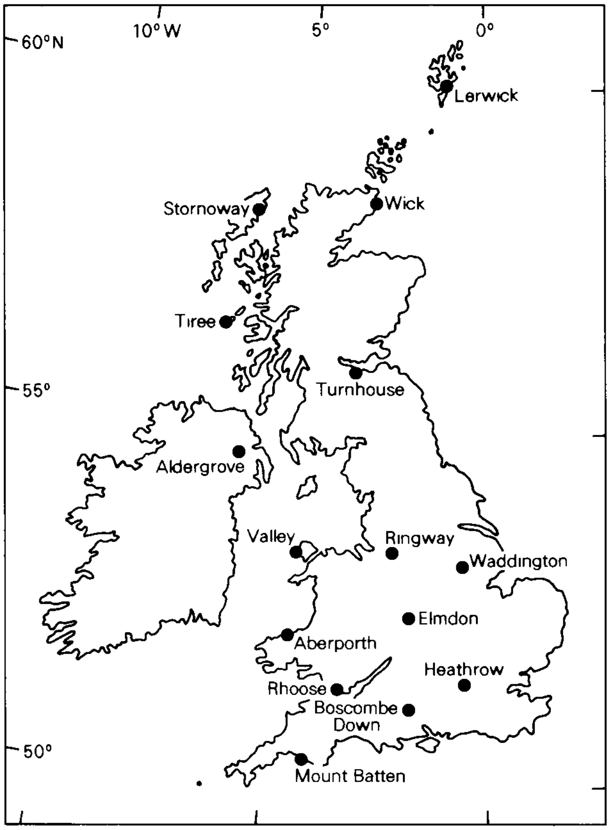

Figure 1. Distribution of stations used in this study.

3. The effects of radiation and advection

3.1 *Radiation*

The effects of radiation are well represented by the distribution of mean hourly temperatures, since advective effects will be self-cancelling. At coastal stations, any advective effects with a regular diurnal cycle, e.g. the sea-breeze, will also be included, but this is not important in terms of a qualitative explanation of the observed behaviour of Δ.

The radiation received from the sun on a horizontal surface is proportional to the sine of the solar elevation, and is therefore more sensitive to solar elevation when the sun is low in the sky than when it is high. Thus the maximum temperature will be more sharply defined in winter than in summer, and this is illustrated in Fig. 3, which displays the mean hourly temperatures at Heathrow during June and December for 1961–80. In December, the temperature spends more time near the minimum than the maximum, the true mean is overestimated from the mean of the maximum and minimum, and Δ is positive. In June, the skewness of the temperature distribution is less marked, but is in the opposite sense, and Δ assumes a small negative value. The seasonal variation in Δ which is caused by radiation is illustrated schematically in Fig. 4(a). For most of the year, the minimum is flatter than the maximum, giving positive values of Δ, and negative values are restricted to June and July. The effects of radiation at coastal sites are similar, but the seasonal variation is less marked, and Δ is close to zero in June and July.

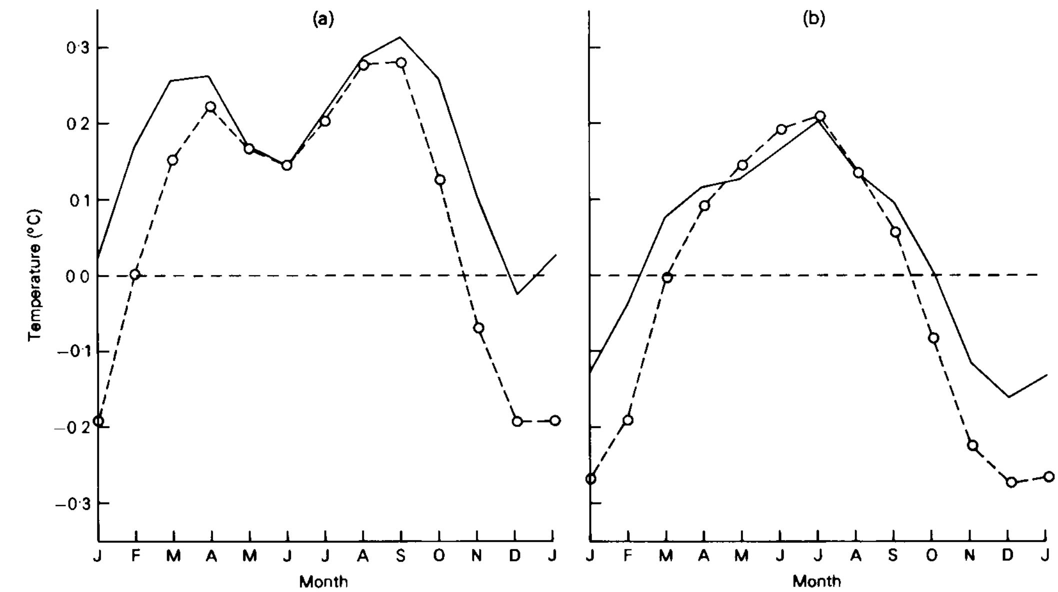

Figure 2. Departure DN from the true mean of ½ (day maximum + night minimum) temperatures recorded at 21 and 09 GMT respectively (Δ_{DN}) and of the mean of the 24-hour maxima and minima recorded at 09 GMT (Δ_9) for (a) inland stations and (b) coastal stations.
——— Δ_{DN} o — — — o Δ_9

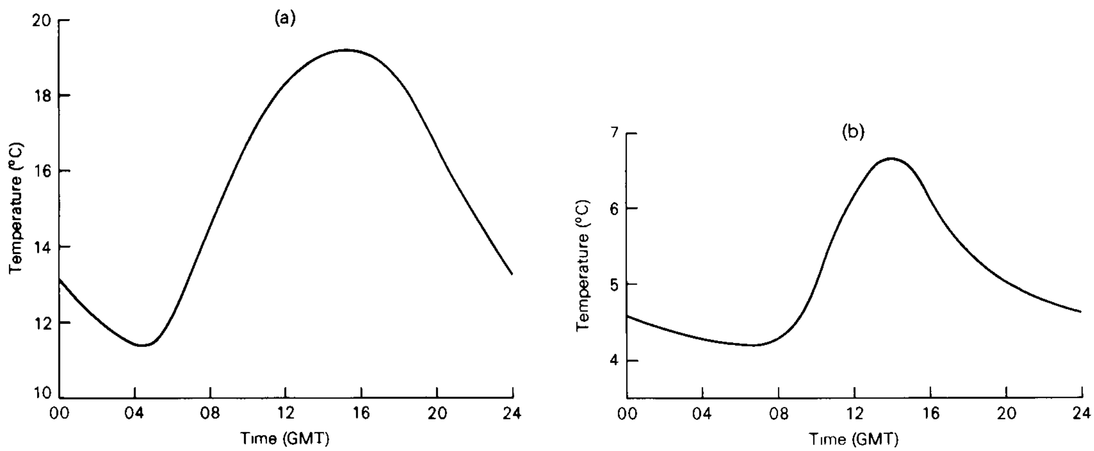

Figure 3. Mean hourly temperatures at Heathrow in (a) June and (b) December during the period 1961–80.

3.2 *Thermal advection*

The effects of steady thermal advection are illustrated in Fig. 5, where advective temperature changes of 1 °C every 2 hours, i.e. 12 °C in 24 hours, have been superimposed on the mean hourly temperatures for December at Heathrow. Thus, for the warm advective case, the sequence of hourly observations has been constructed by subtracting 6 °C from the mean for 09 GMT, 5.5 °C from the mean for 10 GMT,

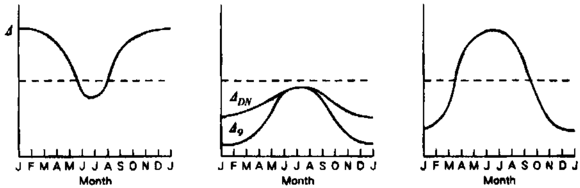

Figure 4. Contributions of (a) radiation, (b) thermal convection and (c) variable cloud cover to departure of means of maximun and minimum temperatures from true means (Δ).

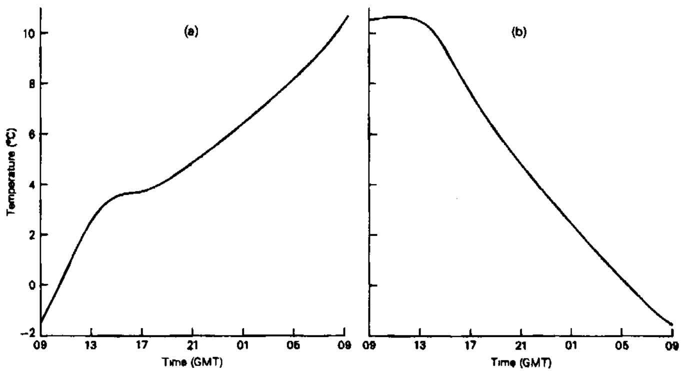

Figure 5. The effects of steady thermal advection, (a) warm and (b) cold, superimposed on the mean hourly temperatures for December at Heathrow.

5 °C from the mean for 11 GMT, and so on, finally adding 6 °C to the mean for 09 GMT the next day. The true mean temperatures for these occasions are therefore the same as in Fig. 3, but the skewness of the distribution of hourly temperatures has been radically changed. The cold advective case in particular shows that the minimum is sharper than the maximum, with a consequent underestimation of the true mean (negative Δ). The warm advective case, although less obvious from the diagram, also has a negatively skewed distribution of hourly temperatures and produces the same negative value of Δ, as the cold advective case. The difference between the cases is that in the cold advective situation, both the 12-hour and 24-hour maximum and minimum are recorded at 09 GMT, whereas with warm advection, the 12-hour values are recorded at 21 GMT. The mean of the 12-hour maximum and minimum is therefore the 21 GMT temperature, and this is close to the true mean. This is because the mean temperature at 21 GMT is close to that for the day in Fig. 3 (the 21 GMT and daily mean temperatures in Fig. 5 are the same as those in Fig. 3).

In winter, therefore, the effects of thermal advection oppose those of radiation, and produce underestimates of the true mean. The effects are greater for 24-hour than 12-hour maxima and minima. In summer, advective effects are small for two reasons. Firstly, thermal contrasts between air masses in summer are less than in winter, while the diurnal variation caused by radiation is much stronger. The result is that maxima and minima are rarely observed at 21 or 09 GMT in summer; in winter, this is not uncommon. Secondly, the observing hour of 09 GMT is close to the minimum in winter but not in summer. The results found by Baker (1975), that the errors in the true mean obtained from 24-hour maxima and minima depend on the observing hour, are due to advection. If the observing hour is close to the time of the minimum (e.g. 09 GMT in winter) one effectively has the choice of two minima; if it is close to the time of maximum, one has the choice of two maxima. If the observing hour is mid-way between maximum and minimum (e.g. 09 GMT in summer or 21 GMT at any time) then the effects of advection are minimized. The seasonal variation in the contribution of advection to Δ are illustrated in Fig. 4(b).

3.3 *Variations in cloud cover*

The effects of variations in cloud cover on the distribution of hourly temperatures are caused by both advection and radiation. The change in cloud cover may well be caused by advection, but the response of the temperature will depend upon the radiation balance at the time the change occurs. Consider a 3-hour cloud clearance in winter, for instance. If it occurs around midday, a slight rise may be produced, but in the long hours of darkness, it will cause a fall. This will cause a sharp minimum to be produced, and so the mean temperature will be underestimated (negative Δ). In general, sensitivity to radiation is greatest at night in winter (which produces negative Δ) and in daytime in summer (which produces positive Δ). The contribution to Δ caused by variations in cloud cover is therefore negative in winter and positive in summer, and this is illustrated in Fig. 4(c).

3.4 *Combined effects*

The combined effects of radiation, thermal advection, and variable cloud cover on Δ can be obtained from an addition of the curves displayed in Fig. 4 and a qualitative explanation of the results presented in Fig. 2 is now clear. At inland stations, where radiation is relatively important, Δ is generally positive. The bimodal distribution is caused by the summer trough for radiation being sharper than the summer peak for advection and variable cloud cover. Although the response to variations in cloud cover is essentially radiative, they will occur most frequently where advective changes are common. Consequently, where advection is important, the greater weight attached to the curves in Figs 4(b) and 4(c) produces a relatively simple distribution of Δ, with positive values in summer and negative values in winter. The differences betwen Δ_9 and Δ_{DN} are caused by the greater advective effects in winter, and are mainly due to the close proximity of the observing hour (09 GMT) to the time of minimum temperature.

Application of these results rests on a knowledge of the extent to which the 'inland' or 'coastal' set of figures applies to any given station. The difference between the two sets may be quantified by the difference of the values of Δ in June and July from those for the whole year. This has a correlation of -0.84 with the mean annual diurnal range and -0.92 with the standard deviation of the monthly mean values of the diurnal range. This latter quantity decreases to the north-west more rapidly than the diurnal range itself. The high correlation must be considered suspect because of the difficulty of distinguishing between coastal effects and distance to the north-west — no coastal stations in the south-east or inland stations in the north-west were used. Nevertheless, the standard deviation of the diurnal range probably offers a reasonable means of deciding how the values of Δ pertaining to a particular station compare with the two sets presented in Fig. 2. A generalized map of the standard deviations of the mean monthly values of diurnal range, based on nearly 600 stations in the period 1951–80, is presented in Fig. 6. The quoted values of Δ for the sets of inland and coastal stations are associated with standard deviations of 1.4 °C and 0.5 °C respectively. Fig. 6 therefore shows that values of Δ associated with a standard deviation of 1.4 °C are probably representative of a large proportion of the country, while those associated with a standard deviation of 0.5 °C are likely to be restricted to the more exposed coastal sites in the north and west.

The difference between the true mean and that obtained from the maximum and minimum on any given day may, of course, vary widely from the values presented above. The standard deviation of both Δ_9 and Δ_{DN} in all months is around 0.5 °C. The assumption that there are 10 independent values in 31 daily measurements of temperature suggests that the standard errors to be attached to the quoted values of Δ is around 0.03 °C, but that the standard deviation of Δ for individual months is 0.16 °C.

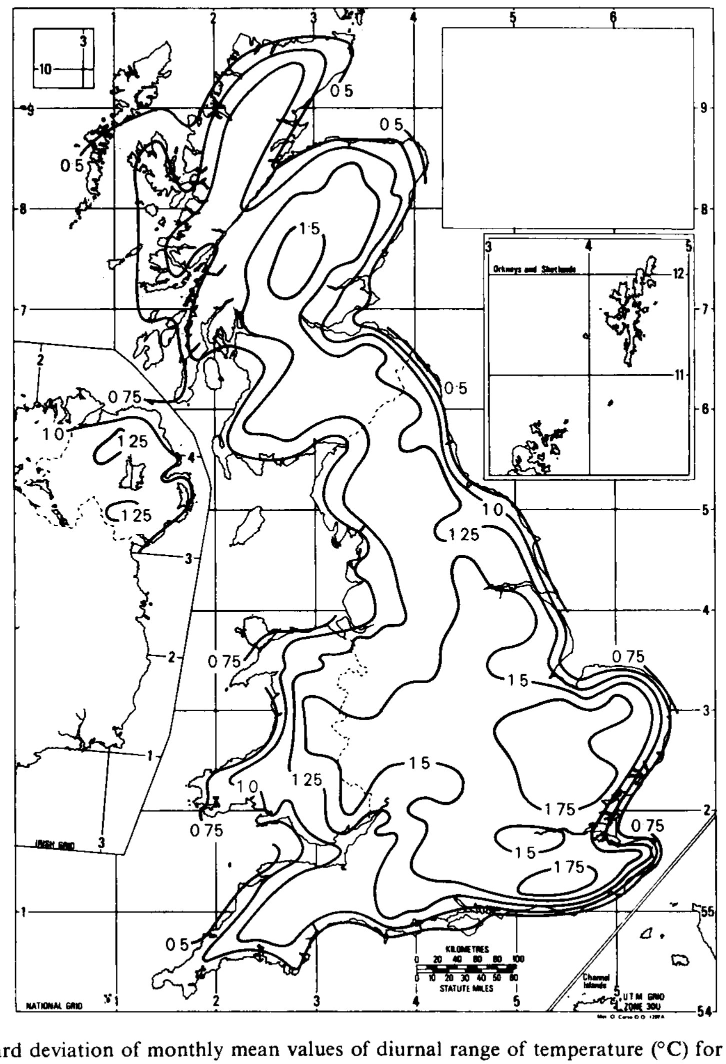

Figure 6. Standard deviation of monthly mean values of diurnal range of temperature (°C) for the period 1951–80.

4. Differences between 12-hour and 24-hour maxima and minima

Thermal advection and variable cloud cover are responsible for introducing the differences between the 12-hour (09–21 and 21–09 GMT) and 24-hour (09–09 GMT) maxima and minima. Fig. 7 shows that the differences are greater in winter than in summer, and for minima than maxima; these features may be attributed to the dominance of radiation in summer and the proximity of the observing hour (09 GMT) to the time of minimum temperature in winter. Geographical variations in these differences may be anticipated. The greater importance of advection on north-western coasts contributes towards larger differences there than elsewhere, but this is counteracted by the greater radiative response to variable cloud cover at inland sites, especially for minima in winter. As a consequence, differences between maxima are likely to be largest on north-western coasts, while in winter, differences between minima are likely to be greatest inland. While such geographical variations are present and are indicated in Fig. 7, the effects are generally small, and do not assume any great practical importance. The findings of the Meteorological Office (1976) concerning the differences between 12-hour and 24-hour maxima and minima are therefore confirmed, both in respect of the size of the differences attained and in the relative absence of geographical variations.

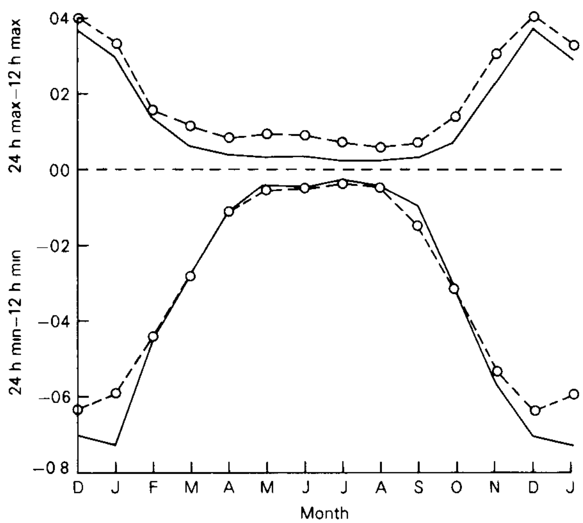

Figure 7. Differences between 12-hour and 24-hour maximum and minimum temperatures at inland stations (———) and coastal stations (o — — — o).

5. Conclusions

The difference between the mean of daily maxima and minima and the true mean temperature has been shown to depend on the effects of radiation and advection. The regular diurnal variation of radiation causes the mean of the maximum and minimum to overestimate the true mean in winter, but this difference is generally opposed by the effects of thermal advection. Irregular variations in cloud cover cause the true mean to be overestimated in summer but underestimated in winter. The combined effect of these factors depends on the relative importance of advection, and this varies widely with location. Where radiation is relatively important, as in inland stations in the south-eastern half of

Britain, the departure of the mean of day maximum and night minimum from the true mean undergoes a bimodal seasonal variation, with maximum differences around +0.2 °C in spring and autumn. Where advection is more important, differences range from +0.2 °C in summer to -0.2 °C in winter. The relationships previously found between 12-hour and 24-hour maxima and minima were confirmed, with only small geographical variations evident.

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A comparison of daily maximum and minimum temperatures with the highest and lowest of 24 hourly observations

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Summary

Automatic weather stations designed solely to make synoptic observations do not report maximum and minimum temperatures, so these parameters have to be estimated from the highest and lowest of hourly observations. The mean difference between the two types of observation was found to be around 0.4 °C, but values at some stations were twice as great as at others, and occasional differences of 2 °C were found. No coherent geographical variations were identified, but the difference between the maximum and the highest hourly observation was twice as great in summer as in winter.

1. Introduction

The Meteorological Office is developing two principal types of automatic weather station, one for making synoptic observations (SAWS), and the other for obtaining climatological data (ACRE). Platinum resistance thermometers housed in Stevenson screens will be used to record temperatures in both systems, with 'one-minute' observations being computed from instantaneous measurements made every 5 seconds. Hourly temperatures will be based on the last 5 such observations preceding the hour and, in synoptic stations, these recordings will be capable of immediate onward transmission. A facility to extract maximum and minimum temperatures from the one-minute observations will be included in the climatological, but not the synoptic, type of station. For the synoptic station, therefore, only the highest and lowest of the hourly observations will be available. It is therefore desirable to have a knowledge of the difference between the maxima and the minima recorded by the two types of automatic station and the conventional manned site in order that direct comparison between the different types of observation may be made.

The response times of platinum resistance and mercury-in-glass thermometers are similar at around 30 seconds. The maxima and minima derived from the one-minute observations at automatic climatological stations are therefore likely to be similar to those obtained from conventional sites. In this paper the likely differences between these values and the most extreme hourly temperatures obtained from automatic synoptic stations are investigated by examining the differences between the conventional maxima and minima and the highest and lowest of hourly observations recorded at manned stations. Hourly observations from the automatic weather stations will be less variable than those obtained manually because the former represent a temperature averaged over 5 minutes instead of, say, 30 seconds. If the difference between the maxima and the highest hourly observations is denoted by D_H, and that between the minima and the lowest hourly observations is represented by D_L, this implies that the variability of D_H and D_L will be less for automatic than for manned stations, although their mean values will be the same.

2. The data and their quality control

Hourly temperature observations together with maxima and minima recorded in the period 09–09 GMT were extracted for the years 1971–80 for 16 stations whose distribution is shown in Fig. 1. Data for earlier years were available, but not used because they were less well quality controlled. In the calculation of D_H and D_L, values less than zero were replaced by zero, while values exceeding 3°C were ignored. Cases in which the maximum or minimum occurred at 09 GMT were excluded from the analysis, as on those occasions either D_H or D_L would be zero.

From 1974 to 1980, data for the conventionally exposed thermometers were supplemented by observations from the aspirated psychrometer and North Wall Screen at Kew; these are analysed separately in section 7.

3. Relations between D_H and D_L and fluctuations in hourly temperature

The simplest means of estimating maxima and minima from the highest and lowest of hourly observations is to assume a constant difference between them. The possibility exists, however, that these differences depend on certain aspects of the weather, and that this dependence can be used to improve the estimates of the maxima and minima. Investigations into the possibilities were restricted to attempts to relate D_H and D_L to features of the hourly temperature record.

The first attempt was to fit a quadratic temperature profile to the extreme hourly and two adjacent observations, and to note the turning points of the parabolic curves. At Elmdon, however, these turning points only differed from the most extreme hourly observations by 0.05 °C, and the variance of the difference between them and the maximum and minimum was scarcely reduced below the variance of D_H and D_L.

The second attempt was to regress D_H and D_L against T_H, T_L, T_h and T_l where

T_H = difference between the highest and second highest hourly temperatures,

T_h = difference between the highest hourly temperature and the mean of the adjacent observations

and T_L and T_l are similarly defined with respect to the lowest hourly temperature. For each of the 16 stations, however, none of the regressions had correlations which much exceeded 0.2.

The reasons for the failure of these attempts must be that the maxima and minima are produced by fluctuations of temperature on a time-scale of much less than an hour, and that these fluctuations bear little relation to the differences between hourly observations.

4. Mean values of D_H and D_L

Mean values of D_H and D_L were found to be 0.36 °C and 0.41 °C respectively but, over the 16 stations examined, values ranged from 0.25 °C to 0.48 °C for D_H and 0.30 °C to 0.58 °C for D_L. These differences, however, seemed to depend on local site peculiarities, and no large-scale variation, either with latitude or

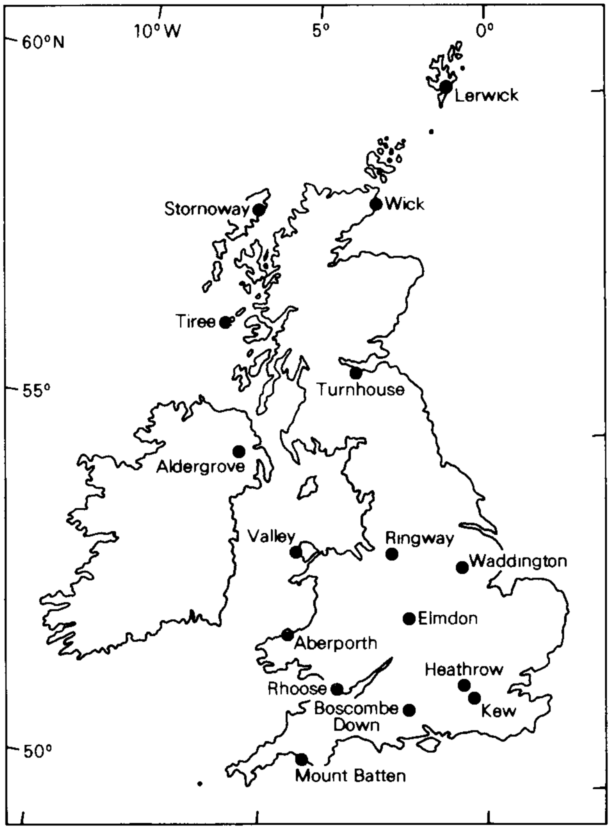

Figure 1. Distribution of stations used in this study.

distance from the coast, could be identified. The dependence of D_H and D_L on local factors is supported by the fact that stations with high values of D_H tended to be associated with low values of D_L, and vice versa ($r = -0.45$). Large values of D_L occur at sheltered sites which favour the development of strong nocturnal inversions, while large values of D_H are more likely to occur at exposed sites where turbulence is stronger.

Mean monthly values of D_H and D_L, averaged over the 16 stations, are represented in Fig. 2, together with figures for the stations with the highest and lowest annual means. A pronounced seasonal variation is revealed for D_H, with values close to 0.2 °C in winter and 0.5 °C in summer. This variation, which is caused by increased convection and gustiness in summer, is fairly general, and the ratio of summer to winter values is similar for all stations. In contrast, nocturnal conditions show little in the way of seasonal differences, and D_L remains close to 0.4 °C.

5. The variability of D_H and D_L

The variability of D_H and D_L is illustrated for a typical station, Elmdon, for which the means of D_H and D_L are close to those for the average over 16 stations. Fig. 3 displays the frequency distribution of D_L for the whole year, and of D_H for summer (May–August) and winter (November–February). A generally

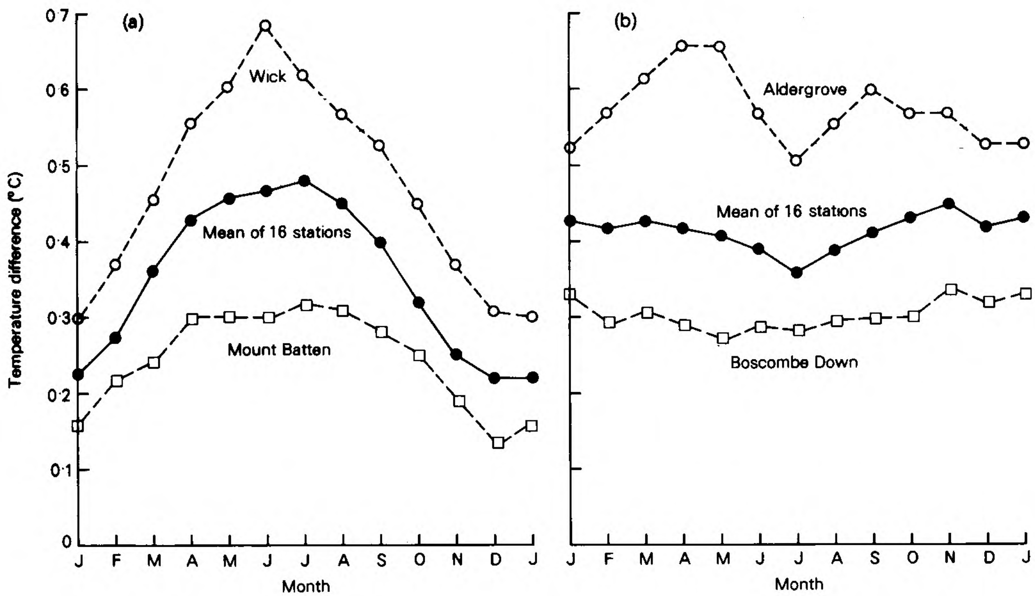

Figure 2. Seasonal variation of the mean values of the difference between (a) 24-hour maxima and highest hourly temperatures (D_H) and (b) 24-hour minima and lowest hourly temperatures (D_L).

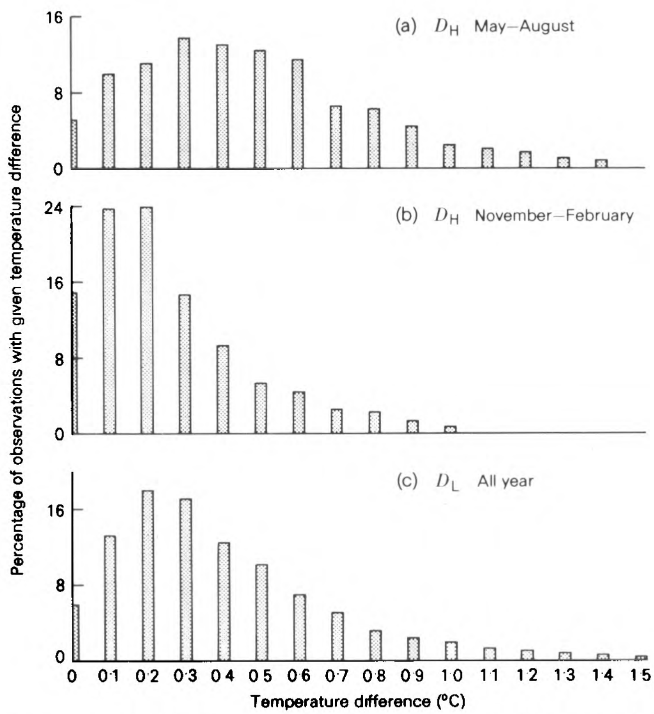

Figure 3. Frequency distribution of the difference between 24-hour maxima and highest hourly temperatures (D_H) and 24-hour minima and lowest hourly temperatures (D_L) at Elmdon.

skew distribution is apparent so that, although the mean of D_L is 0.4 °C, the mode is 0.2 °C and occasional values of 1.5 °C are attained. The skewness of D_H in summer is generally less, but values of 1.5 °C are still possible. For some stations, for which the means of D_H and D_L may exceed those at Elmdon by 50%, occasional values in excess of 2 °C must be expected. It should be recalled, however, that the variability of D_H and D_L will be less for automatic than conventional observations because of the long averaging period (5 minutes) of the automatic hourly observation.

6. 12-hourly maxima and minima

The above analysis has compared differences between the maximum and minimum and the highest and lowest of hourly observations in the 24-hour period 09–09 GMT. This analysis was repeated using data for the 12-hour periods 09–21 and 21–09 GMT. Differences between the day (09–21 GMT) maximum and the highest hourly observation, and the night (21–09 GMT) minimum and the lowest hourly observation, were found to be very similar to D_H and D_L for 24-hour maximum and minimum. The main difference between the night maximum and the highest hourly observation was only 0.2 °C, while that between the day minimum and the lowest hourly observation was mostly 0.4 °C, but nearer to 0.3 °C from July to September.

7. The aspirated psychrometer and North Wall Screen at Kew

The sensitivity of D_H and D_L to the precise siting and nature of the instruments is illustrated by an examination of their values for the aspirated psychrometer and North Wall Screen at Kew. A full description of the site and instrumental details are given by Painter (1970),* but the main non-standard features are the forced ventilation of the psychrometer and the excessive height, 5 metres above most of the ground, of the North Wall Screen.

Mean monthly values of D_H and D_L for the two sites are displayed in Fig. 4. Comparison with Fig. 2

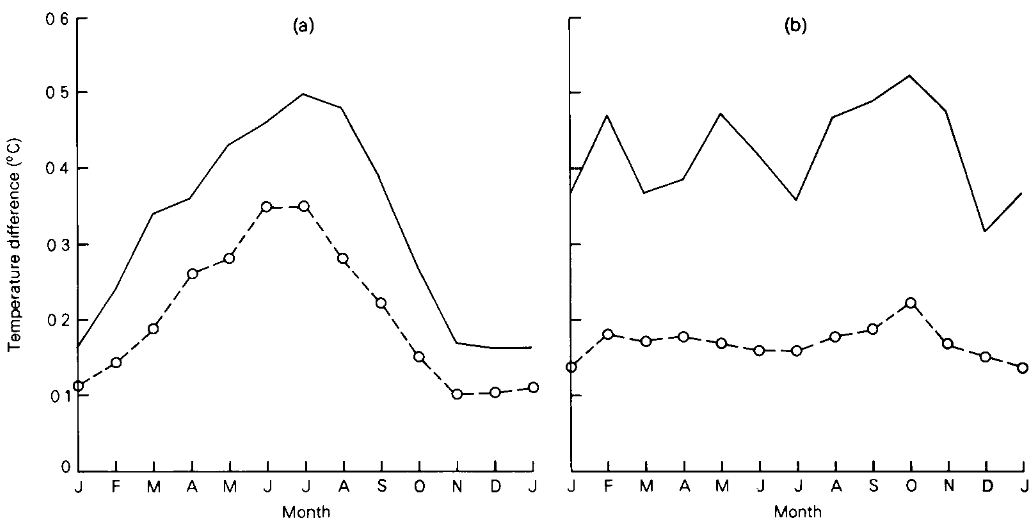

Figure 4. Mean monthly values of the difference between (a) 24-hour maxima and highest hourly temperatures (D_H) and (b) 24-hour minima and lowest hourly temperatures (D_L) at Kew. The higher values are from the aspirated psychrometer and the lower values are from the North Wall Screen.

*Painter, H.E.; A recording resistance psychrometer, *Meteorol Mag*, **99**, 1970, 68–75.

shows that the figures for the aspirated psychrometer are typical of those for standard instruments, while those for the North Wall Screen are much lower, especially for D_L. The reduced amplitude of the short-period fluctuations of temperature in the North Wall Screen can be mainly attributed to the excessive height of the thermometers above the ground.

8. Conclusion

Differences between daily maximum and minimum and the highest and lowest of 24 hourly observations at conventional stations are of the order of 0.3 to 0.4 °C. Values at some stations are twice as great as at others, but there is no coherent geographical variation. The difference between the maximum and the highest hourly observation undergoes a marked seasonal variation, with mean values ranging from 0.2 °C in winter to 0.5 °C in summer. The frequency distribution of the daily values is skewed, with occasional differences of 1.5 °C possible at a typical station and 2 °C at some. The range of values at automatic weather stations, however, will be less than this because of the long averaging period (5 minutes) of the hourly observation. The sensitivity of the differences to local site and instrumental detail are illustrated by observations from the aspirated psychrometer and North Wall Screen at Kew.

Reviews

Variations in the global water budget, edited by Alayne Street-Perrott, Max Beran and Robert Ratcliffe. 165 mm × 245 mm, pp. xiv + 518, *illus*. D. Reidel Publishing Company, Dordrecht, 1983. Price US $69.50.

This volume contains 32 papers presented at the Symposium of the same name held at Oxford in August 1981. The stated purpose of the book is to 'act as a state-of-the-art summary of material on the hydrological cycle, with emphasis on its variability'. There are contributions from climatologists, hydrologists, glaciologists and palaeoclimatologists.

Papers are grouped in five sections with brief introductions to each section. The first two sections deal with techniques of measurement and analysis of water budgets in the atmosphere and on the earth's surface. They include a major analysis of the distribution and transport of water vapour in the atmosphere (Peixóto and Oort) and a clear and valuable summary of our present knowledge of evaporation models (Shuttleworth). There are also several papers on remote sensing of rainfall and water vapour.

The next section deals with variability on timescales from months to hundreds of years and includes papers on rainfall fluctuations in Africa, India, China and Australia. Nicholson and Chervin stress the synchronous occurrence of drought in both hemispheres in Africa and the spatial coherence and persistence of rainfall anomalies in sub-Saharan zones. Almost three years later drought continues in West Africa giving added urgency to the need to investigate further the possible feedbacks between rainfall fluctuations and the general circulation as, for example, presented here by Reiter who relates equatorial Pacific rainfall to the Northern Hemisphere circulation.

Long-term changes during the late Quaternary period are the subject of the next section. These papers cover a wide series of topics, e.g. late glacial circulation over North America, evaporation from Lake Chad and possible atmosphere – ocean feedback mechanisms.

The final section, comprising papers on modelling and prediction, indicates the substantial progress made in recent years in the development of global climate models. Undoubtedly, progress in understanding and predicting climatic fluctuations must come from the development of such models, but it is possible that economically useful seasonal predictions could be made from our present knowledge of teleconnections and persistence. An assessment of the possibilities would have been a valuable addition. Sadly, the book has no mention of the social and economic importance of variations in water budget components, giving the unfortunate impression that the field is scientifically interesting and active but not of great practical importance.

However, the book succeeds in its purpose and will be a useful addition to any meteorological library and a valuable reference book for students, though I do not see it becoming an undergraduate textbook as the publishers suggest. Editors and publishers must be congratulated on producing an attractive and error-free book with excellent layout and diagrams.

M. D. Dennett

A first course in fluid dynamics, by A. R. Paterson. 155 mm × 232 mm, pp. vi + 528, *illus*. Cambridge University Press, 1983. Price £30.00 (paperback £12.50).

This excellent book is based on a lecture course given to second-year honours mathematics students at Bristol University. It was written after the author had formed the opinion that 'the modern texts with the "right" attitude to the subject were too hard for a first course and the older texts were dominated by potential theory and unrealistic examples'.

The first eight chapters deal with mathematical, physical and observational preliminaries, mass conservation and stream functions, vorticity, hydrostatics, thermodynamics and the equations of motion. The remainder of the book discusses solutions to a variety of problems that theoretical dynamicists have to deal with in their studies of flows over a wide range of Reynolds number and Mach number, including flows past obstacles, channel flows, sound waves, water waves, supersonic flows and aerofoil theory. Each chapter ends with a set of useful exercises, answers to and hints for the solution of which are provided at the end of the book, where the author also thoughtfully provides a list of reference books and an index.

The book contains little of direct relevance to meteorologists but it will have a wide appeal amongst scientists in many disciplines who are interested in the fundamentals of fluid dynamics.

R. Hide

Books received

Future weather, by John Gribbin (Harmondsworth, Penguin Books, 1983, £3.50). The author analyses here the causes and effects of climatic change, relating them to the 'greenhouse effect', and asks what the implications are for the utilization of energy for agriculture and for global and local politics. He also considers the evidence that the climatic balance of our world is being destroyed by our short-sighted activities.

Remote sensing applications in marine science and technology, edited by Arthur P. Cracknell (Dordrecht, D. Reidel Publishing Co., 1983, US $78.00) contains the proceedings of the NATO Advanced Study Institute on Remote Sensing Applications in Marine Science and Technology, held in Dundee, Scotland 1–21 August, 1982. The main topics covered are: the general principles of remote sensing with particular reference to marine applications; applications to physical oceanography; marine resources applications; and coastal monitoring and protection.

Atmospheric diffusion (third edition), by F. Pasquill and F. B. Smith (Chichester, Ellis Horwood Ltd., 1983, £35.00) is a study of the dispersion of windborne material from industrial and other sources. It covers two main areas of considerable practical interest: localized industrial air pollution in urban environments and the long-range transport of pollution to areas which are particularly sensitive to resulting depositions.

Human response to tropical cyclone warnings and their content: World Meteorological Organization Tropical Cyclone Programme No. 12 (Geneva, WMO, 1983, free) is a study of the present terminology used for warning messages and of present knowledge and experience of its impact upon the behaviour of the population in cyclone-prone areas. The document is published in loose-leaf form so that new relevant material may be added from time to time as researchers and operational meteorologists gain greater insights into human response to natural hazard warnings.

Tornados, dark days, anomalous precipitation, and related weather phenomena; Earthquakes, tides, unidentified sounds and related phenomena; Rare halos, mirages, anomalous rainbows and related electomagnetic phenomena; compiled by William R. Corliss (Glen Arm, The Sourcebook Project, 1983, US $11.95) are three volumes in the series *A catalog of geophysical anomalies*, and are sister volumes to *Lightning, auroras, nocturnal lights, and related luminous phenomena,* a review of which was published in *Meteorological Magazine,* **113,** 242–243.

Honour

Mr J. B. Lawson (Senior Scientific Officer), formerly Senior Meteorological Officer at Cranwell, now at Headquarters, has been awarded the Air Officer Commanding-in-Chief's Commendation in the Queen's Birthday Honours List. The award has been made in recognition of Mr Lawson's personal contribution to the work of RAF Cranwell.

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NOTICE

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The development of hailstorms along the south coast of England on 5 June 1983

By F. F. Hill

(Meteorological Office Radar Research Laboratory, RSRE Malvern)

Summary

Hailstorms developed rapidly along the south coast of England during the late morning of 5 June 1983. They occurred on the cold side of a narrow baroclinic zone and just ahead of a rather shallow middle-level trough. Although these synoptic features were moving eastwards, satellite and radar evidence indicates that all the storms originated close to the south coast of Devon over a period of three hours, suggesting that some form of localized forcing was occurring in this region.

1. Introduction

During the night and early morning of 5 June 1983, large areas of medium-level cloud covered most of southern England and northern France. Within this cloudy area there existed several bands of thundery rain. At 0600 GMT the main areas of thunder were over the extreme south-east of England and north-east France. By 1200 GMT, however, reports of large hailstones were being received from places close to the Dorset and Hampshire coasts. The radar data from Camborne and Clee Hill show that several distinct thunderstorms with intense cores were moving east-north-eastwards along the south coast of England, with less heavy rain extending for nearly 100 km north-westwards from each of these centres (Fig. 1). The reader may wish to compare this figure with the NOAA-7 satellite image shown in a brief article on these storms by Wells (1983), which shows the same five storms just over two hours later.

This paper first describes the upper-air conditions at the time when the storms developed. Then the positions at which the storms were first observed are related to the cloud structure observed by satellite. Maps show the location of the growing cells and the tracks of the storms while they were within radar coverage. The formation of rainbands to the north-west of each storm is illustrated in section 7, followed by an account of the wind and pressure fluctuations associated with the passage of each storm across a station close to the centres. After showing the total rainfall attributable to the storms, possible reasons for the rapid development are discussed.

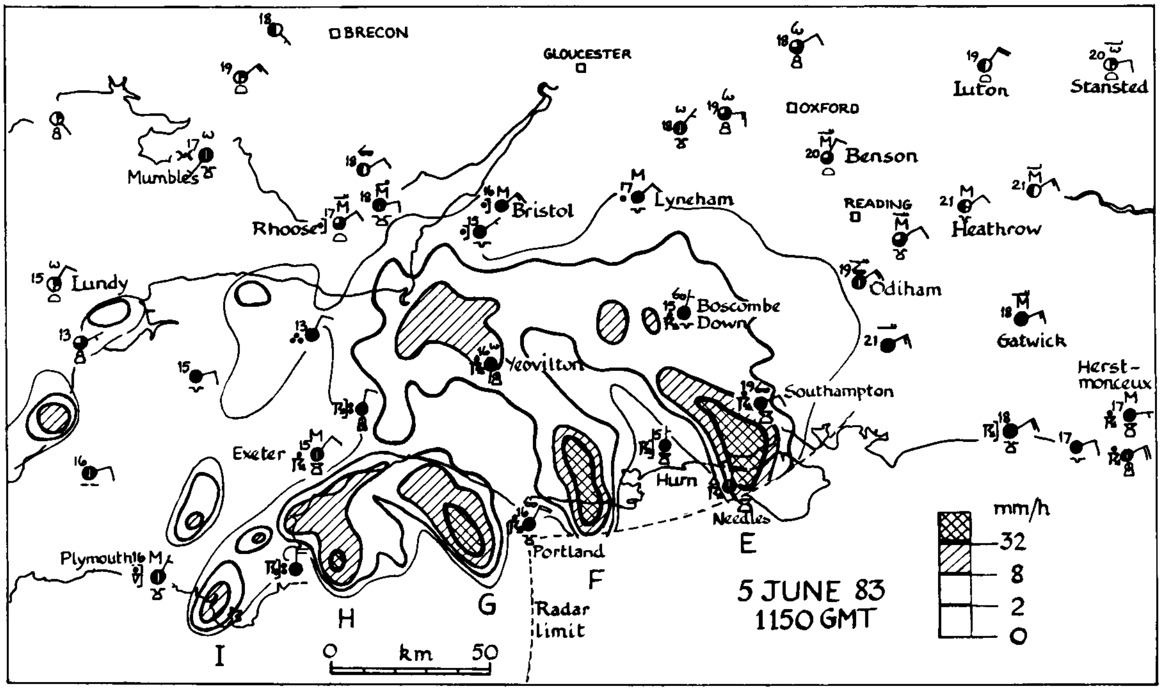

Figure 1. Location of the five main storms over southern England at 1150 GMT on 5 June 1983. Rainfall rates are derived from radar measurements.

2. Surface and upper-air patterns on 5 June 1983

(a) *Surface and 500 mb analyses*

During the night of 4/5 June, a broad band of thundery rain extended across north-west Europe from west of Portugal to north Germany. These thundery areas were not related closely to any surface pressure features; indeed the surface analysis at 1200 GMT on the 4th (Fig. 2) shows high pressure from southern England to central Europe. An anticyclone to the west of the British Isles built across Scotland during the night as a depression over the North Sea moved eastwards, while pressure remained relatively low over Spain and western France. These pressure changes caused the surface wind over southern England and the English Channel to freshen from the east early on the 5th. Surface temperatures over most of continental Europe had been much higher than those over the British Isles on the 4th (mostly 28 °C to 32 °C over France and eastern Spain at 1500 GMT but only 15 °C to 20 °C over Britain) and this contrast was repeated on the 5th. Although the north coast of Spain was cool also, the Corunna ascent showed warm air above 950 mb with wet-bulb potential temperature of about 18 °C. HERMES temperature data (a satellite-sounding technique described by Eyre and Jerrett (1982)) confirm that the warm air over France extended westwards across Biscay. The warm front shown in Fig. 2 corresponds approximately to the northern boundary of this warm air and to the southern boundary of the thundery rain.

The rain was caused by ascent in a baroclinic zone at middle and upper levels. This zone, comprising a broad band of strong south-westerly winds, lay to the south-east of an upper trough which was moving slowly south-eastwards across the British Isles. Both features are evident in Fig. 3 which shows the

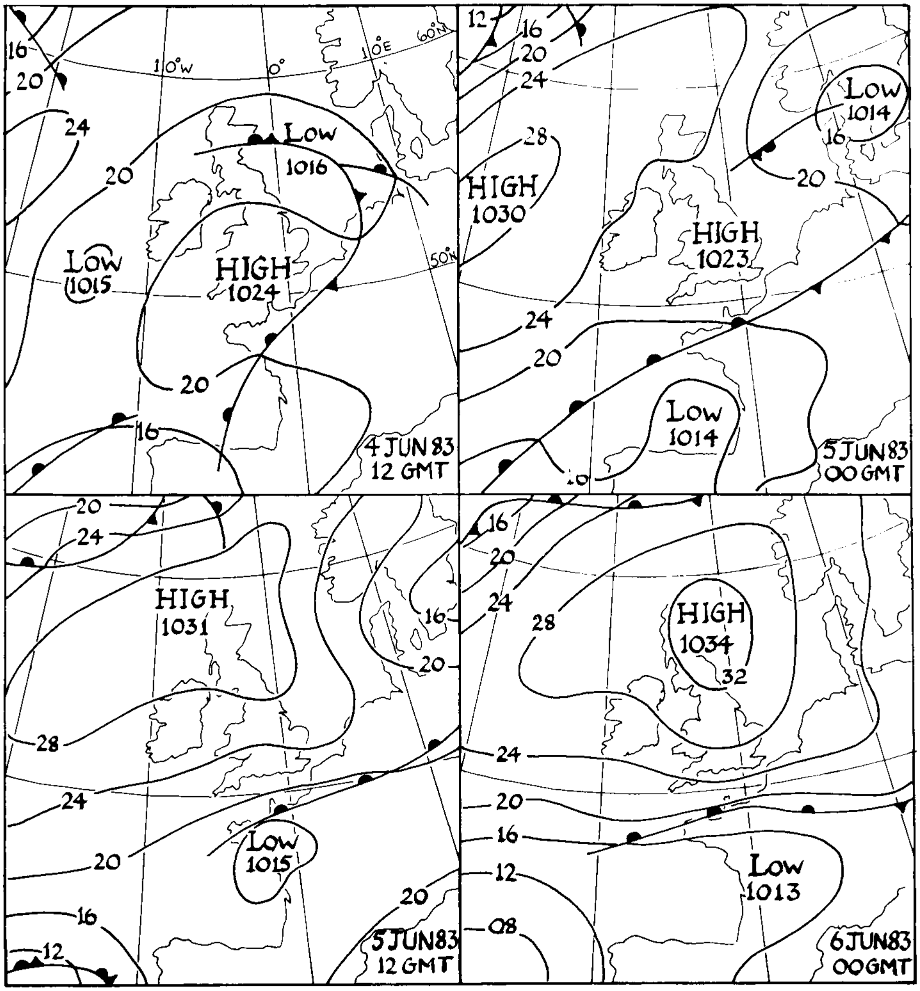

Figure 2. Surface analyses at 12-hour intervals from 1200 GMT on 4 June to 0000 GMT on 6 June 1983.

500 mb contours and 1000–500 mb thickness analyses at 12-hour intervals from 1200 GMT on the 4th to 0000 GMT on the 6th. On the 4th, the trough extended from the Norwegian Sea, where it was broad and fairly fast-moving, to the west of Ireland, where it was sharper and moving only slowly. The analyses show that the southern end of the trough became detached as it crossed Ireland. This portion of the trough can be regarded as a separate feature after 0000 GMT on the 5th; it was also rather shallow, being most evident between 600 and 400 mb. The sequence of analyses shows also that the previously broad and extensive baroclinic zone weakened from the south-west during the night and morning of the 5th as warming occurred to the north-east of a depression over sea area Finisterre; it also veered slightly as a result of cold advection to the east of the British Isles. By the morning of the 5th, the entrance to the baroclinic zone was just west of the English Channel.

There is a difference between the 1000–500 mb thickness analysis for 0000 GMT on the 5th shown in Fig. 3 and the analysis issued by the Central Forecasting Office at Bracknell a few hours later. The

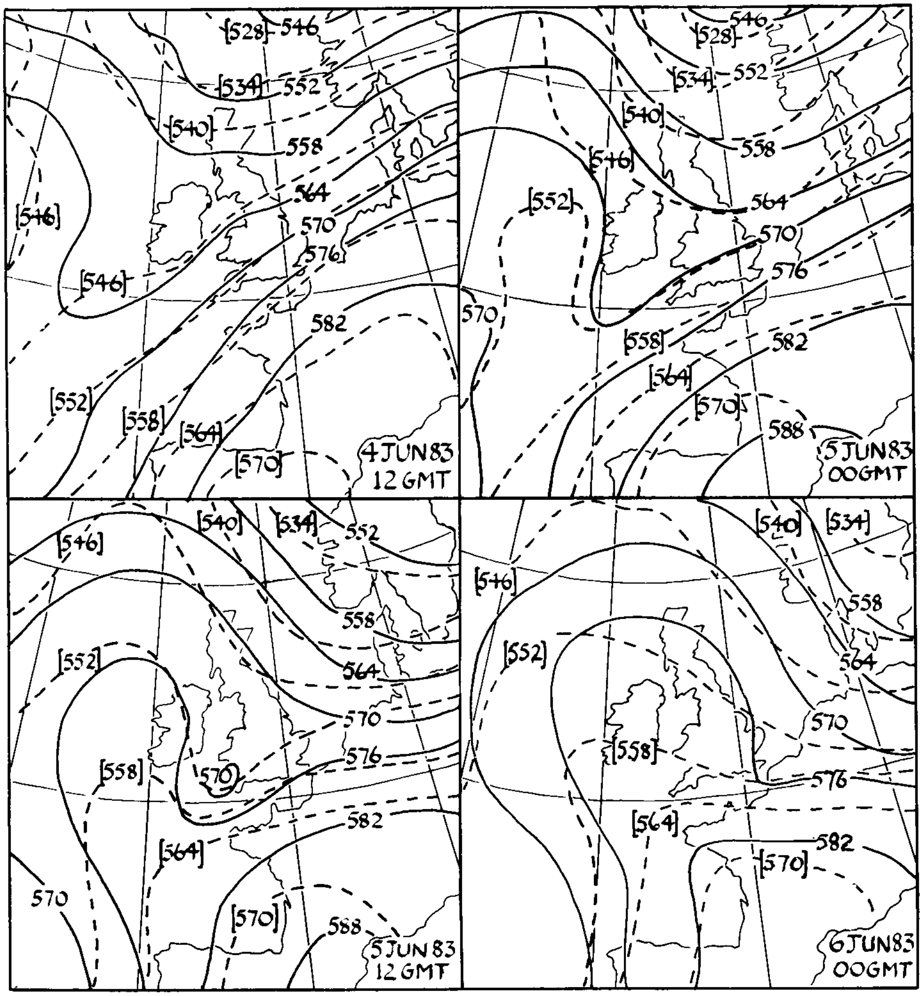

Figure 3. 500 mb contours (continuous curves) and 1000–500 mb thickness (broken curves) at 12-hour intervals from 1200 GMT on 4 June to 0000 GMT on 6 June 1983.

operational analysis does not fit the strong northerly thermal wind implied by the upper winds at Valentia. By accepting these winds as correct, we obtain a sharper trough to the south of Ireland and a thermal ridge to the west, both of which are more consistent with the analysis of the data at 1200 GMT on the 5th.

The Camborne ascent for 1200 GMT on the 5th (Fig. 4) shows that the trough was crossing Cornwall at this time: the wind was still over 50 kn but had veered to 280°. During this ascent, however, the dry-bulb appears to have responded as a wet-bulb element at 730 mb. By comparing HERMES data with radiosonde ascents, it seems likely that the temperature at 700 mb near Camborne should have been at least 0 °C instead of –5 °C. Assuming that the actual temperature profile was similar to the revised curve

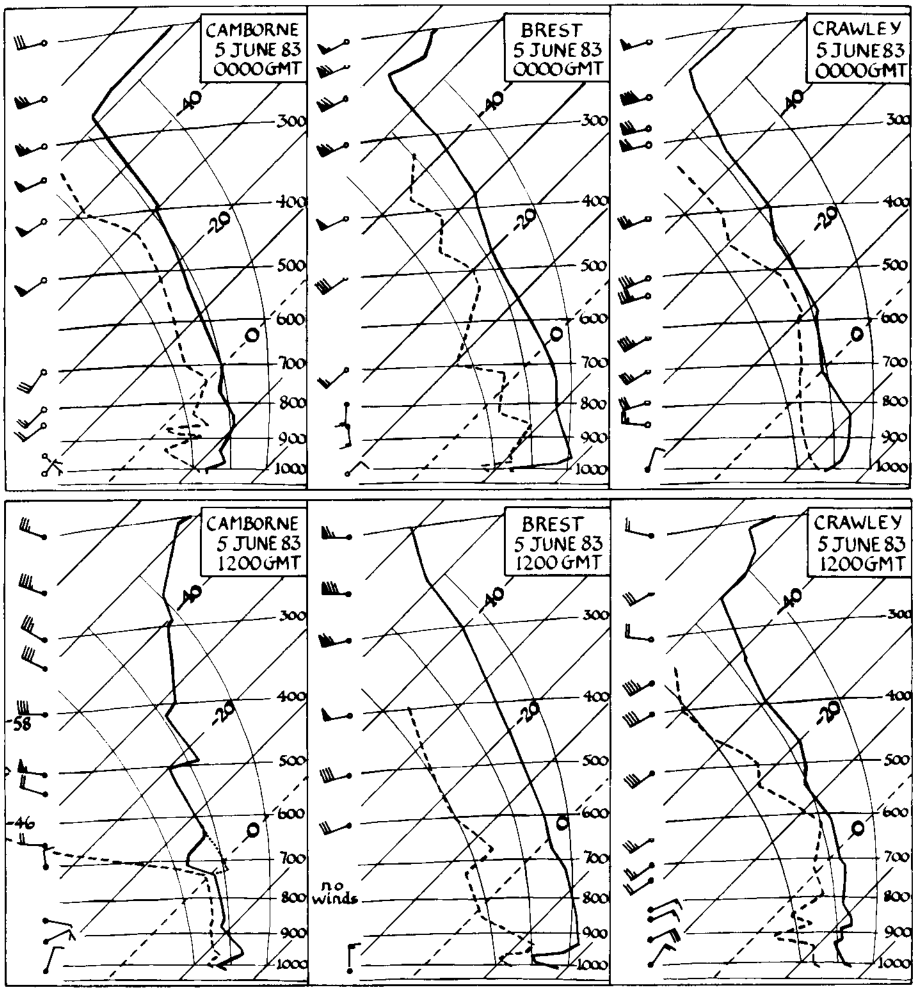

Figure 4. Temperature, dew-point and winds for Camborne, Brest and Crawley at 0000 GMT and 1200 GMT on 5 June 1983. The three saturated adiabats are for wet-bulb potential temperatures of 10, 15 and 20 °C. Dots on the Camborne ascent near 700 mb are an estimate of the environment curve assuming that the temperature element on the radiosonde responded as a wet-bulb between 730 and 710 mb.

shown in Fig. 4, then the heights of the 700 and 500 mb levels should have been respectively 10 and 17 m higher than were reported. This adjustment reduces the area enclosed within the 5700 m contour from that shown in Fig. 3 of Wells (1983) which was identical to the Bracknell operational analysis.

Comparing the 0000 GMT and 1200 GMT ascents at Crawley (Fig. 4), the wet-bulb potential temperature at 400 mb (θ_{w400}) had fallen from 15.2 °C to 14.8 °C whereas θ_{w700} had risen from 13.7 °C to 14.6 °C. Hence θ_{w400} minus θ_{w700} had fallen from 1.5 °C to 0.2 °C which indicates that the middle tropopause was approaching a state of potential instability over a deep layer, well in advance of the upper trough. Cooling of only 1 °C to 2 °C around 600 mb and lifting by about 40 mb would have made the whole layer from 800 mb to 400 mb absolutely unstable with respect to saturated ascent.

(b) *Isentropic analyses*

Because this event occurred on a Sunday, there were no ascents from Larkhill (near Boscombe Down). Additionally, some ascents from Brest had incomplete wind data. These deficiencies have impeded the task of obtaining a detailed analysis of the upper air just forward of the trough.

Although air does not necessarily move along dry isentropic surfaces, such analyses are useful indicators of where broad-scale ascent is likely to be occurring provided that the relative motion of adjacent systems is taken into account. The analyses shown in Fig. 5 are for the 25 °C, 30 °C and 37 °C surfaces at 1200 GMT on 5 June. Over the English Channel, the 25 °C surface lay just above the cool and moist low-level layer; the adjustment made to the Camborne ascent changes the level of this surface from 680 to 730 mb, which accounts for the difference in the height of this surface from that quoted in Wells (1983).

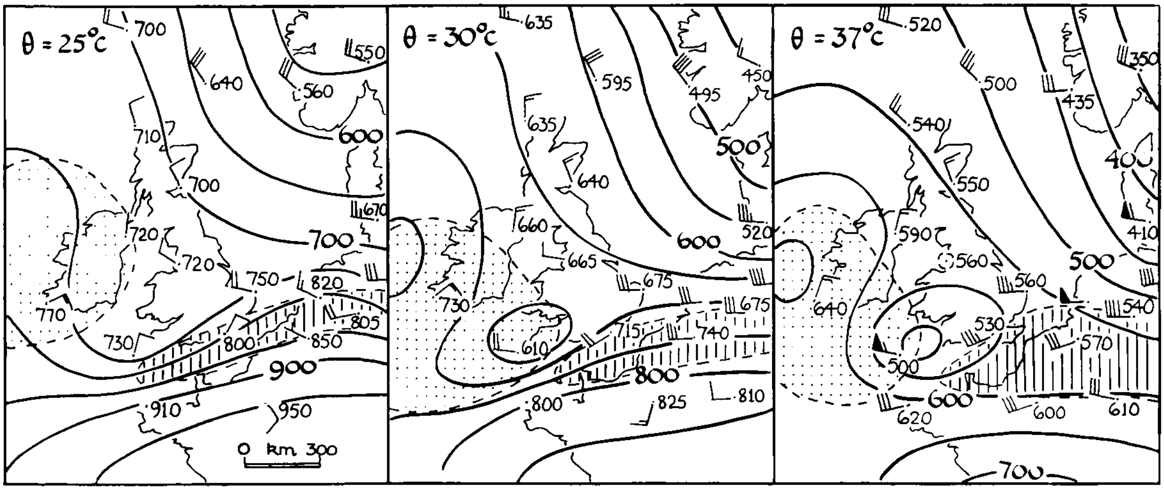

Figure 5. Isentropic analyses of the 25, 30 and 37 °C surfaces at 1200 GMT on 5 June 1983. Figures show heights in millibars. Vertical hatching shows moist air (dew-point depression ⩽6 °C); stippling shows dry air (dew-point depression ⩾20 °C). Based on the surface isobars, the wind at 910 mb over Brest was probably east-north-easterly at about 15 knots. From the 0000 GMT ascent (Fig. 4) the wind at 800 mb was probably south-south-westerly at 15 knots.

From the top of the friction layer to the base of the warm air, the north-easterly winds over southern England backed to northerly before becoming westerly, whereas those over northern France veered. In view of the steepness of the 25 °C isentropic surface over the English Channel, this relative motion suggests that convergence may have been occurring at the base of the warm air. The region most favourable for ascent in this surface at 1200 GMT was over the English Channel, with the warm air originating between Brittany and Paris.

In the 30 °C and 37 °C surfaces the upper trough produced a marked pressure minimum over south-west England and a steep gradient over the western half of the English Channel. The winds over northern France were south-south-westerly at 800 mb, so there would have been ascent in the 30 °C surface relative to the eastward-moving trough. In view of the potential instability which must have existed just ahead of the trough at middle levels, fairly widespread convection is indicated here. At these levels, the warm air had probably arrived over the English Channel via Biscay and the Brest Peninsula. Note the sharp humidity gradient over sea area Plymouth caused by the advection of cooler and drier air from the west.

3. Broad-scale distribution of cloud on 5 June

This section is illustrated by Fig. 6 which shows the main areas of cloud at six-hour intervals on 5 June as observed by Meteosat.

It would be wrong to assume that thundery rain had been occurring near the upper trough on the 4th. In fact there was mainly cumulus and stratocumulus, and a few showers near the trough while it crossed Ireland that afternoon. The broad band of medium-level cloud which can be seen over most of England and South Wales at 0000 GMT on the 5th was moving slowly east-south-eastwards and contained a narrow band of thundery rain which was approaching Cornwall and the Bristol Channel. The Meteosat water vapour channel indicated a band of dry air at upper levels close to the axis of the trough at this time (dotted line in Fig. 6). The thundery rain was about 200 km east of the trough axis.

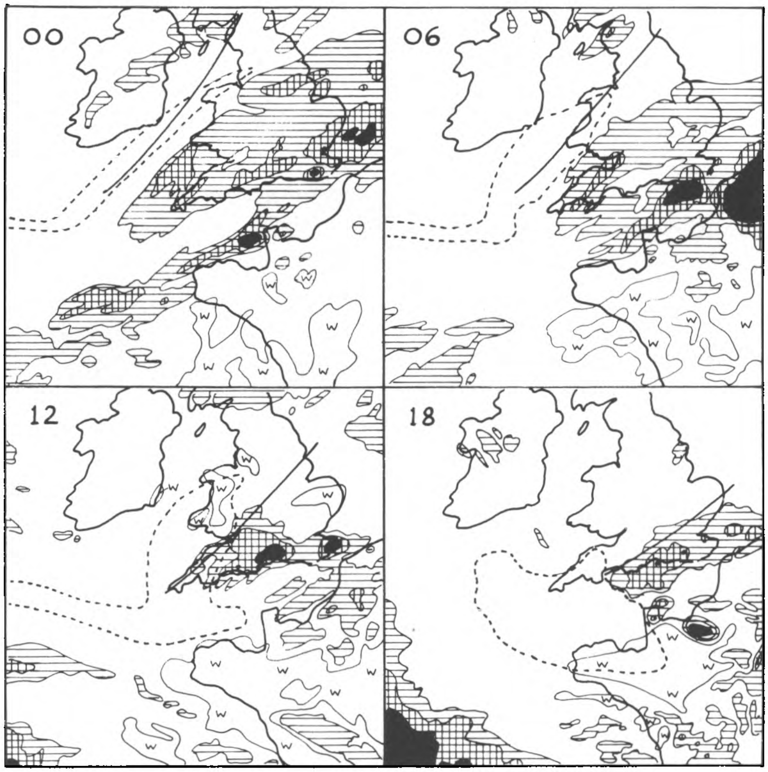

Figure 6. Main cloud distribution at 0000, 0600, 1200 and 1800 GMT on 5 June 1983 as shown by Meteosat infra-red images processed at the Meteorological Office Radar Research Laboratory, Malvern. Horizontal hatching shows cloud tops colder than 0 °C; cross-hatching, −20 °C; solid, −40 °C. Areas marked W were warmer than 20 °C near the surface. The line orientated from north-east to south-west over the British Isles shows the axis of a 500 mb trough. The broken line near the trough shows a region of dry air at upper levels (above about 600 mb) as indicated by the water vapour channel on Meteosat.

The main areas of thundery activity at 0000 GMT on the 5th were embedded in a band of medium- and high-level cloud which extended from sea area Finisterre to the North Sea. This band appears to have been close to the axis of the strongest winds along the baroclinic zone. Some heavy storms moved across the Channel Islands and the coast of north-east France between 0000 and 0600 GMT and a less vigorous storm crossed the English Channel to affect Kent. After 0600 GMT, however, the intensification of the thermal ridge between sea areas Biscay and Shannon eroded the south-westerly flow aloft and cut off the influx of thundery rain. As these storms moved away from south-east England and north-east France, storms developed just ahead of the upper trough and close to the jet entrance. Meanwhile, the narrow band of dry air aloft broadened and moved around the southern end of the trough (Fig. 6, 1200 GMT).

Fig. 6 also shows the areas of warm and mainly cloud-free air as revealed by Meteosat. The radiance values shown here were equivalent to surface temperatures of at least 20 °C. The small areas over the British Isles at 1200 GMT only just reached this threshold, whereas the north-west of France had a sunny and very warm day away from the north coast. Central France was also very warm but there was an extensive cover of cirrus. During the afternoon, cumulonimbus began to build up over north-east France and this became the main area of thunderstorms during the evening as those over southern England decayed.

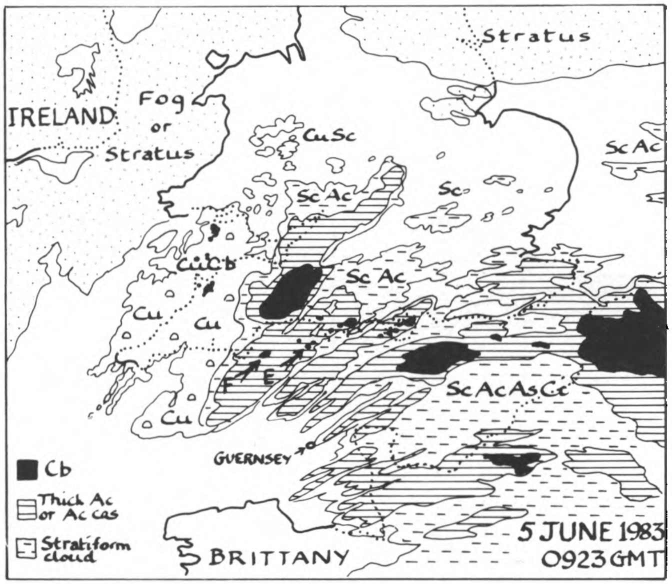

Figure 7. Cloud distribution at 0923 GMT on 5 June 1983, drawn from NOAA-8 visible and infra-red images. Original photographs were processed by the Electronics Laboratory, University of Dundee. The coastline is shown by dots where it was obscured by cloud. Arrows labelled E and F identify the first two of the main storms.

4. Cloud patterns observed at the time of storm development

Fig. 7 shows the cloud over southern England and northern France at 0923 GMT on 5 June. This figure has been drawn from the visible and infra-red images obtained from the NOAA-8 polar-orbiting satellite. At this time, the storms which eventually crossed southern England were beginning to form just to the south-east of Devon.

A broad band of stratus covered northern England and the North Sea. Although the Midlands and East Anglia were mostly clear of cloud at this time, the stratus spread well inland during the day. Over southern England and south-east Wales there was a large cover of medium-level cloud containing several convective areas. From east Devon to northern France the cloud was banded, these narrow bands being orientated from south-west to north-east over central southern England but from west-south-west to east-north-east over south-east England and northern France. Observations from southern England and the Channel Islands show that these were bands of altocumulus which thickened into castellanus along their length. From Meteosat infra-red data it was seen that the tops of the bands were mainly between 500 and 400 mb, but the cumulonimbus tops over north-east France and near the coast of south-east England exceeded 300 mb.

At the time of this satellite image, the axis of the upper trough was probably no more than 50 km to the north-west of Cornwall. Beneath the (probable) closed circulation there were numerous coastal showers, but these lacked clear organization and few of the tops extended higher than 700 mb. The medium-level bands were all located to the south-east of the trough, the approach of which appears to have caused the bands to back into a south-south-west to north-north-east orientation. The broader band across the coast of south Devon may have been formed by the merging of two or three narrow bands. Two of the convective elements in this band are arrowed in Fig. 7. These developed over the next hour to form the leading storms shown in Fig. 1, where they are labelled E and F. Storm E appears to have been an intensification of a cell embedded in the altocumulus castellanus, but it is not clear whether F also formed at castellanus levels or originated at lower levels and grew through the medium-level cloud.

5. Initial formation of the storms as seen by radar

In order to track the storms shown in Fig. 1 back to their earliest point of observation, radar data recorded at 5-minute intervals at Camborne and Clee Hill were analysed (the Upavon radar was not operating on this day). All cells which formed after 0600 GMT were labelled, using C suffixes for cells near the coast of Cornwall and D suffixes for cells over mid-Devon. The most eastward of the five major storms was labelled E and suffixes were used to identify distinct cells contained within each storm complex. This accounts for the labels given to some of the cells shown in Fig. 8, which illustrates this section. (Because the radar measurements are displayed as mean intensities over a 5×5 km grid, the term 'cell' implies a convective area of appreciable size which must be several kilometres from an existing storm to be identifiable.)

From 0600 to 0900 GMT, the thundery rain over south-west England was confined chiefly to a narrow band over Devon (Fig 8, 0843 GMT). This band was moving slowly eastwards, although individual cells were running north-north-eastwards along it. To the west of this band there were isolated showers and a cluster of more widespread showers adjacent to the coast of north Devon. To the east, both the Camborne and Clee Hill radars showed thin bands, less than 10 km wide, lying parallel to the main band over Devon. They were moving slowly eastwards across Lyme Bay but new bands were forming near the Devon coast. From surface observations and satellite images, it is evident that these were bands of medium-level cloud which were just beginning to precipitate.

During the next 30 minutes, small cells began to appear on the Camborne display, embedded in one of these previously weak bands (Fig. 8, 0913 GMT). Cell F_1 intensified and moved over Lyme Bay while weaker cells F_2 to F_4 remained close to the Devon coast (Fig. 8, 0943 GMT). It appears that storm F was basically F_1 but it was enhanced by the growth of cell F_5 just to the south of it (Fig. 8, 1013 GMT). Meanwhile several cells had begun to appear over Lyme Bay; E_1 moved north-eastwards as it intensified and was joined by the developing cell E_2 just before reaching Weymouth (Fig. 8. 0943 GMT). Hence the first two of the five storms appear to have formed almost simultaneously.

Storms G, H and I formed over the sea just south-east of Devon between 1000 and 1100 GMT. G appeared at 1004 GMT as a small cell located 20 km south-east of Start Point. H became visible just to the south of Start Point at 1034 GMT and cell I formed to the south-west at 1058 GMT. All these storms can be seen in Fig. 8 at 1113 GMT. In view of the brief interval between their times of formation, it may seem odd that G, H and I were each separated by at least one hour when they crossed the Dorset

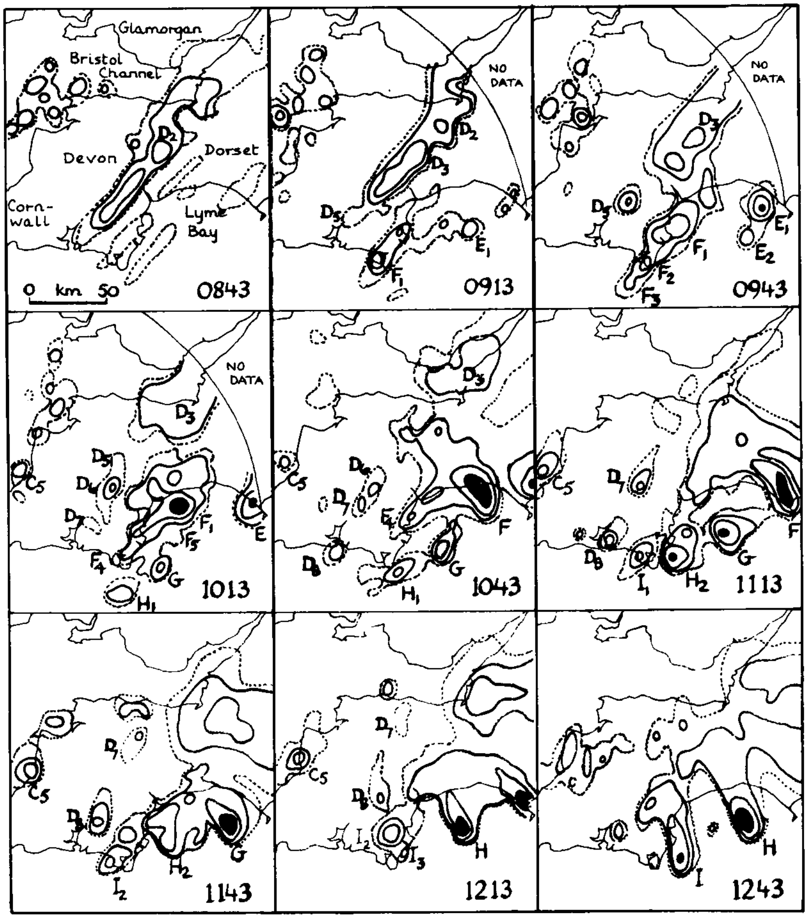

Figure 8. Formation of storms near Devon during the morning of 5 June 1983, as observed by radars at Camborne and Clee Hill. Analyses are shown at 30-minute intervals. Contours show nominal rainfall rates, derived from $Z = 200R^{1.6}$ (where Z is the radar reflectivity factor (mm^6 m^{-3}) and R is the rainfall rate (mm h^{-1})), of 0 (broken lines), 2, 8 and 32 (solid areas) mm h^{-1}. Suffixes are used to identify individual cells contained within each storm complex.

coast. In fact G made a fairly brisk advance across Lyme Bay whereas the cells from which storms H and I eventually grew were initially rather slow moving owing to multi-cell development over the coast of south Devon. Storm H was an intensification of cell H_2, caused perhaps by growth of a new cell very close to it which could not be resolved. Storm I developed from cell I_3 (Fig. 8, 1213 GMT).

A sixth storm (J) began to form about 25 km to the south-east of Start Point at 1330 GMT. After some initial movement north-north-eastwards, the main centre turned east-south-eastwards after 1430 GMT and continued along this track to the limit of radar coverage This storm can be seen in Fig. 6 close to the Cherbourg Peninsula at 1800 GMT. It appears to have crossed the French coast near Dieppe about four hours later.

6. Tracks of the storm centres

The purpose of this section is to record the movement of the areas of heaviest precipitation associated with the storms while they were within range of either the Camborne or Clee Hill radars. If the time at which hail was observed at any site is known, this will enable the storm responsible for its occurrence to be determined. For example, the hailstone of 30 mm diameter which fell at about 1250 GMT at Kimmeridge Bay (10 km south-west of Poole) and is illustrated in Wells (1983), clearly originated from storm G.

Fig. 9 shows for each storm the area bounded by a radar-derived precipitation intensity of 32 mm h^{-1}. These boundaries are shown at 30-minute intervals. Because the most active parts of the storms were characterized by sharp intensity gradients, these contours adequately define the storm boundaries. The actual rainfall rate was not necessarily as high as 32 mm h^{-1} (large hail produces a higher radar reflectivity than rain of normal drop-size distribution); it is likely, nevertheless, that the incidence of heavy rain and hail would have been concentrated within these boundaries.

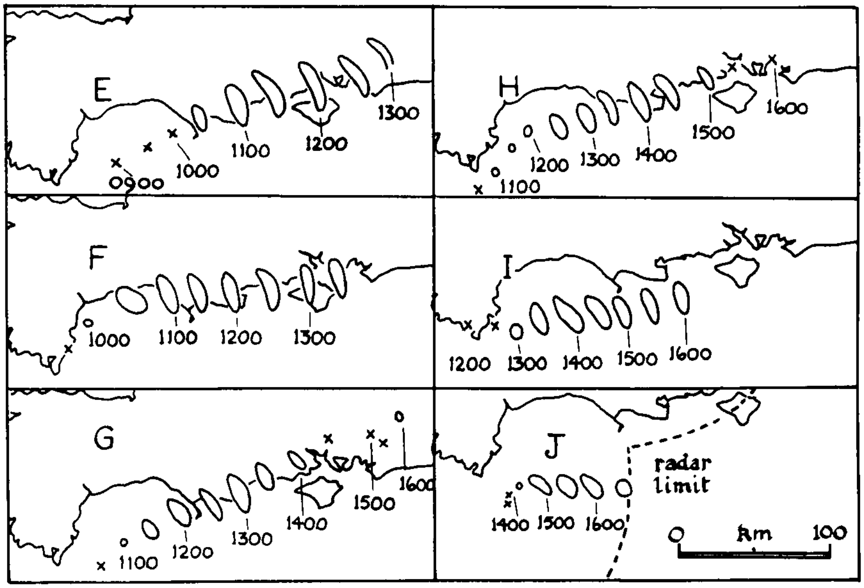

Figure 9. Location of storm centres at 30-minute intervals, shown while they were within range of the Camborne and Clee Hill radars. Elliptical contours show rainfall rates of 32 mm h^{-1} (derived from $Z = 200R^{1.6}$). Crosses show centres which were below this threshold.

With the exception of storm E, all storms began to produce heavy precipitation while they were over Lyme Bay. The intensity of some of the radar echoes at the centres of these storms, which appeared to reach over 100 mm h^{-1} while they were still 30 km or more from the Dorset coast, suggests that hail was already present at this stage although it may not have fallen into the Bay immediately. Storm E had only just reached the 32 mm h^{-1} threshold when it crossed the Dorset coast near Weymouth. Surface reports indicate that all of the storms gave some hail, although very large hail (over 20 mm in diameter) was associated mainly with storms E and G.

One interesting feature of the tracks of the storm centres, compared in Fig. 10, is that four of them (E, F, G and H) intersect over Poole Harbour. These storms were overhead at approximately 1100, 1205, 1305 and 1420 GMT. They appear to have reached their maximum intensity while they were between Weymouth and Bournemouth.

Most of the storms were still intense when they passed out of range of the radars. It will be seen later from the rainfall totals, however, that the heaviest falls had occurred while the storms were just within radar coverage.

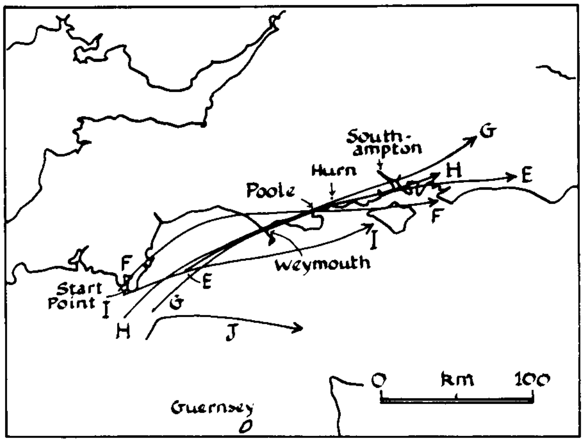

Figure 10. Tracks of the centres of the main storms on 5 June 1983, shown while they were within range of the Camborne and Clee Hill radars.

7. Storm orientation and the development of rainbands

As was illustrated in Fig. 8, most of the storms developed from more than a single convective cell. Usually two or three cells were observed, aligned from south-south-west to north-north-east along the altocumulus bands, with new cells forming to the south of older cells. The intensification of each storm was accompanied by a merging of cells in the south and a change in orientation of the principal axis to south-south-east to north-north-west. This rapid transformation can be seen in Fig. 8 during the passage of storm F across Lyme Bay and is illustrated in Fig. 11 for storm H. From this stage onwards it became more difficult to see new cells forming, although it does appear from the radar intensities that most of the storms underwent intermittent reinvigoration on their southern flank from new cells which were sometimes too close to the main storm to be resolved. The cells which had formed earliest could still be identified for an hour or so because they were moving on a north-north-easterly track, whereas the main centre usually moved east-north-eastwards as a result of cell propagation on its southern flank.

Within one to two hours following the main development of each storm, a band of thundery rain extended north-north-westwards, obscuring the older cells. The bands extended for a maximum distance of 100 km from the storm centres, being longest close to the trough axis. At 1250 GMT, Odiham, Boscombe Down and Yeovilton (see Fig. 1 for location) reported rain and thunder; each station was being affected by different bands which were associated with storms E, F and G respectively, the centre of each storm being 60 km to the south-east of each station. It would be wrong, however, to infer that these bands were solely the product of the coastal storms. The middle levels over central southern England were already cloudy (see Fig. 7) and the decaying cumulonimbus merged with these areas of unstable medium-level cloud. The greater eastward velocity of the coastal storms relative to the decaying cells caused the orientation of the bands to become south-east to north-west as they extended over land.

Fig. 12 is based on the visible and infra-red images of the NOAA-7 satellite taken at 1426 GMT, i.e. at the time of maximum storm activity (for more detail in the cloud structure, see the visible image shown in Wells (1983)). The older storms were beginning to merge, however, presumably because there was less vigorous ascent at middle levels well forward of the trough. Cloud-top radiance levels indicate that the tops of the five main storms reached the tropopause, near 250 mb; the other cumulonimbus tops over

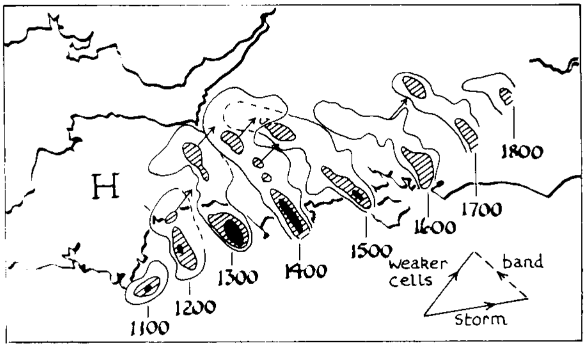

Figure 11. Hourly positions of storm H and its associated cloud band. Contours show nominal rainfall rates of 2, 8 (hatched) and 32 (solid) mm h^{-1}

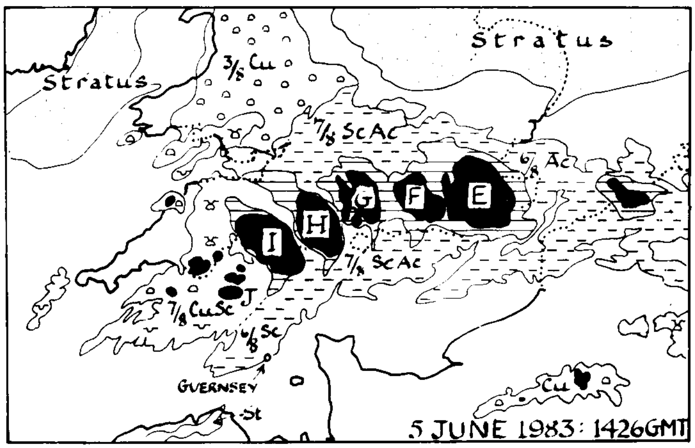

Figure 12. Cloud distribution at 1426 GMT on 5 June 1983, drawn from NOAA-7 visible and infra-red images. Original photographs were processed by the Electronics Laboratory, University of Dundee. The coastline is shown by dots where it was obscured by cloud.

south-west England, including storm J, were nearer 400 mb. Note that the cirrus anvils were not sheared forward of the storms; this implies that, forward of the trough, the winds between 400 and 250 mb decreased to a value equal to the mean storm velocity, which was about 260°, 25 kn. This characteristic is evident only in the Crawley winds at 1200 GMT (Fig. 4).

8. Surface wind and pressure perturbations

Fig. 13 shows the pressure, wind direction and speed, 10-minute rainfall amounts, temperature and dew-point recorded at Hurn (6 km north of Bournemouth) during the passage of the storms. The station was close to the cores of storms E, G and H (see Fig. 10). An enlargement factor of ten was necessary to convert the barograph trace to the same time-scale (one inch per hour) as that used for anemograph charts. Allowance has been made for timing errors; these were indicated by the time marks, which are

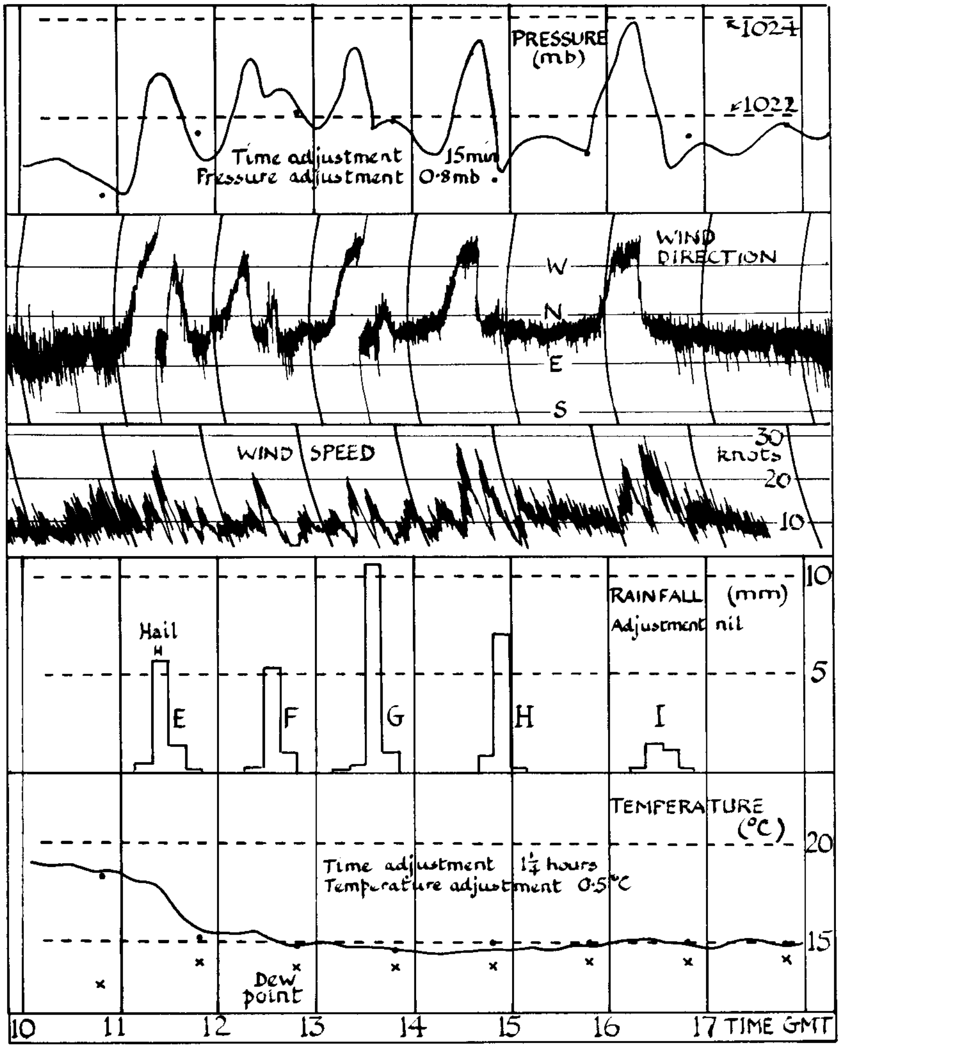

Figure 13. Pressure and wind fluctuations recorded at Bournemouth (Hurn) Airport between 1000 GMT and 1800 GMT on 5 June 1983. Autographic records on which this figure is based were supplied by the Metorological Officer, Hurn. The histogram shows rainfall totals at 10-minute intervals. Dots show hourly (*H*–10) measurements of mean sea level pressure and screen temperature. Crosses show hourly dew-point values.

made once or twice a day. The pressure and temperature reported in the *H*-10 observations were compared with the autographic records: these sometimes indicated a small instrumental error. All adjustments made are noted in the figure.

The 10-minute rainfall totals are plotted with respect to each storm; the wettest 10-minute period of each storm was identified first and then other 10-minute periods were marked off on either side. This procedure avoided the division of wet bursts and hence gives a better indication of the maximum rainfall intensity. Only storm E gave hail at Hurn, some of the stones being 20 mm in diameter. This would have caused the time of clearance of the precipitation as indicated by the rain-gauge to be delayed by several minutes.

A similar analysis was made of the autographic records at Southampton Weather Centre. Provided that the possibility of errors caused by the need to magnify some of the time-bases is borne in mind, these analyses indicate that:

(i) with the approach of each storm, the prevailing north-easterly wind fell light for a minute or two before backing to west-south-westerly and freshening;

(ii) each period of west-south-westerly winds lasted about 10 minutes and was accompanied by a pressure surge of between 1.5 and 3.0 mb;

(iii) the duration of the pressure surge was identical to the duration of the west-south-westerly wind;

(iv) there was usually a lull in the west-south-westerly wind, lasting from 2 to 5 minutes, before the wind returned to east-north-east; at Southampton, which was north of all the storm centres (see Fig. 10), the wind always veered from west-south-west to east-north-east, but there was more fluctuation in the wind direction at Hurn during the passage of storms E and G;

(v) precipitation began to fall while the wind was west-south-westerly but was heaviest during the lulls and for a few minutes after the wind had returned to the north-east;

(vi) the magnitude of the pressure jumps was not directly related to the intensity of the precipitation;

(vii) just to the rear of each storm, there was a minor pressure jump of less than 1.0 mb, sometimes accompanied by a brief fluctuation in the wind direction (this feature was less evident at Hurn than at Southampton);

(viii) very little change in temperature occurred during the passage of the storms, except that the arrival of the first storm (E) caused a general cooling of 3 °C over Dorset and Hampshire and 3 °C to 5 °C further east.

The west-south-westerly winds indicate that a wind reversal of about 40 knots occurred in advance of the storms above the friction layer. Some of the gusts from this direction were as strong as those from the east-north-east; consequently there was sometimes a pronounced double maximum in the wind speed. This feature is evident at Hurn in storms G, H and I (Fig. 13) and also occurred at Southampton in storms E and H.

In spite of the strength of the outflow from the storms, little cooling reached the ground. The temperature fall associated with storm E was too gradual to have been caused solely by the downdraught and was probably due in part to the change from a bright morning to a cloudy one as the altocumulus thickened overhead. Application of the method suggested by Fawbush and Miller (1954) for calculating the surface temperature in downdraughts from cumulonimbus confirms that little fall of temperature was likely. The method is based on the assumption that evaporation of heavy precipitation will cause the downdraught air to be chilled to near saturation, in which case its temperature during most of its descent will follow the saturated adiabat from the wet-bulb temperature at the melting level. Judged from the Camborne and Crawley ascents, the 0 °C level must have been close to 700 mb and the wet-bulb at this level must have been near −2 °C. The saturated adiabat from the wet-bulb to the ground gives 15 °C as the estimated surface temperature in the downdraughts. This was, however, only about 1 °C less than the temperature in the east-north-easterly winds between the storms.

Over south-east England, fluctuations in the pressure and wind were recorded by many stations. Because of the diversity of the storm tracks in the east, however, not all the storms had a major impact at each station. For example, there is little sign of storm G in the wind and pressure records at Gatwick and Herstmonceux although some precipitation occurred there. This storm passed to the north of these stations; hence it is likely that the pressure surge associated with each storm did not extend far to the south of the storm centres.

Fig. 14 is an estimate of the sea-level pressure pattern at 1250 GMT based on surface observations but using the known pressure fluctuations to improve the analysis near the storms. Note that the observations alone indicate the existence of only five 1023 mb isobars, one running from east to west

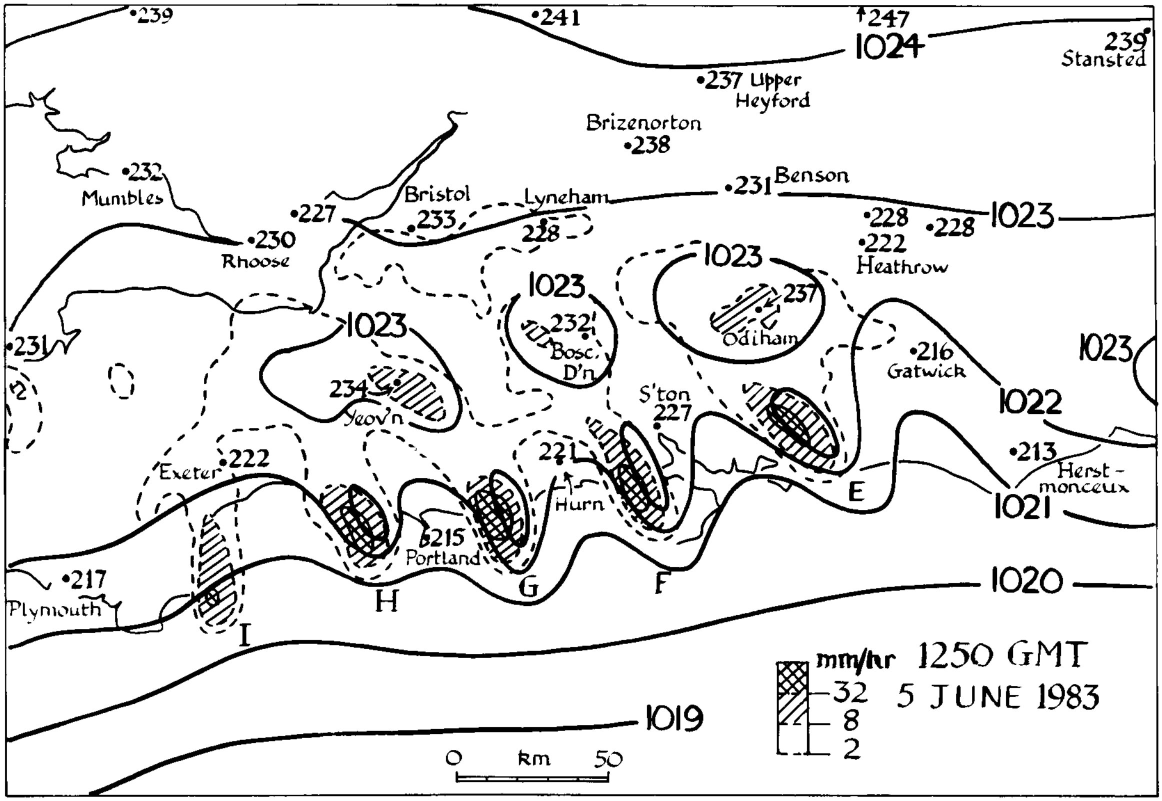

Figure 14. Surface pressure analysis for 1250 GMT on 5 June 1983, with nominal rainfall rates (derived from $Z = 200R^{1.6}$)

across the south Midlands, the others embracing the decaying areas of thundery rain. A further three or four 1023 mb isobars must have existed beneath the mature coastal storms but probably not beneath storm I which was just beginning to intensify.

9. The precipitation totals

Fig. 15 shows the total rainfall caused by these storms. It has been obtained by combining the daily rainfall as measured by rain-gauges over the 24 hours commencing at 0900 GMT on 5 June 1983 with the rainfall derived from radar measurements over the period 0900 to 2100 GMT. The only rain to fall during these periods other than from the storms described here occurred over Sussex and Kent between 0900 and 1400 GMT but amounts were mostly small.

The radar-derived totals were generally larger than the rain-gauge measurements and have been reduced by 30% over Lyme Bay so as to fit the gauge readings over the coast of Devon and Dorset. The radar integration is helpful in showing the growth of heavy precipitation across Lyme Bay and the isolated storm (J) over the English Channel, while the gauges indicate the gradual decrease in rainfall as the storms moved across south-east England. Both the radar and gauge totals showed that the heaviest falls occurred between Weymouth and Bournemouth.

Also shown in Fig. 15 are the distributions of hail, based mainly on the records of official observers. These indicate that large hailstones fell chiefly along a band from near Weymouth to beyond

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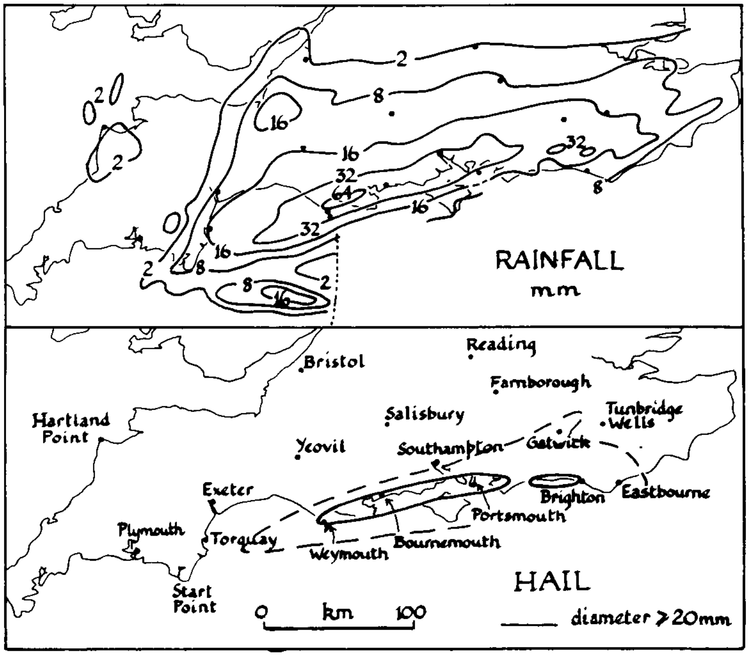

Figure 15. Rainfall totals and distribution of hail associated with the storms of 5 June 1983. Rainfall over land is based on 24-hour totals (commencing 0900 GMT), which were supplied by the Agriculture and Hydrometeorology Branch of the Meteorological Office. Rainfall totals over the sea were derived from radar measurements and adjusted to fit gauge totals over the coast. The distribution of hail is a simplified version of an analysis by E. McCallum, based partly on data supplied by the Climatological Services Branch of the Meteorological Office.

Portsmouth, some of the stones exceeding 50 mm in diameter. This band lies close to, but a little south of, the axis of the highest rainfall totals, suggesting that the larger hail fell in the southern portion of the storms.

Five rain-gauge sites between Weymouth and Poole Harbour recorded total falls of over 60 mm, the highest individual measurement being 74 mm at Winfrith. Bearing in mind that some losses could have occurred through hail bouncing out of the funnels of the gauges and (to a lesser extent) through evaporation of the stones as they lay melting in the funnels, it is probable that the maximum 'rainfall' was about 80 mm.

10. Possible influence of low-level winds and topography on the area of storm development

This section is largely conjectural but is intended to provoke further study into the mechanisms responsible for this type of development.

Arguments in favour of the view that some localized forcing might have influenced development of the storms are that (a) if it is correct that the trough was moving eastwards, then it is surprising that all the storms intensified within such a small area, and (b) once the trough had moved beyond Devon the succession of storms died away. Forced ascent over the hilly land mass of Devon does not seem to have triggered the storms directly. Only cells which formed offshore intensified; hence we require a coastally induced mechanism.

During the night of 4/5 June an east-north-easterly gradient had become established over southern England and the English Channel. By 0900 GMT the geostrophic wind over Lyme Bay was 070°, 30 kn and it probably exceeded 40 kn between Start Point and Guernsey. The flow was stronger over this region of the English Channel than further west because of the movement of a heat low across Brittany (Fig. 2). These east-north-easterly winds were capped by a temperature inversion at about 900 mb, the magnitude of which is hard to judge from the ascents at Brest, Camborne and Crawley (Fig. 4) but may have been only 2 °C near the coast of south Devon. This hilly coast protrudes over 40 km further southwards than the remainder of the English coastline to the east and hence presents a block to the low-level east-north-easterly flow as it crosses Lyme Bay. It is possible that this blocking caused an increase in the depth of the cool air to the east of Devon. Since the warm air over the English Channel above the inversion was probably moving from the south-east quadrant between 900 and 850 mb, its rate of ascent may have increased sufficiently to trigger deep convection before the warm air reached the mainland. The major storms developed from those cells that formed within the bands of altocumulus castellanus, which were regions of maximum instability and moisture. These storms removed the supply of warm air from the broad band over Devon which had been producing thundery rain earlier in the morning, causing this band to decay from the south (Fig. 8).

Recent reports by Rogers and Meaden (1984) of coke being found embedded in hailstones near Bournemouth suggest that the weakly stable surface layer near the coast was readily disrupted by the strong vertical motion associated with the developing cumulonimbus. Pockets of moist air, travelling with a velocity of about 50 kn relative to the cumulonimbus, could have been fed into the base of the storms, accelerating the production of hail.

With regard to the regular 50 km spacing of the mature storms, we have seen that the first two storms (E and F) formed along separate castellanus bands which were moving slowly eastwards (Fig. 8, 0843 GMT). However, the orientation of cells F, G and H at 1043 GMT suggests that several cumulonimbus clouds formed along only one band. Hence the regular spacing of the storms was probably not the result of the eastward movement of equally spaced bands of enhanced medium-level ascent. A more likely explanation is that descending air to the rear of an intensifying storm suppressed convection in its immediate vicinity so that each new development was delayed until the preceding storm had been carried across Lyme Bay away from the generating region.

11. Conclusions

The explosive development of hailstorms over the south coast of England on 5 June 1983 occurred in potentially unstable air on the cold side of a baroclinic zone and just ahead of an upper trough. The trough was rather shallow, being most evident between 600 and 400 mb, and the thickness values along it were rising; nevertheless, it was still fairly sharp and may have contained a small centre as it approached south-west England. Large-scale developments had caused the disruption of the previously broad baroclinic zone from Finisterre to north-west Europe and had displaced the main region of middle-level ascent closer towards the trough. The south-westerly upper winds had remained strong to the south-east of the trough because of the rising thickness values over France and Biscay. Because of the shear across the baroclinic zone, the ascending warm air over the English Channel had become organized into narrow bands of altocumulus castellanus which were producing thundery rain. Drier air, with a relatively low wet-bulb temperature, was moving around the southern flank of the trough as it crossed south-west England; the enhanced convective instability along the forward edge of the cool air led to the formation of cumulonimbus along the medium-level bands. The approach of the trough coincided with the strengthening of a cool and rather moist east-north-easterly flow below 850 mb over the English Channel; this flow was strongest between Devon and the Channel Islands because of the movement of a shallow heat low across Brittany. It is possible that blocking of the cool low-level air by the south coast of Devon may have increased the depth of the cool layer, causing an increased rate of ascent at the base of the warm air as it approached the coast from the south. The production of cumulonimbus was most rapid along the castellanus bands as they moved slowly eastwards across the region. The growing cumulonimbus clouds moved initially north-eastwards along the bands but, as they engaged the stronger west-south-westerly winds around 500 mb, they began to accelerate and veer; cell propagation just to the south of the storms caused the resulting tracks of the storm cores to be east-north-eastwards, which took the storms close to the south coast of England. Vigorous ascent and descent near the cumulonimbus intermittently disrupted the surface inversion, causing pockets of moist low-level air to be fed into the storm. Large hail fell close to the vigorous cores but thundery rain extended north-westwards from each storm as the decaying cells moved more slowly north-eastwards. Each storm developed a well-marked pressure surge and caused sharp wind reversals at sites close to the heaviest precipitation. The succession of storms was ended by a veering and decrease of the upper winds with the passage of the trough, which brought much drier air above 700 mb across southern England during the late afternoon and evening.

Acknowledgements

The author is grateful to Dr J. R. Eyre and D. Jerrett of the Satellite Meteorology Branch of the Meteorological Office for processing the HERMES data. The provision of other data from various sources, referred to in Figs 7, 12, 13 and 15, is also appreciated. Some helpful comments on a preliminary version of this paper were received from Dr K. A. Browning, S. D. Burt and E. McCallum of the Meteorological Office.

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Forecasting road surface minimum temperatures

By J. Roodenburg

(Royal Netherlands Meteorological Institute, De Bilt)

Summary

Nocturnal road surface temperatures were obtained from a recently installed automated network in the central Netherlands. With the use of standard observed weather variables as predictors, regression equations could be derived that calculated the lowest road surface temperature in the network up to 6–12 hours ahead. A test on independent material proved the equations to perform satisfactorily.

1. Introduction

Forecasting road surface conditions for traffic safety purposes has been a notoriously difficult task for as long as the demand for such forecasts has existed. Obviously the ability to forecast road surface minimum temperatures within reasonable margins for up to 6–12 hours ahead would be a step forward.

Literature on this particular subject is scanty. In Britain several experiments have been carried out in attempts to gain a better understanding of surface temperature behaviour. From measurements on motorways near Newport Pagnell and near Bray Wick, Hay (1969) concluded that the best forecast would probably be obtained by simply equating the road surface minimum temperature forecast to the air minimum temperature forecast, for which objective methods are available. Parrey (1969), using readings from a standard grass-minimum thermometer attached to a road surface at Watnall, found a correlation between the date and the difference, minimum air temperature minus minimum road temperature, with a large scatter around individual values. Ritchie (1969) applied Fourier analysis to monthly mean values of minimum air temperature minus minimum road temperature from measurements at Wyton. This resulted in an expression which relates these values to the day of the year. He claimed an accuracy of better than 2 °C throughout the winter season and better than 1 °C on most occasions.

More recently, several physical models have been proposed (Thornes 1972, Rosema and Welleman 1977, Nysten 1980). Although the final word undoubtedly will come from the modellers, as yet their results seem only marginally useful. This is not surprising: the models need input of such variables as net radiation, rates of condensation and evaporation, water vapour pressures, conductivities of road materials — from totally dry to totally wet — cloud amounts, etc. Some of these variables are not accurately known and most of them vary rapidly in space and time.

In this paper a statistical method for forecasting minimum road surface temperatures is presented. The basic material is obtained from a fully automated measuring network in the central part of the Netherlands.

2. The measuring network

By the end of the 1970s a fully automated network, measuring amongst other quantities road surface temperatures, had been installed by the Road Research Laboratories in the province of Utrecht. The network encompasses an area of approximately 1000 km^2; the Royal Netherlands Meteorological Institute at De Bilt (52°06′N, 5°11′E) is conveniently located near its centre. The network consisted of six sites on various four-lane motorways (Fig. 1). At each site thermistors are implanted in the road body at 2 mm below the surface. There is one thermistor for each lane and hard shoulder. A microprocessor at each location provides for assimilation and storage of the data. A central computer at the road authority's main office reproduces, when activated, the road surface temperatures that have been recorded at five-minute intervals over the past hour. The observation sites differ in orientation of the roads (insolation), in number and size of surrounding obstacles, in elevation and in traffic density. Moreover, the roads differ in construction and materials used. In general, however, they consist of a sand bed, a layer of 15–20 cm of gravel asphaltic concrete, a layer of 4 cm of open-textured asphaltic concrete topped by 4 cm of coarse dense asphaltic concrete. The sites were chosen as a result of previous infra-red measurements by the Road Research Laboratories which indicated these locations as 'cold spots'.

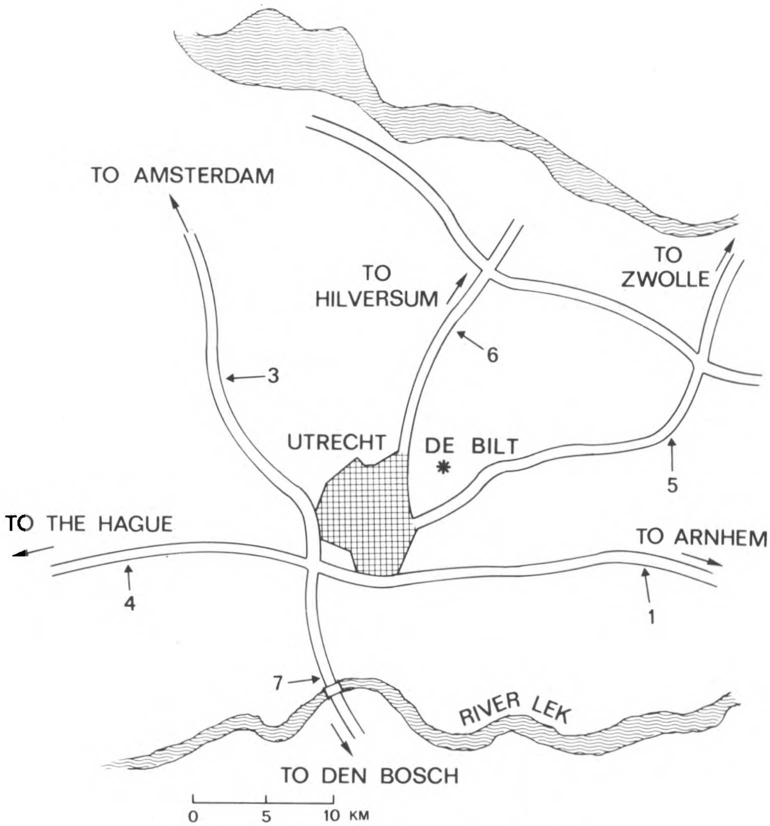

Figure 1. Location of sites used in this study.

3. The data

Every night during the period from 1 November 1981 to 31 March 1982 road surface temperatures were collected directly from the road authority's central computer via a telephone link. To prevent interference with the road maintenance crews, data could be collected only at 0000, 0300 and 0600 GMT. On 10 nights the data were incomplete or missing altogether. From the remaining 141 nights every fifth was set apart to form an independent data set, leaving 113 nights for study. The main computer was instructed to output the lower temperature of any two corresponding (e.g. inner) lanes at all times and at all sites. This seemed sensible from a safety point of view. Frequent calibration of all sensors ensured an accuracy of ±0.2 °C. All other observational material was taken from the records of De Bilt.

Some observations

As little appears to be known about road surface temperatures, it seemed worth while to inspect a few samples in some detail before proceeding to statistical analysis. Three nine-day periods grouped around 15 November, 15 January and 15 March were chosen. Site 3, on the motorway between the cities of Utrecht and Amsterdam, was selected as it is practically free of obstacles. Moreover, the road at that location is oriented north-south, thus giving equal amounts of insolation to all lanes during the, say, six hours around noon. In Figs 2(a)–(c) are plotted the maximum screen temperature and the subsequent 0300 GMT temperature at De Bilt, the lowest road surface temperature recorded between 0200 and 0300

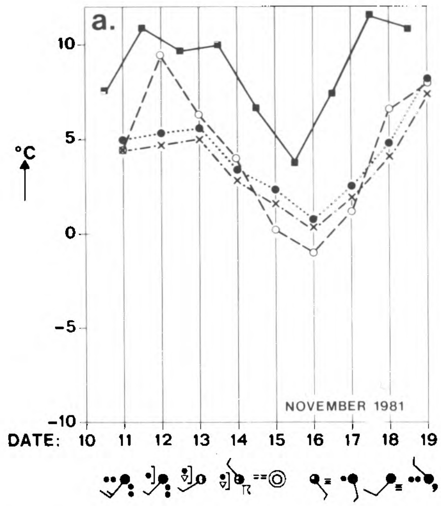

Figure 2(a). Comparison of various temperatures recorded during November 1981. ■ maximum temperature on previous day ○ temperature at 0300 GMT × inner lane ● outer lane

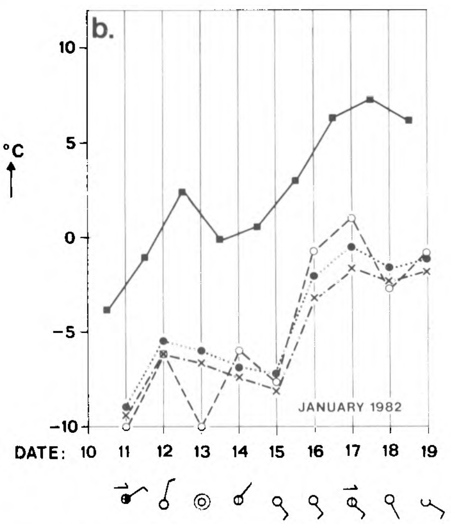

Figure 2(b). As Fig. 2(a) but for January 1982.

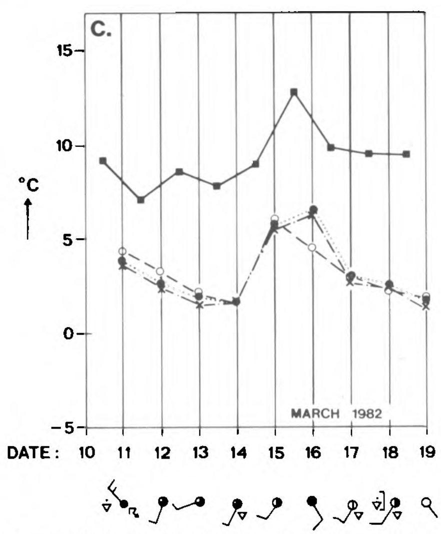

Figure 2(c). As Fig. 2(a) but for March 1982.

GMT on the inner and outer lanes and the relevant part of the 0000 GMT synoptic observation from De Bilt in WMO-standard symbols.

Several interesting features can be inferred from the figures. The large-scale temperature tendencies as depicted by the 0300 GMT temperature curves are reasonably well followed by the road surface temperatures, but the amplitude of the latter is considerably smaller. The screen temperature at De Bilt responds much more quickly to a changing temperature regime than do the road surface temperatures. The day-to-day changes may even differ in sign as on the nights of 12–13 November, 13–14 January and 15–16 March.

The magnitude of this time-lag is thought to depend upon the recent weather history. After a wet spell the thermal conductivity of the road body is at a maximum; even a considerable warming of the air will cause only a moderate temperature rise at the road surface as the absorbed heat is easily transported towards deeper layers. The opposite would occur after a dry spell: the top layers of the road would be thermally isolated from the lower layers and thus be able to follow any air temperature changes fairly rapidly.

Another remarkable effect is the constant positive temperature difference between the outer and inner lanes at site 3; it was the only site that showed this phenomenon consistently. Site 1 (Fig. 1) demonstrated opposite behaviour just as consistently. This could be explained easily as the road's orientation at that location is west–east with extensive sheltering to the south. Therefore the eastbound outer lane (on the Continent one keeps to the right!) will be in shadow most of the time during the low-sun season (remember that the lower temperature of corresponding lanes is registered). At site 6 (Fig. 1) which is also relatively clear of obstacles, and where the road's orientation is south-south-west to north-north-east, no significant differences could be found. According to information from the Department of Traffic Technology the nocturnal traffic density at site 3 is about three times as high as at any other site; this would make the consistent temperature difference between the outer and inner lanes at site 3 plausible.

Screen temperatures usually reach their minimum value near dawn. Road surface temperatures — at least on the roads under discussion — do not. The lowest temperatures are recorded in the middle of the night, after which a general increase can be noted. This is also likely to be ascribed to enhanced traffic density towards morning.

4. Regression equations

During the night, gains and losses of heat by the road surface are governed by various processes. These are listed in Table I, together with those routinely observed and thus easily available weather variables that are assumed to be influential. Moreover, in view of the experiments by Parrey and Ritchie (Parrey 1969, Ritchie 1969) the length of the night was included in the data set.

Table I. *Processes causing changes in road surface temperatures and influential variables.**

Process	Variables
Radiative exchange	Sunshine of previous day, cloud amount during the night, length of night
Advection of sensible heat	Wind speed during the night, maximum temperature of previous day, 0000 GMT screen temperature, presence of snow cover
Advection of latent heat	Ignored in present work
Conductivity of road body	Occurrence of rain
Heat storage in road body	Soil temperatures at various depths, length of night

*All weather variables as observed at De Bilt

Altogether 19 variables were submitted twice to a stepwise forward multiple regression scheme to yield calculated lowest road surface temperatures for the periods 0200–0300 and 0500–0600 GMT. Some of the variables were transformed into binary ones first by splitting them up into classes and assigning a value of 1 to the observed classes and a value of 0 to the remaining classes.

Table II gives a summary of the variables used in order of cumulatively explained variance (period 0200–0300 GMT).

Table II. *Variables used and cumulatively explained variance (per cent).*

1.	Screen temperature at 0000 GMT	85.07
2.	Soil temperature at 5 cm at about 2300 GMT	89.41
3.	Cloud cover at 0300 GMT $\geqslant 7/8$	91.72
4.	Maximum temperature on the previous day	93.39
5.	Cloud cover at 0000 GMT $\geqslant 7/8$	94.47
6.	Snow cover $\geqslant 50\%$	94.90
7.	Sunshine, percentage of possible hours	95.15
8.	Precipitation $\geqslant 0.3$ mm between 0000 and 0600 GMT	95.25
9.	Cloud cover at 0000 GMT $\leqslant 2/8$	95.34
10.	Wind speed at 0000 GMT $\leqslant 3$ kn	95.45
11.	Soil temperature at 10 cm at about 2300 GMT	95.47
12.	Soil temperature at 20 cm at about 2300 GMT	95.57
13.	Length of night	95.59
14.	Precipitation $\geqslant 0.3$ mm between 1200 and 1800 GMT	95.60
15.	Precipitation $\geqslant 0.3$ mm between 1800 and 0000 GMT	95.62
16.	Cloud cover at 0300 GMT $\leqslant 2/8$	95.62
17.	Wind speed at 0300 GMT $\leqslant 3$ kn	95.62
18.	Wind speed at 0300 GMT $\geqslant 8$ kn	95.62
19.	Wind speed at 0000 GMT $\geqslant 8$ kn	95.62

From Table II it is clear that after the seventh variable the increase of variance explained proceeds so slowly as to be virtually negligible. For the period 0500–0600 GMT the same seven variables were picked out by the regression scheme (in a slightly different order) with 94.18% of variance explained. Therefore these variables were again regressed against the lowest road surface temperatures for the periods 0200–0300 and 0500–0600 GMT. This resulted in the following regression equations:

$$T_{R3} = -3.73 + 0.37T_0 + 0.34T_{s5} + 1.30N_3 + 0.22T_x + 1.11N_0 - 1.12s - 1.28S. \qquad (1a)$$

$$T_{R6} = -3.00 + 0.39T_0 + 0.34T_{s5} + 1.17N_3 + 0.19T_x + 0.72N_0 - 14.3s - 2.18S. \qquad (1b)$$

The correlation coefficients were 0.98 and 0.97 respectively.

The symbols have the following meaning:

T_{R3}, T_{R6} : the lowest road surface temperature at any site for the periods 0200–0300 and 0500–0600 GMT, respectively (°C);

T_0 : screen temperature at 0000 GMT (°C);

T_{s5} : soil temperature at a depth of 5 cm (°C);

N_3 : this variable becomes 1 if at 0300 GMT cloud cover is 7/8 or more ('sky indiscernible' included), otherwise it becomes 0;

T_x : maximum screen temperature of the previous day (°C);

N_0 : this variable becomes 1 if at 0000 GMT cloud cover is 7/8 or more ('sky indiscernible' included), otherwise it becomes 0;

s : this variable becomes 1 if at least half of the surrounding area is covered by snow, otherwise it becomes 0;

S : percentage of sunshine possible of previous day divided by 100.

In order to test the merits of the equations, they were applied to the data set that was kept apart (28 days). The results are summarized in Table III; calculated and observed values are plotted in Fig. 3.

Table III. *Performance of equations on independent data*

	T_{R3}	T_{R6}
Correlation coefficient	0.97	0.96
Root-mean-square error (°C)	0.98	1.19
Mean absolute error (°C)	0.71	0.90

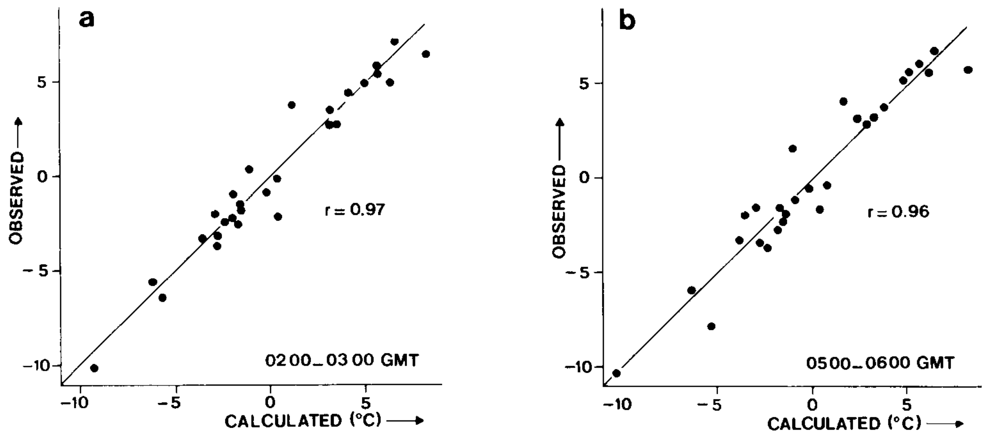

Figure 3. Calculated versus observed temperatures for (a) 0200–0300 GMT and (b) 0500–0600 GMT.

5. Discussion

With one exception, the variables that appear in the equations contribute to the minimum road temperature in the way to be expected on physical grounds. Sunshine, however, seems to lower road surface temperatures. This is undoubtedly due to the net radiation balance being negative in temperate latitudes during winter. Probably persistence is also partly responsible.

Advection of latent heat had to be ignored in the present work as no data were available.

Wind speed does not enter into the equations. This is supposedly due to the differing orientations of the roads, which would average out any effects. There was, however, a weak positive correlation between the class with wind speeds > 8 kn and road surface temperatures, confirming the well-known fact that stronger winds inhibit cooling. Thermal conductivity of the road body was represented by the occurrence or non-occurrence of precipitation. Here there was little or no correlation with road surface temperatures.

It should be noted that the results shown in Table III are optimistic, as the 0000 GMT screen temperatures as well as the cloud conditions during the night were taken from observations, whereas in operational practice these will have to be estimated by the forecaster. From previous experience (Roodenburg 1983) it is assumed that this will not lead to a serious deterioration of the results.

The equations have been programmed for interactive use on a computer. Quantities that have already been measured are fed in automatically. The system works satisfactorily.

6. Conclusions

Despite the limited data set and the rather crude way in which some of the physical processes involved have been represented, it is believed that the present method will be useful in providing the forecaster with guidance as to the lowest road surface temperature to be expected during the coming night.

Acknowledgements

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Closure of the meteorological office at Paphos

By. W. G. Durbin

(Meteorological Office, Akrotiri)

The closure of the meteorological office at Paphos in the south-west of Cyprus on 30 June 1984 marked the end of an unbroken period of hourly weather observations which, from the final site, began in May 1947. They were not, however, the first to be made from the Paphos area, there having been three earlier sites.

The first of these, established in January 1881 in the grounds of the town hospital, was known as Papho (not Paphos). Under the auspices of the local medical authorities, climatological observations were made twice daily at 9 a.m. and 9 p.m. by staff named Thomson, Olive and Young. The elements observed included air temperature (wet- and dry-bulb, maximum and minimum), rainfall (with estimated duration), cloud amount and type, atmospheric pressure and wind (direction in compass points and speed in Beaufort force). There was also what was called solar radiation but as it is unlikely that a Campbell–Stokes sunshine recorder would then have been available, even Kew Observatory having been equipped with one only the previous year in 1880, it was probably 'black-bulb' temperature rather than sunshine duration. Until June 1882 the returns were completed in an exemplary manner, beautifully written and with few errors, by the District Medical Officer Amin Moghabghab who, under an arrangement notified by a 'Fred W Barry Sc' who also countersigned the returns, had been given charge of the instruments from the end of February 1881. The heights of the barometer and rain-gauge were both originally given as 250 ft but in August 1881 the former was changed to 265 ft, possibly as a result of reassessment. In December 1881 they changed to 230 and 204 ft respectively which suggests a minor move to a nearby location. There were no returns for July 1882 but from August of that year they were signed by the new District Medical Officer Elia Malliotis who remained in post until December 1900. In 1901 a Mr Entwistle took over the station and the height of the barometer cistern changed to 243 ft. Thereafter the returns bore various signatures including, from 1908 to 1910, a Mr Ierotheos V. Zachariades who signed himself 'Government Compounder'. In the early days the name of the town was Ktima and it was in favour of this that in 1900 the name Papho was dropped but in December 1911 there was another change with the returns being headed 'Paphos Hospital'.

Observations from the second site, the latitude and longitude of which were given as 34°46'20"N, 32°25'40"E, began in January 1917. At that position, which is half a mile or so south of the first site, the height of the ground above mean sea level is about 160 ft so either that position or the 100 ft given for the height of the rain-gauge is in error. Returns continued from this location until June 1936 when apparently the station closed. From 1922, however, the returns were sent to the Physical Department in Cairo, regrettably without a copy being kept in Cyprus, and it has not been possible to trace them.

For a short period from 5 November 1940 observations recommenced on an hourly basis from the coastguard station which, as the third meteorological site, was at Paphos castle, but in 1941 they became three-hourly, possibly for reasons of staff shortage. The move to the final location, some 400 metres to the north-north-west on what was then open ground, took place at the end of 1944. The heights above mean sea level of the barometer cistern and rain-gauge became and remained at 28 and 33 ft respectively, notwithstanding a further move of 100 metres or so on 21 January 1947.

The Paphos office was the last of three initially set up in co-location with coastguard stations for observational purposes in support of operational flying by the RAF. The others which opened in 1941 were at Cape Andreas and Kyrenia castle. The former provided 3-hourly observations until, owing to problems concerned with the provision of drinking water, it moved in 1954 to Ayios Nikolaos. It was eventually to close in 1977 as a consequence of the opening of the nearby meteorological station at Larnaca airport. The station at Kyrenia moved to Morphou where it closed in 1963. These stations provided advance notification of weather approaching from different directions which would affect RAF airfields of which, after 1974, only Akrotiri remained. The importance of Paphos in this context can be judged from the fact that the next nearest observations to the west are from Crete, about 400 miles away. Paphos is only some 35 miles from Akrotiri but, when the weather is approaching from that direction, its hourly weather observations and four-times daily pilot balloon ascents have enabled changes likely to affect landing conditions at Akrotiri to be forecast more precisely, a matter of greater importance when aircraft having limited fuel reserves are being dealt with.

The Paphos office closed because Cyprus's second civil airport which has been built a few miles away requires its own meteorological station and there is no necessity for two to continue to exist so close to each other. The new airport opened, for day flights only, on 1 November 1983 with observations for 12 hours a day but from late March 1984 they were extended to 18 or 24 hours depending on the use being made of the airport. With the continuous RAF requirement for Paphos observations to be available throughout the 24 hours a period of overlap was necessary but, from 1 July 1984, only the airport meteorological office, administered by the Cyprus Meteorological Service, remained.

Archaeology

As an area of interest in Cyprus, Paphos has a history going back several thousand years and there are many archaeological sites to attract the tourist. One of the most important finds was made in 1962 when about 200 metres north-east of the meteorological office site, diggings brought to light the House of Dionysos, a Roman villa dating from the third century AD. Its rooms, grouped around an open court, are paved with mosaic designs, some of which are geometric while others include subjects taken from Greek mythology and many are in a perfect state of preservation. Two hundred metres or so to the south-south-west another important find, also with well-preserved mosaics dating back to the fourth century, is the Palace of Theseus which probably served as an official residence of the Roman governor of Cyprus. Excavations have continued in the area bringing to light a theatre, the remains of many less important dwelling places and, within the last year or so, yet another important mosaic, this one being at the entrance to the path leading to the meteorological office. It will clearly be a time of great excitement when, with the closure of the station and the handing over of the site of the Cyprus government, excavations can begin to find out what lies underneath.

Staff

Reference has already been made to staff who from 1881 were concerned with the provision of observations from earlier locations of the meteorological station. The last site, occupied since 1944, was of rough grassland and had an abundance of snakes which was a problem to the staff who were required regularly to visit the enclosure, both by day and by night, to read the instruments. In 1963, one of them named Angelos Andreou, having tried other means of keeping them away such as by the planting of

Photograph by courtesy of Mr I. J. W. Pothecary

Staff of the meteorological office at Paphos, May 1984. From left to right: Messrs Pavlos Hajinicola, Pavlos Constantinides, Demetrius Kyriacou, Lewis Deacon and Costas Kyriacou.

garlic, decided to keep a cat. Owing to the apathy of his colleagues, he regularly visited the office during his days off to feed it but with his wife objecting to the extent to which her husband's spare time was being eroded, the problem became more serious when the cat produced four kittens. Andreou decided to refer the matter to the Senior Meteorological Officer at Nicosia and asked for a daily allowance both to buy tinned food for the cats and to oblige his colleagues to feed them. The S Met O consulted the Financial Adviser at HQ NEAF who, to the surprise and amusement of all concerned, authorized the Assistant-in-Charge at Paphos to draw a cat allowance of one shilling and threepence a day to buy tinned food. The cat thus came on to the office strength and the allowance continued until it closed. The last cat, called Tiger, was the third in line, the first having been killed and the second having disappeared — perhaps enticed away to a better-paid job at, for example, one of the nearby fish meze restaurants. The third, which was in post for some five years, was very good, always around the office and on parade at times of inspection, and the snake menace was kept well under control.

At the time of its closure the Paphos office had a staff of five. With its closure two of them, Mr Demetrius Kyriacou and Mr Pavlos Hajinicola have been transferred to Akrotiri but the others, each with 35 years of service, will retire. Mr Lewis Deacon, who was in charge at Ayios Nikolaos when it closed, will retire to Larnaca. Mr Pavlos Constantinides will retire to his village of Aradippou which is near Larnaca, and the brother of Demetrius, Mr Costas Kyriacou, who was in charge, will retire to Nicosia.

All those who have served in Cyprus and who, as visitors to the Paphos office, have enjoyed the warm hospitality of its staff, so much a feature of the Cypriot people, will wish them long and happy retirements.

Notes and news

Retirement of Mr Geoffrey J. Day

When Mr G. J. Day, Assistant Director, International and Planning, retired from the Meteorological Office on 11 September 1984 he completed a career of 34 years in which he had filled at least ten separate posts and had left his own individual mark on all of them.

Geoff Day was educated at Bablake School, Coventry and, following a period of National Service from 1943–46, he went on to gain his B.Sc. (Hons) at St. Andrews University, Fife. After a brief foray into the coal industry, he joined the Office as a Scientific Officer in November 1950. After initial training he was posted to the Meteorological Research Flight where he worked hard and successfully on measurements of the liquid water content of cumuliform clouds and on sampling freezing nuclei using new instruments of his own design.

In autumn 1955, following promotion to Senior Scientific Officer, he moved on to Kew Observatory where he quickly became energetically involved in the problems of measuring solar radiation. It is not surprising that he foresaw the need to implement a nationwide network of radiation instruments, and that he was sorry when the time came for his next move, to Eskdalemuir as the Superintendent in January 1959. At Eskdalemuir, Mr Day was in charge of, as well as routine administration, a wide range of geophysical scientific apparatus covering measurements in geomagnetism, atmospheric chemistry, solar radiation and atmospheric electricity. He suggested and carried out many improvements to the instruments and also made a broader survey, comparing magnetic standards at the Observatories which then existed at Lerwick, Eskdalemuir, Stonyhurst and Hartland.

In 1961, and with some reluctance at first, he moved to a forecasting post at Prestwick Airport. However, he quickly set about learning the new skills required, and his positive approach and alert mind turned out to be well fitted for the shocks and strains of synoptic forecasting. Before the year was out he was promoted to Principal Scientific Officer and had become a Senior Forecaster at Prestwick with all the duties that the post entailed. By August 1963 he was in charge of the Main Meteorological Office at Prestwick, and he was then moved again, this time to take over as the Senior Meteorological Officer at Luqa, Malta. While in Malta he had some of his earliest experiences of negotiating as a UK representative on the AFMED, AFSOUTH Meteorological Committee at meetings in Toulon and Naples, and of the work of WMO as the UK Observer at a meeting of Regional Association I—Africa in Lagos.

In September 1966 Mr Day returned to research and to the post of Superintendent Met R D at Porton Down. There his research effort was directed to the microphysics of the planetary boundary layer, and his negotiating skills were turned to providing co-operative liaison between his Unit, CDE and MRE. He successfully obtained, and ran, the old Mercury computer (ex-Bracknell) while acting as Chairman of a Meteorological Office/CDE/MRE Working Party to specify a suitable ICL 1905 computer system to meet the needs of the whole Porton Down Establishment.

By June 1971 he had spent over four years at Porton, so he was again moved, this time to be Head of the section of the Operational Instrumentation Branch in charge of the development of new operational surface instruments (Met O 16a) and with special responsibilities for automatic weather stations. Once again he took to his new environment with enthusiasm pressing forward in various areas of intrument development and playing an increasing role in international matters, first as Chairman of the COST Project 72 Working Panel on Automatic Weather Stations, then in WMO Commission for Instruments and Methods of Observation affairs, and later in the COST 43 Sub-group on a Faeroes/Shetland data buoy network. His name began to be well known in WMO and IOC (Intergovernmental Oceanic Commission) circles where he created a very favourable impression by his capable and diplomatic manner. He also showed considerable organizational and administrative skills acting as the deputy to the Assistant Director, and few of us were surprised when, in July 1975, he was moved yet again, but this time on promotion to Senior Principal Scientific Officer.

Mr Day was ideally suited to his new post as Assistant Director, Observational Requirements and Practices. His Branch (Met O 1) was concerned with running the network of observing stations and upper-air stations, with trials of new equipment, and with the definition of the requirements of the forecasters for new observations and measurements. The post also gave him an increased involvement in international affairs through participation in the WMO Commission for Basic Systems Working Group on the Global Observing System and as a member of the IOC/WMO Working Group on the Integrated Global Ocean Station System Basic Observing Network.

In December 1977 came his final, and most important move, to the rather special task of Assistant Director, International and Planning. In this post he acted in close proximity to the Director-General as an aide in the preparation of briefs for sessions of WMO and its constituent bodies and as a focal point in the United Kingdom for communications between international bodies, such as WMO and State Meteorological Services, and the Meteorological Office. His skills of diplomacy and tact, his professional knowledge and his shrewd common sense combined to make him a true ambassador for the United Kingdom, and he played an increasingly prominent part in the affairs of WMO and the European Centre for Medium Range Weather Forecasts (ECMWF). As Deputy to the Permanent Representative of the United Kingdom at attendances of WMO Congress and the Executive Committee he earned much respect and goodwill, and as time passed he was to be found as Chairman of the Working Group on Antarctic Meteorology, Chairman of the ECMWF Finance Committee and Chairman of the Programme Board for ASDAR (Aircraft for Satellite Data Relay), all tasks to which he was elected on the basis of the competence and diplomacy that he showed.

Geoff Day had a reputation as a 'bit of a rebel' in his early days, and was given to occasional outbursts of anger. This was no doubt largely due to frustration at the frequency of his moves, which, each time, seemed to occur just as he was beginning to make real progress. He was also often ahead of his time in seeing the need for changes in organization and management, and this too caused his wrath. It is interesting to reflect on the way he has transformed these characteristics, and to note that he will be missed now both in international and national circles for his diplomacy, charm and professional ability. He will be continuing his interests in some WMO activities after his retirement and I hope that he will continue to drop in to see us for many years to come. We wish him and his wife, Barbara, a long and happy retirement.

D. N. Axford

Meteorological observations of the Welsh Plant Breeding Station

In November 1983, Mr 'Wil' Evans of the Welsh Plant Breeding Station (WPBS) Agronomy Department was presented with a barograph to mark 30 years of observations for the Meteorological Office. The presentation was made by Dr J. R. Starr, Regional Agrometeorological Officer for Wales, on behalf of the Director-General and in the presence of the retiring Director of the WPBS, Professor J. P. Cooper, FRS.

WPBS carries out research and development work into the improvement of crops such as grasses, clovers and cereals, which are important in livestock production, particularly in Wales and the west of Britain. Climatological observations have been made at WPBS since soon after its establishment in 1919, initially at Frongoch, a hill site at 138 m above mean sea level (amsl), 2 km east of Aberystwyth.

Investigations into hill land improvement led to the establishment in 1927 of a further climatological site 11 km inland at Llety-Ifan-Hen (290 m amsl). When, in 1953, WPBS moved to Plas Gogerddan, 4

Photograph by courtesy of Cambrian News

Mr 'Wil' Evans (centre) being presented with a barograph by Dr J. R. Starr, in the presence of Professor J. P. Cooper, FRS.

km inland from Aberystwyth, Mr Evans began observations at the new meteorological station (Gogerddan, 31 m amsl).

All three sites became agrometeorological stations. Subsequently, two further stations at Syfydrin, 335 m amsl, 14 km inland, and Pant-y-dwr, 305 m amsl, 40 km inland, were maintained for a time in the 1960s and 1970s. These WPBS sites, situated near a west–east transect running eastward from Aberystwyth along latitude 52°25′N, were considered representative of the main zones of upland grassland production, with the associated climatological, geological and hydrological characteristics.

Frongoch ceased to be an official recording station in 1969; Llety-Ifan-Hen ceased in 1976, having had only two observers in its 50-year history!

The data assembled from these various WPBS sites over the years have emphasized the extent of altitudinal, topographic, seasonal and diurnal restraints on grassland production and have led to breeding and management programs to improve grassland potential.

Meteorological Magazine — increase in price

As from January 1985 the price of an issue of the *Meteorological Magazine* will be £2.30 and the annual subscription will be £27.00 including postage.

Review

Cloud dynamics, by L. T. Matveev. 164 mm × 246 mm, pp. x + 340, *illus.* D. Reidel Publishing Company, Dordrecht, Boston, Lancaster, 1984. Price Dfl 190.00.

This book is primarily a review of the cloud physical research that has been carried out in Russian institutions over the past 10–15 years. It makes fascinating reading, for although all the major subjects are covered, the approach is often totally different from that to which western scientists have become accustomed. As such the book will be of interest mainly to scientists actively engaged in research.

I found the book difficult to read, mainly because many important points were merely hinted at and then followed by a long string of reference numbers, in one case 20; at least if the names had been given, one or two might have been recognizable and the point grasped without constant recourse to the reference section. There was also the difficulty that well over 90% of the papers mentioned were Russian, (and not easily obtainable) and the few foreign papers that were quoted were generally fairly old. It would have been helpful if the references had been equally split between Russian and foreign sources.

The title of the book is also rather misleading. There is little discussion of cloud dynamics as such, the author being more concerned with microphysical processes within real clouds, and how they are influenced by the air motion. This approach is most evident in the mesoscale section where only 6 pages are devoted to the modelling and description of the air motion within convective clouds. Equally disappointing was the section on the prediction of cloudiness and precipitation. This chapter contained a large section on the Meteorological Office 10-level model, and the, now famous, integration of 1 December 1961. There was little description of subsequent results.

The main value of this book is that it is a review of Russian literature and current Russian ideas. As such it provides a useful summary of a vast body of literature that is not easily obtainable in the west. However, it will be of little use to the student trying to understand the subject.

D. A. Bennetts

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