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The use of automatic weather stations in the observational network of the United Kingdom

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Summary
The current policy for the use of automatic weather stations by the Meteorological Office in the observational networks of the United Kingdom is described. Plans have been made for the use of land-based automatic weather stations for synoptic and climatological purposes, and for marine automatic weather stations where appropriate.

1. Introduction

The concept of automatic weather stations (AWS) and automation for meteorological instruments in general has been around for many years, but it is only recently that technology has developed to the point where our ideas and hopes can, by dint of a concentrated and purposeful effort, be put into practice. This is an exciting and challenging area where the Meteorological Office has been working actively for the past decade, and where forward planning extending over the next 10 to 20 years has been necessary.

It is of interest to quote the words of Henri Treussart (1977), the current President of the World Meteorological Office Commission for Instruments and Methods of Observation. In 1977, he wrote:

> 'Automation is a long and exacting task . . . and it is perhaps not without interest to remember that the first Working Group on this question was formed 20 years ago. Since then things have changed considerably. Technology has advanced enormously, but perhaps more importantly in recent years there has been a great change in the concept of the role of automatic weather stations.
>
> 'At first AWS were regarded as a substitute for human observers, but they have now become complementary to them. AWS can be of assistance anywhere where the multiplicity of observations to be made makes the work of an observer particularly difficult, and anywhere where it is necessary for a high spatial density of observations. . . . There can be no doubt that automation will be the main component in the development of observing techniques in years to come.'

He continued by stating his belief that the future of meteorological observing and meteorological observational networks is on the eve of a transformation in kind. This change will be dictated by the evolutionary change in the objectives which are assigned to meteorologists, and in the facilities which will be available to them.

Treussart was describing the current move for observational networks to be designed to provide the meteorologist with a picture of the weather continuous in space and time. The Short-period Weather Forecasting Project is an example of such a move. Here we see the first real efforts to co-ordinate the measurements from satellites, weather radars, upper-air stations, synoptic observations stations and automatic weather stations into a single comprehensive picture of the current weather and to use this combination of new and old facilities to provide better meteorological facilities and services for the community at large.

The Short-period Weather Forecasting Project is, of course, only experimental. That is right and proper since it is necessary to make changes cautiously without disturbing the general work of the Services side of the Office. It is essential that only proven techniques are used, and that long, thorough and exhaustive trials are performed before putting new observational systems into the field.

Before proceeding to describe the plans of the Office for AWS, the four main guiding factors which will control their introduction must be described.

(a) *Economics.* New, modern observing methods involve considerable investment. This investment must be considered in the light of the resources available for meteorological purposes—in our case the Meteorological Office budget of £30 million per annum. We must take a pragmatic, even an evolutionary, approach, bringing in new equipment on an 'as and when' basis as technology allows prices to fall—as it is doing in the field of electronics—and the cost of observations made visually rises.

(b) *Staff.* There are three aspects to this factor. First, it is no longer the case that eager amateurs will necessarily make reliable routine measurements for the Meteorological Office out of interest in the science. Auxiliary and amateur observing stations are closing down and are not always being replaced, so it has been necessary to consider installing AWS to fill the gaps. Secondly, as new techniques are introduced there are problems of training in their use, and an understandable reluctance on the part of the user to depart from the customary. The forecaster of the future will need to know which observations have been made by an observer and which come from AWS since it will be up to him to assess the credibility of the readings and to take the quality control measures he sees fit. Thirdly, there is the problem of training the staff who will be required to maintain the new equipment in operational condition. The steady growth in the size of the Meteorological Office Maintenance Organization (now about 100 technicians), and the consolidation of the structure required to cover the United Kingdom, demonstrates that we are already having to deal with this problem.

(c) *The international factor.* Because meteorology is by nature international, any changes in procedures within national boundaries have to be carried out within certain wider guidelines set for the international community. This implies extensive co-ordination at World Meteorological Organization or European levels, which of course results in the slowing down of any attempts to modify procedures or methods of use. This means that any proposed change needs to be made known long before the date on which it is intended (or hoped) to be implemented. Thus, only by a long and single-minded effort over a period of 5–10 years (or more) can such a change gain the agreement of the international community.

(d) *The basic network requirements.* It has been agreed within the Office that there is a need for a basic network of 'key' synoptic observing stations, each fully manned by professional observing staff. This basic network is required to maintain the standards, quality control and meteorological integrity of all observations in the United Kingdom. Taking into account the international, regional and local requirements of meteorologists and the different synoptic meteorological characteristics which can be found over the United Kingdom, a requirement has been established for a minimum of 30 such key stations at which manual observations are required hourly throughout the 24 hours. This must not be confused with the separate requirement for a climatological network, for which approximately 90 climatologically different zones have been distinguished in the United Kingdom. Again there is a long-term requirement for at least one fully manned principal or 'key' climatological observing station in each zone.

It is against the background of these 'key' manual observing stations that automatic weather stations are being considered to supplement the manned network and, as far as possible, to fill any gaps that exist.

2. Automatic weather stations—the equipment

2.1 *Definitions*

In a paper by a WMO/CIMO Working Group on Automatic Weather Stations at Helsinki (WMO, 1973) an AWS was defined as follows:

'AWS—An automatic facility that measures, transmits and/or records meteorological data, in numerical form, for extended periods of time with, or without, a facility for the manual insertion of data.'

This covers a very wide field including radiosonde systems, automatic weather radar systems and other specialized equipment, which are not the subject of this paper.* The AWS with which we are concerned here may be subdivided for convenience into four distinct categories:

(a) *Synoptic AWS*
(b) *Climatological AWS*
(c) *Specialist AWS:*
Airfield
Agrometeorological
Hydrometeorological
Mesoscale
(d) *Marine AWS:*
Fixed platform
Shipboard including Lightships
Buoy-borne

Whereas the design of an AWS will be modified appropriately for these different purposes, the essential ingredients of any AWS are the same, and there are obvious economic advantages in using common components for different applications where this is suitable.

2.2 *Block diagram*

Figure 1 is a block diagram showing the essential components of any AWS:

(a) Sensors —These can be analog or digital, and ideally should be able to measure all possible types of meteorological variable.

(b) Sensor interfaces —To transform the sensor output to a suitable form to be connected to the central data processor. It is the combination of sensor and sensor-interface that has to have the requisite long-term accuracy, resolution and reliability.

(c) Central data processor —This unit accepts the data input, and reorganizes the data in a suitable format for output to the various peripherals. It can either be a 'hard-wired', special-to-type unit or it can be a micro-computer unit with its exact functions defined by a software program.

* A further article on the design of AWS and the characteristics of the sensors being used or evaluated for United Kingdom use will be published in the near future.

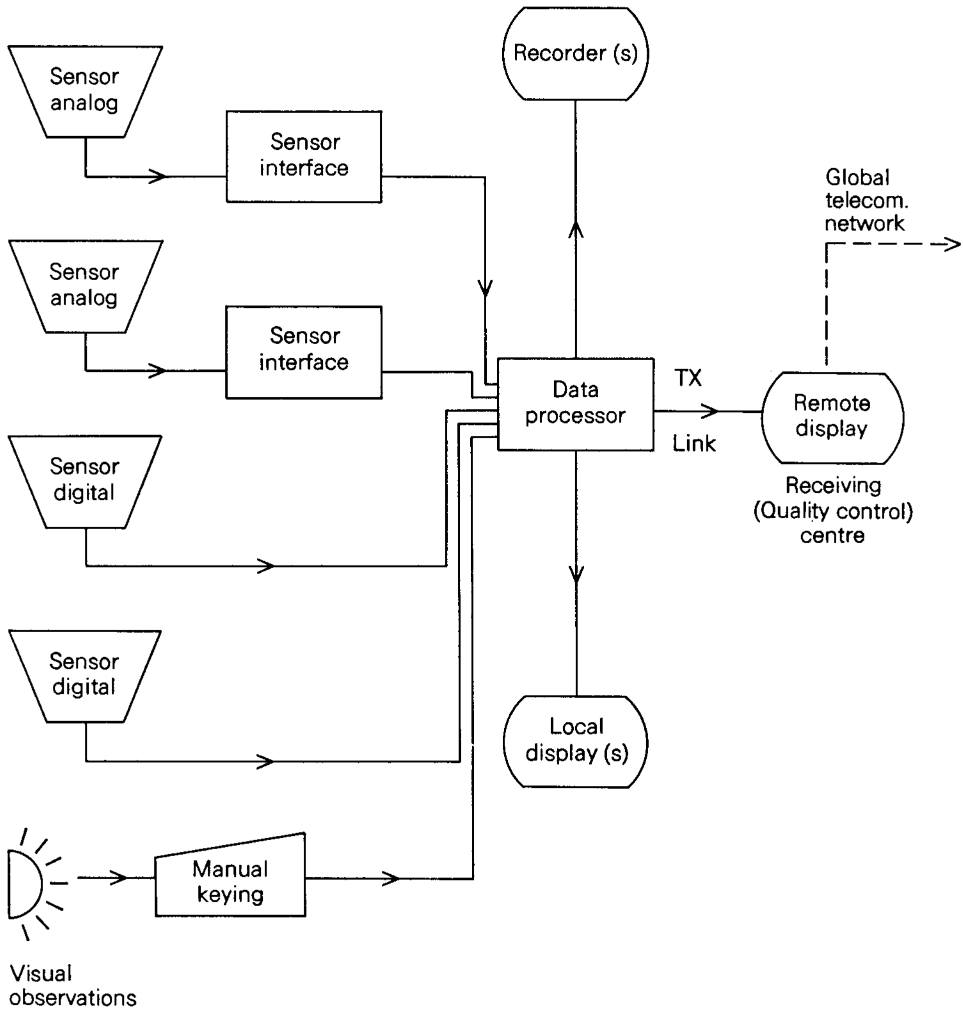

Figure 1. The essential ingredients of an automatic weather station.

(d) Manual input —In some applications it is convenient to enter certain data, either meteorological observations or other data (e.g. ship location), via a manual keyboard. These data are then stored and used with the automatic data to form the output message.

(e) Local peripherals —These may consist of displays such as a VDU or a teletype, and magnetic tape recorders if data is to be stored locally.

(f) Transmission links —In most cases the output message will require to be transmitted via a telephone line, radio or satellite to a remote receiving station. The AWS must incorporate the necessary interfaces to connect to the communication system or systems to be used.

(g) Receiving centre —The receiving station will use remote displays and recorders as necessary in order to ensure suitable quality control of the data. Only after quality control has been applied by human or automatic means is data available to be put into the formal observational communication system.

(h) *Note:* The variables which need to be measured by the AWS depend upon the particular application. For example, the WMO *Guide to Meteorological Instrument and Observing Practices* lists the following elements in defining the accuracy requirements for land-based AWS for synoptic meteorology:

Atmospheric pressure, wind direction, wind speed, air temperature, dew-point temperature, precipitation, visibility, height of cloud base.

3. Automatic weather stations—Meteorological Office applications

While the Office has requirements for all of the types of AWS defined in Section 2.1, it is possible to divide the observational needs into two broad categories, namely, the requirements for synoptic and climatological purposes. The essential difference between the two is that synoptic observations are needed in 'near real time' whereas climatological observations can be stored, and used when required—usually at monthly intervals. Synoptic observations are used to define the present state of the atmosphere and in weather forecasting; climatological observations form the data base from which the Office provides a wide range of weather advice. The synoptic and climatological networks may overlap and reinforce each other, and both types of observation are required from land and sea areas. Thus it is not surprising to find that AWS applications can at times be relevant to both types of network.

The basic requirements which have been considered in defining the use of AWS within the Meteorological Office networks have been as follows:

(a) The need to obtain data from locations which are remote, or in a hostile environment. Examples are locations in the Welsh and Scottish mountains, oil platforms and remote islands.

(b) The need to fill gaps of space or time in the existing networks. This also means filling gaps caused by the closing of Auxiliary stations, where it has not been possible to replace them in the normal manner.

(c) The requirement to complement existing observing stations where appropriate. For example, it is considered essential that professional observers should be present at airfields when flying is in progress. However, where it has not been found economic to provide synoptic coverage outside the period of flying, an AWS can be used to complete the 24-hour observations of the basic meteorological variables.

(d) The need to maintain existing observing stations where these stations are being unilaterally automated. For example, we must be ready to respond when Trinity House and the Northern Lighthouse Board conduct their program of automation on lightships, and where merchant ships' complements have been progressively reduced by new technology, there is a need to make the collection and transmission of each observation as simple as possible.

In the following sections, Meteorological Office progress and plans for the use of AWS for synoptic and climatological purposes, both on land and in the marine environment, are described.

4. Synoptic land-based automatic weather stations

When in 1969 approval was obtained for the establishment of a pilot network of up to ten automatic weather stations, there had already been a lengthy process of development and trials within the Office. Ten systems, known as Meteorological Office Weather Observing System (MOWOS) Mk 2, were purchased. The tendering, production and acceptance of these systems proved a lengthy undertaking, and it was not until 1974 that the contract was completed. Day *et al.* (1973) described the MOWOS Mk 2 system and outlined the pilot network of locations where the systems were put on trial for two years alongside routine observational stations (Plate I). Sands and Tonkinson (1975) and Harrold and Hooper (1976) describe some of the results of these extensive trials which went, in depth, into problems of accuracy, reliability and maintenance of MOWOS in comparison, where appropriate, with the human observer. It was concluded that with some modifications MOWOS can achieve the standards of accuracy laid down by WMO (CIMO) for land-based synoptic AWS in respect of the basic variables, i.e. pressure, wind speed and direction, temperature and wet-bulb depression.

As a result of these trials approval was obtained for the use of MOWOS operationally, and these systems are now being moved to their final locations at Pershore, Holme Moss, Shap Fell, Little Rissington, Great Glen, Grantown-on-Spey, Yeovilton and North Humberside.

This initial batch of synoptic AWS are 'hard wired' systems based on analog modules. However, it is clear that, provided the tried and tested sensors and interfaces are retained, it is possible to replace the MOWOS central data processing unit by any other 'black box' which performs the same, or similar, operations on the input data. It is now considerably cheaper to replace this unit by a micro-computer which allows extra flexibility in usage, a simple modular construction, the use of quality control software modules and the production of a WMO coded message output if required. Plate II shows such a system, developed 'in house'. This system has been described by Harrold *et al.* (1977). It uses CMOS circuitry in order to minimize the power consumption, has a 4 K 12-bit word memory and is compatible with the commercial Digital Equipment Corporation PDP-8 computer, using all the standard PDP-8 software packages.

As a result of the success of the MOWOS trials the Meteorological Office Working Group on the United Kingdom Observational Networks (composed of representatives of the various users and those involved in implementing the user requirements) considered the total United Kingdom network need for land-based synoptic AWS during the next decade. This group made recommendations, which have now been accepted, that state the need for over 60 synoptic AWS in order to meet the operational requirements of the Services Branches. Figure 2 is a map showing the areas and some of the stations where synoptic AWS exist or are now proposed. It will be noted that the overwhelming majority of the AWS sites are at locations from which observations are not obtained at present. These plans have now received financial approval in principle, and the way is clear for an initial purchase of 20 further synoptic AWS to an updated design based on the experience gained in the MOWOS trials.

5. Climatological land-based automatic weather stations

The requirement for climatological AWS is different from the synoptic case in that the observations only need to be recorded and there is no 'real-time' need for the data, Furthermore, desirable climatological sites do not always coincide with synoptic sites, they are often remote, and reliability is even more essential. WMO regulations for climatological observations require the reporting of the following set of variables (or a selection from these) and the accuracy required is somewhat higher than for the synoptic case:

Weather, wind, cloud amount, cloud type, height of cloud base, visibility, temperature (including maximum and minimum), humidity, pressure, precipitation, snow cover, duration of sunshine, soil temperature.

Clearly AWS can only be used to measure a selection of these variables at present, but in 1975 the Meteorological Office obtained agreement in principle to the use of climatological AWS where appropriate. There is a need to improve the existing climatological network, and to avoid the loss of observations when existing stations close due to difficulties in obtaining voluntary observers. Approval was given for the development and trials of an initial batch of ten such AWS.

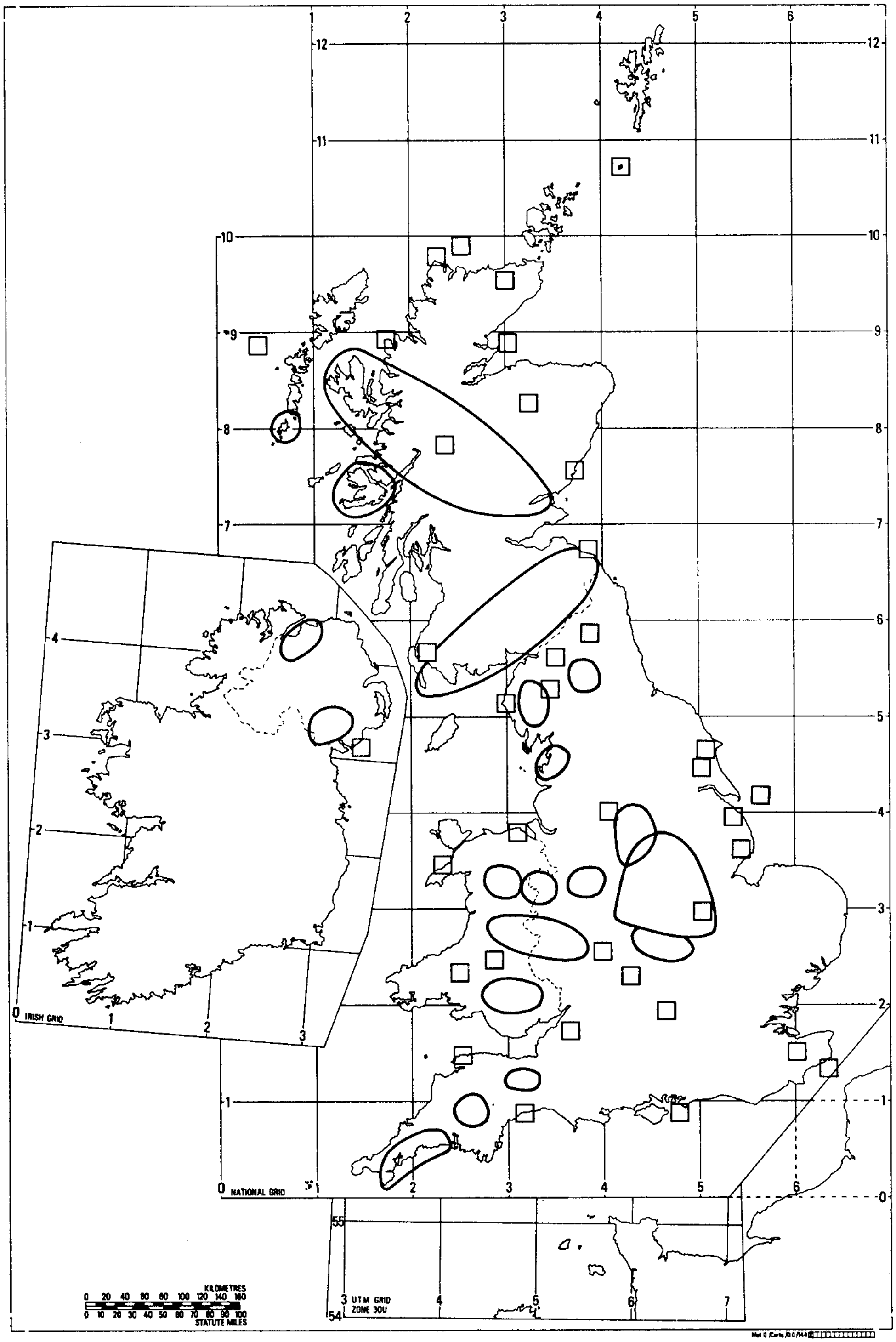

Figure 2. Stations and areas where synoptic automatic weather stations exist or are proposed.

Again, within the Meteorological Office, the requirements of the climatological network come within the province of the Observational Network Group. In 1976 a paper was prepared detailing the requirement as seen by the Climatological Services Branches of the Office, and laying down a broad flexible policy. This involved the use of a number (approximately 90) of Principal, permanently manned, climatological observing stations to cater for the climatologically distinct areas of the United Kingdom (Figure 3), and a much larger number of stations which may be manned (voluntarily by authorities or private individuals) or automated, as proves possible in the circumstances which exist at each station. While a probable requirement for 50–100 climatological AWS can be foreseen during the next decade, it is not considered appropriate to define this number more exactly until the trials of the initial ten AWS have been completed.

Our experience in synoptic AWS development has suggested that the climatological AWS can conveniently and effectively use many of the same modules. Work is now in hand at Beaufort Park on the construction of three pre-production climatological AWS based on the micro-computers already available from work on the synoptic AWS. These stations will have to be evaluated over a period of at least 12 months before the design and specification can be finalized, and the initial batch of ten systems can be procured for more extensive trials.

6. Marine automatic weather stations

The sudden increase of interest in data from the United Kingdom coastal and offshore waters, arising from the activities of the offshore oil industry and the need to look for alternative means of producing energy, has led to an increased requirement for Ocean Data Acquisition Systems (ODAS). At the same time the plans to automate a number of light-vessels (mentioned previously) also imply a need to provide automatic observing systems on these vessels if new gaps in the observing network are not to be created. For these reasons a small development group has been concentrating on marine systems, which have to be extra rugged in order to be suitable for this exacting environment.

Two types of marine AWS are being considered, First, a system designed for installation on a small (2½ m or 8 ft diameter) toroidal buoy has been proved to have a good reliability but is of limited flexibility. Secondly, an adaptation of the updated synoptic AWS is being developed for installation on three oil platforms in the North Sea.

No policy document yet exists on the needs of the Office for a network of marine AWS, but this matter is under consideration within the Observational Network Group, and no doubt a policy will be formulated in the next year or two.

A further, largely separate, need for marine AWS is related to observations from the ships of the Voluntary Observing Fleet (VOF). There have been increasing difficulties in obtaining regular synoptic observations from modern vessels owing to the automation of their central control systems and the consequent reduction in deck and radio officer complements. The observing officers are now hard pressed in carrying out their normal duties, so the greatest number of variables possible should be measured automatically to aid in the preparation of an observation. At certain times no radio officer is on duty, so normal transmission of observations cannot be made on schedule. Observations from the North Atlantic are vital in providing the data base from which forecasts for the United Kingdom are provided.

Development of a Meteorological Office Observing System for Ships (MOSS) has been in hand since 1976, but the principal difficulty has been associated with the transmission of the data (by automatic means or otherwise) from the ships to the United Kingdom. It has been necessary to mount a communications feasibility trial on a few merchant vessels in order to try out alternatives such as High

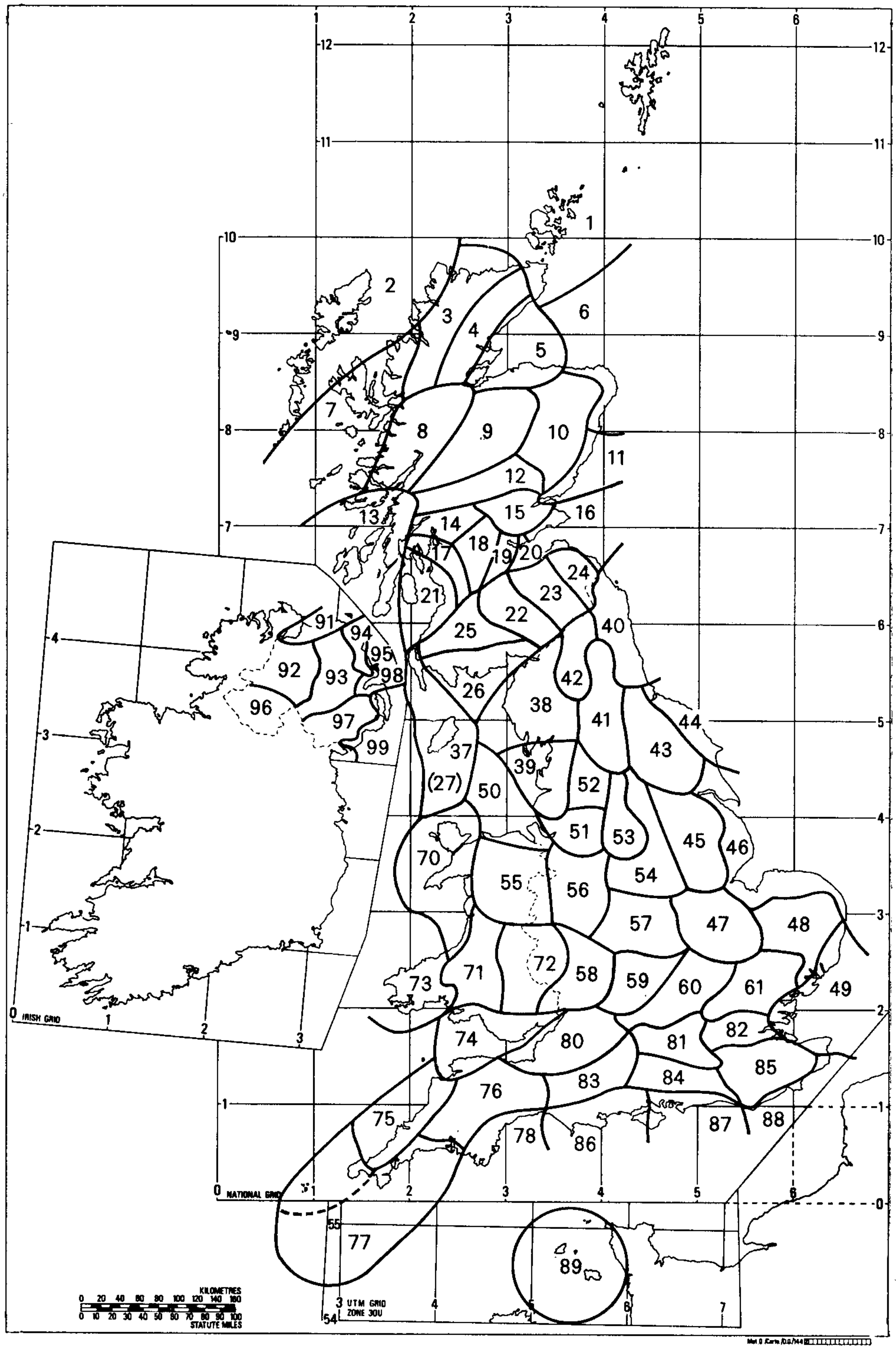

Figure 3. Climatologically distinct areas of the United Kingdom.

Frequency, Telex and Satellite communication links. It seems likely that success in this area will only come from a continuous effort over several years.

7. Conclusions

The use of automatic weather stations will increase in the observing networks of the Office, and more generally all over the world, during the next decade. Plans are being formulated and acted upon, and it will be up to the forecasters and climatologists of the future to make effective use of the greatly enhanced data base which will become available.

The data from AWS have limitations and characteristics which may be different from those of manually provided observations. It will be necessary to provide adequate forms of quality control on the AWS-derived data, and for future users to be aware of the particular nature of the data.

AWS are not to be considered as a means for the wholesale replacement of human observers; indeed new policy documents have recently been produced confirming for the first time the long-term need for observations by professional observers at 'key' stations in both the synoptic and climatological networks. Instead, AWS should be regarded as complementing the 'human' networks, filling in gaps where they exist or occur, and ensuring that data can be provided from remote and uninhabited locations.

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Micrometeorological characteristics of the 1976 hot spells

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Summary

The memorable weather at Cardington during the period June–August 1976 is described from the micrometeorological viewpoint by means of the energy budget over a grass-covered surface. The flux of sensible heat from the surface to the overlying air was a dominant term in the energy budget for much of this period, and reached the exceptionally high value of 300 W m^{-2} on some days in August. However, at the end of June during the hottest period, latent heat of evaporation also constituted a significant component of the energy budget. Measurements are presented to illustrate the noteworthy diurnal variation of soil heat flux (reaching 100 W m^{-2}), and of surface layer temperature during fine weather this summer.

1. Introduction

Much attention has been paid recently to the severe drought of 1975–76 over the British Isles. Perry (1976) has described the 12 month period starting on 1 May 1975 as the driest period over the United Kingdom since records began, with only 60 per cent of normal rainfall in parts of the Midlands and south-west England. The period from 23 June to 8 July 1976, in particular, was exceptionally hot and dry; see Shaw (1977). At Cardington, Beds., the maximum temperature exceeded 30 °C every day throughout this period. The hydrological and dynamical aspects of this drought have been described by Murray (1977), Green (1977), Ratcliffe (1977) and Miles (1977). However, one important aspect has not yet been discussed in detail, and that is the micrometeorology of the surface boundary layer during this period, and particularly the heat budget at the surface. The surface layer, which comprises the lowest few tens of metres of the atmosphere, is a very important region for many reasons. Man's activities are largely confined to it and, of course, many of the basic energy transformations occur within it.

On a cloudless day, incoming solar radiation absorbed at the earth's surface is converted into heat, and the nature of this energy conversion very much depends upon the character of the underlying surface. For a typically rural land surface the incoming radiant energy is converted into (a) latent heat of evaporation, and (b) ordinary (or 'sensible') heat. Some of this sensible heat is conducted down into the ground, and the rest is used to warm the overlying air through a combination of eddy diffusion, and radiative and molecular conduction processes; see, for example, Munn (1966).

At the Meteorological Research Unit at Cardington an experiment is now being carried out to assess the nature of the energy budget over a grass-covered surface, and to study its behaviour on a variety of time-scales. Some measurements were made during the summer of 1976 and they indicate that conditions quite unusual to rural England developed in the surface layer at this time. Before the energy budget is discussed, however, the terms in the balance equation will be defined and the method used to measure them briefly outlined.

2. Definition of the surface energy balance equation

From the principle of conservation of energy it is clear that gains and losses of energy at the earth's surface must balance. For a uniform, horizontal land surface this balance can be described by the equation:

$$R_N = H + G + E \quad \ldots \quad (1)$$

where R_N is the net receipt of radiant energy, H is the flux of sensible heat transferred from the surface to the overlying air, G is the downward flux of heat into the soil, and E is the energy required to evaporate surface moisture. R_N represents a radiation balance between the following components (refer to Figure 1):

Q_1 = direct, short-wave radiation—the solar beam;
Q_2 = diffuse, short-wave radiation—scattered from clouds and the atmosphere;
Q_3 = short-wave radiation scattered by the surface—upwards;
Q_4 = long-wave emission from the atmosphere—downwards;
Q_5 = long-wave emission from the ground—upwards.

Therefore

$$R_N = Q_1 + Q_2 + Q_4 - Q_3 - Q_5 \qquad (2)$$

Positive R_N represents a net gain (or warming), and negative R_N a net loss (or cooling) of radiant energy.

Positive H is associated with an unstable temperature stratification in the surface boundary layer, that is when the (dry-bulb) potential temperature falls with height; whereas negative H occurs with a stable layer ($d\theta/dz > 0$).

The downward soil heat flux G is positive when the temperature of the soil near the surface decreases with depth.

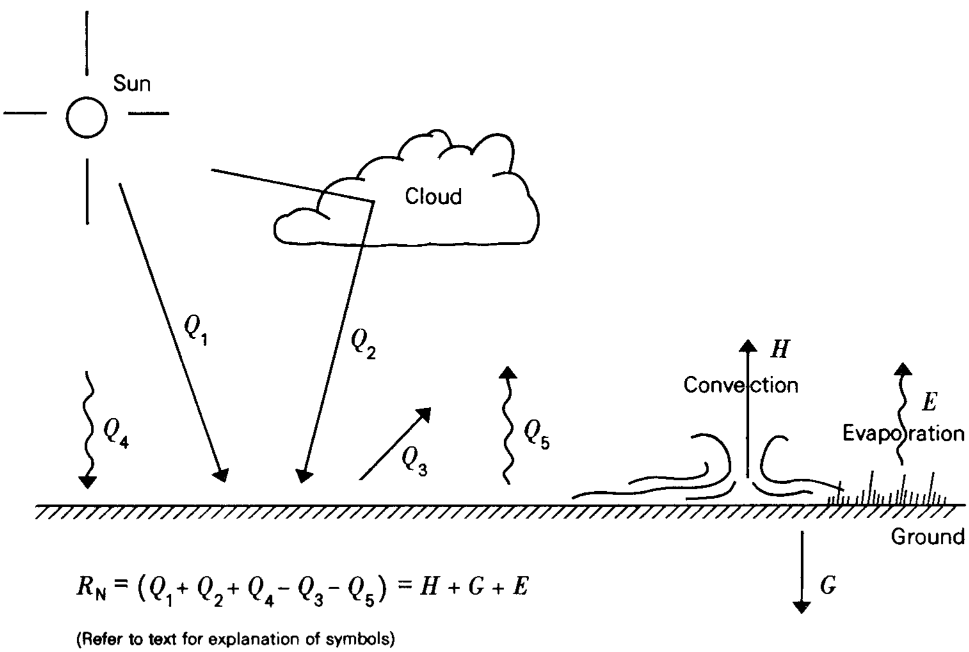


Figure 1. Principal components of the energy balance over a horizontal surface.

The latent heat flux E equals the rate of evaporation $\mathscr{E}$ multiplied by the latent heat of vaporization L_V, thus

$$E = L_V \times \mathscr{E}, \qquad (3)$$

and is positive when the surface is losing moisture to the air. E may be negative, for example, when dew is forming.

The components of the energy balance equation are defined in terms of their flux intensities, and their units are watts per square metre (W m^{-2}). In these units the solar constant S (2.0 cal cm^{-2} min^{-1}) is approximately 1400 W m^{-2}.

For a vegetated surface, E in equation (1) represents the sum of the energy loss due to evaporation of moisture in the surface layer of the soil, together with the transpiration of vapour from the vegetation itself, and is termed 'evapotranspiration'. 'Potential evapotranspiration' is the evaporation which occurs if soil moisture is not a limiting factor, but in practice the actual evaporation depends very much on the available water in the ground. Transpiration is the transfer of water from soil to the atmosphere via a plant, and it tends to short circuit the normal channels of vertical soil moisture transfer, such as capillary action. Water loss through evaporation therefore tends to be faster from a plant-covered soil than from a bare surface, and the available soil moisture supply is likely to be depleted sooner unless replenished by rainfall.

3. Measurement of the energy balance

The experimental site at Cardington lies about 4 km south-east of Bedford, within a broad clay vale which provides an excellent exposure in many directions. Both the site and its immediate surroundings are grass covered, but the surface of the agricultural land beyond is more varied, ranging from arable and cereal crops to rough pasture and small woods. The fetch over grass is limited to between 400 and 800 m, and this restricts the constant flux layer at the site to a depth of little more than 4 m.

Net radiation R_N in equation (1) is measured directly with a ventilated radiation balance meter at a height of around 1 m, and measurements are accurate to between 5 and 10 per cent. Soil heat flux G is an extrapolated estimate of the surface value based on measurements at several levels below the surface; see for instance Blackwell (1963). Five suitably calibrated flux plates were installed in the soil at depths of 5, 10, 20, 40 and 80 cm. The top flux plate lay in contact with the root system of the thick turf which forms the surface. The estimate of G is based on extrapolation of measurements at 5, 10 and 20 cm and one cannot be confident that it is known to within better than $\pm$ 20 per cent. Latent heat flux E is derived from hourly measurements of the evapotranspiration from the short-cropped grass surface of a weighing lysimeter (Blackwell, 1963). The lysimeter is a square tank of surface area 2 m^2 and depth 50 cm, and it contains a sample of soil representative of the surrounding site. The change in the mass of this tank due to evaporation from the grass surface or rainfall upon it is monitored automatically, and E is derived from equation (3). This device has proved to be a direct and quite reliable means of measuring E, with an accuracy of between 10 and 20 per cent. However, it cannot normally be used to measure E over a period of less than one hour. In addition to evaporation from grass, daily measurements are also made of the evaporation from an exposed water surface, using a Meteorological Office British standard evaporation tank.

The sensible heat flux H cannot be measured as readily as can R_N, G, or E. Two indirect methods have been used to estimate H: (a) from the gradient of potential temperature, through the transport equation

$$H = -\rho C_p K_h . d\theta/dz \qquad (4)$$

and (b) through the residual technique, in which H is expressed explicitly in terms of R_N, G, and E, thus

$$H = R_N - G - E. \qquad (5)$$

In the first method K_h is the eddy diffusivity for heat transfer. It is not a physical constant but depends on various turbulence characteristics such as wind shear, stability, and height above the surface. Its height variation in the surface layer is described by a semi-empirical relationship of the form

$K_h = ku_*z/\phi_h$; see e.g. Sutton (1953), or Priestley (1959). The non-dimensional function ϕ_h can be calculated from the Richardson number; see for example Businger *et al.* (1971), and this in turn is derived from the vertical profiles of wind speed and potential temperature, averaged over a suitable period such as 20 minutes. Measurements of wind speed and temperature are made at Cardington at heights of 0.5, 1, 2, 4, 8 and 16 m using light-weight photoelectric cup anemometers and standard platinum-in-steel resistance thermometers, the latter being suitably screened from direct radiation. These measurements enable both u_* and ϕ_h, and therefore K_h and H, to be calculated.

The accuracy with which the sensible heat flux can be calculated from equation (4) is limited by the semi-empirical description of the eddy diffusivity K_h. At Cardington, it is also limited by the restricted fetch over a uniform grass surface, and consequently by the relatively shallow constant flux layer at the site. For these reasons the sensible heat flux cannot normally be measured by this method to an accuracy of better than 20 per cent. The validity of the residual estimate of H using equation (5) depends, of course, upon the energy balance equation (1) being obeyed in the first place. Measurements of R_N, G, E and H, in widely varying conditions at different times of the year, do indeed show that this balance equation is satisfied, within the error limits mentioned above.

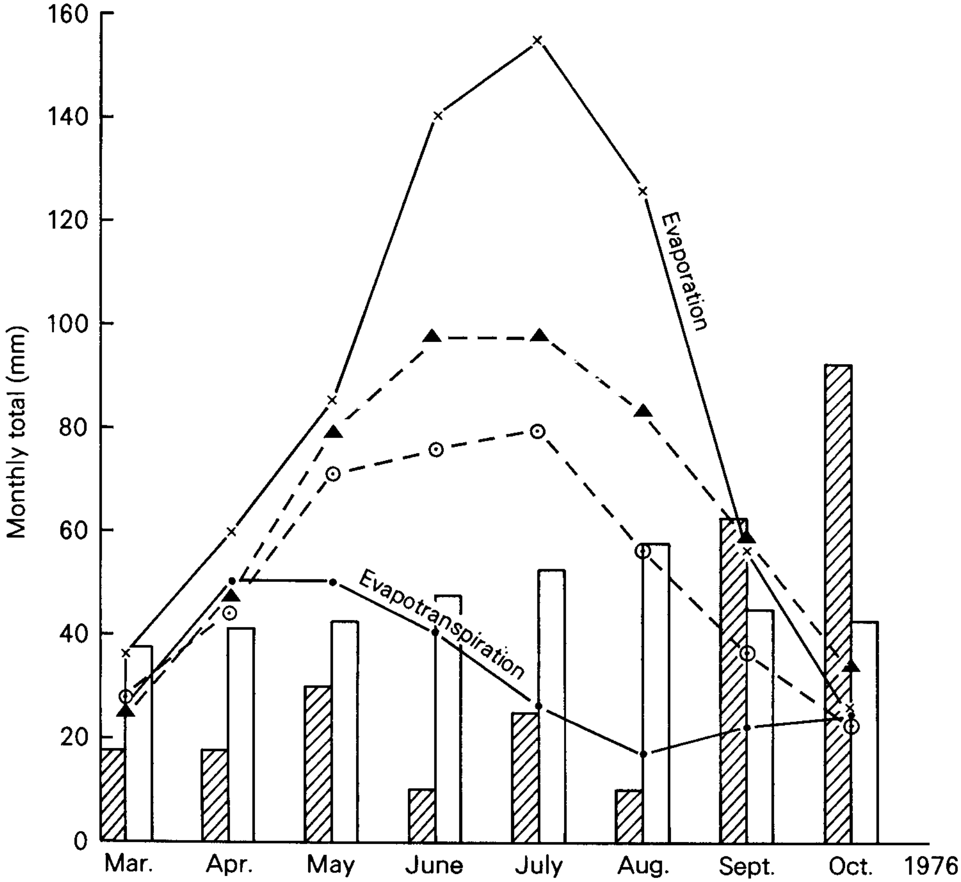


Figure 2. Monthly evaporation and rainfall at Cardington, March–October 1976. ▲– – –▲ Mean monthly evaporation, 1970–75, ⊙– – –⊙ Mean monthly evapotranspiration, 1970–75. Hatched verticals represent monthly rainfall for 1970, unhatched verticals represent mean monthly rainfall, 1951–70.

4. The surface energy budget at Cardington, June–August 1976

Figure 2 highlights the exceptionally dry character of the weather during this summer. This diagram shows the monthly rainfall and evaporation from March to October 1976 at Cardington. The evaporation from an open water surface and the evapotranspiration from grass are both compared with the average for the previous six years. It is noteworthy that evaporation from water reached a maximum of 156 mm during July, 160 per cent of the average, and this figure would probably be typical of the water loss from rivers, lakes and reservoirs. On the other hand, evapotranspiration fell steadily from late spring to the very low values of less than 30 mm during July and August, approximately 40 per cent of the average.

Shown in Figure 3 is the daily variation of the components in the energy budget at Cardington from the middle of June to the end of August 1976. The data presented are averages over the period 06–18 GMT. Daily rainfall is included in the diagram, and it will be noted that more than 1 mm of rain fell on only seven days during this period. The daily maximum temperature is also shown and two hot spells, labelled '1' and '2' respectively have been defined. The first of these, Hot Spell 1, covers the period from 23 June to 8 July, when the maximum temperature exceeded 30 °C daily. The second, Hot Spell 2, represents a fortnight in the middle of August, 11th–26th, when the temperature generally exceeded 26 °C.

It will be noted from Figure 3 that, of the four components in the energy budget, the radiation R_N is typically the largest. The net radiation shows a steady decrease during the summer, falling erratically from a peak during Hot Spell 1 to a minimum in early August, but increasing again slightly during Hot Spell 2. Individual components can change rapidly in magnitude from one day to the next; see for instance the two periods 15–22 June and 15–18 July. The net radiation is usually subject to the greatest change because it is strongly dependent on external factors such as cloud cover and depth, and on turbidity (or pollution). The other components of the budget reflect changes in R_N to a varying degree. The soil heat flux, for instance, falls during the same period as R_N, between Hot Spell 1 and the beginning of August.

A detailed analysis of the hourly energy balance for the four days labelled A to D in Figure 3 is presented in Figures 4(a)–(d), and they illustrate aspects of the diurnal surface energy budget during the summer of 1976. On fine days the mean hourly net radiation reaches a maximum of between 400 and 500 W m^{-2}; see Figures 4(b)–(d). The shape of the R_N curve on a clear day is not perfectly sinusoidal, unlike the incident short-wave component Q_1 (refer to Figure 1). Soil heat flux G tends to lag in phase behind the net radiation by an hour or so, as is illustrated in Figures 4(a), 4(c). This phase lag, to be described in some detail in Section 6, implies that G is not a true 'surface' value, and it probably reflects a limitation of the extrapolation method discussed earlier. It also throws doubt on the validity of equation (5) for estimating H when G is changing rapidly.

During the summer both the latent heat and sensible heat fluxes behave very differently from R_N and G. Well before the arrival of Hot Spell 1 the latent heat flux was a significant term in the energy budget, following rain in the middle of June, and this is exemplified on 20 June, shown in Figure 4(a). Apart from the radiation term, E dominates the energy budget for much of this day. During the morning of 20 June the latent heat flux increases so rapidly in response to the radiation that it drives the sensible heat flux strongly negative for an hour or so until 10 GMT. Shortly after midday, however, the rate of evaporation decreases, and allows the sensible heat flux to build up well into the afternoon. It is worth noting the effect which the large latent heat and relatively small sensible heat fluxes have had on the air temperature. After a gradual increase during the day, a maximum of only 20 °C is reached, and this occurs as late as 16 GMT.

During Hot Spell 1 the latent heat flux falls rapidly to a low level, and the sensible heat component becomes more important. By 30 June (Figure 4(c)) E falls to between 10 and 15 per cent of the net

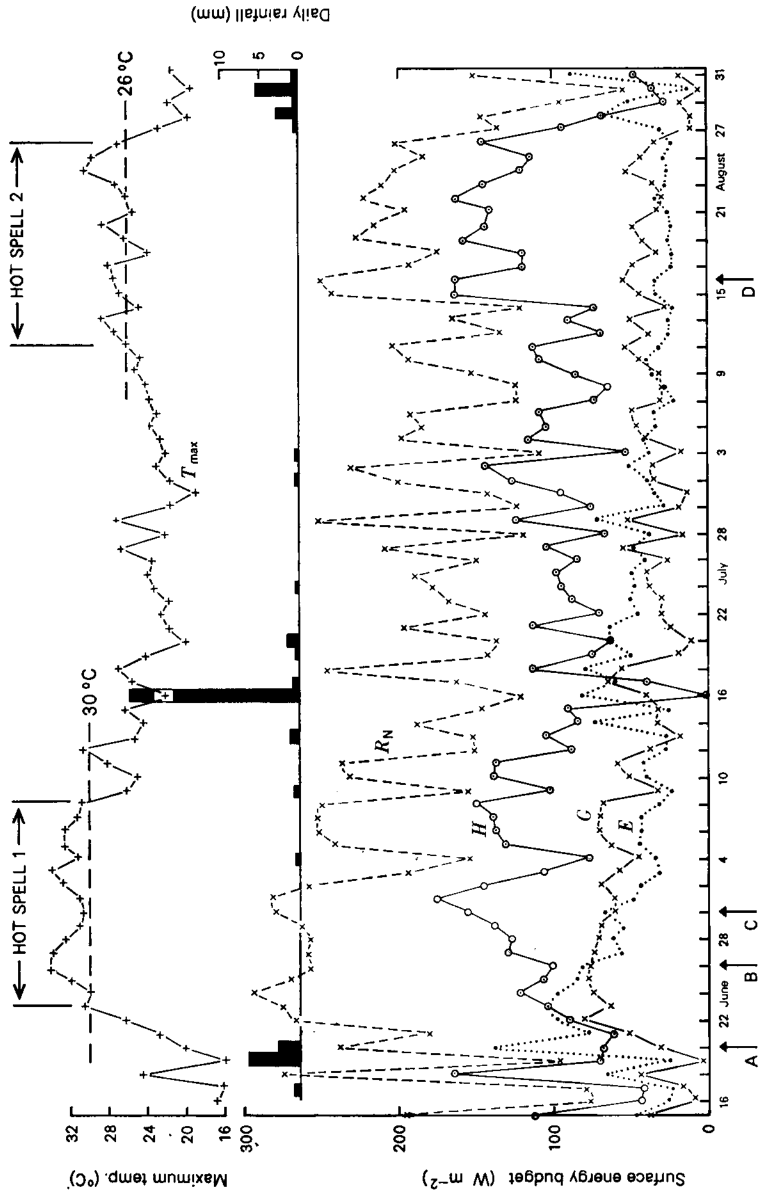


Figure 3. Mean daily (06–18 GMT) surface energy budget at Cardington, June–August 1976, with rainfall and maximum temperature.
R_N is net radiation, *G* is soil heat flux, *E* is latent heat flux, *H* is sensible heat flux and T_{max} is maximum temperature.

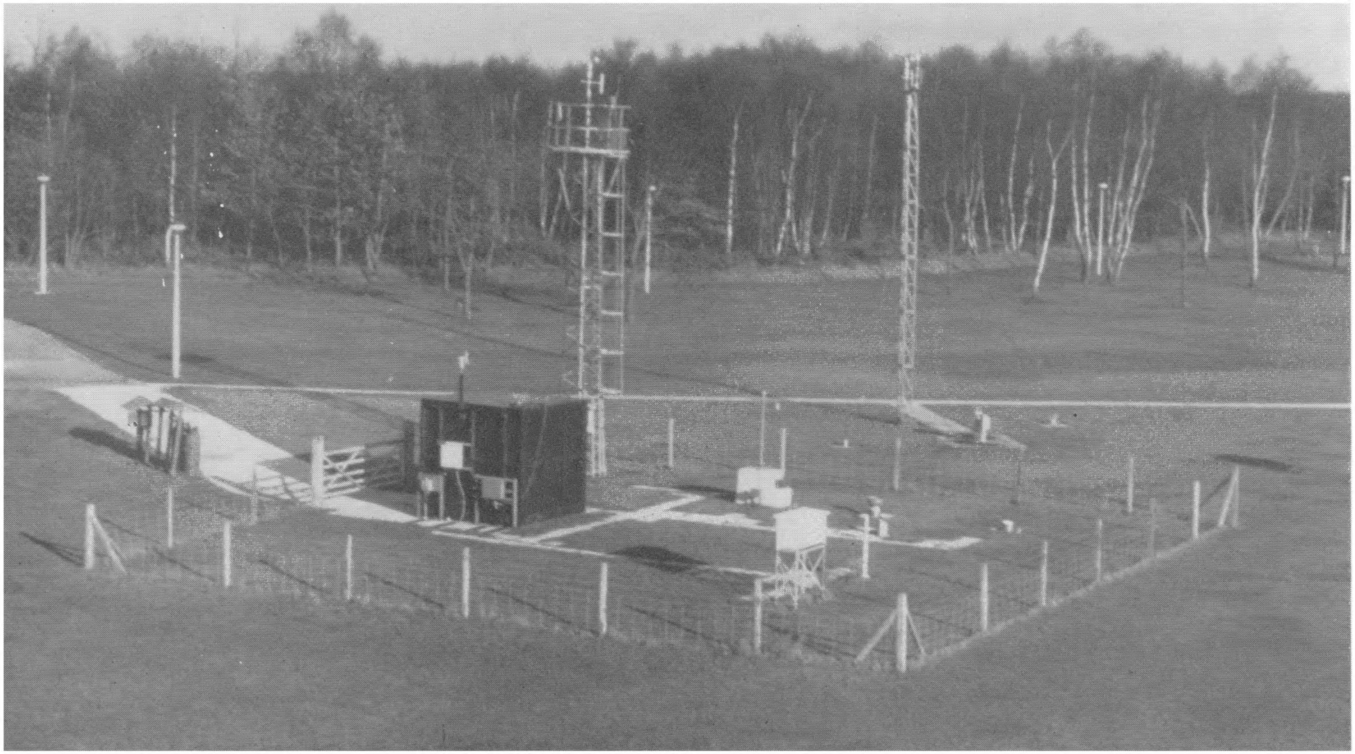


Plate I. The Meteorological Office Weather Observing System (MOWOS) Mk 2 at Beaufort Park.

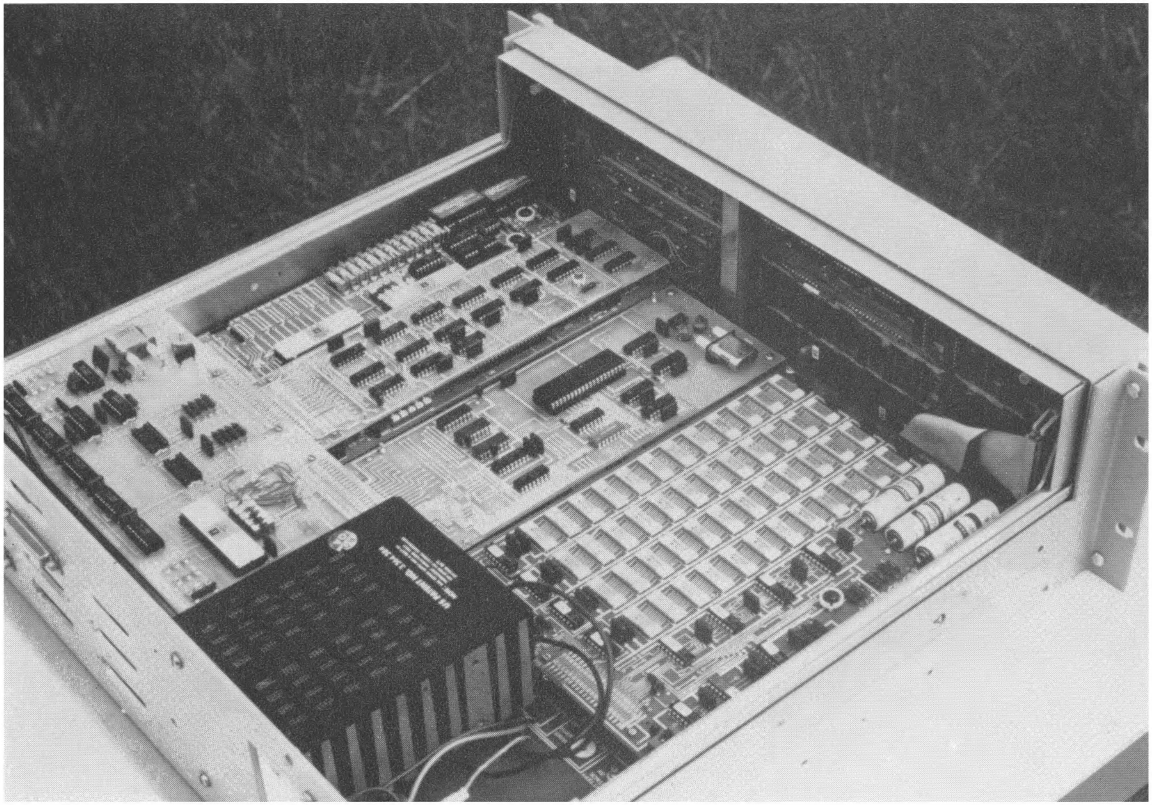
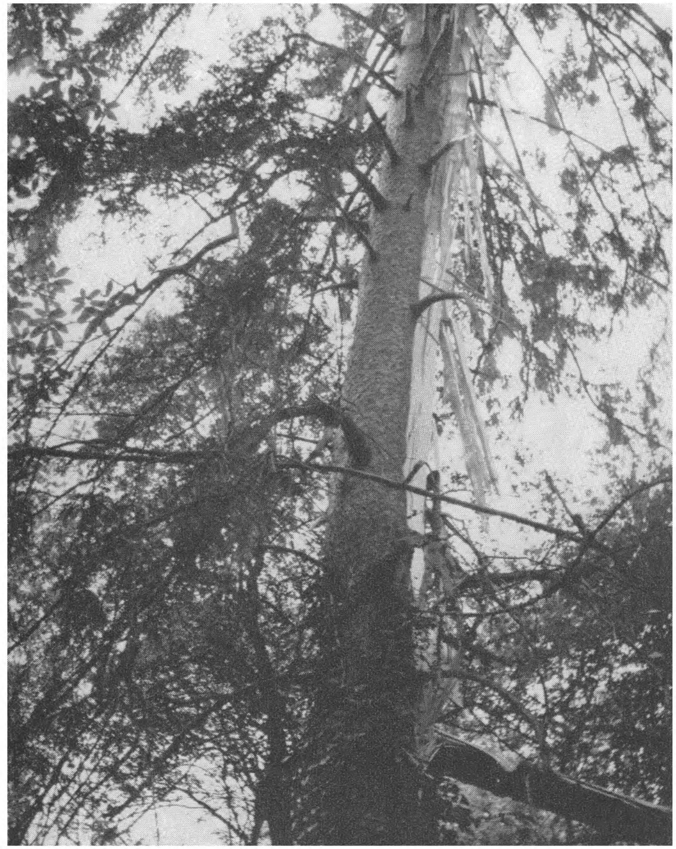


Plate II. The Meteorological Office designed 'Automet' Micro-Computer.



Photographs by H. B. Ridley, F.R.A.S.

Plate III. Lightning near Godalming during the night of 8–9 August 1975

Note the breadth of the image of the discharge caused by recording together during the exposure the leader stroke and multiple return strokes (above, left). The lightning struck a tree about 300 metres from the camera. Photograph (above, right) shows damage to the tree, viewed from the north.

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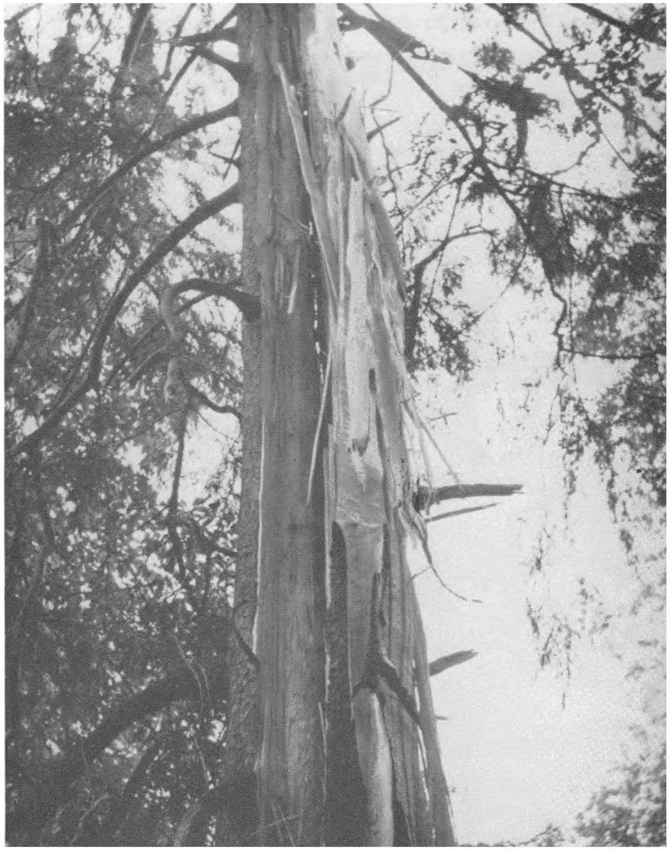
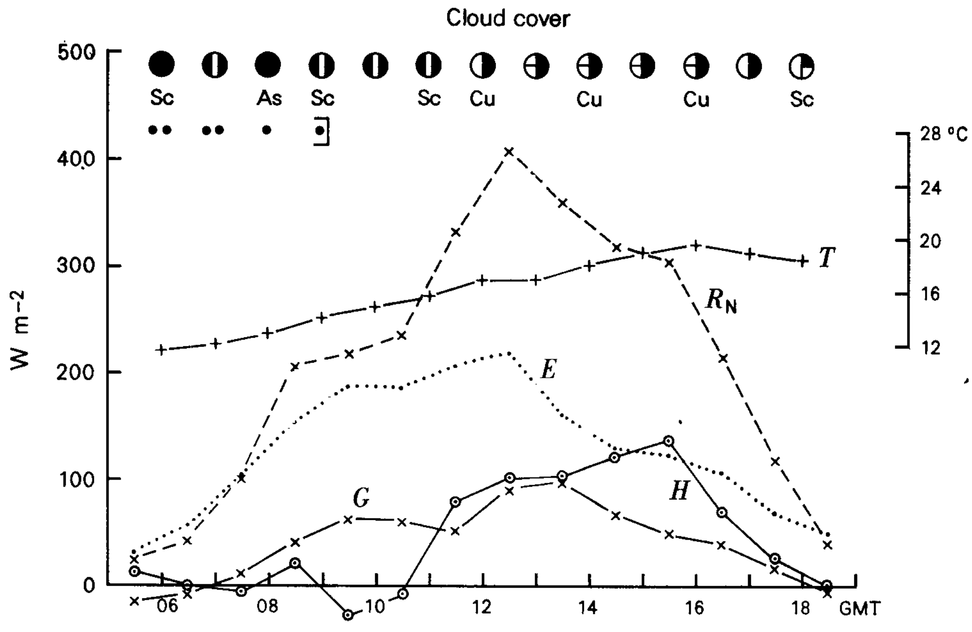
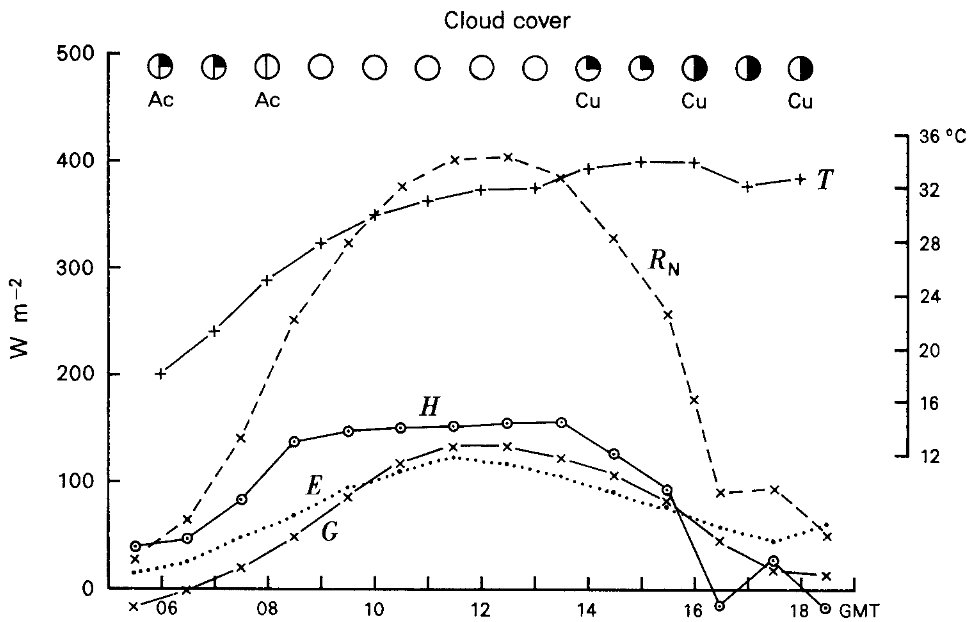


Photographs by H. B. Ridley, F.R.A.S.

Plate IV. Futher views of the damaged tree shown in Plate III; viewed from the south (above left) and from the east (above right)

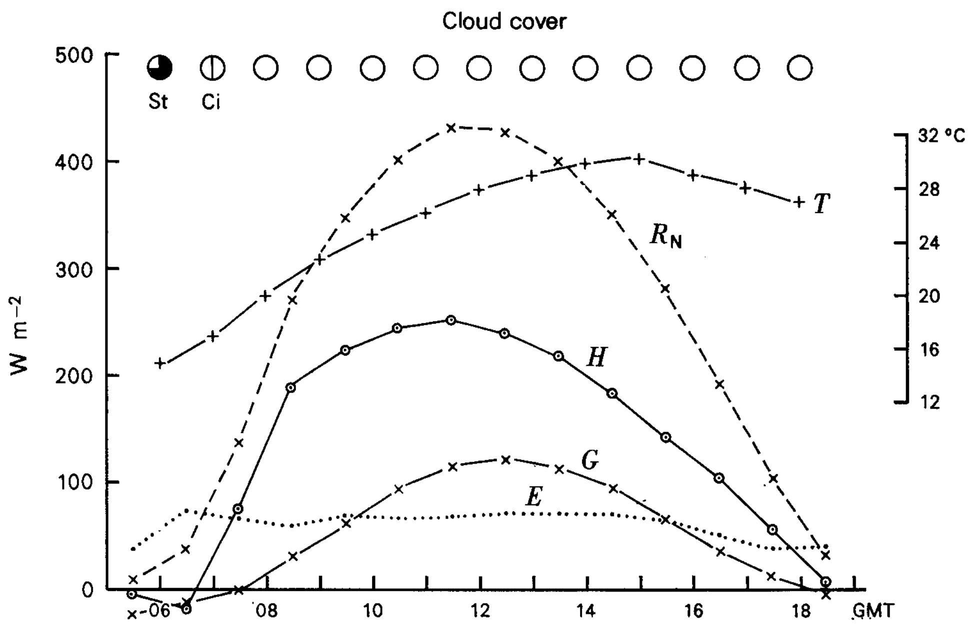


(a) 20 June 1976

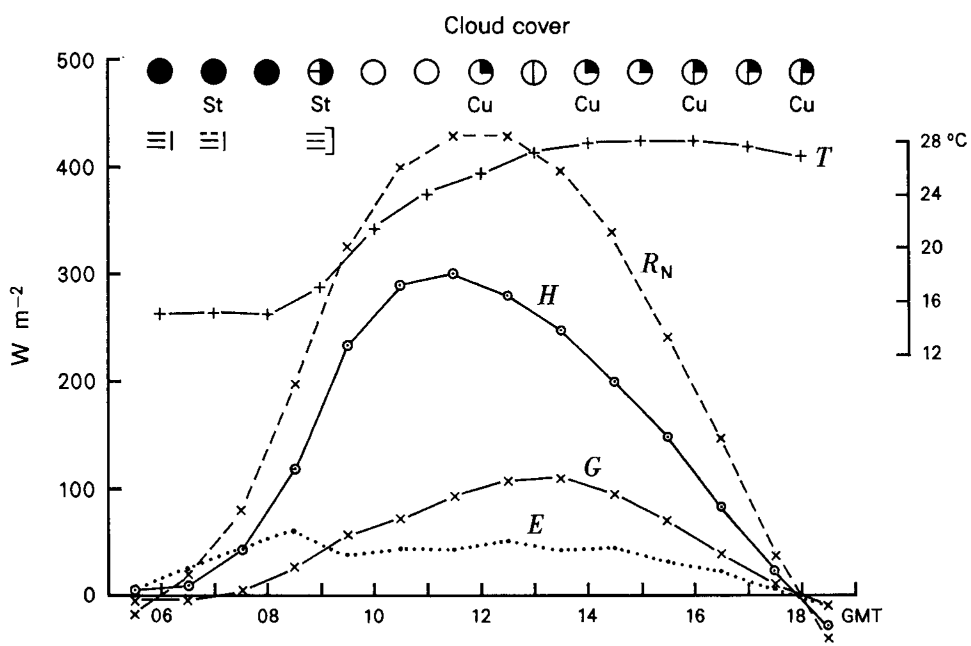


(b) 26 June 1976

Figure 4. Hourly energy budget (06–18 GMT) with cloud cover and screen temperature
R_N is net radiation, G is soil heat flux, T is screen temperature, E is latent heat flux and H is sensible heat flux.



(c) 30 June 1976



(d) 16 August 1976

Figure 4. *continued*

Note: The cloud cover symbol at 0600 in (d) should be for sky not discernible, and not cloudy as shown.

radiation during the midday hours, in marked contrast to the situation at the beginning of the hot spell. During July and August E remains very small, and H dominates the surface energy budget. This pattern is, however, temporarily interrupted in the middle of July after a rainfall of over 20 mm on the 16th. The modest recovery of the latent heat flux in the energy budget afterwards is shown in Figure 3. In the absence of further rainfall, E decreases again during the period leading up to Hot Spell 2. A large reservoir of soil moisture is necessary to support evapotranspiration from a plant cover at the potential rate, particularly during the summer when the relative humidity is low; see Penman (1949). This effect is illustrated in Figure 5, which compares the daily evaporation from water with that from grass during Hot Spell 1. It is worth contrasting the slow but sustained decline in evapotranspiration from grass, from 2 mm day^{-1} to less than 0.5 mm day^{-1}, with the evaporation from water during the period. The latter reaches a maximum of 9 mm on 30 June, coinciding with a minimum relative humidity of 11 per cent that afternoon.

Throughout Hot Spell 2 the sensible heat flux H remains a conspicuously dominant term, alone accounting for around 70 per cent of the available radiant energy. Evaporation from the ground reached its lowest value of the season at this time, with a day-time latent heat flux of only 30–40 W m^{-2}. The detailed budget for 16 August (Figure 4(d)) reflects the diurnal variation of its components towards the end of the summer, and it shows characteristics similar to those measured during the latter half of Hot Spell 1; compare Figures 4(c) and (d). G and E are smaller on the 16th but the sensible heat flux H reaches the remarkably high value of 300 W m^{-2} during the middle of the day.

As evaporation falls during Hot Spell 1, the hourly dependence of E on R_N which is very strong on 20 and 26 June (Figures 4(a) and (b)) also weakens. By July, in fact, the latent heat flux is virtually independent of the incident radiation, and it responds to secondary influences when these become available—e.g. surface moisture. This effect is especially noticeable around dawn, following overnight dew or fog

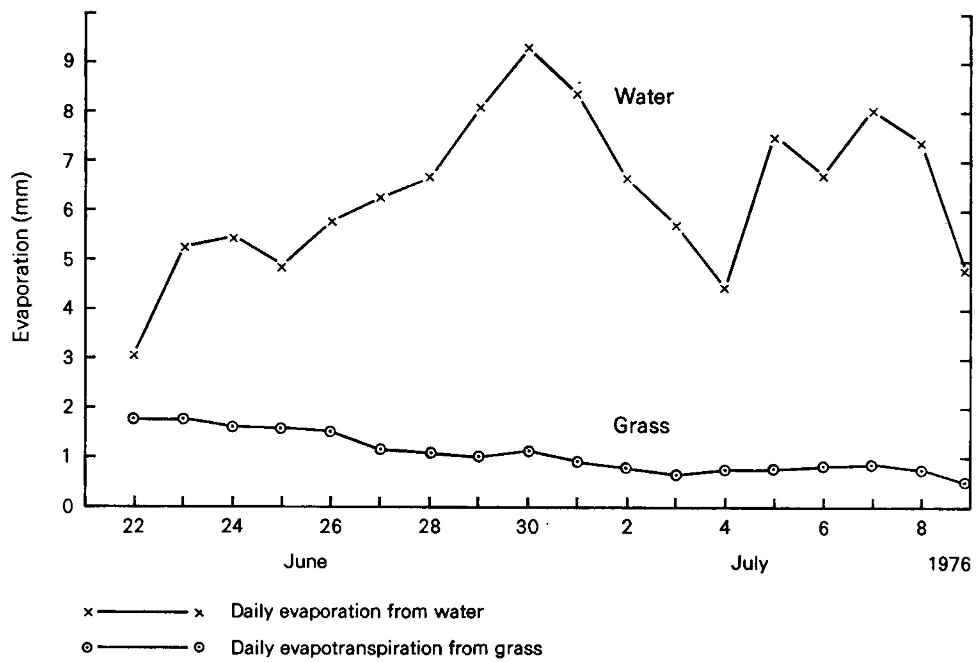


Figure 5. Daily evaporation from water and from grass at Cardington during Hot Spell 1.

deposition, and is then almost as large as it is around midday; see for instance Figures 4(c), (d). On several days during Hot Spell 2 the latent heat flux was at a maximum shortly after dawn. At Cardington the ground was baked hard and cracked during July and August, yet the lysimeter was still recording some water loss through transpiration, although it amounted to only 0.4 mm day^{-1}. Evaporation measurements from non-irrigated lysimeters are often criticized for being unrealistically small during periods of drought. However, during the summer of 1976 the grass cover on the lysimeter remained representative of its surroundings.

5. Energy budget and temperature structure

5.1. *Relation between atmospheric structure, surface energy budget, and maximum temperature*

Although the magnitude of the sensible heat flux H expresses the amount of energy available for warming the lower layers of the atmosphere, the daily changes in H are not, of course, necessarily correlated with those of surface temperature. On some days this correlation is more closely marked, as for instance on 18 and 19 June, and 16 and 18 July; see Figure 3. On the other hand, during the period 26–30 June, H increased by about 50 per cent, yet the highest temperature at Cardington during Hot Spell 1 was recorded on 26 June, when the sensible heat was not much larger than the latent heat flux. The explanation for this is apparent from inspection of Figure 6, which shows the temperature structure of the lowest kilometre or so of the atmosphere at 06 GMT on 26 and 30 June, and 16 August, derived from the Cardington BALTHUM ascents. On 26 June a layer of potentially very warm air was based at the surface, but by the 30th advection from the North Sea had cooled this layer considerably. This had the effect of generally increasing the depth of the convective boundary layer, and consequently restricting the rise in surface temperature on the 30th. The amount of heating on these two days has been calculated from the sensible heat flux curves shown in Figures 4 (b) and (c), neglecting other influences such as advection, radiation, entrainment etc. The arrowed adiabats AB and CD in Figure 6 represent the estimated maximum potential temperature of the convective layer on the 26th and 30th respectively. If

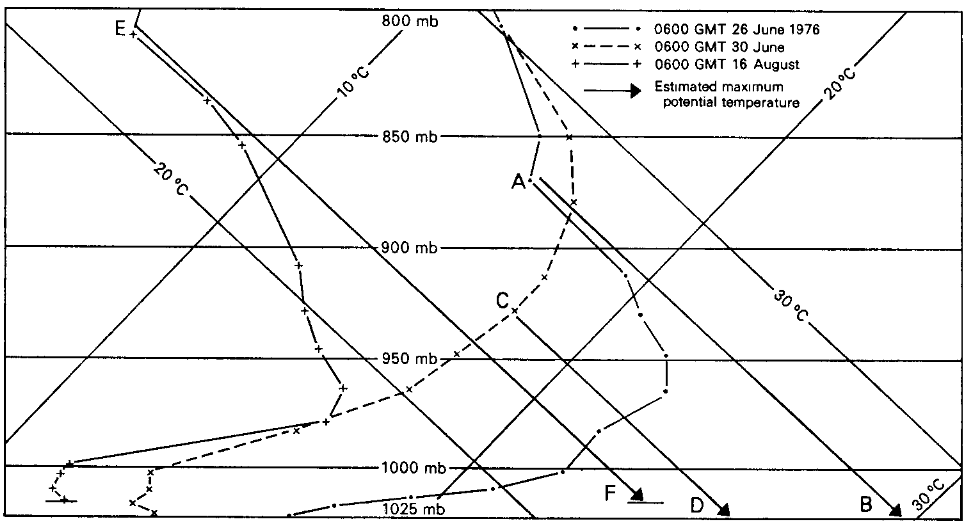


Figure 6. Calculation of boundary layer heating on 3 days using Cardington BALTHUM soundings.

an extra 2 °C is allowed for the superadiabatic near the surface, these adiabats imply afternoon screen temperatures of around 31.5 °C and 28 °C, which compare well with the actual values of 34 °C and 30 °C respectively.

Also shown in Figure 6 is the temperature structure on 16 August, when the surface energy budget was dominated by a large sensible heat flux. The adiabat EF represents the estimated maximum boundary layer depth on this day. An afternoon screen temperature of around 25 °C is predicted, and this compares with an actual temperature of between 26 °C and 27 °C.

5.2. *Diurnal variation of surface layer temperature*

Since the sensible heat flux H and the vertical temperature gradient are related through equation (4), a day has been chosen from Hot Spell 2 to illustrate how the surface layer temperature changed on one particular fine day during the summer of 1976. Figure 7 shows isotherms on a log height vs time plot, and the following points may be noted.

(a) The overnight nocturnal inversion in the surface layer reaches its maximum strength between 04 and 05 GMT, i.e. an hour or so before dawn.

(b) The inversion breaks down from the surface, and a near-neutral layer establishes itself for approximately an hour, during which period air temperature increases quickly.

(c) During the morning the static instability of the layer increases steadily. A superadiabatic temperature gradient develops, with a temperature lapse of between 2 and 2.5 °C being produced through the 0.5 m to 16 m layer. This was fairly typical of the lapse rate on a fine summer day in 1976.

(d) In the late afternoon the layer begins to cool, and it passes through the transitional phase of neutrality at around 18 GMT, i.e. one hour before sunset. During the evening an inversion develops,

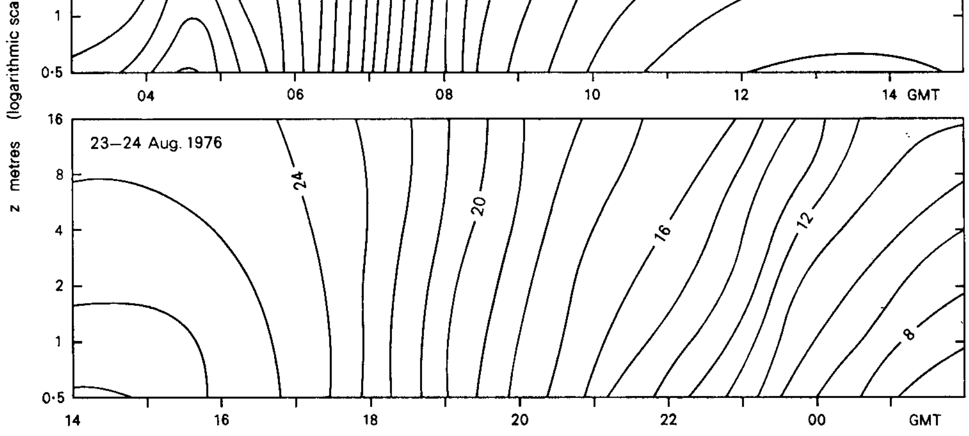


Figure 7. Temperature structure of the surface layer during a clear day.

and this slowly strengthens, accompanied by a steady cooling at all levels. This cooling is considerably less rapid than the warming which occurs immediately after dawn.

6. Diurnal variation of soil heat flux

Before discussing the characteristics of soil heat flux at various depths it is necessary to review briefly the relationships governing heat flow in the ground. All natural ground consists essentially of (a) soil, (b) free water, and (c) air pockets between the soil particles. The relative proportion of these components governs the density ρ and specific heat C of the soil at any depth z. The specific heat per unit volume (ρC) is constant for dry soil, but increases with the water content of the soil; for example see Geiger (1965). The rate of flow of heat through soil G is given by the classic conductivity equation

$$G = -k_S \mathrm{d}T/\mathrm{d}z \quad \ldots \quad (6)$$

where k_S is the thermal conductivity and $\mathrm{d}T/\mathrm{d}z$ is the temperature gradient in the soil. Conductivity varies with density and soil water content, being considerably greater in wet soil than in dry.

The rate of change of soil temperature can be related to the divergence of soil heat flux G through the equation

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{-1}{(\rho C)}\frac{\mathrm{d}G}{\mathrm{d}z}. \quad \ldots \quad (7)$$

Eliminating G from (6) and (7), and assuming k_S is constant with depth, leads to the heat conduction equation in one dimension:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = K\frac{\mathrm{d}^2T}{\mathrm{d}z^2} \quad \ldots \quad (8)$$

where

$$K = \frac{k_S}{(\rho C)} \quad \ldots \quad (9)$$

is the thermal diffusivity of the soil (in units of $m^2 s^{-1}$). If a sinusoidal time-dependent boundary condition, with angular frequency ω is applied at the surface ($z = 0$), in order to simulate the daily radiation wave at the surface, a solution can be derived for the soil heat flux G in the form

$$G(z,t) = G_o \exp\left[-z\sqrt{\frac{\omega}{2K}}\right] \sin\left(\omega t - z\sqrt{\frac{\omega}{K}}\right) \quad \ldots \quad (10)$$

if K is constant with z. This describes a progressive wave of phase velocity v, given by

$$v = \sqrt{(2K\omega)} \quad \ldots \quad (11)$$

whose amplitude decays exponentially and lags in phase with depth. G_o is the surface amplitude. The amplitude A_z of the soil heat wave at any depth z is related to the amplitude A_{ref} at some given depth z_{ref} through the equation

$$\frac{A_z}{A_{ref}} = \exp\left[\left(\sqrt{\frac{\omega}{2K}}\right)(z_{ref} - z)\right]. \quad \ldots \quad (12)$$

This equation can be used to determine the 'penetration depth' of either the daily or annual heat wave into various soils. This depth is defined as the level at which the amplitude of the soil heat wave is reduced to 1 per cent of its surface value.

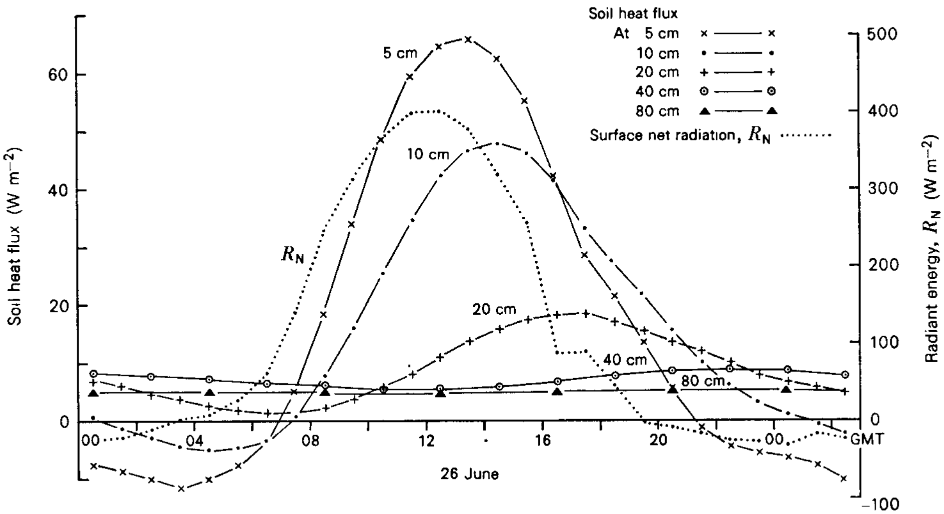


Figure 8. Variation of soil heat flux with depth at Cardington, 26 June 1976.

Hot Spell 1 produced some notable diurnal variations in soil heat flux, with fluxes near the surface regularly exceeding 100 W m^{-2} by day. Figure 8 shows the profiles of soil heat flux on 26 June at depths of 5, 10, 20, 40 and 80 cm, with the surface net radiation R_N included for comparison. Note the increasing time (phase) lag of the profile maxima as the heat wave is conducted down through the soil; this is predicted by equation (10). It takes about 11 hours for the wave to reach a depth of 40 cm, giving a mean phase velocity of around 3.5 cm h^{-1}. The angular frequency ω is obtained from the half period of the wave motion, which is 10 hours. Since ω and v are known, equation (11) gives a value of $K = 0.54 \times 10^{-6}$ m^2 s^{-1} for the mean diffusivity in the top 40 cm layer of soil. The penetration depth of the diurnal soil heat wave can now be calculated from equation (12). This value, 51 cm, fits the experimental data in Figure 8 well, since at 40 cm depth the wave amplitude is very small, and at 80 cm the diurnal influence has disappeared. The steady downward flux of 5 W m^{-2} at this lowest level reflects longer term changes in soil temperature. Equation (12) may also be used to compare the observed amplitude reduction with depth on 26 June with the theoretical ratio A_z/A_{ref}. This reduction ratio is shown in column 2 of Table I, expressed in terms of the peak-to-peak amplitude (i.e. diurnal range), A_5, of the heat wave at 5 cm. Column 3 in this table gives the diurnal range of soil heat flux measured at each

Table I. *Comparison of observed and theoretical soil heat flux amplitudes on* 26 *June* 1976

1 Depth, *z* cm	2 A_z/A_5 *per cent*	3 Diurnal range measured W m^{-2}	4 Diurnal range predicted W m^{-2}
0	156·8	145	122
5	100·0	78	78
10	63·8	54	50
20	26·0	17	20
40	4·3	3·6	3·4

depth, z. (Note that the surface value of 145 W m^{-2} is based on the method of extrapolation mentioned earlier.) If the observed diurnal range at 5 cm is multiplied by the percentages of column 2, the theoretical variation with depth of the peak-to-peak amplitude is obtained, and this is shown in column 4. A comparison of columns 3 and 4 indicates that the observed amplitude decay agrees well with the exponential law of equation (12). The agreement is not perfect because various assumptions are implicit in this equation. One of these assumptions is that soil is a homogeneous medium, and in practice this is not so. The coefficients k_S and K, and therefore the phase velocity v, can vary considerably with depth. In order to illustrate this point, Figure 8 shows that the speed of the soil heat wave through the 10–20 cm layer is twice that through the 20–40 cm layer. It should, however, be noted that K is rather insensitive to changes in soil moisture since it is the ratio of two parameters (refer to equation 9), both of which vary in the same sense with changes in soil water content. However, it is clear that the departure of theory from observation is most noticeable at the surface. If a diurnal minimum value of -25 W m^{-2} is assumed for the surface flux, then a day-time maximum of 97 W m^{-2} is predicted, which is about 25 W m^{-2} less than the extrapolated surface value (refer to Figure 9). Considering that the exponential law seems to fit the observations below the surface, a better estimate of the maximum surface flux on this day would probably be around 110 W m^{-2}, which is a remarkably high value for rural England.

In Figure 9 isopleths of soil heat flux are shown on a depth-time plot over a three-day period during Hot Spell 1. The gradient of the two sloping lines on this diagram gives the mean downward velocity of

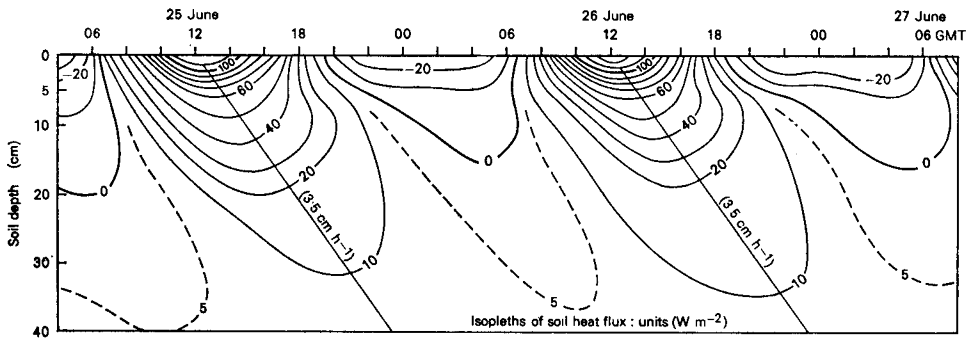


Figure 9. Diurnal variation of soil heat flux at Cardington, 25-27 June 1976.

the heat wave into the ground. The diagram highlights the remarkable changes in heat flux which occurred within the top 20 cm layer of soil during fine weather in the summer of 1976. It also demonstrates how difficult it can be to obtain a realistic measure of the surface heat flux in these circumstances. It is worth while comparing the magnitude of the soil heat flux in this layer with that measured during a more recent hot spell at the beginning of July 1977, when the ground water content was very high. Normalized in terms of the net radiation, the amplitude of the soil heat flux in the top 20 cm layer was between 50 and 100 per cent greater during Hot Spell 1 than in July 1977. However, equations (6) and (7) show that, in the presence of a given heat flux G, the rate of change of temperature and the vertical temperature gradient in the ground are inversely proportional to the specific heat (ρC) and conductivity k_S. Since (ρC) and k_S both decrease with soil moisture content, it is likely that the amplitude of the diurnal temperature change in this top layer of soil during Hot Spell 1 became even more pronounced than that of the soil heat flux.

7. Concluding remarks

For much of July and August 1976 between 75 and 90 per cent of the available incoming radiation was used to heat the ground and the air above, with the rest passing into latent heat of evaporation. During Hot Spell 2 in the middle of August the sensible heat flux regularly reached 250–300 W m^{-2}, by day, with the latent heat flux accounting for less than 40 W m^{-2}. At the start of the June–July hot spell, however, over 30 per cent of the available energy was being used for evaporation, with the latent heat flux then exceeding 100 W m^{-2} during the day. The surface soil heat flux reached notably high values of over 100 W m^{-2} at this time. In order to emphasize the exceptional nature of the energy budget during the summer of 1976, it is worth while considering the change in the Bowen ratio, H/E. In an average summer with a regular rainfall this ratio varies between 0.5 and 1.0 during the day, that is, the latent heat flux often exceeds the sensible heat component. During 1976, however, the Bowen ratio increased to well over 6 during August.

Ratcliffe (1976) has estimated that during June 1976 approximately 70 per cent of the total net incoming radiation was available for heating the ground and air over the country as a whole. This is in excellent agreement with the value of 68 per cent measured on 26 June at Cardington when the highest temperature of the season was recorded. However, sensible heating is clearly not the only factor controlling surface temperature; atmospheric temperature structure is just as important. This point is demonstrated by the variation of the ratio $(H + G)/R_N$ during the summer, which reached a maximum during the hot spell in the middle of August. For example, on the 16th the normalized combined sensible and soil heat flux was 25 per cent greater than on 26 June, yet the maximum temperature on the August day was 7 °C lower. This would suggest that, at Cardington, the depth of the convective boundary layer exerted a more important influence than sensible heating in producing the particularly high screen temperature maxima in the last week in June.

Acknowledgements

I should like to thank all my colleagues at the Meteorological Research Unit for their assistance during this experiment, and especially the technical staff for their invaluable support, both in the field and in the recording laboratory.

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Severe low level turbulence near Cross Fell

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Summary
An incident is described in which an aircraft experienced severe low level turbulence near Cross Fell. The synoptic situation is discussed and it is found that the conditions closely resembled those found by Förchtgott to be necessary for the initiation of rotor streaming. Work by others in the field is discussed and some conclusions drawn as to the strength of the vertical gusts and the size of the turbulent element involved.

Introduction

At 1103 GMT on 27 April 1978 a transport aircraft on a low flying exercise between North Wales and Scotland encountered severe turbulence in clear air. Up to this time the aircraft had only experienced infrequent light turbulence near high ground. When the severe turbulence occurred the aircraft was flying at 108 m/s (210 kn) at a height of 75 m (250 ft) above ground level in a north-north-westerly direction along the Eden valley 5½ km (3 n. mile) to the west of the summit of Cross Fell, 893 m (2930 ft). A map showing the location of the incident and the track of the aircraft is shown in Figure 1. Three crew members who were temporarily unstrapped for operational reasons received slight injuries whilst

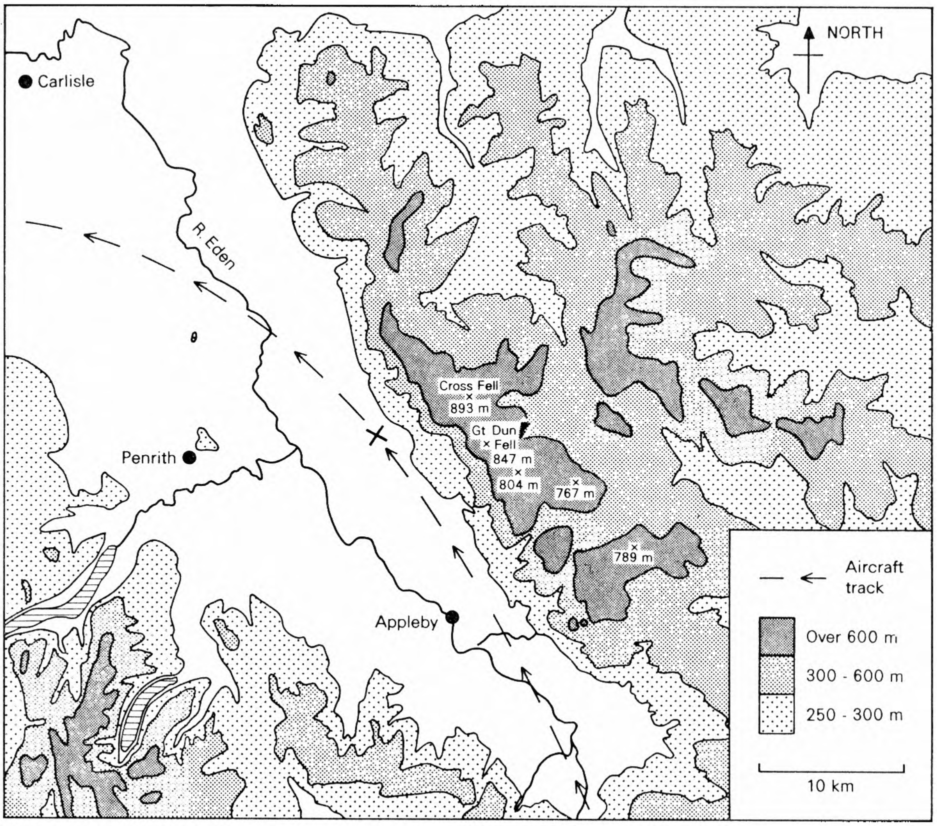

Figure 1. The Cross Fell Range and the Eden Valley. X marks the position where severe turbulence occurred.

the contents of the galley were thrown across the rear of the flight deck. Meanwhile, farther back in the aircraft, the portable toilet fell from its stand, spilling its contents on the floor. The pilot immediately took the aircraft up to 300 m (1000 ft) and the remainder of the flight passed without further incident.

The pilot likened the encounter to a jolt which lasted about a second whilst the aircraft's accelerometer registered vertical accelerations of $+2\frac{1}{4}$ g and $-\frac{1}{4}$ g (the normal reading is $+1$ g). The cloud base at the time was about 600 m (2000 ft) and no unusual or turbulent looking cloud elements were noted; the wind recorded at flight level was 060 deg 10 m/s (20 kn). On the ridge crest to the east the surface wind at Great Dun Fell, 847 m (2780 ft), was 040 deg 16.5 m/s (32 kn) at 09 GMT and 040 deg 15.5 m/s (30 kn) at 12 GMT and slight snow was falling. The pilots of two other aircraft flying at over 206 m/s (400 kn) and 150 m (500 ft) above the ground through the same area about three hours later reported that they had encountered nothing unusual in the way of turbulence.

Synoptic situation

A depression over the Low Countries at 00 GMT on 27 April 1978 had maintained an unstable north-easterly flow across Scotland and northern England. The depression subsequently moved north-west towards Lincolnshire with warm air on its south-eastern flank. As the low moved north-westwards, the surface north-easterly over northern England and Scotland increased in strength while the warm air was pushed northwards over Lincolnshire and south Yorkshire. An area of precipitation spread north-west in association with this warm air and by 09 GMT there was rain over the whole of England north of a line from the Wash to the Mersey with sleet or snow over the hills. By 12 GMT the surface chart showed that warm air had reached as far north as the Scarborough area as shown in Figure 2. The depression, now centred near Waddington, was filling slowly and the precipitation over northern England had begun to peter out to the west of the Pennines.

The upper-air charts showed that a 500 mb low was slow moving to the north-west of Ireland while at 700 mb the low centre was over the Irish Sea. The centre of the upper low was thus a considerable distance from the surface low centre and in consequence there was a marked veer of wind with height over northern England resulting in a south-south-westerly thermal wind in the 1000–500 mb layer.

The Shanwell midday ascent showed warm air above 600 mb, cold air below 750 mb and a well-marked stable layer in the frontal zone between. As can be seen in Figure 3 the difference in potential temperature of the two air masses was quite large, being about 8 °C.

Discussion

The phenomenon of wave streaming to the lee of Cross Fell known as the Helm Wind has been studied in detail by Manley (1945) and is well documented. However, on this occasion the severity of the turbulence encountered by the aircraft and the wind and temperature data suggest that conditions were favourable for rotor streaming. Förchtgott's work, as described by Corby (1954) and Alaka (1960), indicates that the requirements for the initiation of rotor streaming are high static stability and steep lee slopes with a streaming layer of strong winds blowing normally to the mountain ridge at low level. Above the streaming layer there should be a marked reduction with height of the wind component across the ridge. It is also suggested that the depth of the streaming layer should be no more than one and a half times the height of the ridge above the lee terrain. The height of the Cross Fell ridge above the Eden valley floor is generally about 600 m (2000 ft) which suggests that for rotor streaming to occur the streaming layer should extend to a height of no more than 1500 m (5000 ft) above sea level.

The Shanwell 12 GMT wind profile plotted on the hodograph in Figure 4 suggests that the depth of the layer was greater than that required for streaming to occur since a marked decrease in the wind component across the ridge took place only above 750 mb; however, the Shanwell temperature profile

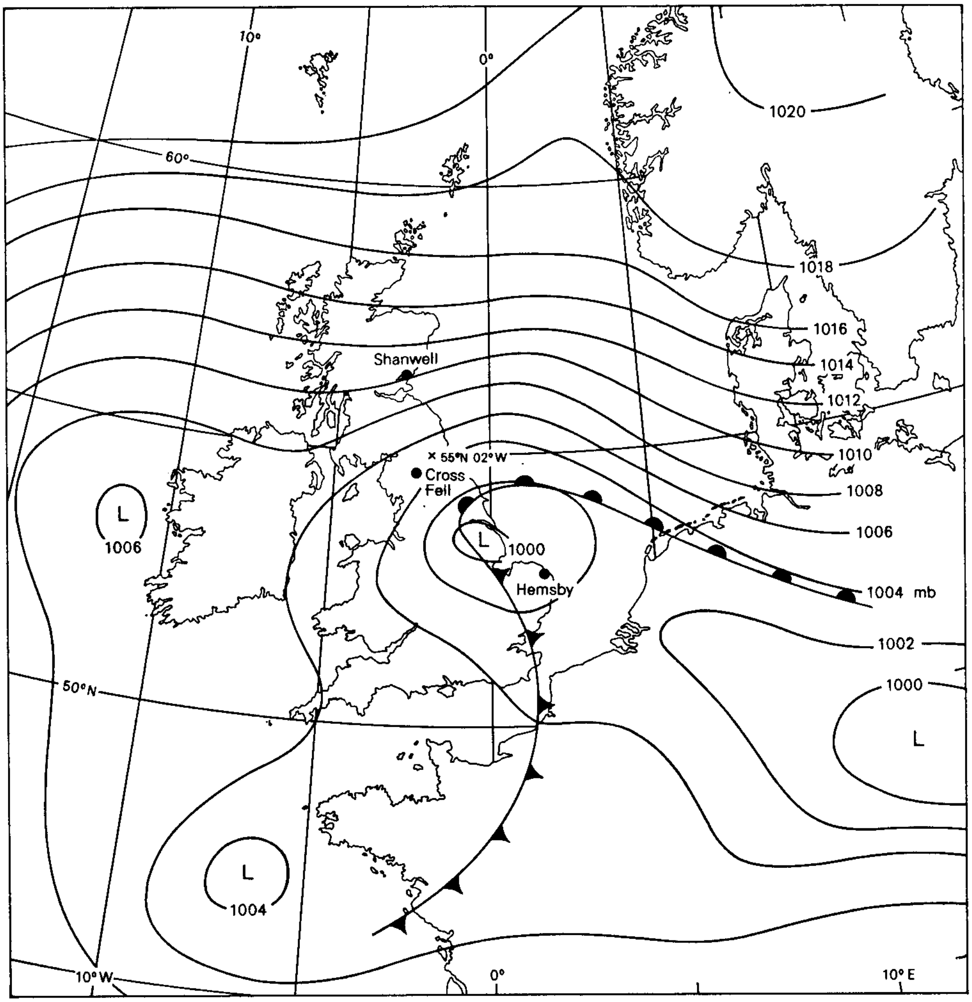

Figure 2. Surface synoptic chart for 12 GMT on 27 April 1978 with isobars drawn every 2 mb.

was a long way from being representative of the undisturbed flow upwind of the Cross Fell ridge. Some attempt has therefore been made to estimate the wind and temperature profiles upwind of the ridge.

An assumed wind profile for a position upwind of the ridge at 55°N, 02°W was obtained by interpolation from charts of upper winds plotted for the various levels up to 500 mb. This profile is also plotted on the hodograph in Figure 4 and suggests that here the streaming layer was a good deal shallower than at Shanwell with marked reverse wind shear all the way up to 500 mb. Some idea of the temperature profile upwind of Cross Fell can be obtained by plotting the midday ascent for Hemsby, which was clearly in the warm air, and that for Shanwell on a tephigram. Assuming a steady frontal slope from the boundary of the surface warm air over Yorkshire at midday to the frontal surface at Shanwell it can be seen from Figure 3 that the base of the frontal surface upwind of Cross Fell would lie somewhere between 800 and 900 mb, that is between 900 m (3000 ft) and 1800 m (6000 ft) above sea level.

It therefore seems clear that Förchtgott's requirements for rotor streaming were well satisfied and it

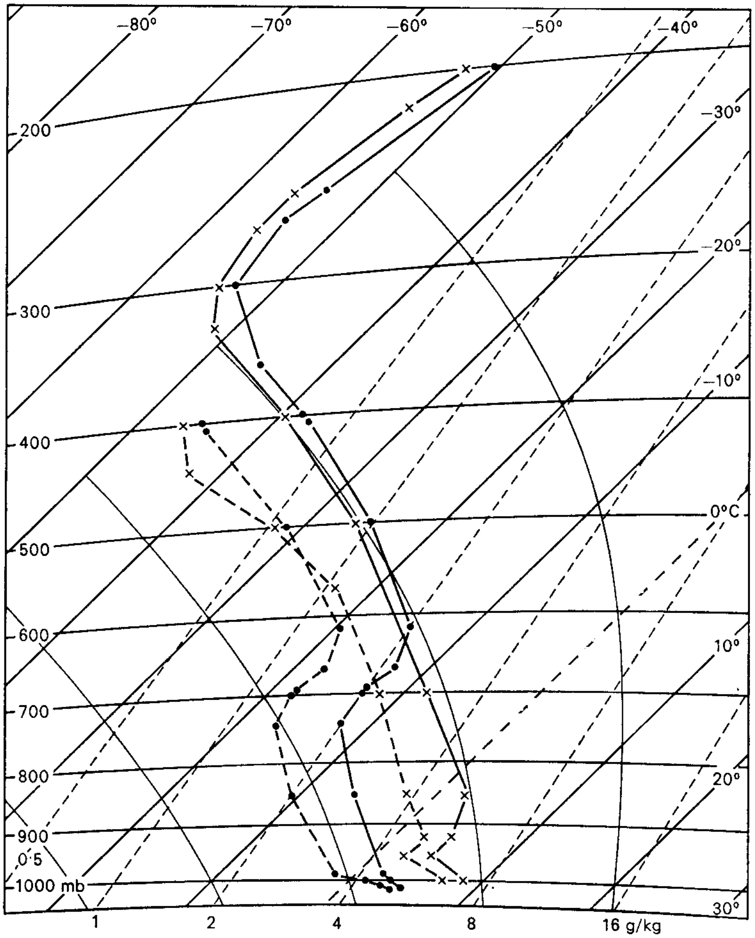

Figure 3. Tephigrams for 12 GMT on 27 April 1978.

•——• •- - - -• Shanwell ×——× ×- - - -× Hemsby

may be that in this particular case the cold air beneath the frontal surface and the streaming layer were one and the same thing.

Several instances of rotor streaming over the United Kingdom have been described by Corby (1957) and rotor streaming to the east of the Pennines has been discussed by Gray and Stewart (1965). Dent and Dyson (1963) who investigated a case of rotor streaming to the west of the Pennines were fortunate in obtaining anemograms which amply demonstrated the extreme gustiness engendered by rotor streaming. Unfortunately anemograms are not available from the Eden valley.

In an article describing a case of severe turbulence at low level ahead of a warm front Cashmore (1966) infers, from work done by Parker (1959), that the strength of the vertical air currents involved can be computed using the accelerations registered by the accelerometer and the aircraft characteristics. Similar computations using the data provided by this incident show that the accelerations recorded would have been produced by a sharp-edged vertical gust of about 12 m/s (23 kn) followed almost immediately by one of equal strength in the opposite direction.

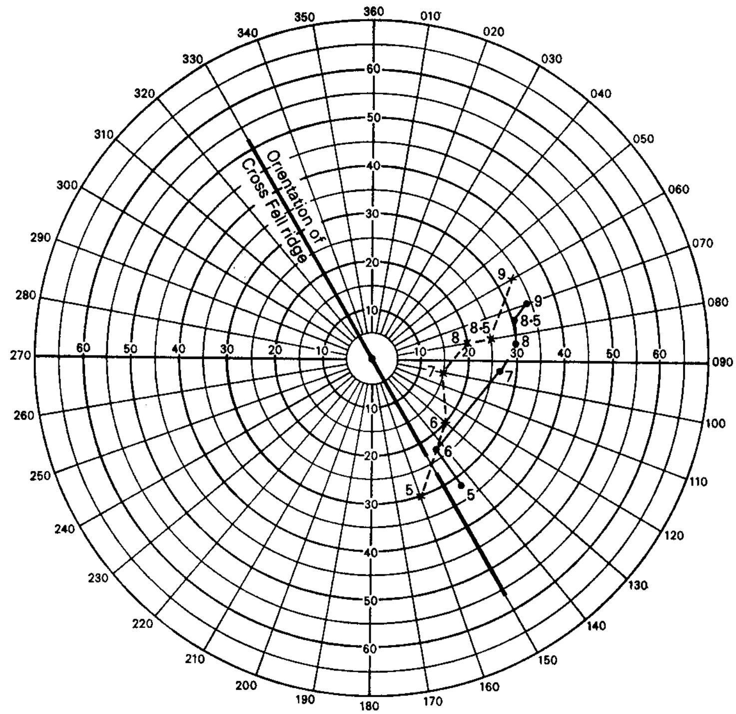

Figure 4. Hodograph showing change of winds with height over Cross Fell ridge at 12 GMT on 27 April 1978.

•———• Shanwell actual winds × - - - × Interpolated winds for 55°N, 02°W

Note. Individual plots are labelled in hundreds of millibars.

Some idea can also be gained of the size of the turbulent element encountered because of the isolated nature of this incident. Using the speed of the aircraft at the time, 108 m/s (210 kn), and accepting the pilot's estimate of one second for the duration of the severe turbulence it can be inferred that the horizontal extent of the turbulent element was of the order of 100 m (330 ft). By comparison with cases of rotor streaming already referred to where severe turbulence was experienced over a wide area it would seem that the scale of the turbulence in this instance was quite small.

Rotor streaming is not a common phenomenon but because of the very violent nature of the low level turbulence associated with it low flying aircraft are particularly at risk. With many more aircraft, including helicopters, flying at relatively low levels nowadays it is vital to aircraft safety that forecasters and aircrew recognize the situations in which rotor streaming may occur.

Acknowledgements

I am grateful to Mr A. D. Prissick for his valuable assistance, Dr A. P. Cluley for his helpful suggestions and the Royal Air Force for making available the data for the investigation from which this article grew.

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Notes and news

The Meteorological Magazine

This month the size of the Meteorological Magazine is increased from Royal Octavo (246 mm × 156 mm) to Crown Quarto (246 mm × 189 mm) and some changes in style are introduced which we hope will make for easier reading. The new cover design was prepared by Mr G. W. Farrow, Head of the Meteorological Office's Cartographic Section.

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NOTICES

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

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THE METEOROLOGICAL MAGAZINE

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The Royal Meteorological Society Exhibition 1978

When the British Meteorological Society, later to become the Royal Meteorological Society, was founded in 1850 much of its work was concerned with the setting up of a basic network of meteorological observations over the United Kingdom. During the century and a quarter of the Society's existence, the science of meteorology has steadily developed and the Society's work has extended to include the stimulation of research and application over the fields of meteorology, climatology and oceanography and the encouragement and organization of meteorological education for both amateurs and professionals.

To mark the move of the Society's Headquarters to James Glaisher House in Bracknell an exhibition was arranged in Bracknell College from 14 to 17 July 1978. Nearly 80 different institutions drawn from universities, government departments and industry provided contributions, so that the current scope of the Society's interest was well represented. Her Majesty The Queen, Patron of the Society, graciously consented to open the exhibition at noon on Friday 14 July. After an extensive tour of the displays Her Majesty visited the Society's Headquarters where she was entertained to lunch before her visit to Meteorological Office Headquarters.

With no less than 14 different displays, some in the entrance hall and the remainder in the main halls, the Meteorological Office was well represented in the exhibition. On entering, the eye of the visitor was immediately caught by the Meteorological Office Radar Research Laboratory display. This consisted of two colour-television monitors, one showing rainfall intensity as observed by an integrated network of radars and the other infra-red radiances from geostationary and orbiting satellites; these illustrated the development and movement of rain and cloud areas. In the main body of the exhibition two neighbouring displays showed working demonstrations of the Mk 3 radiosonde and of 'AUTOMET', the automatic weather station based on a micro-computer. Another display showed a simple laboratory apparatus for observing wave motions in a liquid in a rotating annular tank, with walls maintained at different temperatures; this wave motion is analogous to that of the atmosphere. Apart from working equipment there were several display panels describing various aspects of the work of the Office; these included alternative approaches to long-range forecasting, a description of a rain-gauge network assessment and rationalization exercise and an account of how the Meteorological Office helps to provide the agricultural industry with operational warning systems for pests and diseases.

The impact of the Meteorological Office displays was enhanced by the uniform format of the display panels. These have dimensions of approximately 1·5 metres by 1 metre with the backboard colour washed in an appropriate pale colour. On top of each board was a blue upstand with the words 'Meteorological Office' in white, and individual spot-lighting was provided for each display. These panels and suitable stands may be made available to outstations wishing to arrange small exhibitions of their own.

This short account would not be complete without a word of praise for the Meteorological Office Cartographic Section, which produced the display panels. The enthusiasm and hard work of the Cartographers ensured the success of the Office's contribution to the Exhibition.

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Visit of Her Majesty The Queen to the Meteorological Office, 14 July 1978

On the afternoon of 14 July 1978 Her Majesty The Queen visited the Meteorological Office during the course of a visit to Bracknell. Her Majesty was accompanied by the Lord Lieutenant of Berkshire, Colonel The Honourable Gordon Palmer, and Her Lady-in-Waiting, The Honourable Mary Morrison.

On arrival at the Meteorological Office Her Majesty was greeted by Dr B. J. Mason, the Director-General who presented Dr K. H. Stewart, the Director of Research, and members of the Senior Directorate. The Director-General took the opportunity of showing Her Majesty photographs taken of the occasion of her previous visit on 25 June 1962 shortly after the Headquarters Building had been opened.

Dr Mason conducted Her Majesty to the Central Forecasting Office (CFO) where Mr D. E. Jones, the Assistant Director in charge, described the work of CFO and presented several members of the staff who described their work to Her Majesty. Mr K. F. Sylvester, Chairman of the Institution of Professional Civil Servants Branch Council and representing the Staff Side, was presented to Her Majesty at the end of the visit to CFO.

Her Majesty also visited the COSMOS Computing Laboratory where the Director-General presented Mr G. A. Howkins, the Assistant Director in charge of Data Processing, who described the work of the Laboratory. Individual members of the staff described their work to Her Majesty, who was also given a demonstration of chart-plotting equipment.

On her departure from the Office Her Majesty signed a specially illuminated page of the Visitors' Book which was subsequently put on display at popular request.

During the visit many members of the staff and their families took the opportunity to see Her Majesty from vantage points in the car park, lobbies and corridors.

Subsequent to the visit, the Director-General has received a letter from the Private Secretary to Her Majesty expressing Her Majesty's thanks for 'an extremely interesting afternoon' and commenting on the excellent explanations given by members of the staff. Her Majesty was 'touched by the charming reception given to her'.

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Concerning general circulation models

by A. Gilchrist

(Deputy Director (Dynamical Research), Meteorological Office, Bracknell)

The paper that follows is based on a lecture at the summer meeting of the Royal Meteorological Society, July 1976.

Numerical models of the general circulation are among the most powerful tools available for studying the large-scale behaviour of the atmosphere. They have many applications, actual and potential: for understanding features of the atmospheric circulation, for studying pronounced abnormalities of weather or changes in climate, for investigating the impact of natural or man-made pollution, for weather forecasting and the assessment of atmospheric predictability, for determining optimum observational systems, and so on. They should be of interest not only to those who create and develop them but to everyone concerned about how the atmosphere works, and in particular to the wide cross-section of the meteorological community whose researches stand to benefit from the application of such models to particular problems. To foster a wider, but critical and discerning appreciation of their potential is a worthwhile aim which it is the intention of this article to further. It seems to me that the most useful approach is to discuss certain features of general circulation models and results which sometimes cause perplexity, misunderstanding or even concern, and thereby allay doubts which may be ill founded.

To begin with, consider the global mean-sea-level pressure fields for January and July simulated by the Meteorological Office general circulation model (Figures 1 and 2). They have been obtained in the usual way; that is to say, the global general circulation model was presented with an isothermal, motionless atmosphere of total mass and (by implication) gaseous constitution similar to those of the real atmosphere. The surface temperatures of the oceans and the radiation parameters were set to their climatological mean values for the appropriate month, and the model was then integrated forward numerically until 100 days had been simulated. During this time the motions created by the model took on many of the observed characteristics of the atmosphere. The charts shown were obtained by averaging the mean-sea-level pressure distributions for the last 40 days of the experiments. Details of the model can be found in published papers, e.g. Corby *et al.* (1972, 1977). Comparing the model simulations with the climatological pressure distributions for January and July (Figures 3 and 4) it is evident that the model is capable of reproducing the main observed systems. We may note for example the subtropical anticyclones, the Aleutian and Icelandic lows, and the low-pressure belt around the Antarctic continent, whose positions and seasonal change of intensity are correctly indicated. The change-over from the Siberian anticyclone and the north-east monsoon of January to the low-pressure monsoon trough of July is realistic.

It is, however, not my purpose here to discuss at length the successes or failures of the model. It is, as I have indicated, to try to answer nagging questions which arise when diagrams like these are shown. Perhaps the first matter to clarify is the significance to be attached to the simulated surface pressure maps. There may well be a feeling that reasonably correct simulations of the pressure field might nevertheless be associated with poor values of the bulk properties of the flow, the fluxes and the energy transformations, which are the quantities usually discussed in papers on the general circulation. Our experience indicates otherwise. The surface pressure distribution arises as a result of many complex processes going on within the model, on the divergence of the wind, on the mutual

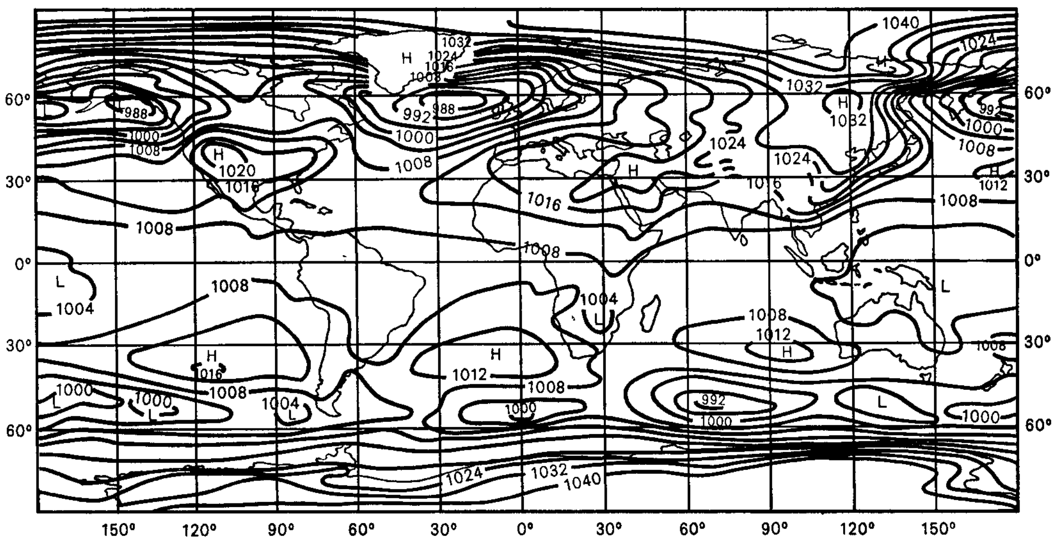

Figure 1. Time-mean chart of pressure at mean sea level from days 61–100 of the January integration. Isobars are at 4 mb intervals.

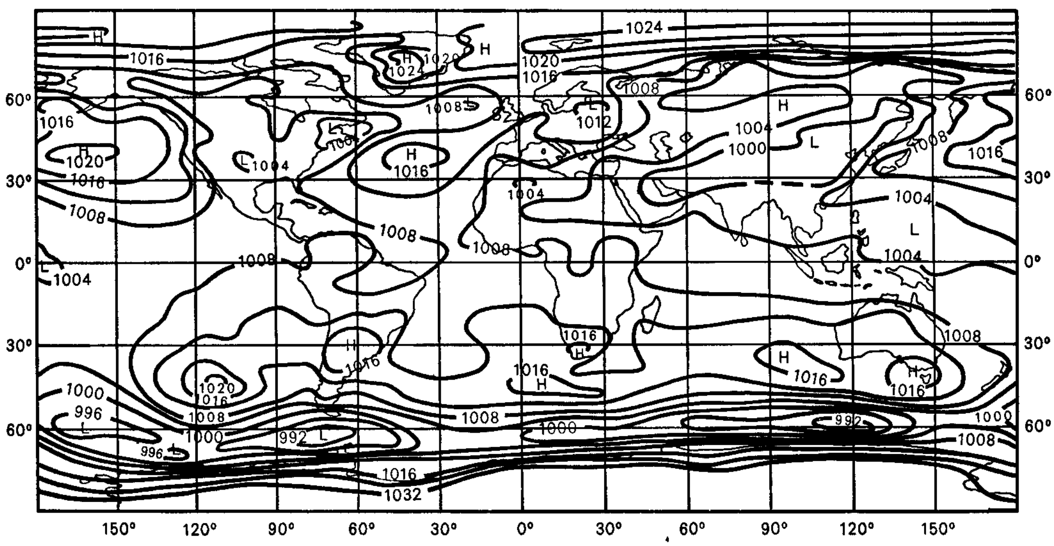

Figure 2. Time-mean chart of pressure at mean sea level from days 61–100 of the July integration. Isobars are at 4 mb intervals.

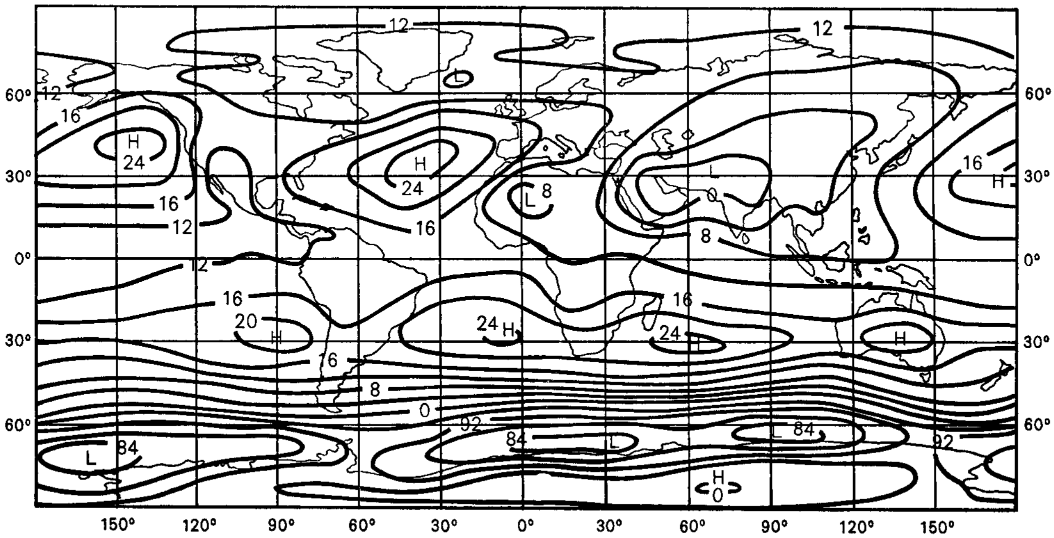

Figure 3. Observed average pressure at mean sea level, January. Isobars are at 4 mb intervals.

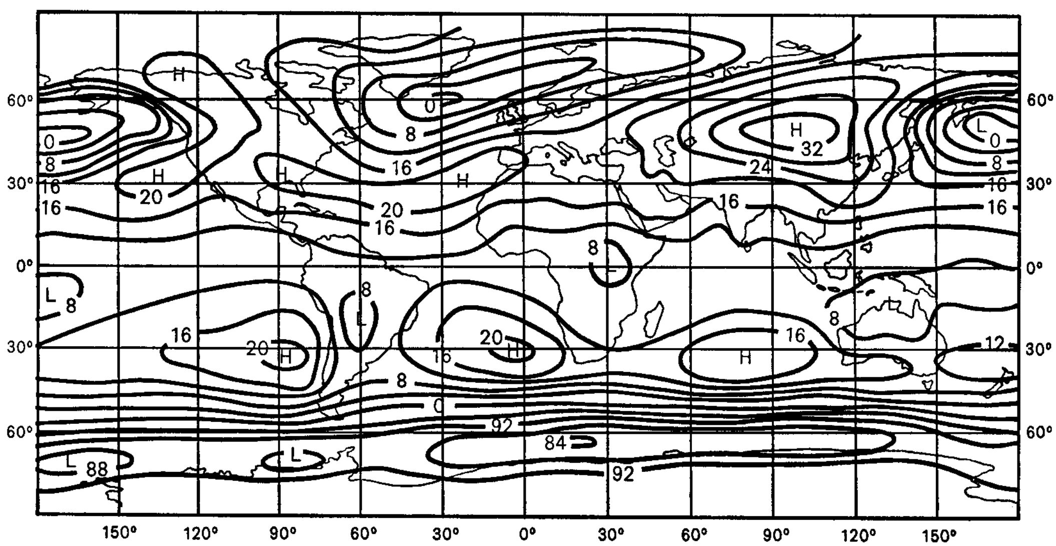

Figure 4. Observed average pressure at mean sea level, July. Isobars are at 4 mb intervals.

adaptation of wind and mass fields, on the ability to reproduce realistic depressions and so on. The surface pressure effectively integrates all these, and is sensitive to errors in them. At least as it has appeared in developing our general circulation model, it is not likely that one will find a poor simulation which does not betray its shortcomings somehow in the surface pressure fields; equally, if the surface pressure field is realistic both in its time-mean values and in its day-to-day evolutions, the bulk properties of the flow are most probably realistic also. On the other hand, many integrated quantities seem to be comparatively insensitive to major defects in the model.

It may also be noted that the surface pressure is the meteorological variable about which we probably have the greatest knowledge both as regards its distribution in space and its variability in time. It is therefore less susceptible than other variables to sampling or observational errors, which can easily complicate the process of comparing model results against actuality. In choosing indicators of the quality of climatic simulations, I doubt if one could do better than give primacy of place to the mean-sea-level pressure field, backed up if possible by a measure of its day-to-day variability.

Following many precedents, I have already compared the model simulations with the long-term climatology. One may well ask if this is appropriate. Certainly it is wrong to consider the climatology as the 'correct' answer, to which the simulations should conform in detail. The model result represents an average of only 40 days, whereas the climatology has been determined from some thousands of days, and there are good statistical reasons for expecting means over such diverse periods to differ. One can indeed assert that if the model's result is closely similar to the climatology, it is unlikely that it simulates the atmosphere realistically on a day-to-day basis. It is obviously more satisfactory to regard the model simulation as representing a single month and then seek an answer to the question: 'Does it differ significantly from the population of observed monthly mean distributions?'. For this, the variability of the monthly mean values is taken into account by calculating 'Student's-t', the distribution of which is shown in Figures 5 and 6 for the area of the northern hemisphere for which mean-sea-level pressure charts were available in the Meteorological Office. [Note: Before calculating 't', a small correction 'ϵ' was added to all model pressure values to make the model and atmospheric masses the same over the area of calculation, it having been noted that the total mass in the model was sightly deficient.] Values of 't' greater than 2 may be expected by chance on about 5 per cent of occasions, but values as large as 3 should be very uncommon. High values associated with mountains may be ignored, since they depend on the method of reduction to sea level and could be largely removed by a less simple-minded method. The figures indicate that the most significant errors in the simulation do not in general coincide with the largest deviations from climatology. In January, north-west Canada has pressures that are consistently low and the area near the pole is too anticyclonic. In July the standardized deviations are larger and more widespread; in particular the deficiency of pressure in the subtropics and the excess in polar regions constitute substantial errors.

It must now be pointed out that in deriving these results, a very important factor has been ignored, namely, that the atmosphere is subject to a variety of effects which differ from one year to another and indeed from one part of a month to another but which have been kept constant in the model. Thus in the model the temperatures of the surface of the oceans and (at least by implication) the cloudiness are not allowed to change. Since one must expect major anomalies of the atmospheric circulation to be associated with anomalies of ocean temperatures and cloudiness, the spread of possible model simulations obtained by starting from different initial situations at the beginning of the 40-day averaging period should be less than that for the real atmosphere. Consequently, the 't'-values as calculated above tend to present an unduly favourable impression of the model results. There is, however, no way of separating out that part of the variability of the atmosphere which is produced by the effects that are kept fixed in the model. The natural way of pursuing this topic is

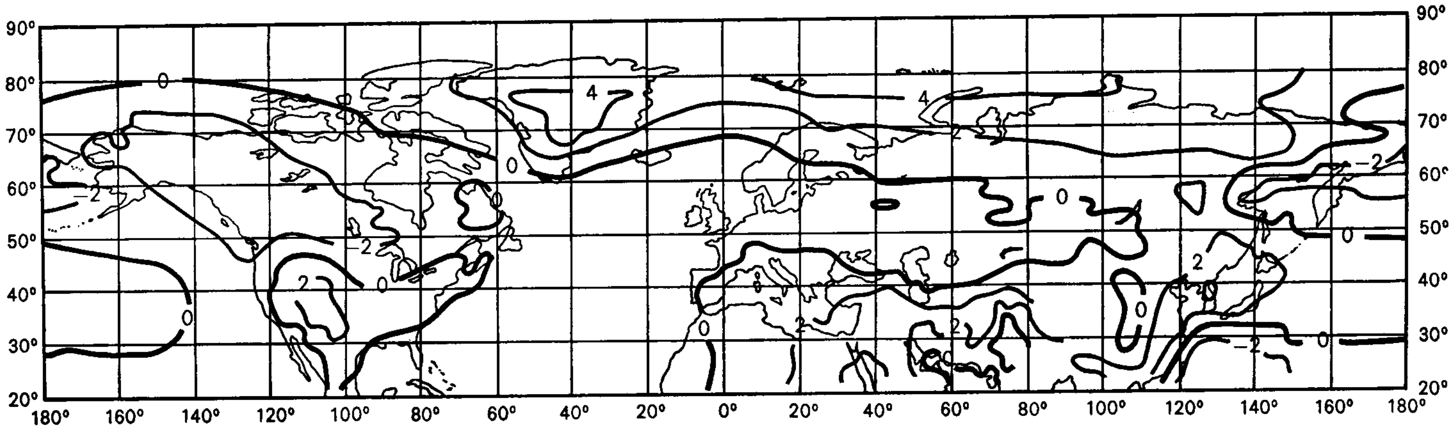

Figure 5. 'Student's-t' for January integration.

$$t = \frac{\text{January integration—observed average pressure at m.s.l.} + \epsilon}{\text{observed standard deviation of January pressures}}.$$

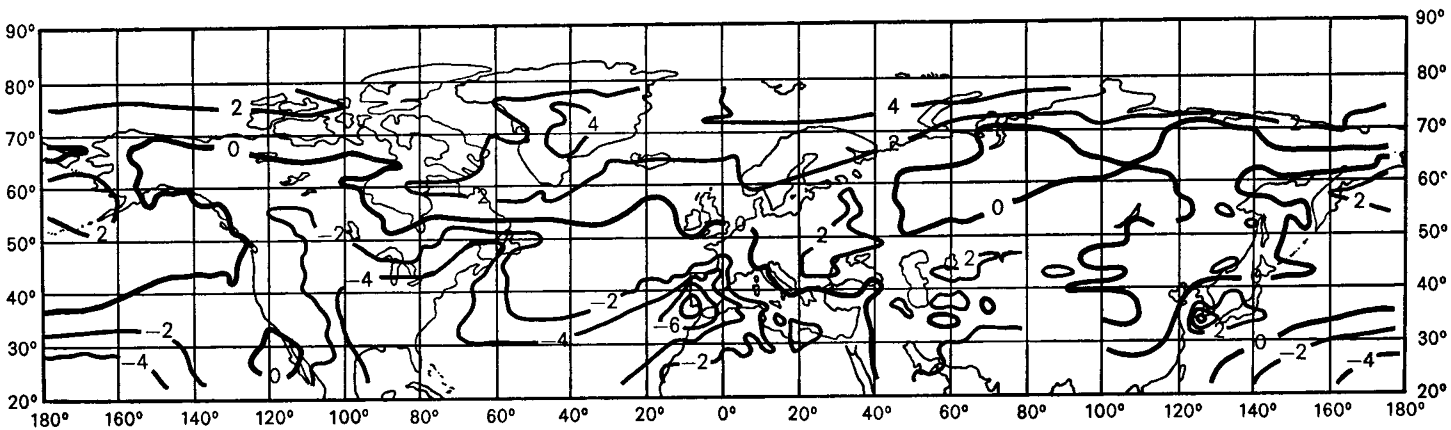

Figure 6. 'Student's-t' for July integration.

$$t = \frac{\text{July integration—observed average pressure at m.s.l.} + \epsilon}{\text{observed standard deviation of July pressures}}.$$

to assess the changes in the model simulations induced by progressively relaxing the constraints that have been imposed; primarily this involves making cloud amount a function of the model variables, and incorporating an ocean model so that the interaction between ocean and atmosphere is properly represented. The process is one that has only just begun; it will be the major preoccupation of general circulation groups during the next few years.

There is one aspect of the interaction of the atmosphere and the ocean which I would like to pursue here since it has caused some misunderstanding. It is the question of the importance and significance to be attached to the use of fixed climatological temperatures for the oceans during the simulations. Thus, replying to a letter from Sawyer (1974) which quoted general circulation model results as demonstrating that a postulated geomagnetic influence on the atmosphere did not appear to be necessary to explain observed 500 mb heights, Dr King of the Appleton Laboratory has written (1974) '. . . the results were obtained using a model which incorporates as a necessary boundary condition, values of the observed sea-surface temperature which were held constant throughout the calculations. The temperature map used by Gilchrist *et al.* is such that the 6 °C isotherm moves 21° towards the north (from 45°N to 66°N) while crossing the Atlantic from America to Europe and 18° northwards while crossing the Pacific from Asia to America. It is obviously not possible to use the results of calculations which incorporate such boundary conditions to decide whether the Earth's magnetic field or any other external phenomenon influences the circulation of the atmosphere.' In a broad philosophical sense Dr King is no doubt correct. The point is, presumably, that it is conceivable that the oceans carry the influence of the geomagnetic field, so that when a numerical integration is carried out using fixed ocean temperatures, this influence is fed back into the atmosphere. I refrain from comment on the inherent plausibility or implausibility of the hypothesis that the atmosphere responds to the geomagnetic field but I am concerned to look at the notion, essential if what Dr King says has any validity, that the sea surface temperatures imply the atmospheric circulation so that if they are fixed at their climatological values, any reasonable model can be expected to reproduce the climatology of the atmosphere as a whole.

We must be clear in the first place why assumptions about the temperatures of the ocean surface are made. The oceans are vast store-houses of heat. The motions within them constitute one of the prime methods of transferring heat from low to middle and high latitudes, where as a result of exchange at the surface it is released into the atmosphere. Because cooling of the surface layers causes the cool surface water to descend and be replaced by warmer water from below, cooling, if continued, spreads through a deeper and deeper layer. Recollecting that the heat equivalent of the whole of the overlying atmosphere is the same as that of the top 2½ metres of the ocean, and that the annual cooling cycle can extend down to 100 metres and beyond, it is obvious that the oceans are such a powerful source of heat that they cannot be ignored in any attempt to simulate a realistic atmospheric climatology. The release of heat from the oceans to the atmosphere must be included in a reasonably realistic way. Because cooling can proceed to considerable depths, the sea surface temperature tends at many times of the year to be fairly conservative, and the assumption of quasi-constant values for integrations of about a month is not too unrealistic.

However, it is not so much the temperatures themselves but rather the difference between them and the temperatures of the continental surfaces, that are of major importance in influencing the atmosphere. Consider for example, the surface temperatures in the model at 61·5°N and 58·5°N for the January simulation shown in Figure 7. Dr King suggested that the geomagnetic field influenced the atmosphere most markedly at about these latitudes. The sea surface temperatures (denoted □) are fixed, while the model determines for itself the temperature of sea-ice and land points, though the positions of the former are also fixed. It is evident that at these latitudes relatively few temperatures are provided for the model and that they in themselves give little hint of the true atmospheric variation in the zonal direction. Nevertheless, the sea points are of crucial importance, because they represent the locations where very cold air streaming off the cold continents extracts heat from the ocean down to considerable depths. Vertical instability spreads the heat through the atmosphere, and conditions favourable for cyclonic development are produced. This is the prime mechanism by which the 500 mb troughs are formed, and therefore it is unlikely that these climatological troughs will ever

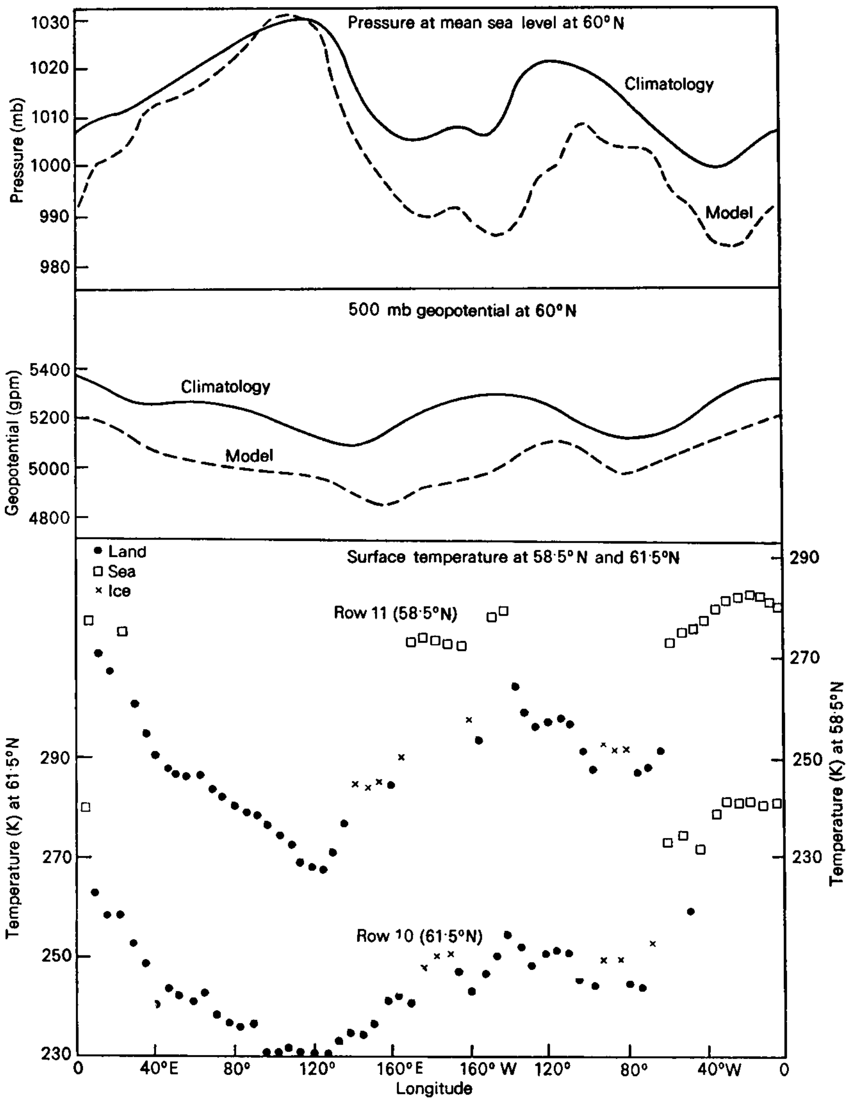

Figure 7. Average pressure at mean sea level and 500 mb geopotential for the January integration as observed at 60°N, and the temperatures of the earth's surface at grid points near 60°N in the integration. The type of surface is indicated as: □—sea, whose temperature is prescribed; ●—land, ×—sea ice, whose temperatures are determined by the model.

stray very far from the position of the boundary between land and sea or ice and sea. In Figure 8 the similar diagram for July is displayed. For this month, the number of points with prescribed temperatures is larger, but there is little indication that their information content about the longitudinal variation of atmospheric parameters is substantially greater. The model does not reproduce the features of the atmospheric climatology to the same degree as in January, but this result has to be viewed in the light of the considerations about testing the quality of simulations dealt with earlier.

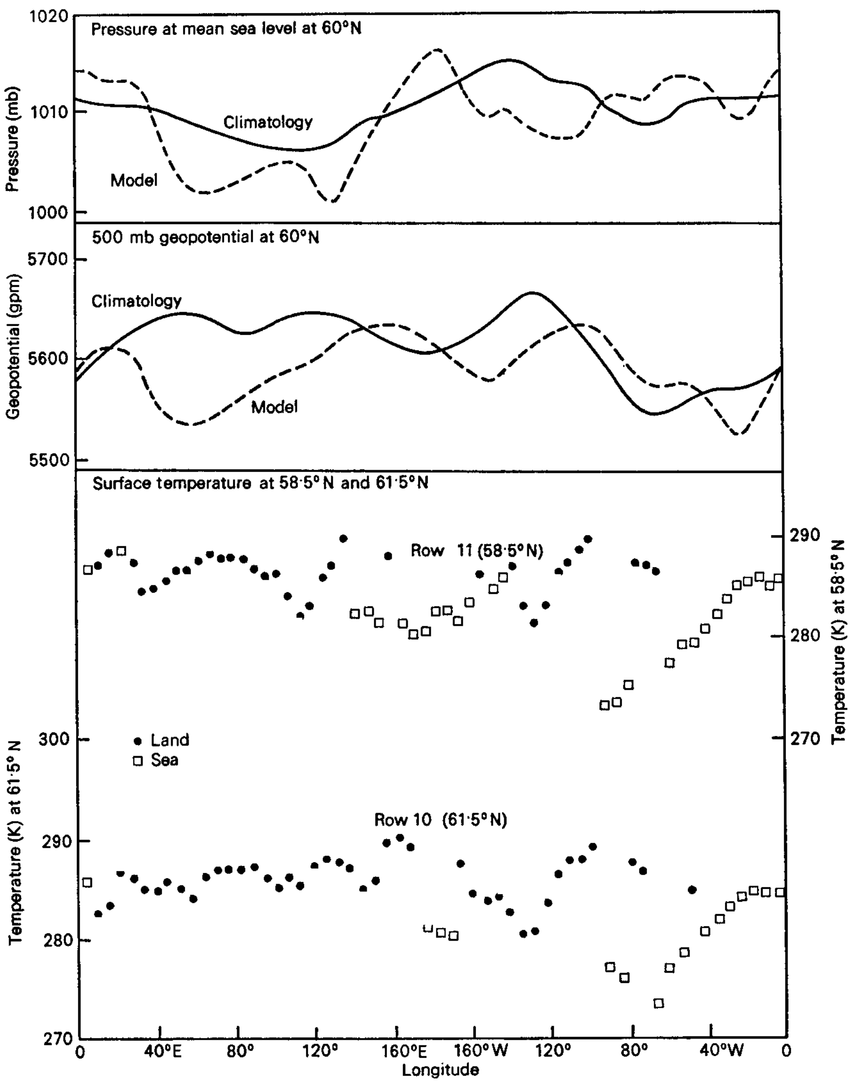

Figure 8. Average pressure at mean sea level and 500 mb geopotential for the July integration as observed at 60°N, and the temperatures of the earth's surface at grid points near 60°N in the integration. The type of surface indication is explained below Figure 7.

Another way of looking at the influence of the sea temperatures is to consider the change in surface pressure between January and July relative to the change in temperature. Thus, in Figure 9 the surface pressures and sea surface temperatures are shown for 30°W and 140°W, two longitudes chosen because they lie for the most part over oceans. It is clear from them that the changes in the atmosphere between summer and winter bear no simple relation to the change in ocean temperatures, which have on the whole a simple form, with winter cooling and summer warming of a few degrees Centigrade. It is also evident that, contrary to what would be expected if the sea surface temperatures were themselves the dominating factor, pressure and temperature are positively correlated. Again, it is the temperature over the sea relative to that over land that is important; in summer, though the sea is warmer than in winter, it is relatively cold, and vice versa in winter.

To sum up, it is clearly true that for a purely atmospheric model to obtain a realistic representation of the general circulation, it is essential that the temperature of the surface of the ocean be prescribed to be at least close to the observed values, but to suggest that the prescription of the ocean temperature ensures a realistic atmospheric simulation is, at best, a gross over-simplification.

Let us turn now to consider another matter which often seems to be misunderstood. It is the question of how far models are 'optimized' to the present climate, since a high degree of optimization* would imply that they are unsuitable for studying changes of climate. The possibility of optimization arises because processes which take place in the atmosphere on scales smaller than the resolution of the model mesh have to be 'parametrized' in terms of the large-scale variables. A parametrization is by its nature a statistical representation which can only be correct by-and-large and on average, since it is clear that the subgrid-scale processes being represented are not uniquely defined by the large-scale explicit atmospheric situation. Further, parametrization often involves quantities which, because they attempt a description of events averaged over a large area (a typical grid square area is about 10^{11} m^2), cannot readily be measured, or which at the present time have not been measured at a sufficiently large number of points over the globe to provide all the information required in a global model. The modeller therefore has to choose values for a number of 'disposable constants' in his model and the difficult question which arises is how far is it scientifically legitimate for him to choose these to obtain the best agreement between the model and the atmosphere as it is now observed.

I shall not attempt to deal with the question philosophically or in generality, but simply content myself with discussing the parameters and how they were obtained in the Meteorological Office general circulation model, some of whose results have been seen.

Perhaps, however, the first point to be made is that results for both January and July, at the extremes of the annual cycle, have been shown. The only difference in the two cases was that the ocean temperatures and the radiation constants were changed. It is obvious that the differences between the winter and summer months are very large, especially in the northern hemisphere where the juxtaposition of oceans and continental land masses plays a dominant role in determining the overall circulation. The difference indeed is greater than the departure of any particular month from the normal for at least the last millenium. It may be claimed with some justification that if a parametrization contributes substantially to a model whose simulations are realistic at both extremes of the annual cycle, it is more than just a device that happens to work; it probably represents the physical situation reasonably well.

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* By 'optimization' is meant the deliberate setting of adjustable parameters to values chosen so as to make the result of a computation as near to reality as possible; such parameters occur in semi-empirical or statistical formulations of physical processes as opposed to formulations derived from fundamental scientific laws.

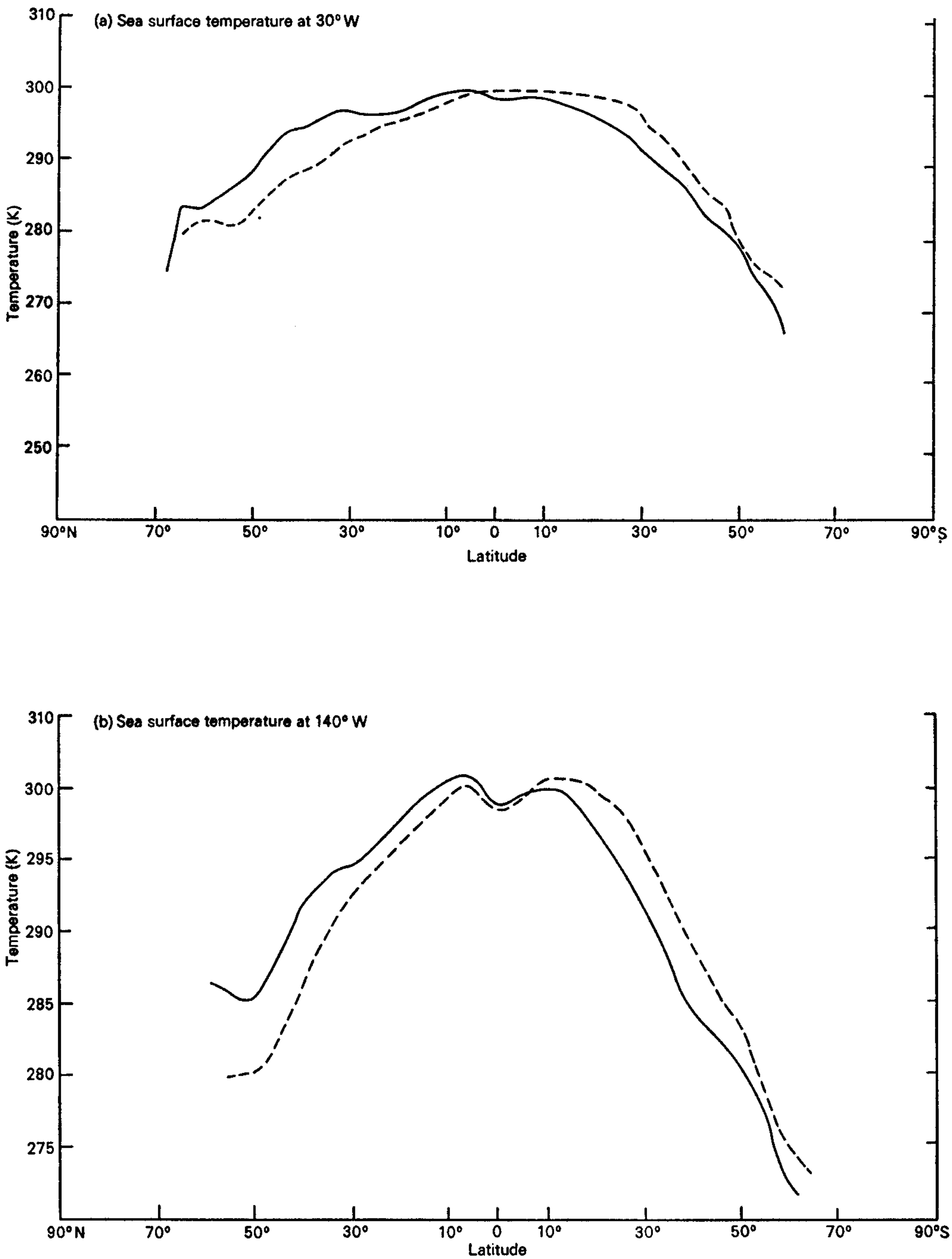
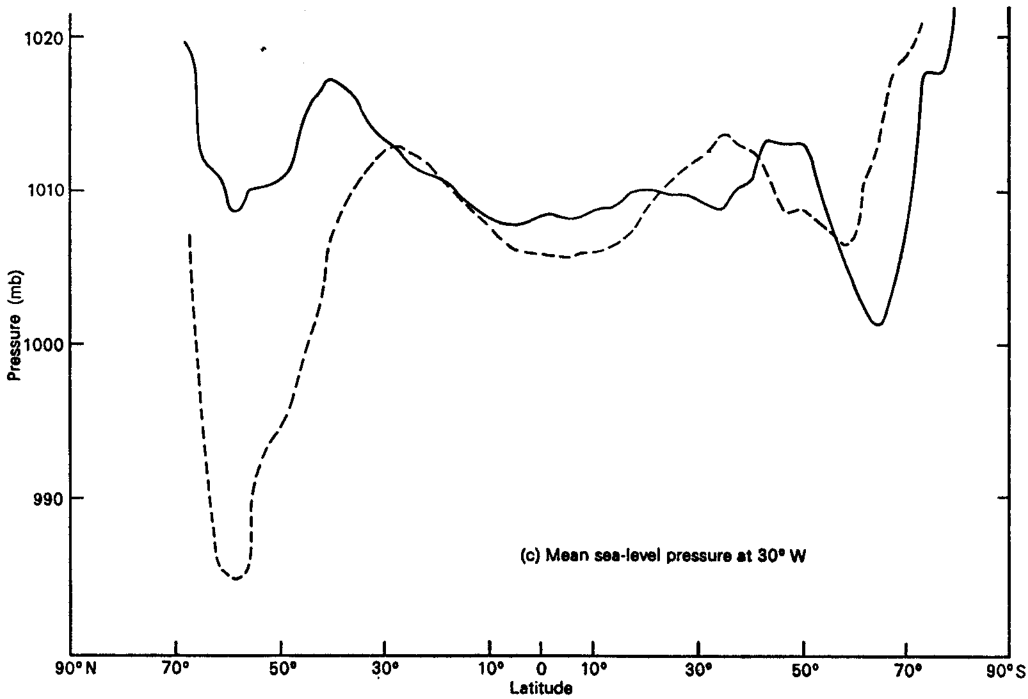


Figure 9. Prescribed sea surface temperature and average pressure at mean sea level in the model simulation for January and July at 30°W and 140°W.
——— July – – – January



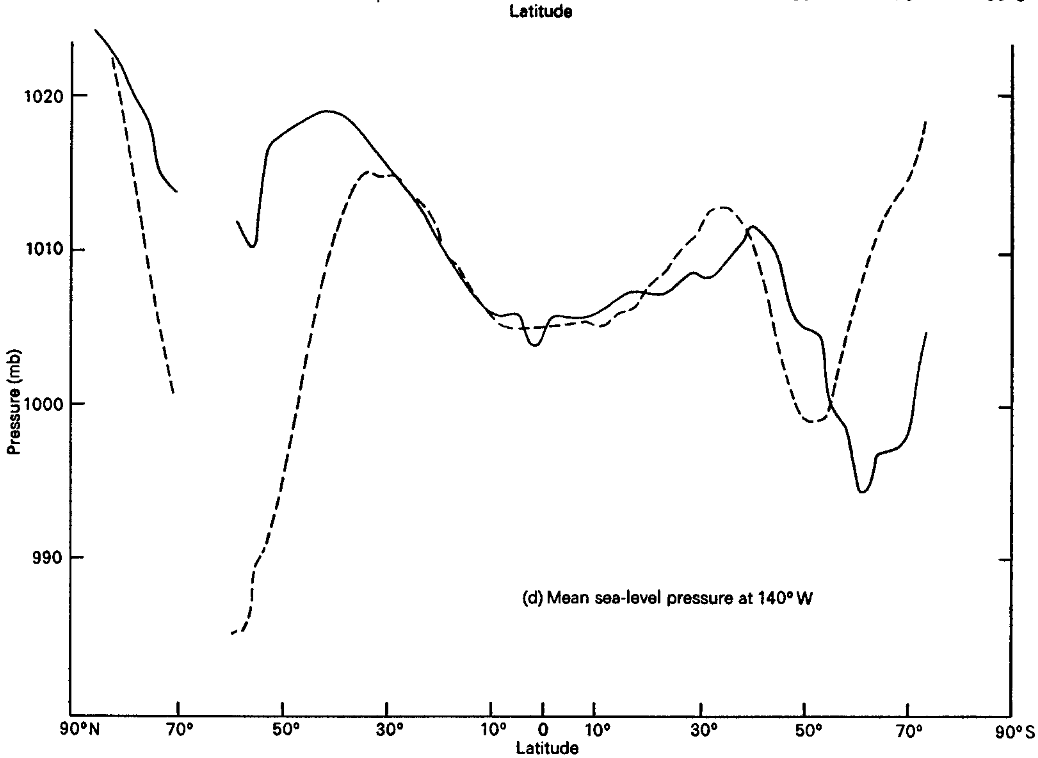


Figure 9—*continued*

Consider now the processes which have to parametrized, and which therefore are susceptible to 'optimization'. They can be thought of as four in number, namely (a) the exchange of heat, water vapour and momentum between the atmosphere and the underlying surface, (b) the transfer of heat, water vapour and possibly momentum vertically through the atmosphere by convective processes, (c) the transfer of energy from the large-scale motions represented explicitly to the subgrid-scale implicit motions and the interaction between the two regimes, and (d) radiative processes. The possibility of optimization arises in all of these processes, but I shall dismiss the first three rather rapidly, for I can see no real evidence that the representations have been 'tuned' in a manner which would limit the use of the model in studying the motions of the earth's atmosphere. (The atmospheres of other planets may be another matter.) In support of this stance, there are listed in Table I the main 'disposable constants' and the methods used to find appropriate values for them.

Table I. *The main 'disposable parameters' in the Meteorological Office general circulation model, and basis for choice of values*

1. Surface exchanges	(a) Surface drag parameters land/sea; stable/unstable.	Taken from published values. See papers to 1967 GARP study conference.
	(b) A: accounts for enhanced heat and moisture exchange coefficients in unstable conditions.	First estimate based on published experimental data; later halved.
2. Convective exchange	(a) 'Rate' coefficient k (b) Excess buoyancy (ϵ^T, ϵ^q) (c) Detrainment (a, b)	Single-column experiments
3. Subgrid-scale dissipation	(a) 'Rate' coefficient K	Empirical

The parameters in the surface exchange formulation have been for the most part chosen directly from published curves, which themselves were based on combined theoretical and observational considerations. Because only four different situations are allowed for, namely whether the surface is land or sea, and whether the atmosphere is stable or unstable, this was particularly easy. An additional constant is required to account for the observation that, with increasing instability, the exchange coefficients for heat and moisture increase relative to that for momentum. The first formulation of this effect, for which quantitative assessment from observations is still rather uncertain, appeared to give too much heat exchange and evaporation from tropical oceans. In a re-formulation the constant was halved. This is a change made in the light of experience, but it is hardly optimization in the sense considered here because it involves the direct comparison with observations of a single process which is not well defined either theoretically or observationally. Potentially undesirable changes presumably involve arguments such as 'the coefficient in the formulation for surface exchanges was altered because certain dynamical features were simulated better as a result'.

The parametrization of subgrid-scale vertical convection involves constants (or pairs of constants) in the definitions of three quantities: the rate at which convection stabilizes an initial vertical instability, the excess buoyancy over its environment of a parcel which tests whether or not vertical instability exists, and the proportion of an ascending mass of air which 'detrains' into a layer through which it is passing. They were determined from single column experiments in which, starting from an initially unstable ascent, convection was allowed to redistribute heat and water vapour to achieve stability. The constants chosen were one set for which the change took a realistic time (an hour or two) and the intermediate vertical profiles appeared in accord with experience. No changes have been made

Photograph by courtesy of the Royal Meteorological Society

Plate I. Her Majesty The Queen being greeted by Professor J. T. Houghton at the entrance to James Glaisher House (see page 33).

Photograph by courtesy of the Royal Meteorological Society

Plate II. A moment during the presentation of an autographic rain-gauge to Her Majesty.

Photograph by courtesy of the Bracknell News

Photograph by courtesy of the Bracknell News

Plate III. During the visit to the Meteorological Office, Her Majesty is shown the Prestel terminal by Mr J. Parker (top), and is briefed by the medium-range forecaster, Mr M. F. Lee (bottom).

Photograph by courtesy of the Bracknell News

Plate IV. Her Majesty talks to Miss D. J. Phillips, the duty British Isles forecaster (top), and has the computer system explained by the shift manager, Mr E. H. Dixon (bottom) (see page 34).

Plate V. Her Majesty signing the Visitors' Book at the Meteorological Office watched by the Director-General, Dr B. J. Mason (see page 34).

Photograph by courtesy of the Royal Meteorological Society

Plate VI. Her Majesty looks at one of the Meteorological Office exhibits at the Royal Meteorological Society Exhibition (see page 33).

in the constants since the parametrization was inserted in the general circulation model. Unless it were proposed to use the model in circumstances where even the processes of convection on subgrid scales were expected to be substantially different from those now observed, there should be no impediment to the use of this parametrization.

Whereas in the boundary layer and convective parametrizations the emphasis of research is currently on observational and numerical experiments aimed at establishing an accurate physical description of the processes, the interaction of the motions represented explicitly with the subgrid-scale implicit motions lends itself to theoretical treatment. Based upon the premise that the smallest scale explicit motions are linked to even smaller scales by a common turbulence structure it has been possible to treat this aspect with a degree of rigour and elegance. This very circumstance tends perhaps to obscure the reality that at least for general circulation models now available, the representation of this effect performs merely the rather menial task of smoothing the variables in the horizontal. This being the case, it can certainly ruin what is otherwise an excellent simulation, but it can never overcome shortcomings in the physical formulation. In practice, the magnitude of the 'rate coefficient' for determining how much smoothing should be applied is determined empirically by the requirement that these simulations are neither excessively rough nor devoid of meaningful detail. This is optimization of a kind, but not, surely, such as to limit the applicability of the model to climatic change experiments.

The list in Table I is not exhaustive, but it contains the parameters which have a substantial influence on the simulations. A number of others which effect useful but comparatively minor improvements (e.g. those which define the method of finding the surface exchanges when there is evidence of a strong surface inversion) have been omitted since they are of little significance in the present context. A more detailed consideration would be tedious and would add little to the general picture that has been described.

For the simulation of radiative processes, the situation is very different in that the model whose results have been shown employs a definite particularization to the present climate. The form this takes is that the infra-red cooling and the solar heating rates are based upon the zonal mean structure of the observed atmosphere, including observed humidity and cloud amounts. Clouds, which are of the greatest significance in determining the radiation balance of the atmosphere, are therefore included implicitly in such a way that variations in time and longitude are not allowed. Figures 10(a) and (b) show the net cooling rate of the atmosphere for January and July. The assumed cloud has a marked influence for example in creating the maximum cooling at middle and high latitudes at around the 700 mb level in the winter hemisphere. There is a dependence of the infra-red component of the net cooling of T^4, allowing some variation along a line of latitude at a particular pressure level, but since there is no longitudinal dependence on humidity or cloud, the cooling is heavily constrained to remain close to the values shown.

This net atmospheric cooling is offset by radiation absorbed at the earth's surface and later released into the atmosphere. Because of the assumption that the temperatures of the oceanic surface remain constant, the model treats explicitly only that part of the absorption which takes place over land. This depends upon the reflectivities of clouds, and the albedo of the surface as well as upon absorption within the atmosphere. A complete description of the physical processes is very complex, but the model circumvents many of the problems by, in effect, prescribing the amount of solar radiation absorbed at a land surface, as a function of latitude only (the prescription is not complete because it depends upon snow cover which is a model variable, and this has an effect upon the values at high latitudes). The values are shown as mean daily amounts in Figures 11 (a) and (b) for January and July respectively. They have been determined from observations and from estimates of quantities such as the zonal mean surface albedo, and therefore contain minor bumps and variations which

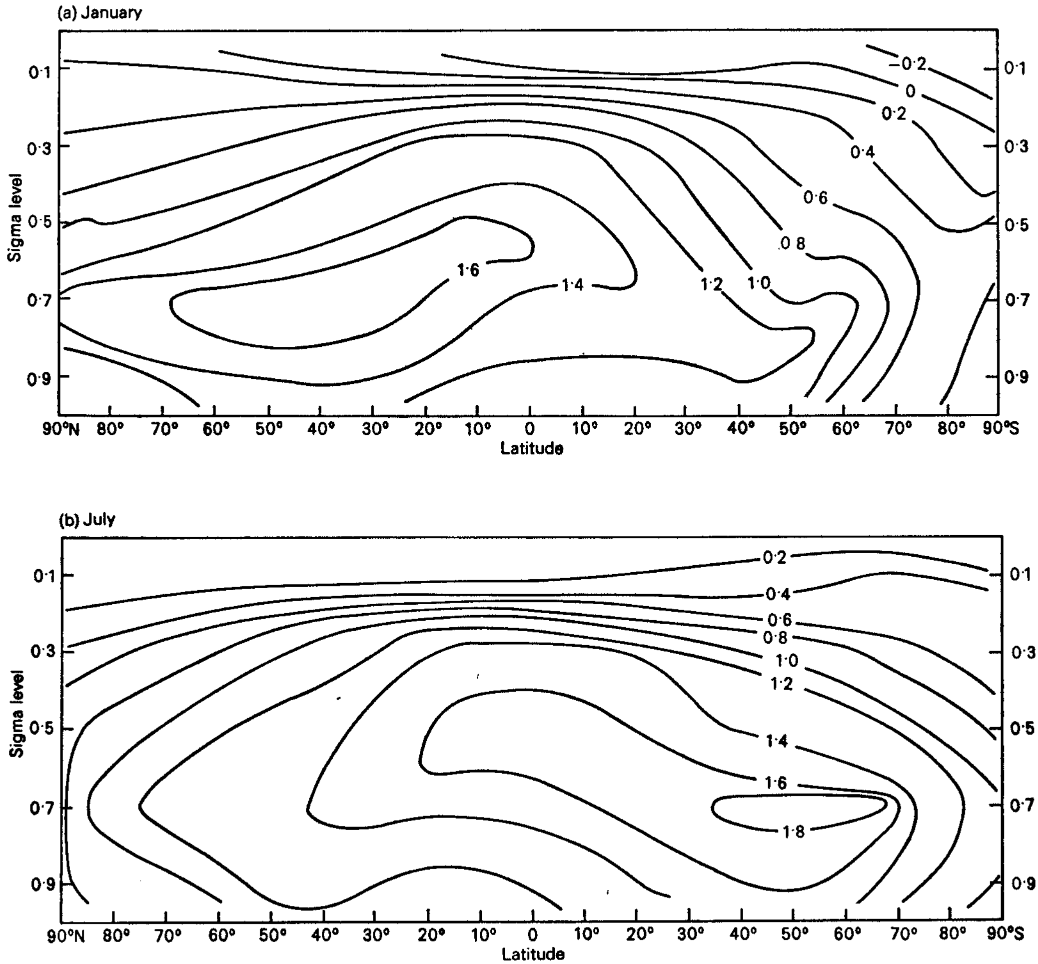


Figure 10. Zonal cross-section of the net cooling rate in kelvins per day in the simulations. The term 'sigma level' derives from the vertical co-ordinate used in the Meteorological Office general circulation model, defined by

$$\sigma = \frac{\text{pressure at point under consideration}}{\text{pressure on the ground vertically below}}.$$

Variations in the height of ground above sea level (i.e. orography) are thus implicitly included in the equations of motion by the use of σ co-ordinates.

probably have little influence on the quality of the model simulations. The effects of clouds and varying surface albedo are the main factors causing the distribution to differ from that of the solar radiation at the top of the atmosphere.

Given the radiation absorbed at the earth's surface, the model determines from its own internal parametrizations how it will be partitioned into radiation back to space, sensible and latent heat exchange with the atmosphere, and storage in the ground. On the assumption that we are dealing with mean daily amounts and that the model has run long enough to be in an equilibrium state, the last of these is probably very small. The zonal mean amount radiated back to space, which depends

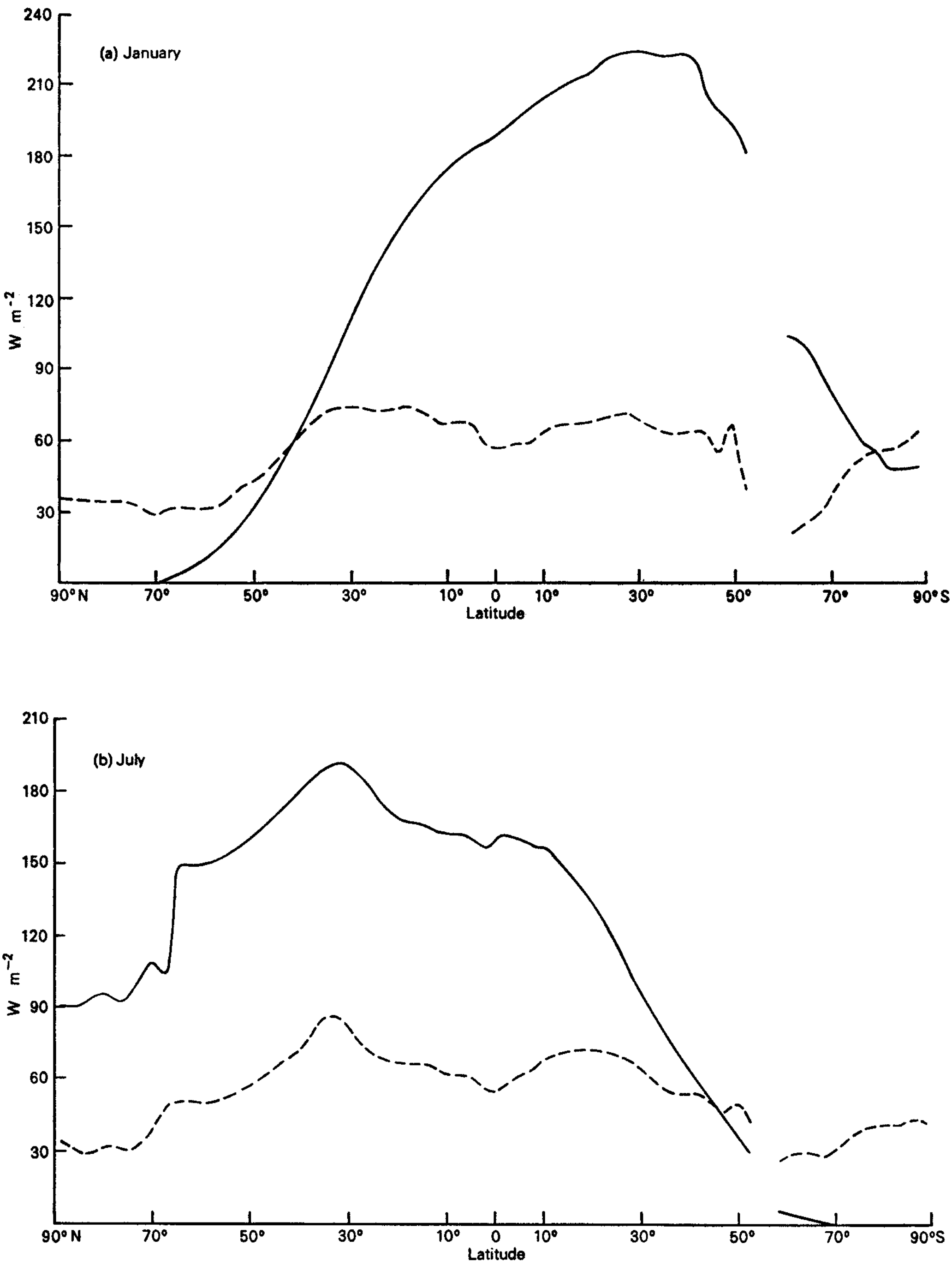


Figure 11. Mean zonal solar absorption by land surfaces in W m^{-2}.
——— Solar radiation reaching the land surface
– – – Infra-red cooling of land surface

on the temperature of the surface carried as a model variable, is shown by the broken line in Figures 11 (a) and (b). The difference in the two radiational quantities is split by the surface exchange parametrization into sensible and latent heat input to the atmosphere. Thus, although some gross features of the radiation at a particular location are largely prescribed, there is still considerable flexibility in the way radiant energy is eventually transmitted to the atmosphere. The resulting spatial variation of surface temperature over land, and sensible and latent heat exchanges have a strong influence on the development of the general circulation.

As well as being clear about the optimization that has been employed, the extent to which it has been deliberately avoided should also be noticed. The radiation scheme is based upon zonal mean values only, and little attempt has been made to account, for example, for the very different radiative conditions likely to exist within air masses at the same latitude over continents and oceans respectively. It is an important aspect of the development of general circulation models to establish how the quality of the simulations depends upon the complication in the parametrizations.

It is evident from the above account that the general circulation model in its present form is simple in many respects, and that, to a degree, this is why it is possible to separate optimized from non-optimized processes. In the period ahead, it will in all probability become more complex as constraints are relaxed and the parametrizations are altered to follow more closely the physical descriptions now being built up from observational evidence. It will at the same time become increasingly difficult to say whether the larger number of disposable parameters are optimized or not. For example, experiments have already been carried out with versions of the model in which the radiation scheme is fully interactive with the humidities and derived cloud. To estimate cloud amounts, formulae relating them to model variables have been determined using as guidance the requirement that the values should be correct for the atmosphere as we now see it. But because of the sporadic nature of clouds and their dependence on subgrid-scale processes, a substantial fraction of the variance is not accounted for and the prescription cannot claim therefore to be very accurate. There is in these circumstances a danger that the formulae chosen will represent an ill-defined mean, which might indeed be unrepresentative in climates not much different from our own. To achieve a cloud prescription of general validity is a problem of great difficulty, to which there may be no fully acceptable solution, but which nevertheless has to be tackled if general circulation models are to be useful in illuminating many of the uncertainties about climate that now concern mankind. Clouds constitute probably the most acute, but certainly not the sole problem of this kind, for similar situations arise with respect to other parametrizations also. The best we can do is surely to make the maximum possible use of the real atmosphere to check numerical simulations, trying to ensure in particular that models are able to reproduce not only average conditions but the most extreme for which ample descriptions exist. Only by achieving acceptable simulations and predictions in a wide range of conditions which can be checked against what happens in the atmosphere can confidence be established in a model's ability to deal with climates beyond those now observed. This will be a long process which will occupy modellers for years to come.

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An eighteenth century rainfall record at Shirburn Castle, Oxfordshire

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Summary

A rainfall record maintained at Shirburn Castle, Oxfordshire, between 1779 and 1795 provides a useful comparison with that of the earliest Oxford rainfall record at the Radcliffe Observatory. The relationship between these two records from 1785 to 1794 is so close to that revealed by modern records at virtually identical sites that the accuracy of the early Shirburn records can be accepted with little doubt.

1. The history of meteorological records at Shirburn Castle

Like many early meteorological records that at Shirburn Castle originated as a consequence of the establishment of a private astronomical observatory. Shirburn Castle, near Watlington, Oxfordshire, was the residence of George Parker, the second Earl of Macclesfield (1697–1764). Elected a Fellow of the Royal Society in 1722, he was President from 1752 until his death. He was a noted astronomer and was one of the principal figures behind the reform of the Calendar in 1752 (Dictionary of National Biography). He was in regular contact with two successive Savilian Professors of Astronomy at Oxford, James Bradley and Thomas Hornsby. About 1739 the Earl built a small private observatory at Shirburn and there is every indication that the building and equipping of the observatory was supervised in collaboration with Bradley who was a frequent visitor at Shirburn (Rigaud, 1832). At this time the facilities available at Oxford for astronomy were certainly inferior to those provided by the Earl at Shirburn (Bell, 1961) and matters were not remedied until Thomas Hornsby, Bradley's successor, was able to obtain funds for the construction of the Radcliffe Observatory (Smith, 1968).

The records of astronomical and meteorological observations at Shirburn between 1739 and 1795 are contained in 28 bound manuscript volumes (Savile MS.) which survive in the Bodleian Library, Oxford. Two of these volumes (Savile MSS. 63 and 64) contain a rainfall record which starts in October 1779 and terminates in October 1795. In addition to rainfall observations the journals containing the principal astronomical observations from 1741 onwards include notes on the weather, principally the state of wind and sky, readings of the barometer and temperatures taken inside and outside the observatory. The meteorological readings are noted for the hours when astronomical observations were made and consequently are mainly during the night. The temperature and barometer readings are almost uninterrupted from 1743 until 1786 and are a most valuable record of daily weather. They supplement and extend Hornsby's Oxford meteorological journal as well as providing confirmation of some notable weather events during this period.

Shirburn Castle is situated some 21 km east-south-east of Oxford (National Grid Reference SU 696959) at an altitude of 107 m. The Observatory was pulled down in the early 19th century when the grounds of the Castle were landscaped (Hassall, 1951) but contemporary accounts (Rigaud, 1832) and an estate plan of about 1800 (Davis, *ca* 1800) describe its size and situation. It was situated 21 m south of the church and 79 m south of the Castle. It was a building measuring about 14 m by 5 m and consisted of three rooms, one of which was fitted as a bedroom. It is not clear whether it was a one or two storied structure, but the plan would suggest that it was on one floor. Presumably since the building was erected as an astronomical observatory the exposure would not have been greatly

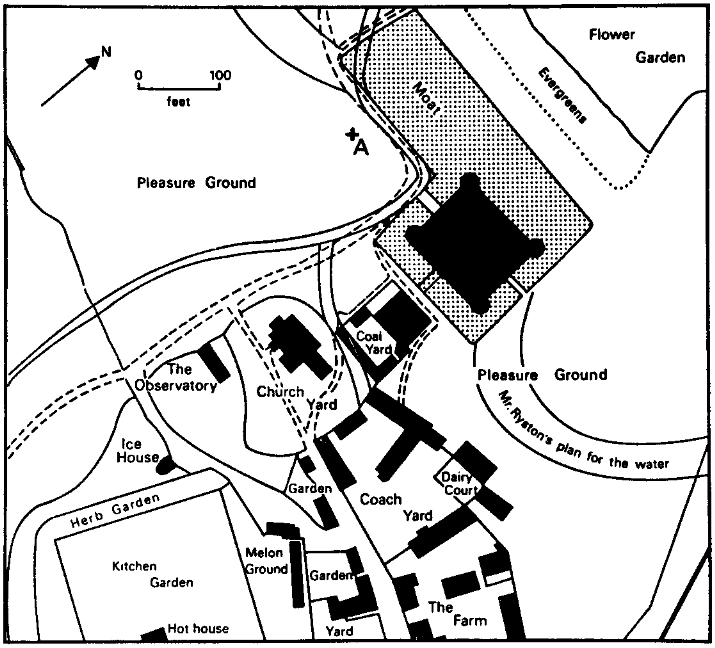

Figure 1. Portion of an estate plan of Shirburn Castle in the late 18th century, showing the site of the Observatory.

oversheltered by trees. Today the site is covered by a small clump of trees. Figure 1 reproduces a part of Davis's map showing the site of the Observatory in relation to other buildings on the estate.

2. The rainfall record

The record of rainfall is contained in two bound notebooks ruled for the purpose and it starts in the middle of September 1779 with a note which reads:

'Wednesday, 15th September 1779. Put up a new funnel for the ombrometer, of a foot diameter and circular, a large glass tube was adapted to the bottom of the pipe for a receiver of the rain, graduated so as to divide one inch of rain into 100 parts. The tube holds $1\frac{2}{10}$ of an inch. N.B. The Observations are supposed to be taken at noon of each day marked against them, unless otherwise—in the remarks.'

The reference to a 'new funnel' in this note suggests that an earlier rain-gauge had existed. The meteorological entries in the earlier astronomical journals make no reference to actual measured quantities of rain, but there is a slip of loose paper in one of them (Savile MS. 77) which reads: 'water fallen in October 1778 and to November 27th at noon October: 3.10156 inches
November: 3.796875 inches'.

This suggests that earlier attempts to measure rainfall had been made; while the monthly totals to five and six decimal places would suggest that this had been done by the weight of water collected, following the method used by Dr Thomas Hornsby from his early measurements at Oxford (Craddock and Craddock, 1977).

The introduction of a new funnel of one foot diameter in September 1779 and the use of a graduated glass measuring cylinder also suggest collaboration with Hornsby who, like his predecessor Bradley, was a frequent visitor at Shirburn. Both Hornsby's own meteorological journal and the Shirburn astronomical journals make occasional reference to Hornsby's visits to the Castle and it seems that the Shirburn observers often sought Hornsby's advice. It is therefore a reasonable inference that the 'new funnel' for the Shirburn gauge may have been similar to one of the same dimensions purchased by Hornsby from P. and J. Dolland in 1774 (Gunther, 1923) for use at the Radcliffe Observatory. The fact that Hornsby's own rainfall record at Oxford apparently ceased from September 1776 until renewed again in 1785, presumably because of the building work at the Radcliffe Observatory (Craddock and Craddock, 1977) may have encouraged Hornsby to urge that a rainfall record be maintained at Shirburn. The Shirburn journals make no reference to the actual site or elevation of the gauge but, as is discussed below, there is good reason to believe that it was comparable to a modern standard exposure.

The manuscript record is neatly maintained and written and, during the earlier years, the measuring cylinder was read daily. The vessel was emptied only when a substantial amount of water had accumulated and the amount emptied was then noted in the journal. Although there is no record that the vessel ever filled and overflowed during heavy rain, so that some of the catch was lost, this possibility cannot be entirely discounted; maybe the observers were always alert to this danger and read the gauge before it overflowed? After 1787 readings became less frequent until, from 1791 onwards, the gauge appears to have been read only after significant falls of rain. However, the gauge was read on the last day of each month right up until April 1795, after which the entries become even fewer and the writing suggests a rapid deterioration in the observer's physical powers through age or infirmity. The monthly totals entered in the journal have been checked against the daily entries and in only a few cases was a discrepancy found; these were mostly small and could be attributed to an error of addition or to an illegible figure.

3. The identity of the observers

The journal contains no clues to the identity of the observers. The third Earl, Thomas Parker, died in February 1795 and there is nothing to suggest that he personally maintained the record which ceases with the last entry in October of that year. The rainfall record must have been maintained for most of the period described here by some servant in the Earl's employment who succeeded Phelps and Bartlett, the two astronomical observers trained by George Parker, the second Earl. Although George Parker at first made most of the astronomical observations personally, various descriptions exist of how he trained two of his servants, Thomas Phelps (1694–1777 or 1778) and John Bartlett (1722–83), to assist him. There is a contemporary engraving of these two men in the act of taking an observation; it is dated 1776 and is in the possession of the Royal Astronomical Society. There is an undated memorial tablet to Phelps in the vestry of Shirburn church which records that he died in his 84th year and praises his mathematical skill, 'acquired by his own industry'. The tablet refers to his having 'for many years the Management of the Observatory belonging to the Earl of Macclesfield'. Phelps was originally a stable boy and Bartlett a shepherd in the Earl's employment, but both were clearly men of parts who, either through schooling or training, were both literate and numerate (Dictionary of National Biography and Mary Frances, Countess of Macclesfield). Phelps was dead by the time the surviving rainfall record started, but Bartlett may have been concerned with it, for an entry in the journal for 19 October 1783 reads 'John Bartlett died this day'. This is the only fact other than rainfall measurement entered in the two volumes discussed here.

4. The relationship between Hornsby's Oxford rainfall record and that at Shirburn Castle

The monthly and annual totals of rainfall recorded at Shirburn between October 1779 and October 1795 are set out in Table I. Table II sets out the monthly and annual mean values for Shirburn during

Table I. *Monthly and annual rainfall at Shirburn between October 1779 and October 1795*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total for year
							inches						
1779										2·76	2·06	4·67	
1780	1·12	0·63	1·11	2·19	1·37	1·44	2·08	1·19	2·92	2·86	2·40	0·07	19·38
1781	1·66	1·75	0·08	1·14	1·56	3·36	1·78	1·39	2·67	0·32	2·95	1·87	20·53
1782	2·07	0·62	2·73	2·56	3·77	1·35	5·13	4·38	2·51	1·18	1·46	0·74	28·50
1783	1·59	3·16	1·33	0·57	2·35	2·70	2·33	2·05	2·74	0·64	1·56	0·94	21·96
1784	1·60	0·65	1·97	3·23	2·30	2·45	2·51	2·40	2·00	0·34	2·73	1·80	23·98
1785	1·62	1·02	0·25	0·28	0·76	1·61	1·40	2·33	4·63	2·54	1·89	1·91	20·24
1786	2·85	0·59	1·21	0·82	2·31	1·21	0·49	1·66	2·99	3·83	2·12	2·10	22·18
1787	0·32	1·96	2·75	0·87	1·60	1·13	5·65	1·17	1·49	2·57	1·56	2·81	23·88
1788	0·79	2·58	0·91	0·50	0·48	2·78	0·92	4·00	2·38	0·20	0·59	0·37	16·50
1789	2·46	1·90	1·69	1·24	2·43	4·66	4·13	1·19	2·89	3·48	1·43	1·53	29·03
1790	1·48	0·20	0·43	2·02	2·87	1·24	2·36	2·35	0·70	0·65	3·73	2·69	20·72
1791	3·17	1·52	0·80	1·48	0·91	0·59	2·76	1·42	0·70	3·15	4·45	2·15	23·10
1792	3·23*	0·57	1·92	3·20	2·06	2·95	3·15	3·52	4·00	3·83	0·93	1·48	30·84
1793	2·42	1·28	1·73	2·04	1·82	0·65	2·52	1·70	4·61	0·97	1·80	1·98	23·52
1794	0·53	1·06	1·36	2·20	2·23	0·65	2·84	1·98	2·86	3·33	5·09	2·19	26·32
1795	0·66	1·93	2·55	1·05	0·68	1·73	2·06	1·44	0·53	4·12.			

* Reading could be 2·73. Underlined values are doubtful.

Table II. *Comparison of Shirburn and Oxford rainfall in the 18th century*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
							inches						
(a) Shirburn 1780–94	1·79	1·30	1·35	1·62	1·92	1·92	2·67	2·18	2·67	1·99	2·31	1·64	23·38
(b) Shirburn 1785–94	1·89	1·27	1·31	1·47	1·75	1·75	2·62	2·13	2·73	2·45	2·36	1·92	23·63
(c) Oxford (Hornsby) 1785–94	1·86	1·21	1·22	1·41	1·70	1·69	2·53	2·00	2·61	2·42	2·28	1·87	22·81
							per cent						
c) as a percentage of (b)	98·4	95·3	93·1	95·9	97·1	96·6	96·6	93·9	95·6	98·8	96·6	97·4	96·5

the 15 year period 1780–94 and the 10 year period 1785–94 during which there is available Hornsby's rainfall record for Oxford. In the same table Hornsby's values for Oxford are set out corrected by the Knox-Shaw and Balk conversion factor used by Craddock and Craddock (1977) and Craddock and Smith (1978) in their examination and homogenization of the Oxford rainfall record. From a comparison of the Oxford and Shirburn annual values the factor required to convert the Shirburn values to those of Oxford works out at 0.965; this is slightly smaller than the value found by Craddock and Craddock (1977) but the difference can be accounted for by some doubtful and revised figures in the Shirburn manuscript and a doubtful value given by the Craddocks for the annual rainfall at Oxford in 1792.

5. The relationship between a modern record at Shirburn and that at Oxford

It so happens that a modern rainfall record exists at two separate but closely adjacent sites at Shirburn from 1965 onwards. This record appears in *British Rainfall* as Shirburn Castle and in the *Monthly Weather Report* as Shirburn (Model Farm) and has been maintained by members of the Parker family who still reside at Shirburn. From 1965 until the end of 1967 a rain-gauge was sited on the lawn to the west of the Castle (shown at Point A on Figure 1), which is about 90 m north of the site of the Observatory. Since 1 January 1968 the record has been continued with a gauge sited at Shirburn Model Farm, situated 1100 m north of the Castle, at virtually the same altitude. This modern Shirburn record is compared with the present Oxford record at the Radcliffe Meteorological Station in Table III. From this comparison it appears that a conversion factor of 0·967 is required to bring the Shirburn values to those of Oxford during the 10 year period 1965–74. Since the Oxford values for the modern and the 18th century decades form part of a homogeneous record and those from Shirburn are from virtually identical sites, assuming that the exposure of the gauges is approximately the same, this agreement is to be expected but it is most reassuring that the conversion factors for the two periods are so nearly identical. The conversion factor for the 13 year period 1965–77 is 0·966.

Table III. *Oxford (Radcliffe meteorological station) and Shirburn annual rainfall compared during the period 1965–77*

Year	Oxford (Radcliffe)	Shirburn		Oxford as a percentage of Shirburn
	inches	*inches*		
1965	25·87	28·23	(a)	91·6
1966	29·53	32·09	(a)	92·0
1967	27·52	30·51	(a)	90·2
1968	31·97	30·94	(b)	103·3
1969	23·94	21·97	(b)	109·0
1970	25·20	28·07	(b)	89·8
1971	29·17	26·42	(b)	110·4
1972	22·68	23·86	(b)	95·1
1973	19·49	21·10	(b)	92·4
1974	30·87	32·24	(b)	95·8
1975	21·18	20·79	(b)	101·9
1976	20·04	21·30	(b)	94·1
1977	27·95	29·61	(b)	94·4
Mean for 10 years 1965–74	26·62	27·54		96·7
Mean for 13 years 1965–77	25·80	26·70		96·6
Mean for 10 years 1968–77	25·25	25·63		98·5

(a) Castle (b) Model Farm

The annual variations of the difference Shirburn minus Oxford during the earlier and recent periods are shown graphically in Figure 2. As is to be expected at two sites separated by this distance there is some variation from year to year, reflecting different local rainfall events, but the interannual fluctuations are of the same order of magnitude. Further confirmation that the relationship between the rainfall at Shirburn and that at Oxford is of the right order can be obtained from the existence of another rainfall record close by with a continuous record reported in *British Rainfall* since 1886. This is at Pyrton Manor (National Grid Reference SU 686956, altitude 99 m) situated 1100 m west of Shirburn Castle. The factor required to convert the mean annual rainfall at Pyrton to that of Oxford over the period 1916–50 is 0·952 and for the earlier period 1881–1915 the factor is 0·936.

Rainfall readings were maintained intermittently at Shirburn Castle between 1894 and 1964 but only some parts of the record have been found. According to the Earl of Macclesfield (personal communication) the gauge was probably located in the kitchen garden near the site of the old Observatory. The annual totals of this gauge for 1894 and 1895 appear in *British Rainfall* for those

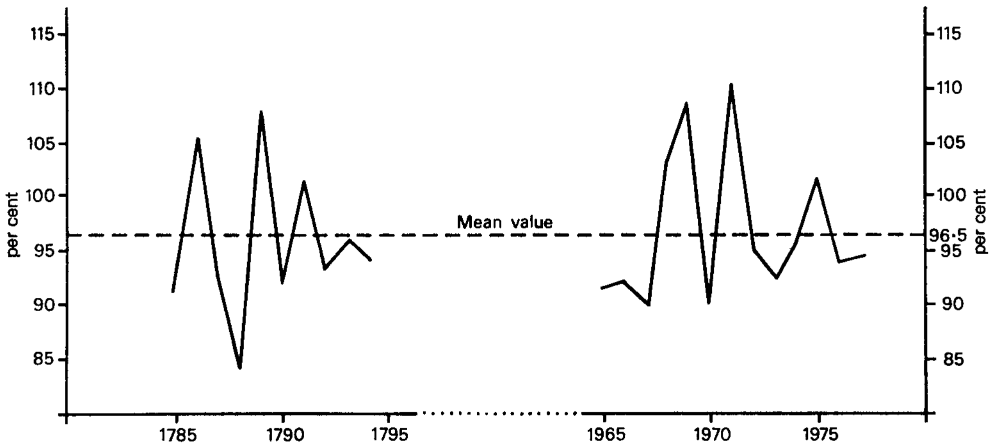

Figure 2. Annual differences of rainfall, Oxford as a percentage of Shirburn, in the 18th and 20th centuries.

years but subsequent daily readings, up to and including November 1909, were found in a notebook at Shirburn Castle. The internal evidence of this record suggests that some of the readings may not be very reliable. The author has checked these readings and recalculated monthly and annual totals to correct some arithmetical errors. The annual mean for Shirburn over the 15 year period 1894–1908 works out at 26·64 inches compared with means of 26·09 inches for Pyrton Manor and 23·86 inches for Oxford (Radcliffe) over the same years. The Oxford mean is thus only 89·6 per cent that of Shirburn and 91·4 per cent that of Pyrton for this period. It would appear from this and other evidence that the Pyrton readings are more representative and the Shirburn record is defective at this time.

6. Discussion and conclusion

Although it only covers a short period of 15 years the 18th century Shirburn Castle record is extremely valuable in confirming some doubtful points about the early rainfall record of Hornsby at the Radcliffe Observatory, Oxford. The remarkable agreement between the records at Shirburn and Oxford during two different periods in the 18th and 20th centuries suggests that the early Shirburn record is from a well-exposed gauge and allows it to be compared with modern records.

The histograms at Figure 3 show the monthly distribution of rainfall at Shirburn over the two periods, 1780–94 and 1785–94. They indicate that this was a time when the annual rainfall regime of the south Midlands was rather more continental, with drier winters and wetter summers, than has been the case during the present century. The regime resembles that noted by Smith (1974) as prevailing at Oxford between 1831 and 1900. There remains however the doubt, noted by Craddock and Smith (1978), concerning the problem of whether and how winter precipitation in the form of snow was measured. In an average year this could reduce the winter precipitation by as much as half an inch if snow was not measured. The annual rainfall totals and period mean for Shirburn in the 18th century also indicate that this was a time of rather low annual rainfall. However, the dryness of this period is within the range of fluctuation experienced at Oxford during the last two hundred years. The driest ten years in the Oxford rainfall record occurred between 1893 and 1902 with a 10 year mean of 22·16 inches. The 15 year mean for Shirburn between 1780 and 1794, when multiplied by the factor 0·965, is 22·56 inches and the 10 year mean 1785–94, when similarly reduced to the equivalent value for Oxford, is 22·80 inches.

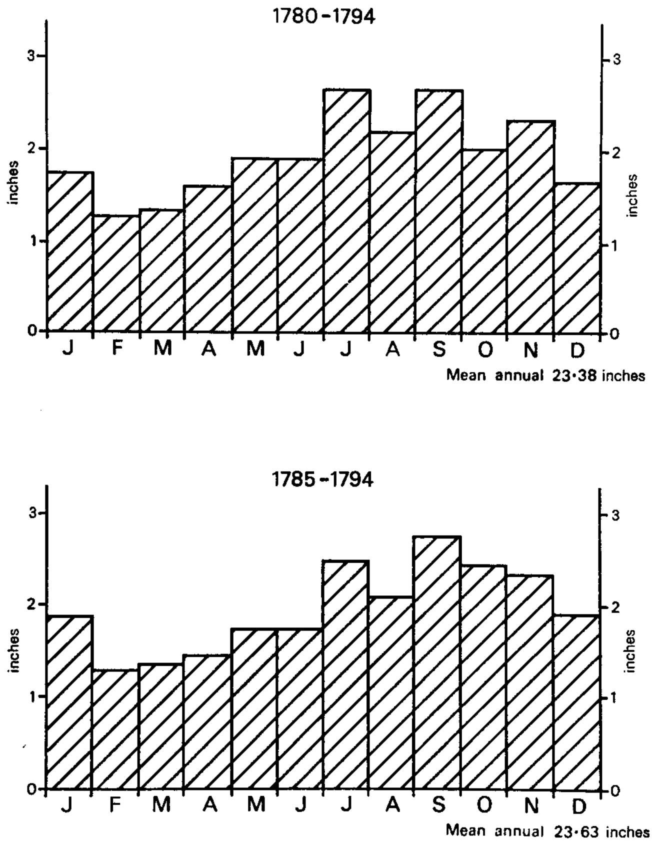

Figure 3. The mean monthly distribution of the annual rainfall at Shirburn in the 18th century.

Acknowledgements

I am indebted to Professor Gordon Manley for drawing my attention to the existence of the 18th century Shirburn rainfall record and to the Earl of Macclesfield and the Honourable David Parker for allowing me access and for discussion of the history of the site. Mr J. M. Craddock has encouraged me to pursue this matter and so add a long footnote to his own work on early British rainfall records.

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Notes and news

The World Climate Conference, 12–23 February 1979

It was announced some time ago that the World Meteorological Organization (WMO), in collaboration with other organizations (the Food and Agriculture Organization, Unesco, the World Health Organization, the United Nations Environment Program, the International Council of Scientific Unions, and the International Institute for Applied Systems Analysis) was to convene the World Climate Conference (WCC)—A Conference of Experts on Climate and Mankind. The Conference is being held in Geneva, Switzerland, from 12 to 23 February 1979.

Mr M. F. Taha, the President of WMO, has been designated by the WMO Executive Committee as the Honorary President of the Conference and Dr Robert M. White of the United States National Academy of Sciences has been appointed Chairman.

The Conference was originally conceived as a scientific preliminary to the convening of a high-level (Ministerial-level) conference at which the need to take climatic factors into account in taking decisions in the economic and social fields would be stressed. It is now expected that the Conference will provide useful proposals for the plan for a World Climate Program which will be considered and, it is hoped, approved by the Eighth World Meteorological Congress to be held in April/May 1979.

The Conference will be at the expert level, and attendance will be by invitation. During the first week of the Conference 24 review papers will be presented and discussed, before about 400 invited participants. (One such review paper, on the results of climate models, will be presented by the Director-General of the Meteorological Office, Dr B. J. Mason.) The second week will be devoted to the formulation of a plan of action, including arrangements for a subsequent high-level conference and proposals for the World Climate Program.

The object of the Conference is to examine the impact of climate, and especially of climatic fluctuations on all time scales, on various aspects of human welfare. In recent years there have been many severe impacts of climate on food production, on energy supply and consumption, on high-latitude marine navigation and on many other aspects of the world economy. The Conference will examine these impacts, and will consider measures to reduce climate-induced crop and livestock losses, damage to soil and natural vegetation, dislocation of fisheries, and of the future exploitation of other marine sources.

In addition, the Conference will address the broader questions: 'How can human economy be better attuned to the probable future course of world climate? Will, for example, expanded use of fossil fuels lead to climatic change through the build-up of carbon dioxide in the atmosphere? Will other pollutants have similar or different effects? Are the effects likely to be good or bad, and who will gain or lose? And what measures can be advocated to avoid the bad outcomes, and to take advantage of the good?'

Participants in the Conference will include many leading atmospheric scientists, but most of the invited experts will be drawn from other sciences or the socio-economic field so that these far-reaching questions may be searchingly discussed.

(Adapted from a WMO Press Release.)

Awards

Awards to the Director-General

We note with great pleasure the following awards to the Director-General of the Meteorological Office, Dr B. J. Mason, C.B., F.R.S.

The London Mathematical Society has awarded Dr Mason its Naylor Prize and Lectureship for distinguished contributions to the application of mathematics. Dr Mason is the second recipient of the Prize, the first having been Sir James Lighthill.

The Queen's University of Belfast has elected Dr Mason to the Sir Joseph Larmor Lectureship for 1979.

Obituary

We regret to record the death on 8 October 1978 of Miss Patricia Lutt, re-employed Assistant Scientific Officer. Miss Lutt joined the Office in May 1941 and spent most of the early part of her career at Dunstable. In September 1950 she was posted to London Airport at Heathrow and remained there—apart from occasional temporary postings—until she retired in April 1977 as a Senior Scientific Officer. At Heathrow she became widely known for her participation in the social life of the Office—serving on committees, working behind the scenes in various ways, writing a monthly news-letter, conducting a widespread correspondence with many past members of the staff, and keeping a friendly eye on the interests of juniors and new entrants. She performed many acts of kindness and practical helpfulness for her colleagues and friends. In recognition of her services to the social life of the Meteorological Office she was awarded the Sutton Rosebowl in 1971. At the time of her death she was employed in the observational practices branch (Met O 1).

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NOTICES

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Performance of conventional operational forecasts of clear-air turbulence during the 1976 Turbulence Survey

By M. J. O. Dutton

(Meteorological Office, Bracknell)

Summary

During the 1976 Turbulence Survey the pilots' reports of clear-air turbulence (CAT) from about 4500 flights over the North Atlantic and north-west Europe were collected. In addition to a continuing investigation into the relationship between reports of CAT and synoptic-scale meteorological variables computed by the operational 10-level model, an assessment has been made of the skill of conventional forecasts of CAT prepared in the Central Forecasting Office (CFO) during the survey; that assessment is presented here. The results indicate that the CFO forecasts showed some (significant) skill in discriminating between regions more prone than average and those less prone than average to moderate or severe CAT. The frequency of encounter, per unit distance flown, with moderate or severe CAT within regions forecast to contain moderate or severe CAT was about double the frequency of encounter outside these regions.

1. Introduction

Following the earlier 1972 Turbulence Survey (Sparks *et al.*, 1977) a much more extensive survey, organized by the Meteorological Office, was carried out during the spring of 1976, with the co-operation of the meteorological services and airlines of Austria, Belgium, Denmark, Federal Republic of Germany, France, Republic of Ireland, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland and U.S.A. On ten pre-selected reporting days (9, 12, 15, 18, 21, 24, 27, 30 March and 2, 5 April) spaced at regular 3-day intervals during spring 1976, pilots were issued with specially printed maps covering the North Atlantic (Figure A1 in Appendix) and north-western Europe (Figure A2 in Appendix), and asked to record on them complete turbulence histories of their flights (cruise phase only). Information about the survey and an example of the type of report required were printed on the back of each map (Figure A3 in Appendix).

Pilots' response was quite good; a total of 4378 usable maps were received (3·9 million kilometres of flight) of which 3805 (2·1 million km) were 'EUROPEAN' and 573 (1·8 million km) 'ATLANTIC'. Digitizing and quality control of the reports proved a lengthy task. The clean data have been stored on magnetic tape for analysis; this will include comparison of pilots' (mainly subjective) reports with forecasts of synoptic-scale meteorological indices produced by the operational 10-level numerical model (Burridge and Gadd, 1977). Some basic statistics of the reports themselves are shown in Tables A1, A2 and A3 of the Appendix to this note; overall, 0·013 per cent of flight distance was reported as severely turbulent (only eight reports in all), 1·26 per cent as at least moderately turbulent while 9·92 per cent of distance was flown in at least light turbulence. These figures relate specifically to turbulence in clear air (clear-air turbulence, usually referred to as CAT).

Figures 1(a) to 1(d) show the 12 GMT 300-mb contour charts, with surface fronts indicated, for four of the ten reporting days; areas of forecast CAT (verifying time 12 GMT) are indicated and locations of encounters with moderate and moderate to severe CAT and severe CAT are superimposed. Only those encounters within the time period 03–21 GMT each day are included. The pecked lines enclose areas for which *at least ten* aircraft submitted full reports and therefore highlight the areas of densest air traffic.

The main object of the survey and subsequent analysis is to develop an operational scheme for objectively deriving forecast probabilities (per unit distance flown) of encountering moderate or severe clear-air turbulence, using the 10-level numerical model. A composite index will be derived including the most relevant synoptic-scale meteorological variables, such as wind shear (horizontal and vertical), vertical motion, rate of change of (100-mb layer) Richardson number, etc. (as computed by the numerical model). Multiple linear regression and discriminant analysis techniques will be used to derive this empirical CAT index; any given value of the index will imply a given probability, per unit distance of flight (for example 100 km), of encountering moderate or severe CAT.

This project includes an assessment of conventional forecasts of CAT, prepared in the Central Forecasting Office (CFO), occasionally amended at Heathrow's Forecast Office and issued to aircrew at Heathrow during the 1976 survey. The results of this assessment are presented in this note; they confirm the previously purely intuitive feeling that such forecasts show comparatively low skill; in addition they give no indication of the probability of encountering CAT.

The individual performance of each of several meteorological variables as predictors of CAT is currently in progress, along the lines followed in the analysis of pilots' reports from the 1972 survey.

The view, expressed in the report on the 1972 survey, that CAT forecasts must be stated in terms of probability if they are to convey the maximum possible information to the recipient, is still held. That report also tentatively concluded that 'forecasts produced by the 10-level model contain information which allows positive predictions of bumpiness which are about as good as those based on recent pilots' reports'.

2. CFO forecasts of CAT and pilots' experience

(a) *The CFO forecasts.* For each of the ten reporting days the CAT forecasts, prepared in CFO in chart form and issued to aircrew at Heathrow, were assessed by comparing pilots' reported experience with the relevant forecasts. The 'EUMED' (covering north-west Europe and the western Mediterranean) and 'N ATLANTIC' forecast significant-weather charts for verification times 06, 12 and 18 GMT, on each day, were digitized on a grid-square (100 km × 100 km) basis (the grid squares corresponding to those of the rectangle (fine-mesh) area of the 10-level model) by assigning, as appropriate, 'MODERATE CAT' or 'MODERATE OCCASIONALLY SEVERE CAT'* to each grid-square or level lying within regions forecast to be turbulent (see Figure 2 for symbols and abbreviations used in this context). All other grid-squares or levels were, by default, assigned 'NIL CAT'. The 'EUMED' chart was used for areas east of 10°W, while the 'N ATLANTIC' chart was used for areas west of 10°W.

* 'MODERATE LOCALLY SEVERE CAT' was much less frequently used.

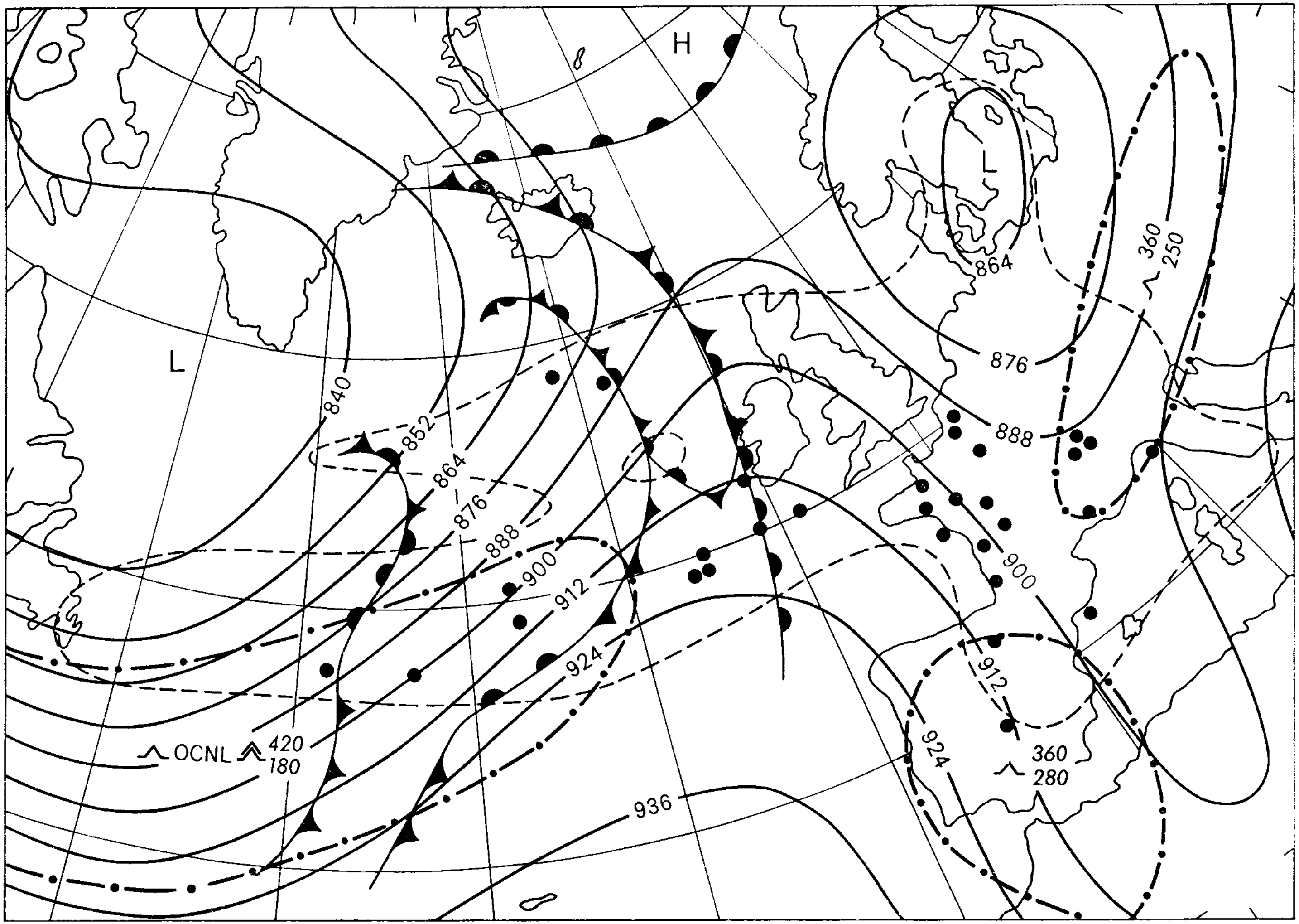

Figure 1(a). 300 mb contours at 12 GMT on 9 March 1976

Heights are in decageopotential metres. Surface fronts are indicated. Locations of encounters with moderate and moderate to severe CAT are indicated by black dots and those of encounters with severe CAT by encircled black dots. Areas of forecast CAT (verifying time 12 GMT) are indicated by symbols explained in Figure 2; the adjacent figures represent flight levels in hundreds of feet. Pecked lines encircle areas for which *at least ten* aircraft submitted full reports and therefore highlight the areas of densest air traffic.

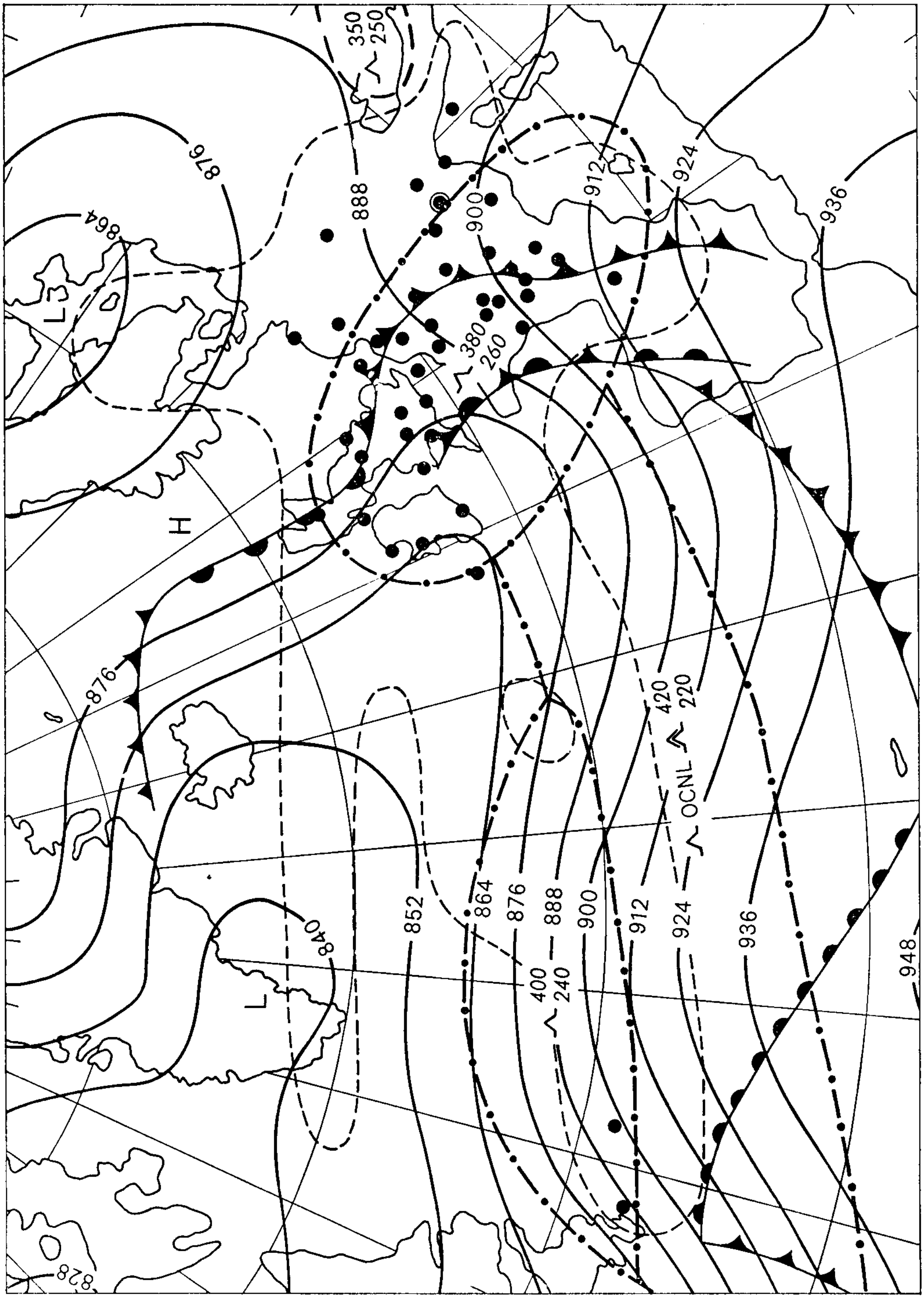

Figure 1(b). 300 mb contours at 12 GMT on 12 March 1976 (remarks as for Figure 1(a))

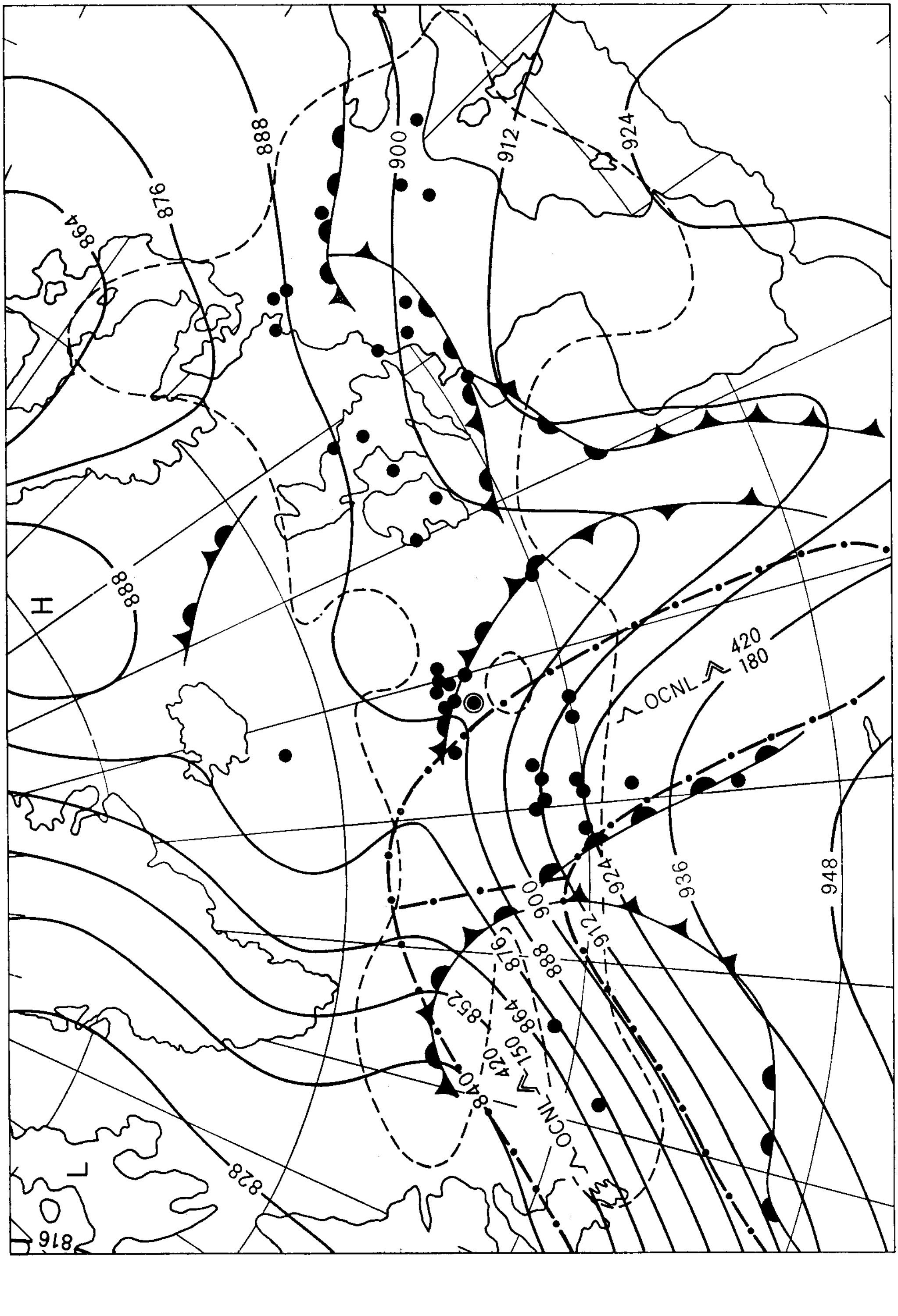

Figure 1(c). **300 mb contours at 12 GMT on 18 March 1976 (remarks as for Figure 1(a))**

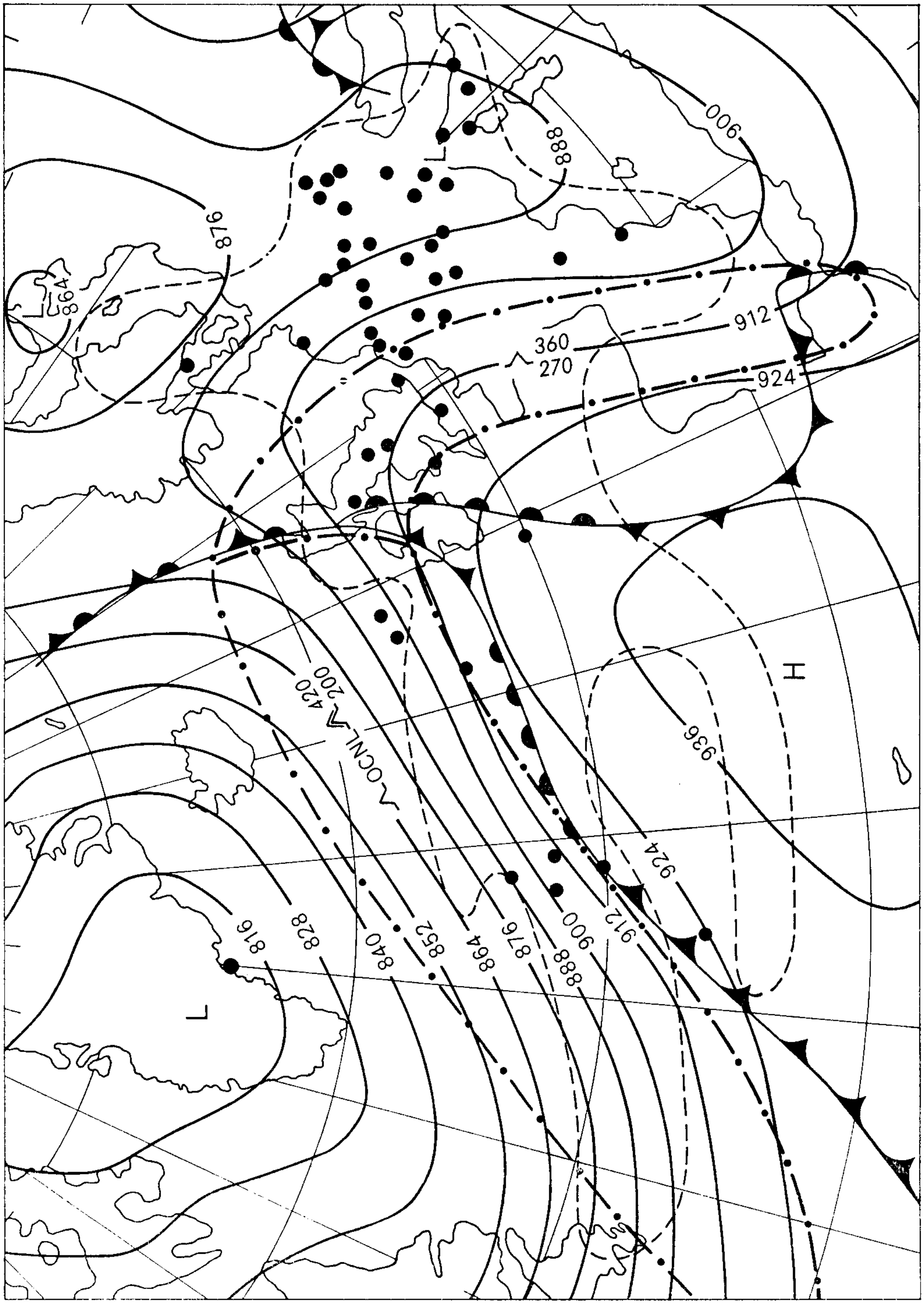

Figure 1(d). **300 mb contours at 12 GMT on 24 March 1976 (remarks as for Figure 1(a))**

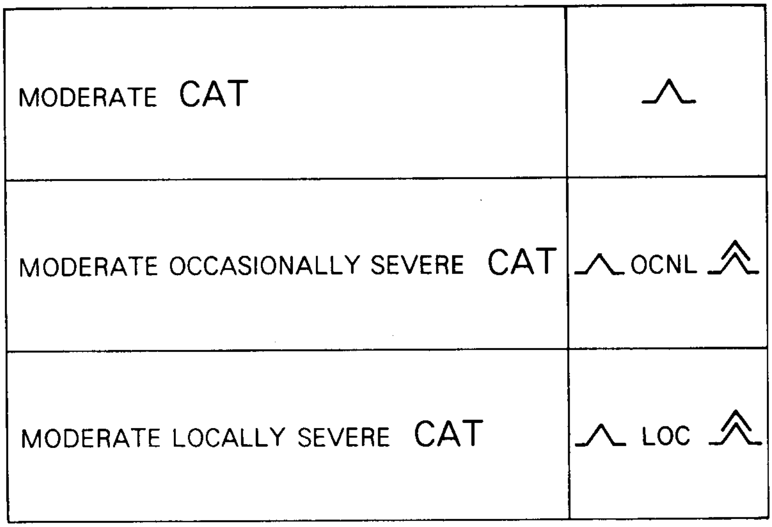

Figure 2. Symbols and abbreviations used for indicating the severity of CAT

(b) *The pilots' reports.* In the digitizing of the pilots' reports the CAT history of each flight was divided into 'elementary' observations; each elementary observation included the grid-square (10-level model fine-mesh area), height, time, length of track in the grid-square and intensity of CAT along that length of track. This format allows easy comparison of pilots' reported CAT experience with computed 10-level model variables.

(c) *Comparison of CAT forecasts and pilots' reports.* The CAT forecasts for verification times 06, 12 and 18 GMT were compared with pilots' reports within the time periods 0300–0859, 0900–1459 and 1500–2059 GMT respectively, for each of the ten reporting days; a total of 30 'EUMED' and 30 'N ATLANTIC' forecasts were therefore assessed. Comparisons between European and North Atlantic flights were analysed, both separately and combined.

3. CFO forecasts of CAT versus pilots' reports: results

Tables I(a–c) show the results of the comparisons between the forecasts of CAT and the pilots' reported experience. A brief explanation of these tables is appropriate at this stage. Each set of results (all flights, Atlantic flights, European flights) is presented in Tables I(a), I(b) and I(c). Note that 'MODERATE' and 'MODERATE OCCASIONALLY SEVERE' forecast categories are combined into a single category, while the pilot-report categories are also reduced to two, 'Nil or Light' and 'Moderate or Severe'. Each table gives the total distances flown in each category, and the associated percentages of the total distances flown within the regions designated by the various categories of forecast CAT. For instance, in Table I(a), 811 604 km was flown within regions designated 'MOD CAT' or 'MOD OCNL SEV CAT'; 794 925 km, or 97·94 per cent, of this was reported as containing 'NIL' or 'LIGHT' CAT, while the remainder, 16 679 km or 2·06 per cent, was

Table I(a). *Distances* (km) *flown in* CAT : CFO *forecasts versus reported bumpiness for all flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	2 835 510 98·97%	794 925 97·94%	3 630 435 98·74%
Moderate or Severe	29 614 1·03% (0·82)	16 679 2·06% (1·63)	46 293 1·26%
All	2 865 124	811 604	3 676 728

Table I(b). *Distances* (km) *flown in* CAT : CFO *forecasts versus reported bumpiness for Atlantic flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	1 110 298 99·68%	534 863 97·83%	1 645 161 98·40%
Moderate or Severe	14 868 1·32% (0·83)	11 889 2·17% (1·36)	26 757 1·60%
All	1 125 166	546 752	1 671 918

Table I(c). *Distances* (km) *flown in* CAT : CFO *forecasts versus reported bumpiness for European flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	1 725 212 99·15%	260 062 98·19%	1 985 274 99·03%
Moderate or Severe	14 746 0·85% (0·88)	4 790 1·81% (1·87)	19 536 0·97%
All	1 739 958	264 852	2 004 810

* In Tables I(a–c) total distances (km) flown in each category are given; below each distance the percentage of the distance flown within that forecast category is given; figures in parentheses are the ratios of these percentages to the overall (background) percentages (see text).

reported to be at least moderately turbulent. In regions with 'NIL CAT' forecast* on the other hand, 98·97 per cent of flight distance was reported to contain 'NIL' or 'LIGHT' CAT, and 1·03 per cent was reported to be moderately turbulent.

The figures in parentheses are the ratios of the given percentages to the overall (background) percentage, given in the right-hand column under 'ALL'; for instance, in Table I(a) again, 1·03 per cent represents 0·82 of the overall frequency of encounter with at least moderate CAT (1·26 per cent, as given in the right-hand column), while 2·06 per cent is 1·63 times this background frequency.

* Throughout this note, the 'NIL CAT' forecast category is simply used as the default category; it is never the intention of the forecast to imply that areas outside those designated as being particularly prone to CAT will be entirely free from CAT.

(a) *Results for all flights combined.* Table I(a) shows that, grouping all flights together, moderate or severe CAT was experienced over 1·03 and 2·06 per cent of the respective distances flown in regions designated 'NIL CAT' and 'MOD CAT' or 'MOD OCNL SEV CAT'; relative to the background frequency of moderate or severe CAT (1·26 per cent) these figures become 0·82 and 1·63. Note that 63 per cent of all moderate or severe CAT was encountered in regions designated 'NIL CAT'. Overall, 22 per cent of flight distance was in regions designated 'MOD CAT' (8 per cent) or 'MOD OCNL SEV CAT' (14 per cent).

The main conclusion arising out of Table I(a) is that the frequency of moderate or severe CAT in regions designated 'MOD CAT' or 'MOD OCNL SEV CAT' is about double that in regions of 'NIL CAT'.

(b) *Atlantic flights.* Table I(b) shows that, on Atlantic flights, moderate or severe CAT was experienced over 1·32 and 2·17 per cent of the distance flown in 'NIL CAT' and 'MOD CAT' or 'MOD OCNL SEV CAT' regions respectively. In fact the 'MOD CAT' category was used comparatively infrequently, relative to the 'MOD OCNL SEV CAT' category, on the North Atlantic forecast charts; 7·5 per cent of all flight distance was in regions designated 'MOD CAT', while 25 per cent was in regions designated 'MOD OCNL SEV CAT'. Fifty-five per cent of all reported moderate or severe CAT on Atlantic flights was encountered in 'NIL CAT' regions.

(c) *European flights.* Table I(c) shows that, on European flights, moderate or severe CAT was encountered over 0·85 and 1·81 per cent of the distance flown in 'NIL CAT' and 'MOD CAT' or 'MOD OCNL SEV CAT' regions respectively.

Overall, 13 per cent of flight distance was in regions designated 'MOD CAT' (9 per cent) or 'MOD OCNL SEV CAT' (4 per cent). Seventy-five per cent of all reported moderate or severe CAT on European flights was encountered in 'NIL CAT' regions.

The figures presented so far tell us what *proportion* of distance flown fell into various categories; for example, in regions of 'NIL CAT' the proportion of distance flown in moderate or severe CAT was 1·03 per cent. To get an idea of the probability per unit flight distance (say 100 km or 1000 km) of an encounter with moderate or severe CAT we need to approach the problem slightly differently.

One approach is first to re-format the pilots' reports by defining a pilot's CAT experience of any single 100 km × 100 km grid-square as equivalent to the most severe CAT encountered within that grid-square. In this way, if a pilot encounters moderate CAT anywhere within a grid-square, albeit for only a few kilometres, his CAT experience of that grid-square would be classified as 'moderate'. If this procedure is followed for all pilots' reports then the pilots' grid-square experiences (so-called 'elementary' grid-square reports) can readily be compared with the CAT forecasts (or computed 10-level model meteorological indices) for the corresponding grid-squares.

On the basis of this alternative method of analysis, contingency tables, similar to those already presented, can be constructed giving the number of these elementary reports falling into the various categories (Table II(a–c)). The percentages in these tables now approximate to the percentage probabilities of encountering CAT per traversed grid-square; these figures will provide a standard against which to compare the performance, as CAT predictors, of various meteorological indices forecast by the 10-level model.

As expected the results in Tables II(a–c) confirm the main conclusion arising out of Tables I(a–c), namely that the probability of encountering moderate or severe CAT in 'MOD CAT' or 'MOD OCNL SEV CAT' forecast regions is about double that in 'NIL CAT' regions; it is not necessary here to describe the results in Tables II(a–c) in any detail.

Chi-square tests indicate that the apparent degree of skill, albeit rather low, in forecasting areas of CAT (moderate or severe) or NIL CAT is highly significant, well beyond the 0·01 per cent level, for

Table II(a). *Elementary observations of* CAT : CFO *forecasts versus reported bumpiness for all flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	39 630 98·62%	10 317 97·17%	49 947 98·32%
Moderate or Severe	555 1·38% (0·82)	300 2·83% (1·68)	855 1·68%
All	40 185	10 617	50 802

Table II(b). *Elementary observations of* CAT : CFO *forecasts versus reported bumpiness for Atlantic flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	13 773 98·20%	6 475 97·13%	20 248 97·85%
Moderate or Severe	253 1·80% (0·84)	191 2·87% (1·33)	444 2·15%
All	14 026	6 666	20 692

Table II(c). *Elementary observations of* CAT : CFO *forecasts versus reported bumpiness for European flights**

Pilots' experience	Category of forecast CAT		
	NIL	MOD or MOD–SEV	ALL
Nil or Light	25 857 98·85%	3 842 97·24%	29 699 98·64%
Moderate or Severe	302 1·15% (0·85)	109 2·76% (2·03)	411 1·36%
All	26 159	3 951	30 110

* In Tables II(a–c) the numbers of 'elementary' (grid-square) reports in each category are given; below each number is the percentage of these 'elementary' reports within areas designated by the forecast category; figures in parentheses are the ratios of these percentages to the overall (background) percentages (see text).

both Atlantic and European flights. However, it should be pointed out that strict validity of such tests is conditional on the assumptions of random sampling and normal distribution of the variables. The data presented here satisfy neither condition since:

(1) the definition of the 'elementary' grid-square observations often results in the same (continuous) patch of CAT being counted as two or more 'elementary' observations, one for each grid-square traversed within the patch, and

(2) areas of forecast CAT occupy specific synoptic-scale regions; 100 km × 100 km (mesoscale) grid-square categories of forecast CAT therefore obviously exhibit considerable spatial coherence, so that the categories for adjacent grid-squares are significantly correlated. This argument also applies, although to a lesser extent, to the actual reports of CAT, since turbulent patches often occur in conglomerates that have synoptic scale.

Sparks *et al.* (1976) have shown that, subject to certain simplifying assumptions, if the mean probability of encountering a given event (for example, moderate turbulence) in a grid-square (100 km × 100 km), P_8, is known, then the probability of encountering such an event in 100 km of linear flight, under the same conditions, can be calculated; for $P_8 \leqslant 0{\cdot}2$, $P_{100} = 1{\cdot}24\ P_8$. Given P_8 or P_{100}, it is possible to estimate the probabilities for greater flight distance; for example, if $n \times 100$ km of flight-path traverses a region in which P_{100} is approximately constant (and known) then

$$P_{n\times 100} = 1 - (1 - P_{100})^n.$$

Table III gives overall probabilities of encountering moderate or severe CAT over flight distance L, in, on the one hand, 'NIL CAT' regions and, on the other hand, 'MOD CAT' or 'MOD OCNL SEV CAT' regions, using the basic P_8 (probability per grid-square) figures in Table II(a), and assuming that P_8 is constant over the distance L.

Table III. *Probabilities of encountering moderate or severe* CAT *over flight distance L, assuming that P_8 is constant*

	L = 100 km	L = 500 km	L = 1000 km	L = 2000 km
		Per cent		
'NIL CAT' regions (P_8 = 1·38 per cent)	1·7	8·3	15·8	29·2
'MOD CAT' or 'MOD OCNL SEV CAT' regions (P_8 = 2·83 per cent)	3·5	16·4	30·0	51·1

4. Concluding remarks

The analysis of data collected during the 1976 survey is continuing. If the promising results arising out of the analysis of the 1972 survey are confirmed by the much more extensive 1976 data set, then it is highly likely that probability forecasts of clear-air turbulence, derived entirely from 10-level model fields, can be introduced on an operational basis at some time during 1979. Of the individual synoptic-scale meteorological indices, forecast by the numerical model and so far tested as predictors of moderate or severe CAT, it appears that vertical and horizontal wind shear perform significantly better than most other indices such as vertical velocity, deformation, vorticity, Richardson number and rate of change of Richardson number (following the flow). Indeed, preliminary results indicate that both vertical and horizontal wind shear, considered separately, performed as well as, or slightly better than, the CFO forecasts assessed in this note. It is therefore confidently expected that forecasts of CAT based on a composite index incorporating the predictive ability of several indices, will perform markedly better than current CFO forecasts.

Typically, on the form of forecast chart currently envisaged, the highest probabilities of moderate or severe CAT (per 100 km of flight) indicated would be about 15–20 per cent, and regions with this level of probability (or greater) would typically cover about 1 per cent of total chart area; regions with a forecast CAT probability of 10 per cent or more would on average be expected to cover about 5 per cent of chart area.

It is felt that such forecasts will prove more reliable and useful to airlines and pilots than those prepared using current methods; they may be particularly useful for flight-planning purposes when a choice of routes is possible (across the Atlantic for example), since overall route-probabilities can easily be calculated from the readily available grid-square values of P_{100} (probability per 100 km of flight).

The main purpose of this note has been to give some quantitative feel for the skill of current clear-air turbulence forecasts prepared in CFO, by comparing 30 such forecasts, covering north-west Europe and the North Atlantic, with pilots' reported CAT experience. The results have shown that the proportion of distance flown in moderate or severe CAT in areas of 'NIL CAT' (1·03 per cent—about 0·8 of the background frequency) was half that in areas designated 'MOD CAT' or 'MOD OCNL SEV CAT' (2·06 per cent—about 1·6 times the background frequency).

Acknowledgements

Thanks are due to all the national meteorological services and airlines, most particularly their pilots, who co-operated to make a success of the 1976 Turbulence Survey, on which the results of this note are based.

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APPENDIX

Table A1. *Percentages of distance flown in clear-air turbulence—all flights*

Flight level	Reported CAT Light+	Moderate+	Severe+	Total distance flown (km)
<100	9·17	1·09*	0·242*	13 245
100–149	8·29	0·44*	0·077*	38 816
150–199	8·29	0·53	0·061*	111 895
200–249	9·19	0·67	0·018*	236 872
250–299	10·72	1·43	0·006*	686 695
300–349	8·87	0·90	0·012*	1 385 671
350–399	10·92	1·72	0·005*	1 415 676
≥400	5·30	0·24*	0·236*	16 557
All	9·92	1·26	0·013	3 905 427

Table A2. *Percentages of distance flown in clear-air turbulence—European flights*

Flight level	Reported CAT Light+	Moderate+	Severe+	Total distance flown (km)
<100	9·17	1·09*	0·242*	13 245
100–149	8·29	0·44*	0·077*	38 816
150–199	8·51	0·55	0·062*	108 970
200–249	9·31	0·70	0·019*	229 460
250–299	11·25	1·46	0·007*	644 742
300–349	9·73	0·61	—	744 909
350–399	10·82	1·25	—	317 504
≥400	6·01*	0·72*	0·717*	5 441
All	10·21	0·97	0·012	2 103 087

Table A3. *Percentages of distance flown in clear-air turbulence—Atlantic flights*

Flight level	Reported CAT Light+	Moderate+	Severe+	Total distance flown (km)
<100	—	—	—	0
100–149	—	—	—	0
150–199	—	—	—	2 925
200–249	5·48*	—	—	7 412
250–299	2·48	0·91*	—	41 953
300–349	7·88	1·22	0·027*	640 762
350–399	10·94	1·86	0·006*	1 098 172
≥400	4·96*	—	—	11 116
All	9·58	1·59	0·013*	1 802 340

* Denotes that the percentage is based on fewer than 5 encounters with CAT. Flight levels are expressed in hundreds of feet.

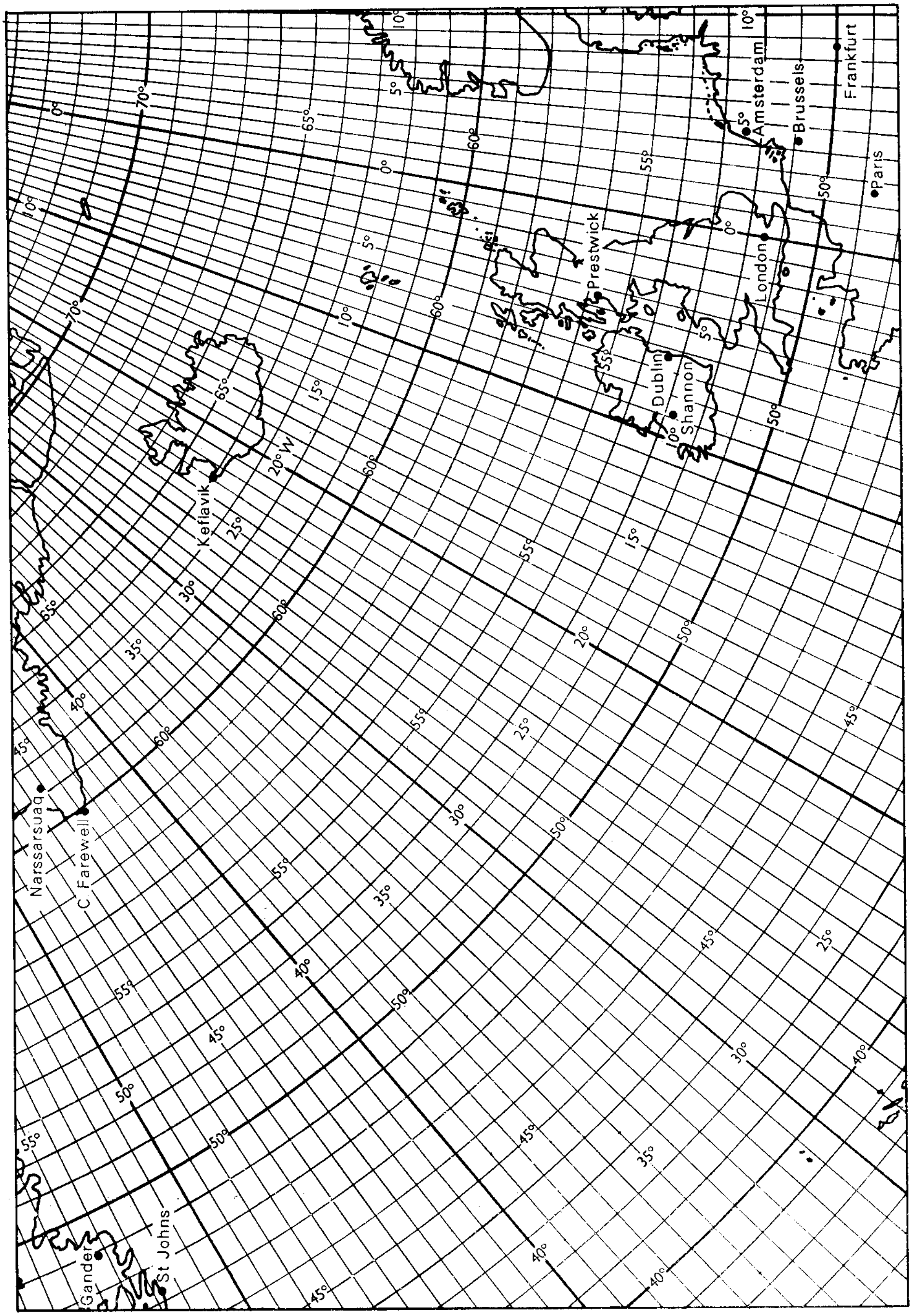


Figure A1. Turbulence Survey (1976) reporting map—ATLANTIC flights

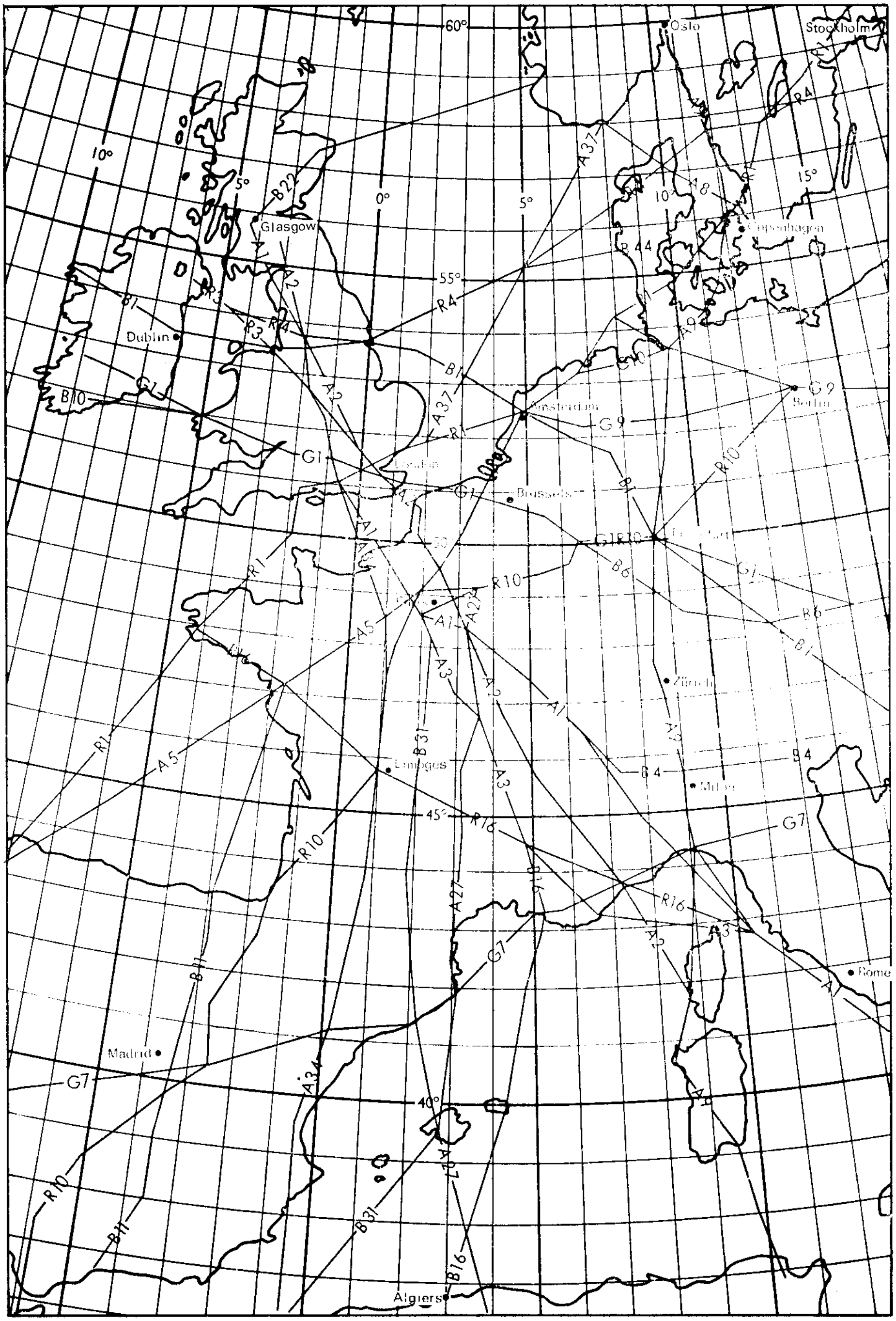


Figure A2. Turbulence Survey (1976) reporting map—EUROPEAN flights

METEOROLOGICAL OFFICE TURBULENCE SURVEY

These maps are being issued on a few chosen days in order to help assess techniques of forecasting CAT. Captains are asked to complete the flight information section on the right and to describe the turbulence history of the cruise stage of their flight on the map overleaf. All turbulence, whether in cloud or in clear air, should be reported.

REPORTS OF NO TURBULENCE ARE AS IMPORTANT AS REPORTS OF TURBULENCE

For all points of the cruise stage within the area of the map indicate the track, flight level, and turbulence encountered. Mark the time (GMT) at convenient intervals. When LIGHT, MODERATE, or SEVERE turbulence is encountered show any cloud in the vicinity as in the example below.

Flight information

Date ....

Aircraft type ....

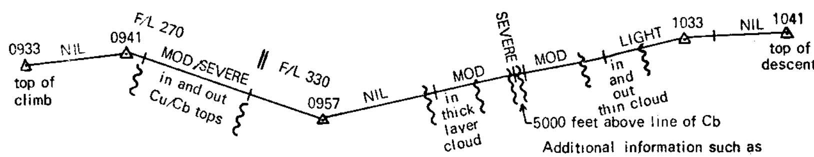
Company/Unit ....

Flight number ....

Departed .... at .... GMT

Arrived .... at .... GMT

Example



Additional information such as wind measurements would be most welcome

Key

NIL MOD — Boundaries of turbulent zones

in thick layer cloud — Boundaries of cloudy zones

F.L 270 || F.L 290 — Changes of flight level

△ — Time mark

Turbulence criteria

(Based on ICAO Doc.8812, AN-CONF/6, 1969)

Description	Effects
Moderate	Moderate changes in aircraft attitude and/or altitude but the aircraft remains in positive control at all times. Variations in air speed are usually small. Loose objects move about. Occupants feel strain against seat belts. Peak changes in accelerometer readings at c.g. of 0.5 g to 1.0 g.
Severe	Abrupt changes in aircraft attitude and/or altitude. Variations in airspeed are usually large. Loose objects tossed about. Occupants are forced violently against seat belts. Peak changes in accelerometer readings at c.g. of more than 1.0 g.
Light/extreme	may be reported when effects are less/greater than these.

The reasons for this survey

A CAT survey in 1972 showed that a report of CAT from another pilot within one hour was more reliable than a forecast of CAT, but when the other pilot's report was more than three hours old the forecast was better.

The objects of this survey are to improve CAT forecasts and to find ways of combining recent reports from pilots with meteorological forecasts to make CAT warnings more reliable

Captains are asked to hand maps to a British meteorological office or to their company representative at their destination to be sent to The Director-General, Meteorological Office (Met O 9), London Road, Bracknell, Berks RG12 2SZ, U.K.

Figure A3. Turbulence Survey (1976)—Reverse side of reporting maps shown in Figures A1 and A2

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AUTOPREP—the Meteorological Office data preparation and telecommunication terminal for use at Collecting Centres

By C. E. Goodison and R. J. Sowden

(Meteorological Office, Bracknell)

Summary

In order to ensure smooth and rapid operation of the automated telecommunication system now installed at HQ, Meteorological Office, Bracknell, meteorological messages being passed to the system from Collecting Centres must conform rigidly to a standard uniform layout or protocol.

Several Main Meteorological Offices as well as sending reports to Bracknell transmit meteorological data to external organizations, such as Regional Gas Boards, which also require high-quality data input for computer processing.

These requirements, for the maintenance of strict discipline in regard to the telecommunication format of meteorological messages, will be met in the near future with the assistance of AUTOPREP terminals which are to be installed at major Collecting Centres. This paper describes the principles and operation of the AUTOPREP system.

1. Introduction

The Telecommunications Centre of the Meteorological Office Headquarters at Bracknell is responsible for the collection and dissemination of meteorological information throughout the United Kingdom. These operations are effected through a computer-based message switching system, (AUTOCOM), which also provides connections to an international network for the exchange of information with other Centres in Europe and the U.S.A.

The handling of telecommunication traffic at the Meteorological Telecommunications Centre (Met. T.C.) is carried out automatically at extremely high speeds. The AUTOCOM computers use, for message distribution, a routeing system which requires the identification details of each meteorological message to be free of errors, so that they match precisely the message heading contained within the routeing list held in the computer. Each message is checked in detail by the computer on receipt, and any which fail this check are sent to an operator for inspection and correction before re-insertion of the message into the system. At peak traffic hours a high rate of rejected messages can cause the operator to be unable to handle all corrections immediately, with a resulting slowing up of the operations. It is thus important for the smooth operation of the system to reduce the number of rejected messages to a minimum.

In the United Kingdom 12 Regional Collecting Centres collect observations which are made regularly at more than 240 stations. These reports are assembled into meteorological bulletins which by the addition of special groups of characters at the beginning and end of the bulletins, e.g. ZCZC, NNNN, etc., are made ultimately into meteorological messages which are then in the form acceptable to the Bracknell telecommunication computers.

AUTOPREP terminals installed at these Centres will help staff to fulfil these detailed and laborious tasks quickly and accurately.

Most of the Regional Collecting Centres are located at Principal Forecasting Offices and the handling of the observations is only part of the telecommunication task. Much extra effort is involved in the preparation of paper tapes to facilitate the transmission of forecasts, warnings, reports, etc. to subsidiary stations and external users. These messages are prepared in a variety of formats, many of which contain a large proportion of fixed data. The AUTOPREP equipment is intended to aid the preparation of these messages and at some Centres will include an autodial telex to simplify message transmissions.

As a result of a prolonged tendering exercise a contract for 12 AUTOPREP terminals was placed at the beginning of 1978. The first unit of production is expected at HQ, Meteorological Office, Bracknell early in 1979, followed by a further 11 sets of equipment during the following six months.

2. Requirement

The features specified to meet the requirement were as follows:

(a) Visual Display Unit (VDU) with at least 24 lines of 69 characters, a standard 'QWERTY' type keyboard and a separate function key layout to control frequently used system functions such as 'SEND', 'CLEAR SCREEN', etc.

Dedicated keys to provide for the fast movement of the cursor, i.e. a movable line underneath any one character on the display screen, and a facility for highlighting special fields or groups of characters, e.g. dual intensity, inverse video, were also specified.

(b) A processing unit to control system functions and to provide monitoring and scheduling of system activities.

(c) Storage for programs and formats in non-volatile but alterable form which would provide security against mains supply failure.

(d) Connection of up to eight duplex communication channels with a capability of operation at 50, 75 and 100 bits/second using ITA2 asynchronous signals.

(e) Expansion capability to include attachment of additional VDUs and the operation of communication lines at higher speeds and the use of other line protocols. Another desirable function included in the specification was the ability of the equipment to be used for ancillary purposes such as simulation of a remote job entry (RJE) terminal, and the possibility of use in a stand-alone mode for mathematical operations.

(f) A facility enabling development of programs by Meteorological Office personnel and the addition of such programs to the delivered system, was also required.

3. Description of the system

(a) (Hardware). The equipment which will be provided in response to the above requirement consists of a minicomputer housed in one pedestal of a standard office desk on which stands a Visual Display Unit and keyboard which are used to control operation of the system. (See Plate I.)

The minicomputer has a micro-processor based Central Processing Unit, 32 K of semiconductor main memory, VDU controller, floppy disc controller, communication multiplexer, and line termination cards. These functional units are linked by a multiple path 'bus' connector. These modules are similar to those used in the Sperry proprietary 'SCAMP' distributed message switching system.

(b) The Central Processing Unit is based on a Digital Equipment Corporation micro-processor LSI/11/2.

(c) The main memory consists of 32 K 16-bit words of MOS semiconductor memory with a cycle time of 300 nanoseconds.

(d) The floppy disc backing storage system is based on a flexible replaceable magnetic disc such as those in common use on small data-entry systems.

(e) A teleprinter will normally be connected to provide hard copy.

To face page 78

Photograph by courtesy of Sperry Rand Ltd

Plate I. The Meteorological Office data preparation and telecommunication terminal 'AUTOPREP' (see page 77).

Plate II. L. G. Groves Memorial Prize and Award winners with Lt.-Col. J. Groves and Mrs Groves.
Seated with Lt.-Col. J. Groves, M.C. and Mrs Groves are, left, Air Marshal Sir John Nicholls, K.C.B., C.B.E., D.F.C., A.F.C., and right, Air Commodore K. W. Hayr, C.B.E., A.F.C. Standing, left to right, are Flight Lieutenant J. A. Cowan, Sergeant R. T. Guy, Dr A. F. Tuck, Mr D. B. Hatton, and Mr F. P. Sims. (See page 92.)

Plate III. Dr A. F. Tuck being congratulated by Lt.-Col. J. Groves. (See page 92.)

Plate IV. Mr D. B. Hatton receiving a Cumbria Crystal ship's decanter. (See page 93.)

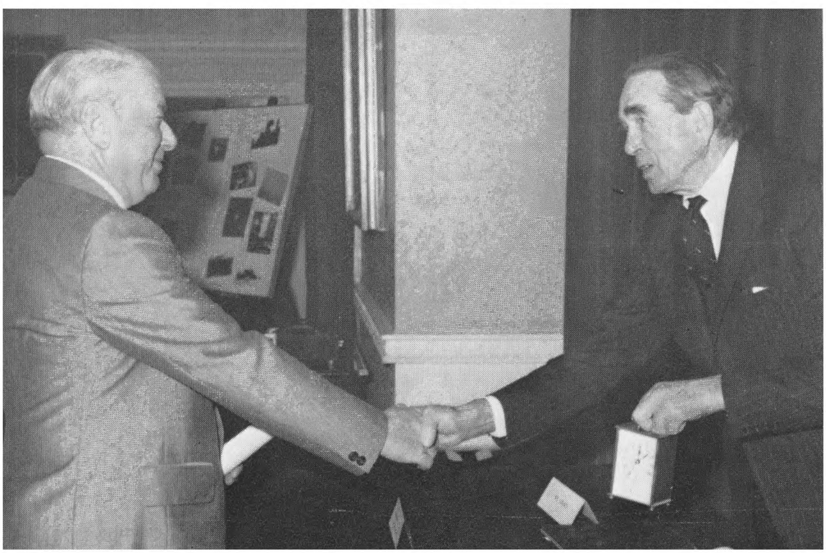

Plate V. Mr F. P. Sims receiving a brass carriage clock. (See page 93.)

(f) A special socket on the equipment rack enables the VDU to access a separate Read Only Memory (ROM) module which provides programs to aid the diagnosis of equipment or software faults.

(g) On the right-hand pedestal there will be space for Post Office equipment which will connect the AUTOPREP and Post Office lines.

4. System facilities

(a) *The operator–machine interface.* The programs for the running of AUTOPREP reside on the floppy disc. On switching on the system these will be loaded automatically into the main store of the processing unit. This initialization process involves self-checking by the system and on completion an indication will be given of the system state. The system clock will be brought up to the actual time by the operator.

Control of the system is effected through the VDU keyboard. A number of commands will be provided to select data or forms, to edit the information displayed, to 'page' through any data more than 20 lines long, to set the system clock, etc. The screen display includes 4 lines which are reserved to display current time of day, the last command entered, the current command, and a line reserved for error reports generated by the system. These latter reports will indicate entry of invalid commands or system malfunctions.

In the first instance maintenance and repair facilities are to be provided by the manufacturer.

(b) *Collection of observations.* Present arrangements at Collecting Centres for the collection of observations include the use of Post Office Conference Units which direct information received from a number of outstations to a single teleprinter in the Collecting Centre communication room. There are often three or four such units at a typical Centre and in order to collate and transmit these reports to Bracknell, page copy from the Conference printers is inspected, the reports are separated and sorted, and paper tapes are prepared with the data re-ordered into appropriate bulletins. The tapes are transmitted to Bracknell and other recipients via a Post Office Broadcast Unit.

An AUTOPREP installation will retain the Conference and Broadcast Units and the *modus operandi* will be analogous to the present-day method just described but much faster.

Inputs will be received from the Conference Units into 'pigeonholes', i.e. specific areas of semiconductor main storage, within the system, from which they are available on request for display on the VDU screen.

By use of the console keyboard, reports can be displayed for identification, checking and editing. On completion of these actions a keyboard command for transmission will cause the system to compile the required bulletin, add the necessary heading and ending patterns, and transmit messages to the Broadcast Unit. Copy of all input and output data will be directed to a local teleprinter for monitoring. Identification of various data types, i.e. rainfall, CLIMAT, etc. within reports from stations will require insertion of two or three identifiers which will uniquely define the data to the processing system. However, if these characters are included with the received reports from the reporting outstations, operation of AUTOPREP at the Collecting Centre is reduced to inspection and editing of any obvious meteorological errors. Messages can then be compiled and transmitted by the system automatically at pre-defined times.

(c) *Preparation for forecast and warning messages.* At most Centres a number of messages consist of actual or forecast data added to a variety of standard forms. Tapes are prepared of these messages for later transmission through the Meteorological Office teleprinter network or over PO telex lines. The VDU terminals on the AUTOPREP system will provide an alternative method of preparation of these data.

The floppy disc system provides storage for up to 50 different forms, and operators will be able to select, by use of the keyboard, the required form, type in the forecast or other variable data, and place the completed message in a queue for transmission. The editing facilities of the VDU keyboard can be used to ensure preparation of 'clean' messages. Local copy outputs will include time of issue or receipt added automatically by the system, which includes a clock. The automatic telex facility will include dialling, recognition of 'Answerbacks', and transmission of the message. Several attempts will be made if necessary to dial each of the telex numbers included on any list related to particular forms. Incoming data from the telex system will be directed to the local copy teleprinter. In the event of two messages being received simultaneously one will be stored and 'queued' for eventual output.

(d) *Specification of formats.* A special 'off-line' program which is not normally in use, will be used to enable changes or additions to the formats held in the system. Facilities for changing lists of telex addresses and for changing of time-activated tasks will also be provided.

(e) *Diagnostics.* The processor unit and other boards housed in the equipment rack include indicator lights which can be used to help diagnose any equipment errors which may occur. A special floppy disc with diagnostic programs will probably be provided to assist operators and engineers to locate equipment faults.

5. Implementation and future developments

The first terminal which will become available as the result of this contract will be delivered to the Telecommunications Centre at Bracknell. It will be used initially to ensure that the services provided by the system meet the requirement specified by the Meteorological Office. Following acceptance it will be available for the training of selected staff from each Regional Collecting Centre for a short period just before delivery of an AUTOPREP system at their station and may be used as a local data entry terminal for AUTOCOM. An installation team from the manufacturing organization will deliver each terminal to its site and will be accompanied by representatives of the Telecommunications Branch to assist with the introduction of the system into its operational role.

The equipment delivered to all sites will be designed to fulfil the functions described above but is clearly capable of supporting other tasks. The system at Bracknell will be provided with additional peripheral equipment which can be used to develop new programs for any special outstation requirements. A support team in the Telecommunications Branch will be available to write programs which could provide useful facilities at any Centre, and will also be able to assist with any problems which may arise.

6. Conclusions

The AUTOPREP data preparation and telecommunication terminal described above is intended to help to improve the quality and punctuality of receipt of observational data which is so important for the operation of the United Kingdom automated telecommunication system. Simplification of other data preparation tasks will also be provided.

When the complete AUTOPREP network is fully operational and has achieved its design expectations in respect of improvement in punctuality and accuracy of reports, further exploitation of these modern data entry techniques in the U.K. Meteorological Office outfield may be expected.

551.525.4

The effects of altitude on soil temperature

By F. H. W. Green and R. J. Harding

(Department of Agricultural Science, University of Oxford)

Summary

It has been widely thought that, in studying seasonal soil temperatures, it is difficult to separate the meteorological effects from the effects of the physical characteristics of the soil. In this paper it is demonstrated that, at least in Great Britain, the latter are quite subsidiary to the former. A second difficulty has existed through the majority of the available soil temperature records being at the fixed hour of 0900 GMT; it is shown how careful consideration of the limited continuous observations available can, to some extent, surmount this second difficulty.

Finally, it is shown that, while in the summer there is a large decrease of soil temperature with altitude (considerably larger than that of air temperature), in the winter the decrease with altitude is small, or sometimes negative, much smaller than that of air temperature. Possible explanations of this interesting effect are considered.

Introduction

On a global scale the atmospheric climate determines the major soil groupings, such as podsols, brown earths, etc., but on a more local scale the parent rock imposes very considerable modifications on the properties of the soil. Soil climate, and in particular soil temperature, is affected by both the climate above and the physical properties of the soil, such as thermal diffusivity and capacity; thus in some aspects soil climate is spatially more variable than that of the atmosphere. This is a particular problem in the comparison of upland and lowland soil temperatures, because frequently there are large changes of soil type with altitude; but only in some respects do the soil characteristics play an important role, and many workers, such as Mochlinski (1970) and Gloyne (1971), have been able to demonstrate coherent patterns of soil temperature variation across the British Isles which are independent of the soil properties.

The thermal regime within the soil is affected by many factors including the type of air mass above the soil, the radiation received at the surface, the nature of the surface and the soil type. Of the incoming solar radiation approximately 25 per cent is reflected and a further 30 per cent is lost as net long-wave radiation; the residual, the net radiation, is partitioned into fluxes of heat and water vapour into the atmosphere, and a heat flux into the soil. The flow of heat into the soil will depend on the temperature contrast between the soil and the ground surface; the fluxes into the atmosphere will depend not only on the temperature and humidity structure in the lower atmosphere but also on the water availability at the surface (determined by the soil type, the vegetation type and the rainfall regime). The flows of energy into both the soil and the atmosphere will increase with increasing surface temperature; for a given radiation input the surface temperature will adjust until the sum of all fluxes equals the incoming energy.

Provided that the physical properties of the soil are known, it is possible, using diffusion equations, to extrapolate to all depths the diurnal and annual temperature cycles at the surface (or any particular depth). Unfortunately, the amplitude of the diurnal variation in surface temperature is dependent on the physical properties of the soil and the exchanges with the atmosphere. Using a very simple parametrization of the atmospheric fluxes Van Wijk and De Vries (1966) were able to calculate the effects of soil properties on the amplitudes of the cycles of soil temperature. While these are only rough calculations the results are both physically reasonable and can be supported by observations.

One important result is that the effects of differences on physical characteristics of the soil increase as the period under study decreases. Van Wijk and De Vries calculated the temperature regimes in peat and in sand, two soils with very different thermal characteristics; it was found that the amplitude of the annual wave of surface temperature was only 10 per cent less in sand than in peat, but for the diurnal wave the amplitude was considerably reduced in the sand (by 40 per cent). In addition the transmission of the diurnal wave through the soil is considerably different in the two soils (but again at shallow depths the annual wave is little affected). Thus, for true mean daily temperature the differences between the monthly (or seasonal) averages in different soils will be small at all depths (probably less than 1 °C). The differences at a fixed time in the day can be appreciable, but only at shallow depths; at a depth of 30 cm the amplitude of the diurnal wave is negligible in peat, and in sand is only 10 per cent of that observed at the surface. Thus at 30 cm, and below, the maximum temperature difference between the two soils is unlikely to be greater than 1 °C.

In studies of the atmospheric boundary layer Belasco (1952) and, among more recent authors, Carson (1973) and Harding (1976), have shown that in the lowest kilometre of the atmosphere lapse rates of temperature develop which are characteristic of a particular air mass, and can be broadly explained by the recent history of that air mass. Recent work (Harding, 1979a) has strongly suggested that the observed decrease of screen-level temperature with altitude (the altitudinal gradient) is highly correlated with lapse rates in the free atmosphere but modified to some extent by the energy exchanges at the surface and the atmospheric circulations over the upland. It might have been expected that interaction with the surface would totally dominate the altitudinal gradient of soil temperature, but Gloyne (1971) has shown that a gradient of the annual mean was reasonably well defined. Additionally it has been seen in the previous paragraph that the effects of the spatial variation of the soil characteristics are probably less than 1 °C for the seasonal means of mean temperature. Such a variation of temperature is small compared with the observed changes of temperature with altitude, and thus altitudinal gradients of the seasonal mean of soil temperature would be expected to be well defined.

The observations

Of the 569 reporting climatological stations within the U.K., 182 made an 0900 GMT observation of soil* temperature (sT_9). Of these there are only seven above 300 m, and there are currently (1978) only two above 400 m. Many of these stations take observations at more than one depth; agro-met stations (in particular) generally make observations at 10, 20, 30, and 100 (formerly 122) cm, although only those at 30 and 100 cm are published in the *Monthly Weather Report*. In addition there are a number of upland observations which, because of their short duration or non-standard nature, have not been archived by the Meteorological Office. These include the observations described by Oliver (1961) and Harrison (1975), but considered below are additional sets of analyses which have never been published.

There have been published very few studies of upland soil temperature. Oliver (1961) made extensive observations in upland peat in South Wales, but because observations were made only at one altitude no estimate of the elevation component can be made from these observations. Harrison (1975) made observations of maximum and minimum temperatures at 5 and 10 cm, for 21 months at two altitudes, at a site in the Dyfi estuary (altitude 3 m) and on the west side of the Plynlimon Range (altitude

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* The Meteorological Office usage is to reserve the term 'soil temperature' for depths down to 20 cm, the term 'earth temperature' being used for greater depths than this. But for the purposes of this paper, it was felt better to use the former term throughout.

450 m). These observations demonstrate a number of interesting features, one of the more striking of which is a large seasonal variation in the difference in the maximum temperature between the two sites. This variation Harrison attributes to the effects of solar radiation and soil moisture.

Gloyne (1971) investigated the altitudinal variation of the annual mean of sT_9 soil temperature and found an altitudinal gradient which was similar to that of mean air temperature but had a slight east–west variation across the British Isles. The 0900 GMT observation roughly corresponds to the daily minimum and thus will underestimate the mean soil temperature by an amount which will depend on the amplitude of the diurnal temperature wave. Because the true mean soil temperature is invariable with depth the mean annual sT_9 will increase with depth; Gloyne was able to make a simple, and accurate, correction to the 0900 observation and so use the whole network of climatological observations. Unfortunately such an adjustment is not possible if the seasonal variation of soil temperature is to be investigated. In the analysis that follows records of daily maximum, minimum and 0900 soil temperature from three stations in mid-Wales are used to identify the effects of using an 0900 observation to calculate altitudinal gradients of mean soil temperature. The identification of these effects allows the 0900 observations to be used in other upland areas of the U.K.

For the last 10 years the Welsh Plant Breeding Station (WPBS) has made observations at three sites of soil temperature at 10 cm, using mercury-in-steel thermographs. These sites are: Gogerddan, altitude 30 m and 4 km from the coast; Syfydrin, altitude 335 m and 14 km from the coast; and Pant-y-dwr, altitude 305 m and 43 km from the coast. The daily maxima and minima are available from these records and Figure 1 shows the differences between the lower station and the two high stations. Although there are minor differences between the two pairs, both show a very striking seasonal variation; for the maximum temperature the difference ranges from 1·0 °C in the winter to 6 °C in the summer, for the minimum from 0 °C to 4 °C. This seasonal variation of the gradient between the pairs of stations is very similar to that observed by Harrison (1975) between his high-level and low-level sites—although he found this pattern only for maximum temperatures—and also by Smith (1976) for the Pennines and North Wales.

These observed differences in soil temperature could be due to a number of factors, the most obvious of which is altitude, but it is also possible that the differences in soil types and the increased distance inland of the higher stations may be important. It is also important to establish whether this effect is confined to mid-Wales or is a feature of soil temperatures in all upland areas of the British Isles. To investigate these points use has to be made of the only other upland observations available, those taken at 0900 GMT at climatological stations. It can be seen from Figure 1 that the differences between the 0900 observations at the WPBS sites are, as expected, close to those of minimum temperature, and the altitudinal gradients of the 0900 observations will show the characteristic patterns of the mean. The three climatological stations above 400 m for which observations of soil temperatures are, or have been, published in the *Monthly Weather Report* of the Meteorological Office are:

MOOR HOUSE, Cumbria	556 m, 1957–	30 cm
WIDDYBANK FELL, Co. Durham	508 m, 1968–	10 cm, 20 cm, 30 cm
ONECOTE, Staffs.	411 m, 1959–68	30 cm and 120 cm

When compared with those at their nearest available lowland climatological stations, the observations at these sites show that the distinctive seasonal pattern observed in Wales is also characteristic

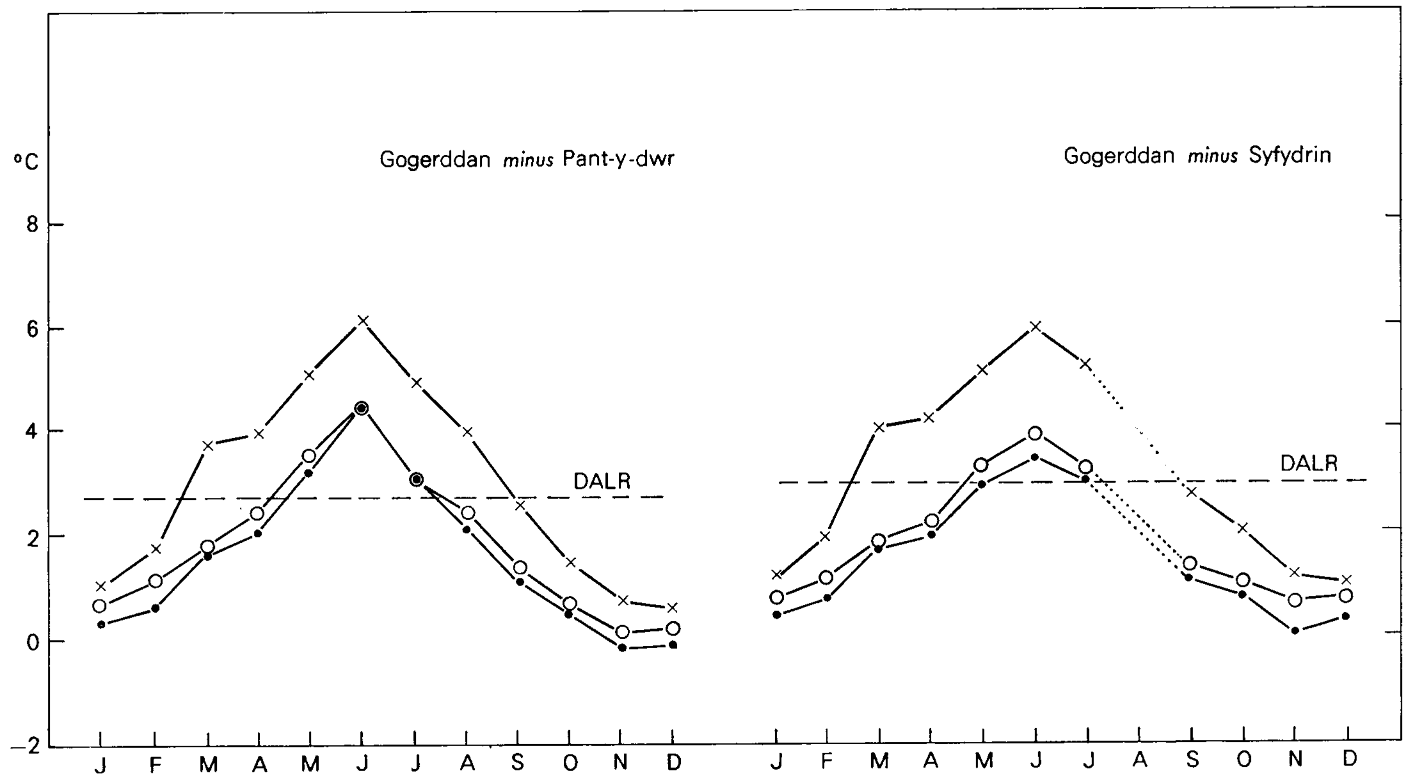

Figure 1. The differences between maximum (×), minimum (·) and 0900 GMT (○) 10 cm soil temperatures recorded at a low-level station, Gogerddan (alt. 30 metres), and two high-level stations, Pant-y-dwr (alt. 305 metres) and Syfydrin (alt. 335 metres) in mid-Wales (1967–72). The dashed lines marked 'DALR' indicate temperature differences consistent with the dry adiabatic lapse rate.

of the Pennines (Figure 2). The Onecote observations also demonstrate that the pattern extends to a depth of 120 cm, with no sign of diminution, and is probably a feature of the entire temperature profile in the soil. The lowland stations used in the Pennine comparison are well away from coastal influences, indicating that the pattern observed is solely an effect of altitude.

The two upland stations of Widdybank Fell and Moor House have very different soil types; Moor House has a peaty clay and Widdybank Fell an alkaline soil with a small organic content and thus these are two extremes of thermal diffusivity. As the stations are only 7·5 km apart and have similar exposures, the differences between them show the effects of two very different soils on the seasonal pattern of the sT_9. In the summer the peaty clay is $\frac{1}{2}$ °C warmer, which is consistent with the differences calculated earlier; it is also confirmation that for the seasonal variation the effects of the differences of soil properties are secondary to those of altitude.

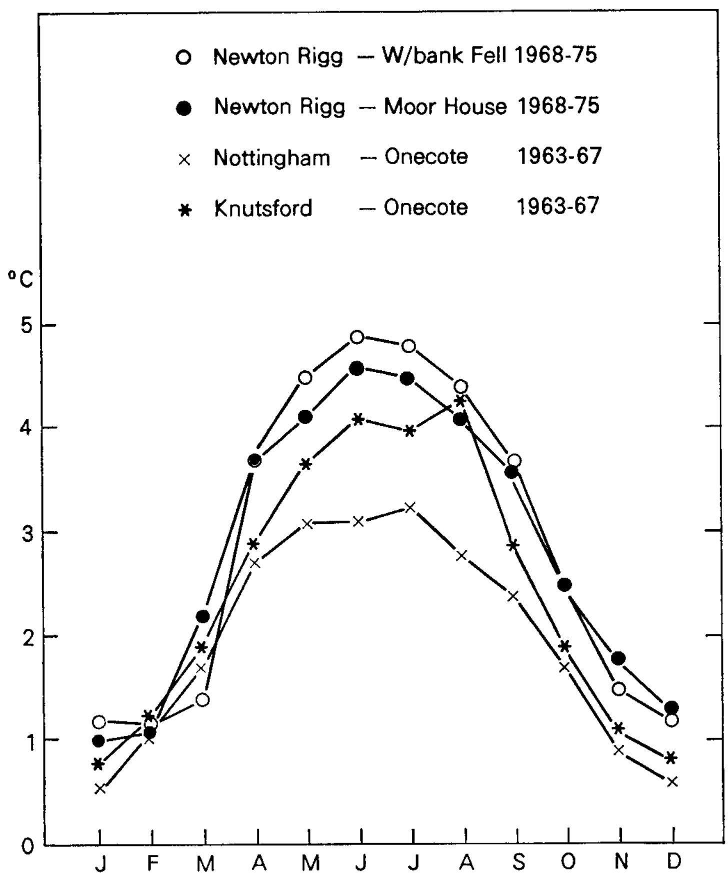

Figure 2. The differences between the mean 0900 GMT (30 centimetre) soil temperature observations for four upland/lowland pairs of stations in, and around, the Pennines.

Other upland observations

Unfortunately there are in Britain, outside the Pennine area, no climatological observations of soil temperature above 400 m. There are, however, a number of stations between the altitudes of 400 m and 200 m and it is possible to identify a number of upland/lowland pairs for which the altitude differences are greater than 200 m (Table I and Figure 3). These data need to be regarded with some care because the temperature differences due to altitude will be of a similar order to differences which might arise because of variations in soil type.

Table I. *The available upland/lowland pairs with an altitude difference greater than* 200 *metres*

No.	Upland station	Altitude *metres*	Lowland station	Altitude *metres*	Altitude difference *metres*
1	Achnagoichan (Inverness-shire)	305	Forres (Morayshire)	50	255
2	Achnagoichan	305	Faskally (Perthshire)	94	211
3	Eskdalemuir (Dumfriesshire)	242	Edinburgh RBG	26	216
4	Spadeadam (Cumbria)	274	Southport (Merseyside)	5	269
5	Silpho Moor (North Yorks.)	203	Hull (Humberside)	2	201
6	Bwlchgwyn (Clwyd)	386	Knutsford (Cheshire)	65	321
7	Lake Vyrnwy (Powys)	303	Knutsford	65	238
8	Buxton (Derbyshire)	307	Huddersfield (West Yorks.)	99	208
9	Crumbland (Gwent)	345	Swansea (West Glamorgan)	8	337
10	Helmshore (Lancashire)	261	Southport	5	256

In some cases there are large spatial separations, again leading to the possibility that influences other than the altitudinal component may be influencing the differences between the stations. The pairs listed in Table I were chosen by the criterion that there be an altitude range in excess of 200 m. Three stations above 200 m have not been used (Kielder Castle, Loggerheads and Llandrindod Wells) because they are near to stations of higher altitude which have already been investigated. Achnagoichan has been compared with two lowland stations, Forres, which is approximately one kilometre from the coast, and Faskally, an inland station. All the observations are taken from *Climatological Memorandum* 77 of the (British) Meteorological Office, are at 30 cm depth, and are corrected to the period 1961–70. The characteristic seasonal pattern observed in mid-Wales and the Pennines is evident between all but one of these pairs (Figure 3) suggesting that it is a general feature of upland areas in the U.K. The exception to this general picture is the Buxton/Huddersfield pair, but Buxton/Knutsford is similar to the other pairs and so it is the lower site, at Huddersfield, which is exceptional.

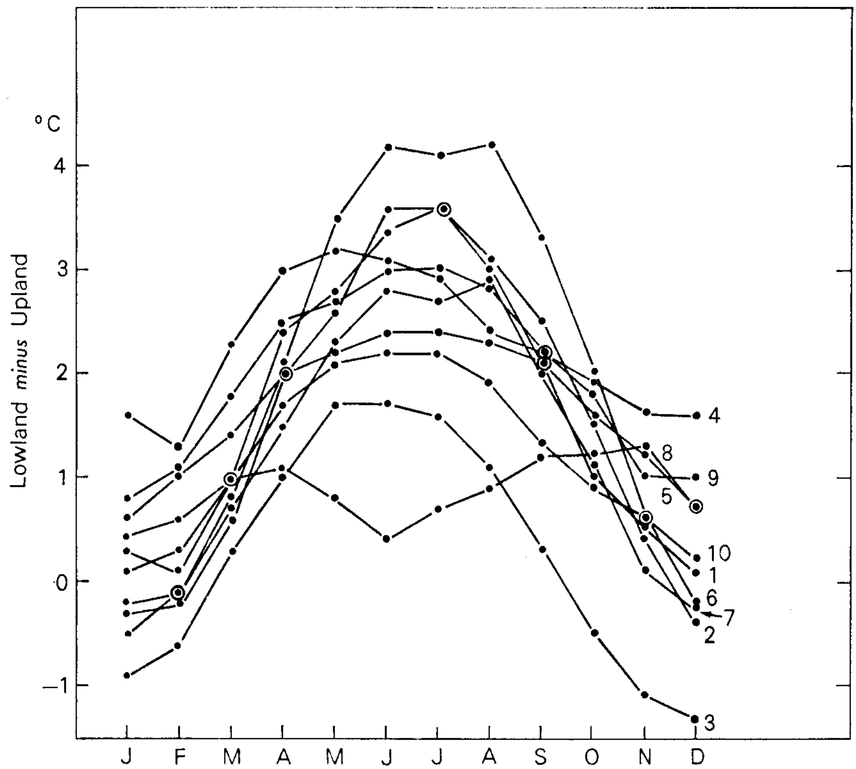

Figure 3. The differences of the mean (1961–70) 0900 GMT 30 centimetre soil temperatures between the 10 available upland/lowland pairs with an altitude separation greater than 200 metres (not including those described earlier). For details of the pairs see Table I.

Table I contains no sites in the southern half of England, or in Ireland; there are, however, pairs of stations within these areas which have an altitudinal difference of less than 200 m but still show a marked seasonal variation of the altitudinal component. These pairs are:

(a) Two stations at the top and bottom of the Chiltern Escarpment, within the Aston Rowant National Nature Reserve, which were operating between 1966 and 1971; they have an altitudinal difference of only 94 m but they are less than one kilometre apart and have very similar chalk soils.

(b) Yarner Wood (195 m) and Starcross (9 m), two stations south-east of Dartmoor, Yarner Wood being a standard climatological station, run by the Nature Conservancy and South West Water Authority since 1966.

(c) Lislap Forest (Co. Tyrone, 175 m) and Moneydig (Co. Londonderry, 34 m) in Northern Ireland.

It thus appears that this seasonal variation is evident over the entire U.K., is independent of soil properties and exposure of the sites, and extends up to at least 550 m.

Comparison with air temperature

The annual mean altitudinal gradients of air and soil temperature are similar (Gloyne, 1971). The gradient of air temperature has, however, only a small seasonal variation, with a typical range of 2 °C km^{-1} (Harding, 1979a), compared with a typical seasonal range of the gradient of soil temperature of between 10 and 11 °C km^{-1} (Figure 4).

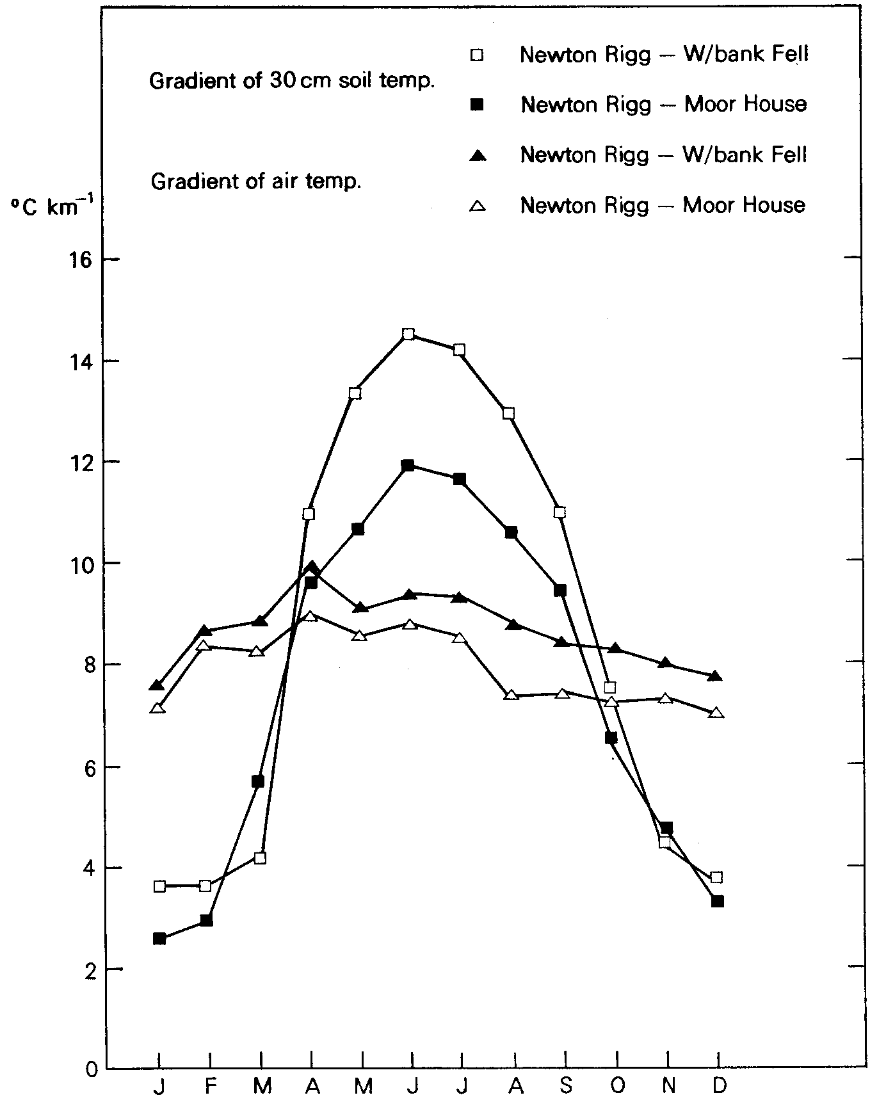

Figure 4. The altitudinal gradients of air and soil temperatures between the two high-level stations in the Pennines and a representative lowland station (Newton Rigg, alt. 171 metres, 1968–75).

One interesting consequence of the differing seasonal cycles of the altitudinal gradients is that the differences between the temperature in the air and that in the soil vary with altitude. Figure 5(a) illustrates this point; at the lower station (Gogerddan) the soil is warmer than the air in the summer and at approximately the same temperature in the winter; at the upper station (Pant-y-dwr) the soil is warmer than the air throughout the year, and, significantly, between one and two degrees warmer in the winter. A similar picture emerges for the other upland/lowland pairs discussed previously, although in the case of the 0900 observations the observed air–soil temperature difference is complicated by the underestimate of the mean soil temperature in summer (by use of the sT_9).

The lowland pattern of the air–soil temperature difference is understandable, being almost zero in the winter, when the surface energy exchanges are small, and large and negative in the summer, when there is a large net flow of heat from the surface to the atmosphere (supplied by the net radiation input). The lower magnitude of the difference in the upland in the summer is also understandable, the radiation input and the Bowen ratio being probably lower in the summer (in the upland) and thus a reduction in the transfer of sensible heat from the surface to the atmosphere would be expected. The relatively large, and negative, difference observed in the winter poses, however, a problem. The temperature difference between the soil and the air cannot result in a flow of heat from the soil, since neither the low radiation input in the winter nor the heat capacity of the soil could maintain the upward flux of sensible heat which can be calculated from a simple mean flux/gradient relationship (Figure 5(b)).

While it is not possible at present to explain the relatively high observed upland soil temperatures, it is instructive to consider a number of possible explanations and to examine their deficiencies. Even in the upland the winter soil temperature rarely drops below 0 °C although it frequently approaches this value, and thus at least a proportion of the moisture in the surface layers must be freezing regularly, but remaining frozen for only short periods of time (too short for the sub-zero temperatures to penetrate to the measurement depth). This frequent freeze/thaw will tend to moderate the extremes of the diurnal cycle of soil temperature; thus if this were an important mechanism, the upland minima would be increased and the maxima decreased, relative to both the air temperature and the lowland soil temperature; this is not what is observed, the mid-Wales observations showing increased maxima and minima. Snow would similarly moderate the diurnal extremes rather than elevate both the maxima and the minima.

A further possible influence is the effects of the variations, both spatial and temporal, of soil moisture; in the summer the upland soil will be wetter than the lowland, and this will lead to increased evaporation and a larger thermal diffusivity of the soil in the upland, which may well explain the relatively low soil temperatures observed in the summer. In the winter, however, there is little difference in the soil moisture between the upland and lowland; in addition the radiation levels are low and therefore the temperature of the soil should be similar to that of the air.

It must be expected that the cause of the anomalously high upland soil temperatures lies in the energy exchanges in these areas; it is not possible to model these exchanges simply, but the observations of soil temperature presented above do indicate that the transfers of heat, water vapour, and radiation are very different in upland areas from those encountered in the lowlands.

Conclusion

It has been demonstrated that in the winter there is very little change of soil temperature with altitude but in the summer the decrease with altitude is large, considerably larger than that of the air temperature. Although the relatively high upland soil temperatures in the winter result from only a small amount of additional heat storage in the soil, the maintenance of a high soil temperature, relative to the air, requires a large input of energy, additional to that provided by radiation, or a suppression of the heat exchange between the soil and the air. The physical mechanism behind this

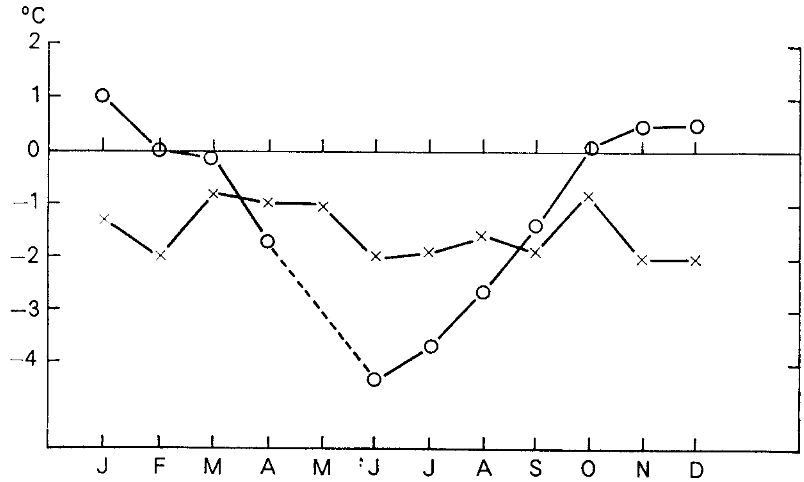

Figure 5(a). **The differences between mean daily air temperature and mean daily (10 centimetre) soil temperature for Gogerddan (○) and Pant-y-dwr (×).**

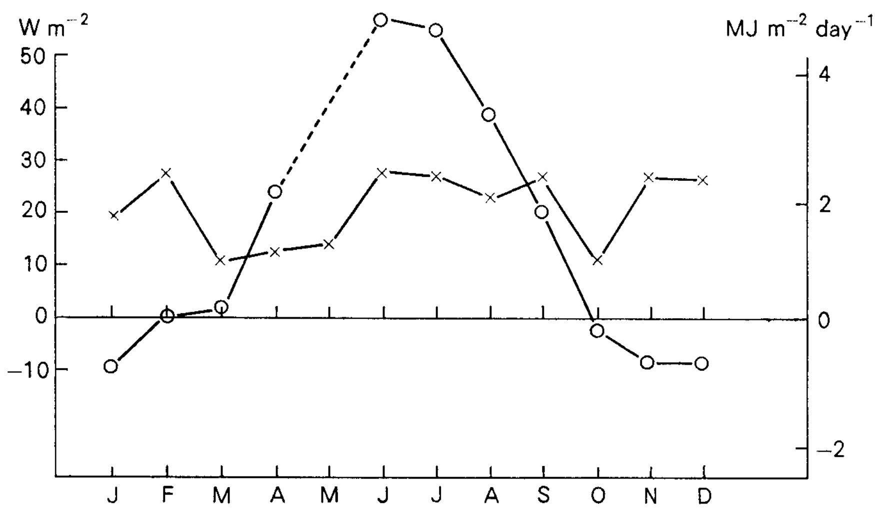

Figure 5(b). The mean, upward heat fluxes calculated from the differences shown in Figure 5(a) using a simple flux/gradient relationship: Gogderddan (○); Pant-y-dwr (×).

behaviour of soil temperature cannot at present be explained; there can be no doubt, however, that a large seasonal variation of the altitudinal gradient of soil temperature is observed in every upland area of the British Isles (and is also observable in other parts of western Europe), independent of soil type or exposure.

The characteristic pattern of soil temperature in upland regions must have important consequences for the productivity and survival of upland plant and animal communities. There is considerable evidence to suggest that many plant physiological processes are more dependent on the temperature of the soil than on that of the air (Alcock *et al.*, 1968) and further, that temperature, along with wind speed, is the major constraint on ecological productivity in upland regions (Harding, 1979b). The prediction of relatively high winter, and low summer, upland temperatures is obviously an important aspect of the assessment of this productivity.

Acknowledgements

We thank the Director of the Welsh Plant Breeding Station for permission to use their observations, and the staff of the Institute of Hydrology, Wallingford, and the Department of Agricultural Science, University of Oxford for many helpful discussions. This work is part of a study of upland climate supported by the Natural Environment Research Council.

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AWARDS

L. G. Groves Memorial Prizes and Awards

The annual award of prizes took place on Friday 24 November 1978 at the Main Building, Ministry of Defence, Whitehall (see Plates II–V). For the first time since the awards were instituted—the first were made in 1947—Major and Mrs K. G. Groves were unable to be present at the ceremony; Major Groves's nephew, Lt.-Col. J. Groves, M.C., who was accompanied by his wife, took the place of his uncle and presented the prizes. The Air Member for Supply and Organization and Vice Chief of the Air Staff designate, Air Marshal Sir John Nicholls, K.C.B., C.B.E., D.F.C., A.F.C., presided.

In his introductory remarks Lt.-Col. Groves explained that his aunt had most unfortunately broken a leg a few weeks before, but that she was making good progress and both she and Major Groves intended to be present at the 1979 prize-giving. Lt.-Col. Groves gave an entertaining account of his own rather negative contribution to aircraft safety in the 1930s when he was a subaltern; while on a liaison flight with the Royal Air Force he forgot to remove his spurs, with consequences that were unfortunate and might have been quite unpleasant!

The 1978 Aircraft Safety Prize was awarded jointly to Flight Lieutenant J. A. Cowan of Royal Air Force Kinloss and Sergeant R. T. Guy of Royal Air Force Cosford for their work in the design and manufacture of an Emergency Locator Transmitter Homer with the following citation:

'The difficult task of locating persons who have abandoned ships or aircraft can be simplified if the survivor uses an Emergency Locator Transmitter (ELT) and the rescue force are equipped with a suitable homer. The success of the ELT in aviation has led to its carriage in ships of the merchant fleet. ELT homers are carried by military aircraft and by a small number of military rescue boats assigned to search and rescue duties. However, there have been occasions when a VHF signal from a civilian ELT has been intercepted but rescue has been delayed because the U.K. military search and rescue forces can only home on to UHF transmissions. This time-consuming and potentially dangerous situation could be reduced if ships of the merchant fleet were fitted with a suitable homer. This fitment would also help military search and rescue forces from being over-burdened because of their unique homing capability. To this end Flight Lieutenant Cowan and Sergeant Guy have designed an effective but inexpensive homing aid—known as 'The Brawdy Homer'—which provides homing indications on VHF or UHF transmitter signals. The introduction of their homer to merchant ships, particularly those assigned to search and rescue duties, would permit them to home on to all Emergency Locator Transmitters in current service.'

The 1978 Meteorology Prize was awarded to Dr A. F. Tuck of the Meteorological Office with the following citation:

'The Meteorology Prize is awarded to Dr A. F. Tuck for his contributions to our understanding of the complexities of the interaction of atmospheric chemistry and dynamics in controlling the amount of ozone in the atmosphere. His work has helped in the appreciation of the limitations of current numerical techniques in assessing possible changes in the total ozone caused by man's injection into the atmosphere of pollutants such as nitrogen oxides or fluorocarbons. In addition, he and his colleagues under his leadership have made important suggestions about possible interaction between the atmospheric carbon dioxide amounts and the ozone chemistry.'

The 1978 Meteorological Observer's Award was awarded to Mr D. B. Hatton of the Meteorological Research Flight, Royal Aircraft Establishment, Farnborough, with the following citation:

'Mr Hatton joined the Meteorological Research Flight in 1970 and, in addition to carrying out his main task of instrument maintenance and development, soon became a recognized observer in the Varsity and Canberra aircraft. In 1974, with the arrival of the Hercules, he rapidly became the senior flight leader in this aircraft, later also becoming one of the team of aircraft scientists. His competence in these tasks and his calm, dedicated manner earned him the respect of all members of flight and indeed he became accepted by the aircrew as being a completely integrated member of the Canberra team. His knowledge of the relevant instrumentation and his expertise in the air have, throughout the past six years, contributed significantly to the advancement of many of the Meteorological Research Flight projects.'

The 1978 Second Memorial Award was awarded to Mr F. P. Sims of the Meteorological Office, Akrotiri with the following citation:

'In 1976, some 37 years after beginning his career with the Meteorological Office, Mr Sims was appointed to the post of Principal Meteorological Officer at Royal Air Force Akrotiri, where he is still serving. In an aircraft accident early on the morning of 7 December 1977 the Main Meteorological Office at Akrotiri was totally destroyed. Five of the seven staff on duty were killed and two were severely burned. Mr Sims showed outstanding qualities of initiative and resourcefulness in re-establishing full meteorological services at Akrotiri within 24 hours, making a major contribution to flight safety in the disturbed weather of the winter season in Cyprus. In addition, the involvement of Mr Sims with the families directly affected by the accident was marked by a sensitivity and humanity which helped to share some of the burden of the personal tragedies of Cypriots and British alike.'

Reviews

Methods in Computational Physics, Volume 17, General Circulation Models of the Atmosphere, edited by Julius Chang. 230 mm × 155 mm, pp. x + 337, *illus.* Academic Press Inc., Publishers, New York, 1977. Price US $35.50.

Understanding climate and its variations, and authoritative assessment of the risks of climatic change, are clearly going to provide massive problems for meteorologists for many years to come. Though the attack on the climate problem will have many prongs, it is the general circulation models (GCMs) which will provide the heavy artillery. The appearance of this major new work is very timely, and especially welcome in that it concentrates on the practical problems which modellers encounter.

The book comprises five articles. The first by Kasahara on general computational aspects of numerical models contains much of interest to modellers themselves as well as providing also a very useful introduction to the whole subject for newcomers. Though the science abounds with difficulties it is the most obvious ones which are most intractable. The problem of choosing a grid array on a spherical earth was one of the earliest to be recognized when global models were formulated and nothing wholly satisfactory has yet emerged—the polar regions require some sort of special treatment. Again the vertical coordinate may be specified in different ways, by height, pressure, potential temperature and others, each with their drawbacks. The most widely favoured, the sigma coordinate system, sidesteps a problem at the lower boundary, yet modifications have to be introduced over mountainous regions. The effects of orography are still not properly introduced into model formulation. Again we have the upper boundary problem, some theoreticians claiming that its formulation is crucial, and modellers on the other hand finding crude assumptions satisfactory—indeed deriving surprisingly little benefit from improved vertical resolution. Arakawa is well worth reading on these problems. On differencing schemes, an area in which he has published his best-known work, I found him disappointing and hard to follow in parts, but on the difficult concept of non-linear instability his brief discussion is very illuminating.

The book continues with detailed descriptions of the formulation of four GCMs by groups at the National Center for Atmospheric Research (NCAR), Boulder, Colorado, the University of California at Los Angeles (UCLA), the Meteorological Office, and the Australian Numerical Meteorology Research Centre. While the UCLA model description is confined to the design of dynamical processes—and goes into great detail for instance on model energetics—the NCAR and U.K. groups include in their contributions the detailed formulation of physical processes. These processes, in many respects imperfectly understood and defying precise specification, lie at the heart of the modelling problem, and years of painstaking research into methods of incorporating them lie ahead. The inclusion of solar and terrestrial radiation poses severe difficulties, particularly the role of clouds in the radiation budget. One process which does not appear at all in the present version of any model in this book, though some groups such as the Geophysical Fluid Dynamics Laboratory (GFDL) of NOAA, U.S.A. are beginning to tackle it, is the interaction of atmosphere and ocean. Essential for any complete simulation of climate, the inclusion of the effects of two-way exchange of heat and momentum between sea and air adds a new dimension to the problem and calls for an interdisciplinary approach.

Special interest attaches to the final chapter contributed by the Australian group. Besides the work reported here, general circulation spectral models are employed by GFDL, while a spectral model is in operational use for short-period prediction in Canada. In this book the authors outline several important advantages accruing from the use of spectral coordinates. There are also drawbacks—apart from some practical difficulties; physical processes of course do not lend themselves to spectral treatment, while the representation of meteorological systems in a predetermined functional form may seem artificial to many meteorologists. Yet the advantages too are undeniable, real representation of a continuous fluid by continuous variables eliminating the truncation errors of grid-point schemes. The economy too is obvious—much time is wasted by grid-point models in calculating negligible changes at a succession of points, for instance in the subtropical anticyclone.

The progress made already with GCMs is remarkable. The U.K. and Australian contributors illustrate mean charts derived from long-period model runs which are seen to reproduce all the main features which go to make up the mean state of the atmosphere. Several groups have demonstrated that beginning with an atmosphere at rest and of uniform temperature it is possible to achieve integrations where the full annual climate cycle is reproduced. The next stage provides a sterner challenge still for numerical modellers. Will it also prove possible to simulate the whole range of variations of climate, and eventually provide a convincing solution to the problem of long-term climatic change?

Many scientists will be grateful that in a fast-moving subject such as this, the large number of distinguished contributors to this book have found time to pause and to assemble material available otherwise, if at all, only in widely scattered papers.

P. Graystone

Water data 1976, by the Department of the Environment, Water Data Unit, Reading, Berkshire, 295 mm × 210 mm, pp. iv + 85, *illus.*, 1978. Price £2.

Water data 1976 is the third in an annual series, intended to present summaries of the data which have been collected each year from the various branches of the Water Industry, including water abstraction, treatment and supply, hydrology, water quality, fisheries and finance.

The standard of presentation of the figures and tables is good, although there are a number of clerical errors (for example, the dates of the heavy rainfall at Spelga Dam shown in Tables 12 and 13 do not agree).

For reference purposes, the volumes in the series are likely to prove to be very important. However, people who are not closely involved with the Water Industry, but who are simply interested, will probably find them rather heavy going and may fail to accept that connecting themes or interpretation are not essential to a source book of data.

It is assumed that readers will be fully conversant with the many disciplines covered by the volume, and are therefore able to interpret the numbers for themselves and to understand their significance. In fact, most people will be familiar with only a few of the topics. A fuller explanation of each set of data and a discussion of them could have brought home to the average reader the extent of the largely unpublicized activities behind the flow of water from a household tap. Why, for example, is the average daily consumption of water 431 litres a head in Scotland but only 292 litres a head in England and Wales? The seven excellent photographs would have contributed far more to the report if they had been accompanied by an expanded text.

The interest value of this reference material, obviously prepared with great care, could have been much enhanced for the general reader by the addition of a few sentences showing the uses of the data presented and drawing attention to the important features. The famous drought of 1975–76 might have been further exploited for this purpose, and one must hope that future issues in this series may move in this direction.

C. A. Nicholass

The Guinness Book of Weather Facts and Feats, by Ingrid Holford. 235 mm × 175 mm, pp. 240, *illus.* Guinness Superlatives Ltd, Enfield, Middlesex, 1977. Price £6.50.

This is a welcome addition to popular books on meteorology and weather which will appeal both to amateur meteorologists and to professionals (many of whom will find it fascinating although at times irritating). There is an interesting amalgam of facts, feats and historical information presented in a concise form, and the introduction claims that all the recorded absolute weather extremes are listed.

There are 17 chapters, each concerned with a separate aspect of weather. Chapter 1 is entitled 'The Radiating Sun' and after considering each of the weather elements in turn the book finishes with 'Forecasting the Weather'. The chapters in between give lots of facts and feats ('feat' is used here to indicate a notable weather event) on Dew, Frost, Fog, Clouds, Rain, Flood, Drought, Snow, Hail, Atmospheric Electricity and Thunderstorms, Whirlwinds, Tornadoes and Waterspouts, and even Optical Phenomena. There is a very poorly presented Appendix of miscellaneous information (principally of some Meteorological Office services) and a good Index. Each chapter is headed with one of many stamps issued to celebrate the International Meteorological Organization–World Meteorological Organization centenary in 1973. This would have been excellent if each stamp had been pertinent to its chapter—for instance, a windfinding radar heads the chapter on 'Water'. A Tunisian stamp heading the chapter on 'Forecasting the Weather' is annotated as being the Headquarters of the World Meteorological Organization, Geneva—it is not!

Most chapters begin by introducing the subject matter, giving a little of its history—together with a mention of some of the earliest scientists involved in the field—and then record the 'feats'. The scientific descriptions are highly simplified and although usually adequate at an amateur level will often not satisfy the professional. The scientists recorded in the text belong mainly to the 17th, 18th and 19th centuries and there are occasional references to Greeks and Romans. Modern scientists are infrequently mentioned. The 'feats' of the weather cover the world, but, naturally, those of the British Isles are given much greater coverage than they warrant from a global viewpoint. One is left with the impression that most occurred either in the last 20 years or around the turn of the century. A more even time coverage would have been preferable. The book is in the style of an encyclopedia with paragraph headings in bold type followed by short descriptive text. It is usually satisfactorily written with occasional touches of humour, but is sometimes colloquial and at times confused. Chapter 17 on 'Forecasting the Weather' seems particularly bad and gives the impression of a hastily written addition with an inadequate description of current forecasting methods.

Many facts are given as positive statements (for instance on page 158 it is stated that 'Snow lies on the ground whenever air temperature is below 37 °F (3 °C)') when qualifications or generalizations are required. There are poor descriptive terms (e.g. 'light pressure winds' on page 124 and 'A ridge of high pressure is an elongated extension of isobars from an anticyclone' on page 76) and some statements which could have been expressed better (e.g. it would be more precise to say '30-day predictions from numerical models do not yet provide useful forecasts' rather than '30-day forecasts are still not possible by numerical forecasting' on page 221).

The book is full of good diagrams, some helpful charts and many photographs (which are usually excellent—although that of Arctic Sea Smoke opposite page 112 is technically poor and that on page 161 must be rather old). Many of the tables are good but those with their title at right angles to the contents (as on page 39) are irritating and some lack vital information (e.g. distance to sea is omitted from the table on page 34). It is a great pity that the diagrams etc. are not numbered and rarely mentioned in the text—such reference would simplify some sections (e.g. in the description of optical phenomena on page 202 *et seq.*). Most measurements are given in both imperial and metric units and temperatures in both Celsius and Fahrenheit. This is inevitable at the present time, but is it really necessary to devote most of pages 22, 23 and 27 to explaining and illustrating the temperature conversion process?

There are few references to other works and a Bibliography which included original data sources—particularly of climatological information—would have doubled the value of the book. There is irrelevant information (e.g. a photograph of the harbour at St Tropez 'warming in the sun' opposite page 48 and a comment on motorway lights being left on for no apparent reason on page 110).

The radiosonde is perhaps the most important instrument of modern meteorology and it deserves more space than some 80 words on page 50 and further mention in a poorly written section on pages 218–219. The coverage of weather ships is minimal and meteorological satellites (although providing a few good photographs) could have been written about in more detail.

The book concludes with 'Machines may continue to provide increasing information on which forecasts can be made, but nothing is ever likely to substitute for the eyes and logical reasoning of human beings'. Who can tell how forecasting will develop? Computers have been in use for only 10 to 20 years and perhaps the 21st century will see machines which can reason even better than man!

There are many points, some of which are mentioned above, which are easy to criticize in a book of this sort, but one is attracted by the overall layout and finds much of interest. This is a book principally for browsing and it will find a welcome home among those with an existing interest in weather and those who like to ponder over facts and feats. E. A. Spackman

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NOTICES

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A spectral and filter analysis of long-period rainfall records in England and Wales

By R. C. Tabony
(Meteorological Office, Bracknell)

Summary

Four long-period rainfall records in England and Wales have been subjected to maximum entropy spectral analysis in order to identify any regular periodicities which may be present. Unitary filters were used as a coarse form of spectral analysis in support of the maximum entropy technique, and the series were filtered to examine the temporal variations in the amplitudes of some of the periodicities. A wide range of seasons and epochs was examined, and although some regular periodicities were evident, random fluctuations were dominant. Cycles that could be regarded as permanent were located at 2·1 and 2·4 years, of which the latter, associated with the summer half-year, was the most important. Cycles that were less prominent, but which attained 5 per cent significance over the complete length of all the series examined, were found at periods of 3·9, 5, and 6 years.

1. Introduction

Major searches for periodicities in meteororological data were carried out in the 1920s and 1930s, a notable investigation being due to Brunt (1927). Later the search for cyclic behaviour fell from favour, but the advent of computer techniques renewed interest, and Ward and Shapiro (1961) made power spectral analyses of a wide variety of meteorological parameters on a world-wide basis. A general review of investigations into cyclic behaviour in the atmosphere is provided by Lamb (1972), but the majority of studies have dealt with temperature or pressure. Recently, the well-known rainfall record for England and Wales has been augmented by three homogeneous series representative of particular sites in England. In addition, the last 20 years or so have seen rapid developments in the field of power spectral analysis, with the latest techniques providing much finer resolution than the earlier methods. In the search for periodicities in rainfall in this paper, therefore, the latest techniques of spectral analysis are combined with the long-period rainfall series which have only recently been published.

In this paper the complete lengths of the four rainfall series are spectrally analysed and the significant spectral peaks are tabulated for a number of seasons. The analysis was repeated on component 80 year epochs of the series to determine the degree of permanence of the spectral peaks. A quasi-orthogonal unitary filter analysis applied to the complete records was used as a coarse form of spectral analysis in support of the maximum entropy technique, while filtered time series were used to examine in more detail the amplitude of some of the periodicities found.

2. Data

The four series of monthly rainfall totals analysed were

(i) England and Wales from 1727, first compiled by Nicholas and Glasspoole (1932) and since maintained by the Meteorological Office.
(ii) Kew from 1697, first prepared by Wales-Smith (1971) and revised in 1978.
(iii) Pode Hole, Lincolnshire, from 1726, assembled by Craddock and Wales-Smith (1977).
(iv) Manchester from 1786, published by Manley (1973) and revised in 1976.

Decadal means of annual rainfall for the four series are presented in Figure 1. The two main features of interest are the rise in the totals for England and Wales, most of which occurred before 1820, and the convex nature of the graph for Pode Hole, with low values in the early eighteenth century and high totals in the first half of the nineteenth century. These features contrast with the relative absence of long-period trends at Manchester and Kew. However, the relatively large changes in rainfall indicated by the series for Pode Hole and England and Wales may not be real. The first 40 years of the England and Wales series are based mostly on data from only two or three stations with unorthodox sites by modern standards. During the next 60 years the number of stations used was only about 10, and they are not evenly distributed over the country. From 1820 onwards, the number of stations was sufficient to enable a mapping technique to be used to derive the areal rainfall, and thus it is only from this date that the England and Wales series can be regarded as reliable. The compilation of the series for Pode Hole, a rural site, was inevitably based on less evidence than the series for Kew and Manchester, yet both the latter have been subject to revision. It may well be that the Pode Hole series will require revision in future, with the probability that the large fluctuation in decadal rainfall in the present record will be diminished.

The uncertainty attached to the values accorded to the earlier portions of the records casts doubt on the reality of trends or long-period cycles in the data. Fluctuations of shorter periods will be less affected, however, and cycles of wavelengths less than about 25 years may be regarded as being relatively undistorted.

3. Spectral techniques used

3.1 *Brief survey of methods of spectral analysis.* When a series of observations is transformed from the time to the frequency domain, and the square of the amplitude (i.e. power) is plotted against frequency, the result is known as a power spectrum. The area under the curve in a power spectrum is proportional to the variance. A good account of spectral analysis in general is provided by Bath (1974). The transformation from the time to the frequency domain may be made by taking the Fourier transform of the time series (direct method) or of the autocorrelation function of the series (indirect method).

In the pre-computer era, harmonic analysis (the direct approach) was used, and the results were usually displayed as a plot of amplitude against frequency (the periodogram). Later, Blackman and Tukey (1959) developed a method for computers based on the indirect approach, but Cooley and Tukey (1965) then derived the Fast Fourier Transform (FFT). This is essentially the direct method, but the ordinary 'direct' formulae are replaced by more computationally efficient ones. These methods are efficient when operating only on M^n data points where M can equal 2, 3, 4, ... In practice, therefore, the series is often truncated or extended at both ends with mean values until the number of points equals a multiple of M.

Jenkinson (1977) has described a direct method which produces a quasi-continuous form of the periodogram. The increase in resolution obtained is especially pronounced at long wavelengths because the frequency elements are chosen to be logarithmically spaced.

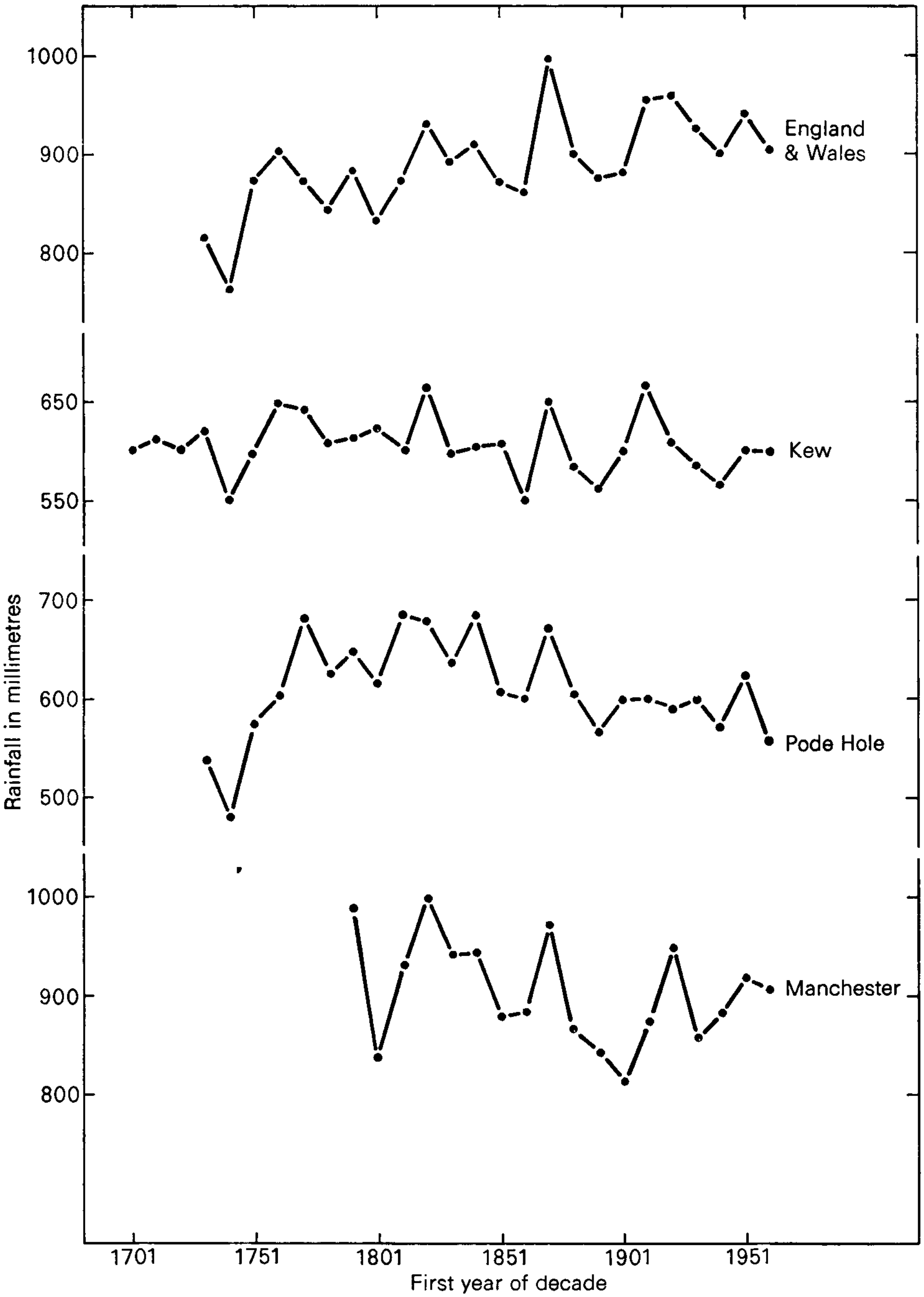

Figure 1. Decadal means of annual rainfall.

The maximum entropy method, first suggested by Burg (1967), is described by Lacoss (1971) and Ulrych and Bishop (1975). It is an indirect method, based on the transformation of an autoregressive process which neither adds information to nor subtracts information from the data (the concept of maximum entropy). The resulting extension of the original data series means that the method is capable of much higher resolution than the earlier methods.

In this paper a maximum entropy package due to Ross (1975) has been used.

3.2 *Calculation of variance and significance of spectral peaks.* Spectral peaks have arbitrarily been taken to lie between those frequencies where the power is one-third of its peak value. The variance attributed to a given peak has therefore been limited to the area contained between the one-third power points, as illustrated in Figure 2.

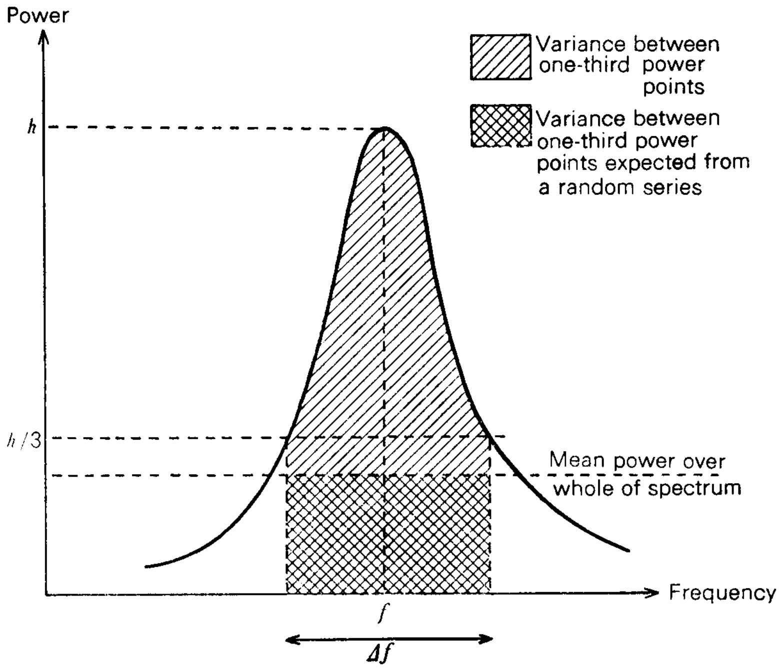

Figure 2. Definition of spectral peak by one-third power points.

The estimation of the statistical significance of a peak is based on the variance ratio, that is to say the ratio of the variance observed to that expected from a random series. If the width of the peak defined by the one-third power points is Δf, the mean power over the frequency range Δf is h_p, and the mean power over the whole of the spectrum is h_A, then the variance ratio R is given by h_p/h_A. As serial correlation was absent in the rainfall data examined, the number of degrees of freedom associated with the frequency range 0 to 0.5 was set at N, the number of data points in the original series. The degrees of freedom were assumed to be uniformly distributed in frequency space, so the number attributed to the frequency range Δf was taken as $n = N \times \Delta f/0.5$. The significance of a peak was estimated from statistical tables of Snedecor's F distribution using the variance ratio R and the number of degrees of freedom N and n.

There are two important criticisms of the procedure described above. The first is that the use of the F test to assess the significance of the variance ratio R applies only when the frequency range Δf is arbitrarily defined as, for example, when the frequency range 0 to 0.5 is divided into M equal parts. By choosing the width and central frequency of Δf to suit the peak under examination, a systematic overestimation of significance results. In this paper, however, the significance of a given peak relative to another is just as important as its absolute value, and the procedure described above leads to more accurate values of this than if the spectral peaks had been assessed over arbitrarily pre-defined frequency ranges.

The second criticism relates to the uncertainty in the number of degrees of freedom when $N \times \Delta f/0.5$ is close to unity. This uncertainty only applies to narrow peaks for which Δf is small, however, and in most cases dealt with in this paper the estimate of $N \times \Delta f/0.5$ will be reasonable.

3.3 *Comparison between maximum entropy and other methods of spectral analysis.* The maximum entropy method of spectral analysis is not universally accepted, and so it is pertinent to make comparisons with other methods, such as the FFT and Jenkinson periodogram. In the maximum entropy method the number of autoregressive coefficients used to extend the data has to be chosen by the user, and this is perhaps the most frequent criticism of the technique. The number of coefficients determines the resolution or 'spikiness' of the spectrum. A small number of coefficients produces a highly smoothed estimate but the resolution becomes finer as the number of coefficients is increased, as illustrated in Figure 3. With other methods the resolution of a spectrum increases with the number of data points N, and is fixed for a given length of input data. Akaike (1970) suggested that the number of coefficients to be used in the maximum entropy method should be such that any further increase would produce a reduction in variance that is not statistically significant. This is of little value, as it determines the length of the autoregressive series from a measure of its predictive power. A much greater length may be needed to display periodicities of scientific interest which may not have much predictive power. A practical solution is to use $N/3$ coefficients for N less than 100, and then to use a decreasing fraction of N as N increases beyond 100.

The significant spectral peaks obtained from an analysis of annual rainfall at Kew from 1697 to 1975 are presented in Table I. The results are obtained from the FFT, Jenkinson periodogram, and the maximum entropy method using 25, 40, 60 and 100 coefficients. The variances and significances were obtained using the procedures described in section 3.2, and only peaks which were significant at 5 per cent or better have been entered in the table.

Considering first the results of the maximum entropy method, the number of peaks produced in each spectrum was about 40 per cent of the number of coefficients used (see Figure 3). Thus, as the number of coefficients and the number of peaks increases, the proportion of the variance accounted for by each peak decreases. In contrast, the estimated significance of a given peak increases with the number of coefficients. This fact, combined with the greater number of peaks produced for the larger number of coefficients, means that the number of significant peaks produced increases rapidly with the number of coefficients. Thus a tabulation of the significant spectral peaks derived from a maximum entropy spectral analysis is highly dependent on the number of coefficients used. A large number of coefficients produces a relatively large number of significant peaks each of which accounts for only a small proportion of the variance, while a small number of coefficients produces a relatively small number of significant peaks each of which accounts for a more substantial portion of the variance. Despite this variation in the absolute values of the variances and significances associated with a given fluctuation, the relative importance of the peaks is independent of the number of coefficients. In the analysis of long-period records which follows, the maximum entropy method has been used with 26 coefficients for 80 year epochs, 60 coefficients over the complete length of record (about 250 points) and 100 coefficients for the complete records divided into three month seasons (about 1000 points). In all cases, the linear trend was removed from the data before the power spectra were produced.

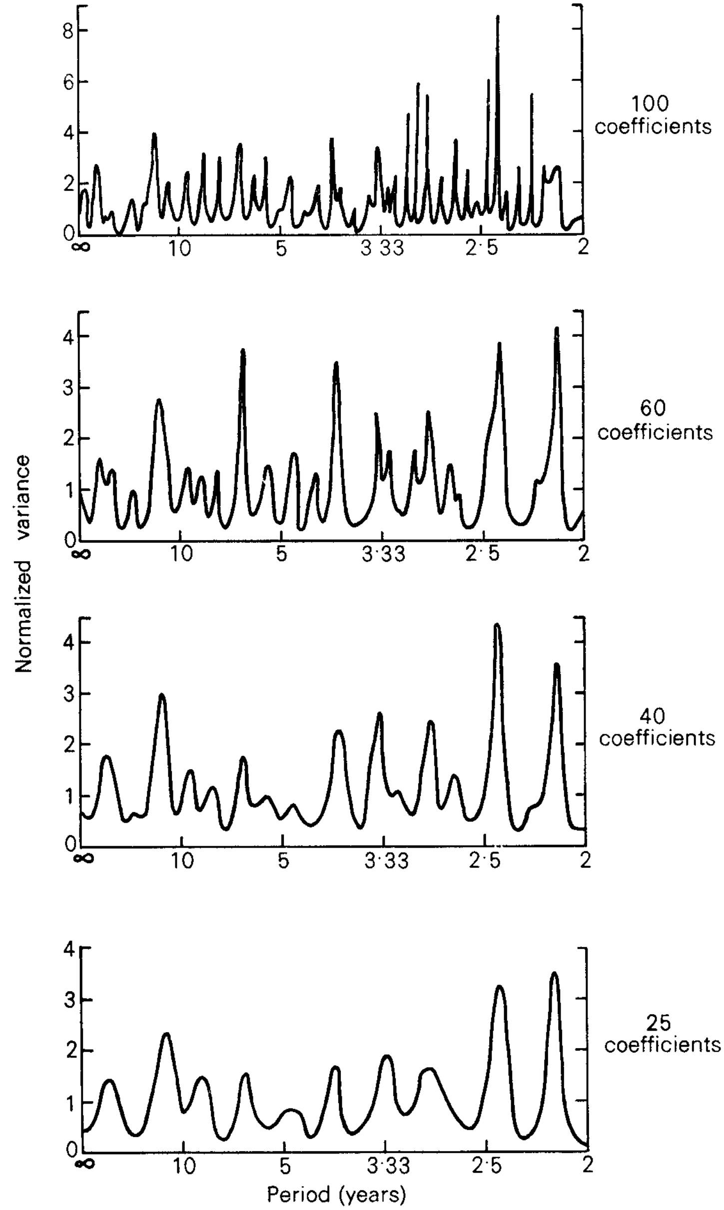

Figure 3. Maximum entropy power spectra of annual (calendar year) rainfall at Kew from 1697 to 1975 using 100, 60, 40, and 25 coefficients.

Table I. *Significant spectral peaks of annual rainfall at Kew from 1697 to 1975. Comparison of FFT, Jenkinson and maximum entropy methods of spectral analysis*

	FAST FOURIER TRANSFORM								
T	11·9	6·02	3·91	2·93		2·45	2·40		2·12
V	9·3	4·8	5·2	3·1		3·6	4·2		8·2
S	5	5	5	3		0·9	0·3		0·9
	JENKINSON PERIODOGRAM								
T	12·3		3·90	2·95		2·46	2·40		2·12
V	4·2		4·7	2·3		2·7	5·5		7·4
S	4		5	4		4	0·9		2
	MAXIMUM ENTROPY (100 COEFFICIENTS)								
T	12·3	6·00	3·89	2·94	2·85	2·46	2·40	2·21	2·13
V	3·8	2·6	4·5	2·2	2·2	2·5	3·9	1·5	7·4
S	3	4	4	4	5	3	0·3	5	3
	MAXIMUM ENTROPY (60 COEFFICIENTS)								
T	12·6	6·11	3·90				2·40		2·11
V	7·8	3·4	4·1				9·4		6·9
S	1	5	5				0·8		2
	MAXIMUM ENTROPY (40 COEFFICIENTS)								
T	12·3						2·41		2·12
V	6·0						8·1		6·6
S	5						0·8		4
	MAXIMUM ENTROPY (25 COEFFICIENTS)								
T							2·41		2·13
V							9·6		7·8
S							2		2

T = period (years); *V* = proportion of variance (%); *S* = level of significance (%). Peaks are listed only if significant at 5% level or better (similar remarks apply to Tables V–XIII). The horizontal displacement from the left-hand margin of a column in this and similar tables is roughly proportional to the associated frequency, i.e. inversely proportional to the period.

The results of the FFT and the Jenkinson periodogram agree well with one another and also with the maximum entropy analysis for 60 coefficients. Table I shows that an analysis made by any of these methods will enable the variance associated with a given fluctuation to be estimated to within a factor of about 2, and its statistical significance assessed to within a factor of about 5. The degree of absolute accuracy is therefore poor, but the assessment of the relative importance of peaks is much better. The main aim of this paper is to analyse rainfall data to see if any periodicities of a permanent nature are present and if so, whether they account for a useful proportion of the variance. The results presented in Table I show that if any major periodicities are present, then all three methods of spectral analysis examined here will detect them, and they will also agree as to their relative importance.

4. Quasi-orthogonal filter analysis

Sixth-order unitary filters due to Craddock (1968) are used in this section, and the combinations chosen are described in Table II (using the notation of Craddock). In a random series, the band pass filters labelled 1 to 5 pass approximately 1/6th of the total variance around the peak periods indicated in Table II, while the low and high pass filters labelled 0 and 6 pass approximately 1/12th of the variance around wavelengths of ∞ and 2 respectively. The variance obtained from a given series can be compared with the variance expected to be obtained from a random series, and the ratio between the two is known as the normalized variance. The significance of a departure of the ratio from unity is assessed using

Table II. *Description of quasi-orthogonal filters used*

Number of filter	Composition	Peak period	Half-power points	
		Number of data points		
0	$1{\cdot}0\,F_{0,6} + 0{\cdot}2\,F_{1,6}$	∞		23·5
1	$0{\cdot}2\,F_{0,6} + 1{\cdot}0\,F_{1,6} + 0{\cdot}2\,F_{2,6}$	10·7	18·6	7·50
2	$0{\cdot}2\,F_{1,6} + 1{\cdot}0\,F_{2,6} + 0{\cdot}2\,F_{3,6}$	5·91	7·88	4·74
3	$0{\cdot}2\,F_{2,6} + 1{\cdot}0\,F_{3,6} + 0{\cdot}2\,F_{4,6}$	4·00	4·81	3·42
4	$0{\cdot}2\,F_{3,6} + 1{\cdot}0\,F_{4,6} + 0{\cdot}2\,F_{5,6}$	3·02	3·49	2·68
5	$0{\cdot}2\,F_{4,6} + 1{\cdot}0\,F_{5,6} + 0{\cdot}2\,F_{6,6}$	2·46	2·72	2·24
6	$0{\cdot}2\,F_{5,6} + 1{\cdot}0\,F_{6,6}$	2·00	2·19	

Snedecor's F test, as first suggested by Craddock (1957). The results of an analysis of rainfall for England and Wales, Kew, Pode Hole, and Manchester for a variety of seasons are presented in Table III. In this paper, the word 'season' is used to describe a period of consecutive months starting in a specified month. The summer half-year refers to the period April–September and the winter half-year to October–March. The rainfall totals were not serially correlated, and so the number of degrees of freedom allocated to each series was equal to the number of data points involved. Only significances of 5 per cent or better have been entered in the table.

In Table II most of the normalized variances are close to unity, showing that the variances of the filtered series are not significantly different from those which would be expected from a random series. The exception is for filter 0, which measures the variance associated with long-term fluctuations. It can be seen that large departures from a random series have occurred at Pode Hole, especially in the autumn, and also over England and Wales during the winter half-year. These findings quantify the magnitude of the long-period variations in the data illustrated in Figure 1 and discussed in section 2. Apart from those with long periods, the only other filtered series to attain significance at the 5 per cent level is that for periods of around 2.5 years in the spring at Kew. No great importance is attached to this, as 1 in 20 random filtered series could be expected to reach the 5 per cent significance level by chance.

It is interesting to compare the results for 12 months starting in January with 12 months starting in July. For longer periods, the behaviour of rainfall totals summed over 12 months will be independent of the starting month, but for shorter wavelengths this is not necessarily the case. The biggest differences between starting months are found at Kew, where the variance for filters 5 and 6 is less for 12 months starting in July than for 12 months starting in January.

So far only the rainfall occurring in individual seasons has been examined. A chronologically ordered data set comprising all seasons mixed together, i.e. spring followed by summer, autumn, winter, spring, and so on, would not necessarily give the same results. Accordingly, data sets were formed of rainfall summed over the conventional three month seasons with departures from average being expressed in terms of the standard deviation for each season. The number of data points was four times as many as for the previous series examined, and the shortest period that could be examined fell from 2 years to 0.5 year. The results of the filter analysis are presented in Table IV, but they show only a continuation of normalized variances close to unity. As a result of the half-power points of filter 0 dropping from 23.5 years to 5.9 years, the normalized variances associated with filter 0 are less than those displayed in Table III, and only the series for Pode Hole achieves significance at better than 5 per cent.

5. Maximum entropy spectral analysis

5.1 *Analysis of individual seasons.* A maximum entropy spectral analysis of the complete series for England and Wales, Kew, Pode Hole, and Manchester was made for a wide range of seasons—the winter and summer half-years and the conventional three month seasons are supplemented by 12

Table III. *Normalized* variance (V_N) and corresponding level of significance (S per cent)† associated with quasi-orthogonal filter analysis of seasonal rainfall*

England and Wales 1727–1975

Number of filter	Peak period (years)	Degrees of freedom	12 months from Jan V_N	S	12 months from July V_N	S	Winter half-year V_N	S	Summer half-year V_N	S	Winter V_N	S	Spring V_N	S	Summer V_N	S	Autumn V_N	S
0	∞	22·0	1·62	5	1·59	5	2·12	0·1	1·25		1·80	1	1·14		1·09		1·60	5
1	10·7	42·1	0·73		0·75		1·04		1·00		1·12		1·01		1·07		0·88	
2	5·9	43·4	0·82		1·05		0·88		1·18		0·86		1·00		1·12		0·87	
3	4·0	43·4	1·04		1·10		0·95		0·96		0·80		1·04		0·79		0·70	
4	3·0	43·4	1·08		0·98		0·83		0·78		0·86		0·84		0·88		1·09	
5	2·5	42·1	1·10		0·80		0·76		1·22		0·91		1·08		1·30		1·07	
6	2·0	22·0	0·82		0·97		1·08		0·83		1·11		0·80		0·87		0·80	

Kew 1697–1975

Number of filter	Peak period (years)	Degrees of freedom	12 months from Jan V_N	S	12 months from July V_N	S	Winter half-year V_N	S	Summer half-year V_N	S	Winter V_N	S	Spring V_N	S	Summer V_N	S	Autumn V_N	S
0	∞	24·8	0·81		0·88		0·79		0·98		1·19		0·86		0·72		1·02	
1	10·7	47·4	1·04		1·06		1·26		1·06		1·25		1·01		1·10		0·92	
2	5·9	48·8	0·92		1·13		0·90		1·22		0·81		1·23		1·03		0·91	
3	4·0	48·8	0·89		1·01		1·03		0·87		0·98		0·68		0·82		0·88	
4	3·0	48·8	1·13		1·07		0·88		0·86		0·78		0·87		0·84		1·24	
5	2·5	47·4	1·13		0·87		0·89		1·02		1·05		1·35	5	1·24		1·12	
6	2·0	24·8	0·97		0·77		1·29		0·97		1·21		0·92		1·19		0·70	

Pode Hole 1726–1975

Number of filter	Peak period (years)	Degrees of freedom	12 months from Jan V_N	S	12 months from July V_N	S	Winter half-year V_N	S	Summer half-year V_N	S	Winter V_N	S	Spring V_N	S	Summer V_N	S	Autumn V_N	S
0	∞	22·2	2·07	0·2	2·01	0·2	1·85	1	1·66	4	1·47		0·84		1·15		2·16	0·1
1	10·7	42·5	0·92		0·82		0·85		1·19		1·14		1·17		1·11		0·74	
2	5·9	43·7	0·86		0·89		0·86		1·03		0·95		1·01		1·07		0·79	
3	4·0	43·7	0·98		0·94		1·10		0·96		0·93		0·95		1·07		0·71	
4	3·0	43·7	1·01		1·10		0·99		0·80		0·67		0·91		0·91		0·97	
5	2·5	42·5	0·87		0·90		0·89		0·99		0·98		0·92		1·17		1·09	
6	2·0	22·2	0·83		0·60		0·79		0·76		0·97		1·07		0·63		0·99	

Manchester 1786–1975

Number of filter	Peak period (years)	Degrees of freedom	12 months from Jan V_N	S	12 months from July V_N	S	Winter half-year V_N	S	Summer half-year V_N	S	Winter V_N	S	Spring V_N	S	Summer V_N	S	Autumn V_N	S
0	∞	16·9	1·65	5	1·72	5	1·11		1·59		0·84		1·57		1·35		1·73	5
1	10·7	32·3	0·84		0·75		0·94		0·92		1·05		0·96		0·87		0·84	
2	5·9	33·2	0·81		1·05		0·98		0·98		1·11		0·76		0·99		1·03	
3	4·0	33·2	0·95		1·16		0·82		0·82		0·94		1·06		0·72		0·81	
4	3·0	33·2	0·93		1·03		1·14		0·69		0·94		0·76		1·09		1·26	
5	2·5	32·3	0·91		0·68		1·04		1·14		0·94		1·34		1·29		0·72	
6	2·0	16·9	0·98		0·72		1·17		1·00		1·09		0·69		0·97		0·88	

* See section 4 of text. † Listed only if 5% or better.

months starting in January, April, July and October. The number of coefficients used was 60 and the significant spectral peaks are presented in Tables V–VIII. Only peaks significant at 5 per cent or better have been entered in the tables.

Of the features common to all four series, the most impressive are the quasi-biennial peaks at periods of around 2.1 and 2.4 years. The most important of these is the 2.4 year cycle which is essentially a phenomenon of the summer half-year. This is illustrated in Figure 4, where the large quasi-biennial peaks for rainfall at Kew summed over 12 months starting in January (which preserves the summer half-year) are seen to disappear when the rainfall is summed over 12 months starting in July (which

Table IV. *Normalized* variance (V_N) and corresponding level of significance (S per cent)† associated with quasi-orthogonal filter analysis of rainfall summed over consecutive three-month periods*

		England & Wales 1727–1975			Kew 1697–1975			Pode Hole 1726–1975			Manchester 1786–1975		
Number of filter	Peak period (years)	Degrees of freedom	V_N	S	Degrees of freedom	V_N	S	Degrees of freedom	V_N	S	Degrees of freedom	V_N	S
0	∞	88	1·06		99	0·97		89	1·44	0·6	67	1·19	
1	2·7	169	1·03		190	1·15		170	1·11		129	0·93	
2	1·6	174	0·83		195	1·04		175	0·86		133	0·87	
3	1·0	174	1·17		195	1·06		175	1·01		133	1·04	
4	0·75	174	0·86		195	0·85		175	0·90		133	0·96	
5	0·6	169	1·05		190	1·01		170	0·87		129	1·11	
6	0·5	88	0·96		99	0·84		89	0·92		67	1·03	

* See section 4 of text. † Listed only if 5% or better.

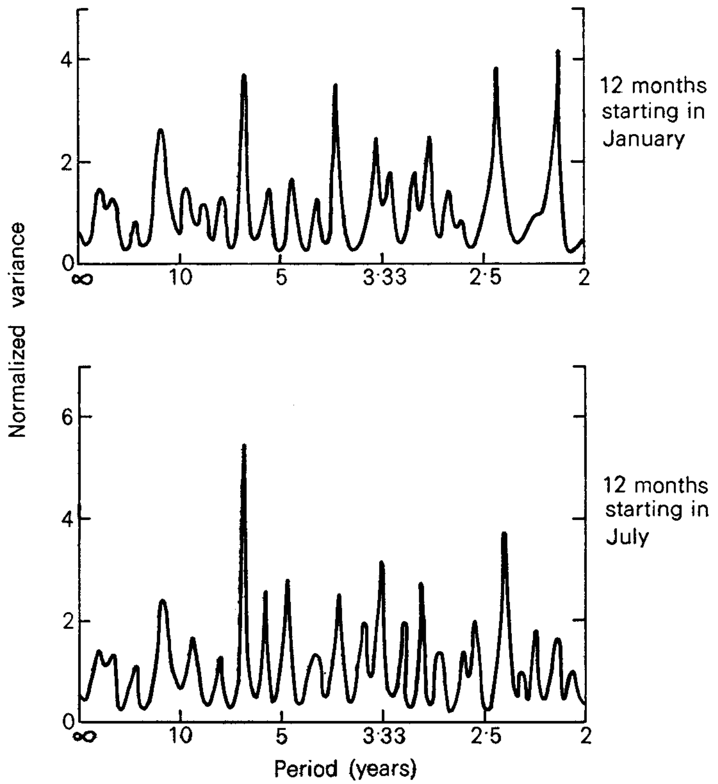

Figure 4. Maximum entropy power spectra (60 coefficients) of rainfall at Kew summed over (a) 12 months starting in January, and (b) 12 months starting in July, during the epoch 1697–1975.

Table V. *Significant spectral peaks of England and Wales rainfall from 1727 to 1975*

Results were obtained from the Maximum Entropy Method using 60 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

	Trend													
						12 months starting in January								
T	—	51·2				3·90						2·39	2·11	2 00
V	5·5	4·6				4·2						7·5	3·1	3·1
S	—	1				5						0·3	2	5
						12 months starting in April								
T	—	52·6				3·89				2·75		2·41	2·20	
V	5·5	4·1				4·3				3·6		4·2	4·0	
S	—	1				3				2		0·8	5	
						12 months starting in July								
T	—	52·5		6·03	4·92	3·87			2·96			2·42		
V	5·5	4·2		3·5	4·6	4·3			2·8			2·2		
S	—	2		4	5	0·9			5			5		
						12 months starting in October								
T	—	52·6		6·07	4·95			3·38			2·54			2·06
V	5·5	4·6		4·4	6·0			3·8			4·7			3·3
S	—	1		4	2			0·4			2			5
						Winter half-year								
T	—				4·97					2·75				2·07
V	9·6				5·7					3·5				3·9
S	—				2					5				1
						Summer half-year								
T	—		10·3	6·05			3·78					2·40	2·13	
V	0·0		4·4	5·5			5·1					6·4	2·8	
S	—		5	5			2					0·1	3	
						Winter								
T	—					3·88								2·07
V	7·4					2·8								4·8
S	—					5								2
						Spring								
T	—		9·25	5·47				3·47				2·38		
V	1·3		4·7	3·9				4·1				6·1		
S	—		1	5				0·9				2		
						Summer								
T	—		10·2				3·79		2·98	2·44		2·37		
V	0·3		3·9				4·7		4·6	6·9		6·2		
S	—		5				5		4	1		1		
						Autumn								
T	—	58·8						3·39		2·76				
V	1·6	5·1						3·3		9·4				
S	—	0·9						2		0·8				

divides the summer half-year). The 2.4 year periodicity has previously been identified by Alter (1927) in northern Europe and the Pacific coast of the U.S.A., and by Jenkinson (1975) in East Africa. The relationship of the 2.1 and 2.4 year cycles to the quasi-biennial oscillation in tropical stratospheric winds is uncertain, as there are insufficient data available for the latter phenomenon to enable proper comparisons to be made. Since observations became available in 1954, the tropical stratospheric winds have displayed a mean periodicity of around 2.2 years.

Other periodicities of note include a 3.9 year cycle in annual and winter rainfall, most evident in the record for England and Wales, but also visible in the other series. Rainfall summed over the winter

Table VI. ***Significant spectral peaks of Kew rainfall from 1697 to 1975***

Results were obtained from the Maximum Entropy Method using 60 coefficients.
T = period (years); *V* = proportion of variance (%); *S* = level of significance (%).

	Trend												
						12 months starting in January							
T	—		12·6		6·11		3·90				2·40		2·11
V	0·1		7·8		3·4		4·1				9·4		6·9
S	—		1		5		5				0·8		2
						12 months starting in April							
T	—				6·07		3·92	3·27			2·41	2·20	
V	0·1				3·9		3·5	8·6			4·2	3·6	
S	—				5		5	5			4	4	
						12 months starting in July							
T	—				6·04			3·36					
V	0·2				4·8			5·0					
S	—				0·8			4					
						12 months starting in October							
T	—		12·6		6·03			3·37					2·13
V	0·1		5·2		4·2			3·6					6·0
S	—		3		1			2					0·3
						Winter half-year							
T	—			8·84		4·92						2·19	
V	0·0			3·6		4·0						9·3	
S	—			2		5						5	
						Summer half-year							
T	—	48·7			6·09						2·42		2·12
V	0·3	3·4			5·9						5·2		2·7
S	—	4			3						1		4
						Winter							
T	—									2·56		2·23	
V	0·0									4·7		6·7	
S	—									2		5	
						Spring							
T	—			8·88	5·95						2·39		
V	0·3			4·3	5·6						6·5		
S	—			2	4						1		
						Summer							
T	—		12·7		6·10						2·45		2·13
V	0·2		5·7		4·1						9·1		5·3
S	—		0·3		2						<0·1		0·2
						Autumn							
T	—	∞						3·45	2·78	2·59		2·34	
V	0·0	2·9						10·7	6·7	2·1		7·4	
S	—	5						3	0·5	4		5	

half-year displays a periodicity of 5 years in all the series, but is least well developed at Kew. A periodicity around 6 years in annual and summer half-year rainfall is evident at Kew, and although absent at Pode Hole is also present for England and Wales and Manchester.

Peaks important only in individual series include a 50 year cycle in annual rainfall over England and Wales (using data from 1727), but this feature is probably detected as a periodicity of 40 years at Manchester (using data from 1786). A 2.9 year cycle is also prominent at Manchester for annual and winter rainfall, while the Kew data indicate a 12 year periodicity in annual and summer rainfall. At Pode Hole peaks at 3.3 years and very long periods are present, the latter being the attempt by the

Table VII. *Significant spectral peaks of Pode Hole rainfall from 1726 to 1975*

Results were obtained from the Maximum Entropy Method using 60 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

	Trend													
						12 months starting in January								
T	—	∞		9·61						2·93				2·11
V	0·2	14·2		3·6						4·6				3·4
S	—	<0·1		5						4				2
						12 months starting in April								
T	—	∞		9·65			3·92		3·33					
V	0·1	13·7		4·1			3·5		4·4					
S	—	<0·1		5			5		5					
						12 months starting in July								
T	—	∞			6·05				3·35			2·56		
V	0·1	14·1			3·9				6·0			3·6		
S	—	<0·1			5				2			5		
						12 months starting in October								
T	—	∞							3·37					
V	0·1	15·2							4·6					
S	—	<0·1							4					
						Winter half-year								
T	—	133·2	21·5			4·95	3·93	3·57	3·35					
V	0·7	7·4	3·3			4·5	3·3	2·8	4·0					
S	—	0·6	3			0·8	3	5	3					
						Summer half-year								
T	—	∞		7·96		4·64	3·74							2·12
V	1·4	3·7		3·9		3·7	3·2							2·7
S	—	4		2		3	4							4
						Winter								
T	—	99·9	10·1			4·96							2·33	2·07
V	0·7	4·8	7·8			3·7							3·1	3·2
S	—	5	5			1							5	3
						Spring								
T	—		15·5		5·40		4·31		3·46					2·10
V	0·4		4·5		3·4		3·1		5·0					4·7
S	—		4		3		5		5					3
						Summer								
T	—					4·62	4·00			2·92			2·45	
V	1·7					5·3	3·2			4·4			6·0	
S	—					3	4			3			0·5	
						Autumn								
T	—	400·0			5·47						2·75	2·57	2·38	2·12
V	0·3	15·1			3·2						7·9	4·4	3·4	3·3
S	—	0·1			5						5	4	2	5

maximum entropy method to resolve into a sine wave the convex curve displayed by the (Pode Hole) data in Figure 1. Peaks at periodicities of 11 and 22 years, which could possibly be associated with the sunspot cycle, are generally absent, the closest approach being the 12 year cycle at Kew.

5.2 *Analysis of 'mixed' seasons.* The spectral analysis over the complete length of records was repeated when the data were arranged chronologically into mixed seasons as described in section 4. The larger number of data points than were available for the single season analysis permitted greater resolution to be obtained, and the power spectra were produced using 100 coefficients. As a result, more peaks were obtained than for the single season analysis (see section 3.3) and the larger number of data points available also reduced the threshold of the various levels of significance. These facts would lead one to

Table VIII. *Significant spectral peaks of Manchester rainfall from 1786 to 1975*

Results were obtained from the Maximum Entropy Method using 60 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

	Trend												
							12 months starting in January						
T	—	41·6					3·85		2·90	2·56	2·41		2·00
V	3·6	8·0					4·1		5·4	2·8	3·9		3·3
S	—	0·7					5		4	4	0·5		1
							12 months starting in April						
T	—	42·5			6·15		3·87				2·42		
V	3·3	7·3			4·0		3·9				3·9		
S	—	0·7			3		4				0·9		
							12 months starting in July						
T	—	41·2					3·79					2·30	
V	3·6	7·8					6·7					2·8	
S	—	0·3					4					5	
							12 months starting in October						
T	—	41·6			6·11	4·93			2·93	2·54			2·08
V	3·2	8·3			3·6	3·7			3·1	5·0			4·3
S	—	0·7			2	5			5	2			5
							Winter half-year						
T	—			8·36		4·97			2·93				2·07
V	1·2			4·3		4·4			4·7				4·6
S	—			3		1			1				0·8
							Summer half-year						
T	—	39·2			6·18					2·55	2·41		2·00
V	0·3	7·3			4·8					6·2	3·9		2·1
S	—	0·3			2					0·8	3		5
							Winter						
T	—		14·9	8·50	7·35				2·93	2·54			
V	0·0		5·2	5·1	3·6				5·3	5·2			
S	—		0·4	5	5				0·9	5			
							Spring						
T	—	45·4	23·0			4·28	3·88	3·49		2·54	2·43		
V	0·5	5·3	7·5			3·1	4·3	3·7		4·4	5.1		
S	—	4	0·1			5	4	2		1	1		
							Summer						
T	—		16·2	8·39	6·16					2·54			
V	1·4		4·0	2·9	5·0					6·7			
S	—		5	4	0·2					1			
							Autumn						
T	—	76·8	12·6		6·94				2·87				2·06
V	4·0	10·0	2·9		5·5				11·0				3·4
S	—	2	5		4				2				5

expect more significant peaks than were obtained with the single season analysis. The results, presented in Table IX show only about the same number of significant peaks as before. This indicates that fewer features of interest are present when the data are formed into mixed seasons than when they are arranged into individual seasons. The major peaks found in section 5.1 are in general absent, but another common peak emerges at a period of around 1.14 years. This had been observed by Brunt (1927) in London rainfall, but only a small proportion of the variance is accounted for.

5.3 *Analysis of 80 year epochs.* The single season form of spectral analysis was repeated when the complete records were divided into 80 year epochs. This enabled one to examine the stability of the significant spectral peaks found in section 5.1 and, more generally, to see how the structure of the variance

Table IX. *Significant spectral peaks in rainfall summed over consecutive three month periods*

Results were obtained from the Maximum Entropy Method using 100 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

	Trend									
					England & Wales 1727–1975					
T	—					1·15	1·00			0·60
V	1·2					2·7	4·0			2·7
S	—					5	0·1			3
					Kew 1697–1975					
T	—		3·35	2·40	1·88	1·14	1·08			
V	0·0		2·4	4·5	3·0	3·2	2·8			
S	—		5	5	1	4	3			
					Pode Hole 1726–1975					
T	—	∞	3·37							
V	0·0	3·6	2·7							
S	—	<0·1	5							
					Manchester 1786–1975					
T	—	35·7				1·13		0·75	0·71	0·55
V	0·0	3·5				2·3		2·5	2·4	4·1
S	—	0·3				3		5	2	5

evolved with time. The seasons examined were spring, summer, autumn and winter, together with the calendar year and the winter half-year, and the number of coefficients used was 26 (i.e. $N/3$). The reduced number of coefficients led to a smaller number of peaks being produced than for the analysis of the complete records, and the smaller number of data points involved also increased the thresholds of the various significance levels. As a result, the number of significant peaks obtained was less than in section 5.1. The results, presented in Tables X–XIII, show that no spectral peak achieved 5 per cent significance in all the epochs examined. There were also large differences in the power spectra between one epoch and another. This is illustrated in Figure 5 for the winter half-year rainfall over England and Wales.

The differences in the structure of the variance between one epoch and another are not surprising. Consider a model of rainfall variance in which random fluctuations predominate, but in which regular oscillations are also present. Over any given frequency range, the power or variance may be regarded as being composed of random and regular components. The regular cyclic component may be assumed (in the model) to be constant with time, but the random component will vary with respect to epoch. In 19 epochs out of 20, the random component of the variance will be contained by the lower and upper 5 per cent levels of significance, but over a narrow frequency band, these limits will be wide. In a series of 250 data points, variations in the mean noise level of a power spectrum, i.e. the variance over the complete frequency range 0 to 0.5, will be determined by the standard error of the variance derived from 250 points. The standard error of the variance over 1/10th of the frequency range will be equivalent to the standard error over the whole frequency range based on only 1/10th of the data, i.e. 25 points. The regular fluctuations found in section 5.1 generally occupied even narrower frequency bands. Thus the power over a narrow frequency band which contains a regular cyclic fluctuation is still subject to large random variations. When the random component of power is large, the spectral peak due to the regular periodicity is boosted, while when the random component is small, it is depressed. It is therefore not surprising that the spectral peaks found in section 5.1 did not maintain a regular level of significance over epochs as short as 80 years.

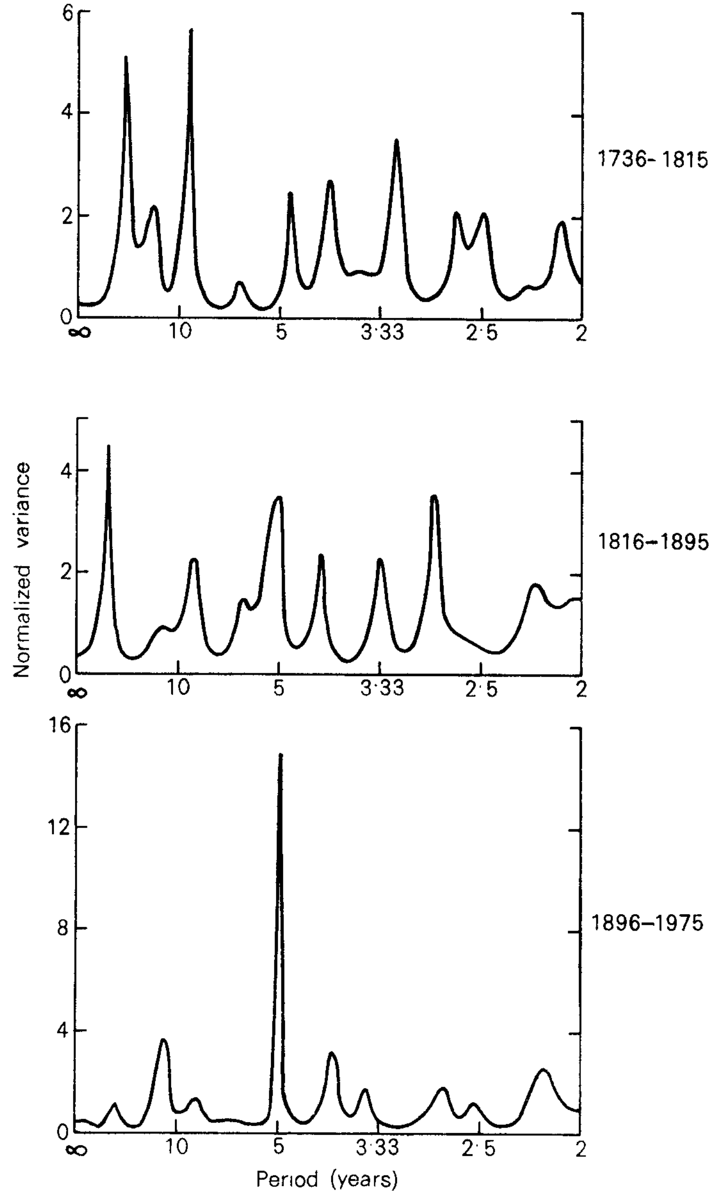

Figure 5. Maximum entropy power spectra (26 coefficients) of winter half-year rainfall over England and Wales during the epochs 1736–1815, 1816–95, and 1896–1975.

Tables X–XIII show that the most regular of the spectral peaks are those at 2.1 and 2.4 years. The 2.4 year cycle is the most important, and is most developed in the first and last epochs. The 3.9, 5 and 6 year cycles do not receive regular support, but the 5 year periodicity in winter half-year rainfall is very pronounced in the most recent epoch (see Figure 4). An 11th-order filtered series of the 5-year cycle for

Table X. *Significant spectral peaks in England and Wales rainfall during 80 year epochs*

Results were obtained from the Maximum Entropy Method using 26 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

Season	Epoch		Peak	Peak	Peak
12 months starting in January	1736–1815	T	2·39	2·11	
		V	12·6	5·2	
		S	0·1	5	
	1816–1895	T	34·4	4·04	3·35
		V	8·3	7·7	10·3
		S	5	5	3
	1896–1975	T	3·92		
		V	9·0		
		S	4		
Spring	1736–1815	T			
		V			
		S			
	1816–1895	T			
		V			
		S			
	1896–1975	T	16·8	5·43	
		V	9·0	11·1	
		S	2	2	
Summer	1736–1815	T	29·4	3·88	2·98
		V	12·7	6·2	5·5
		S	3	5	5
	1816–1895	T	2·39		
		V	9·3		
		S	5		
	1896–1975	T	18·9		
		V	16·1		
		S	5		
Autumn	1736–1815	T	40·0	2·13	
		V	13·1	6·5	
		S	5	4	
	1816–1895	T	3·34	2·81	
		V	7·0	14·5	
		S	4	0·1	
	1896–1975	T	2·97		
		V	12·2		
		S	1		
Winter	1736–1815	T	15·1	2·62	
		V	21·5	19·0	
		S	2	2	
	1816–1895	T	40·0	8·39	2·88
		V	8·3	6·7	9·1
		S	5	5	3
	1896–1975	T	11·2	3·97	
		V	9·3	9·4	
		S	4	4	
Winter half-year	1736–1815	T	22·0	9·00	
		V	9·6	6·9	
		S	5	5	
	1816–1895	T			
		V			
		S			
	1896–1975	T	5·02		
		V	11·7		
		S	0·3		

England and Wales rainfall summed over 12 months starting in October is displayed in Figure 6. The fluctuation is seen to have been well developed between 1860 and 1885, and after 1925, since when the filter has passed 25 per cent of the variance. Over the complete length of the England and Wales record, the filter has passed 15 per cent of the variance, which is significant at the 5 per cent level.

Another feature of the winter half-year rainfall which is unlikely to be permanent, but which has been well developed this century, is an 11 year periodicity. This is illustrated in Figure 7 by means of a sixth-order filtered series which has accounted for one-third of the total variance since 1908. The fluctuations have not, however, maintained a constant phase relationship with the sunspot cycle.

6. Conclusions

Four long-period rainfall records for England and Wales have been subjected to a maximum entropy spectral analysis. The data used, the spectral techniques employed and the method of calculation of variance and significance attributed to each fluctuation, are all imperfect and open to many criticisms. Unitary filters, however, were used to support the main findings of the maximum entropy analysis, while the effect of imperfections in the data were lessened by the fact that four independent series were used.

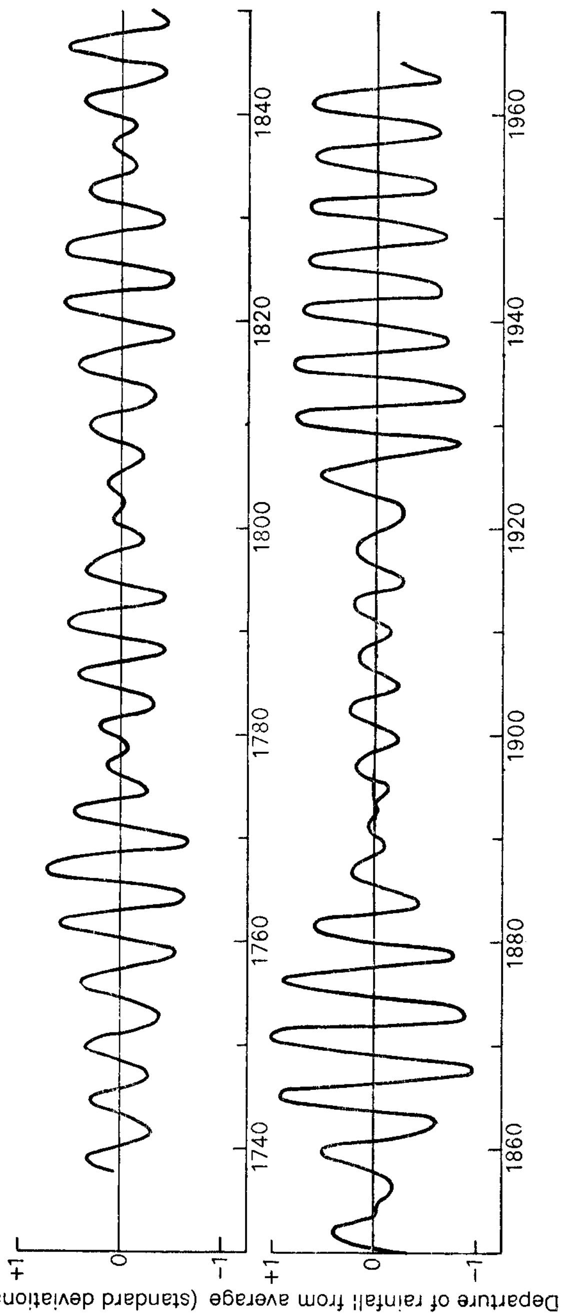

Figure 6. Eleventh-order filtered series illustrating five-year periodicity in England and Wales rainfall summed over 12 months starting in October.

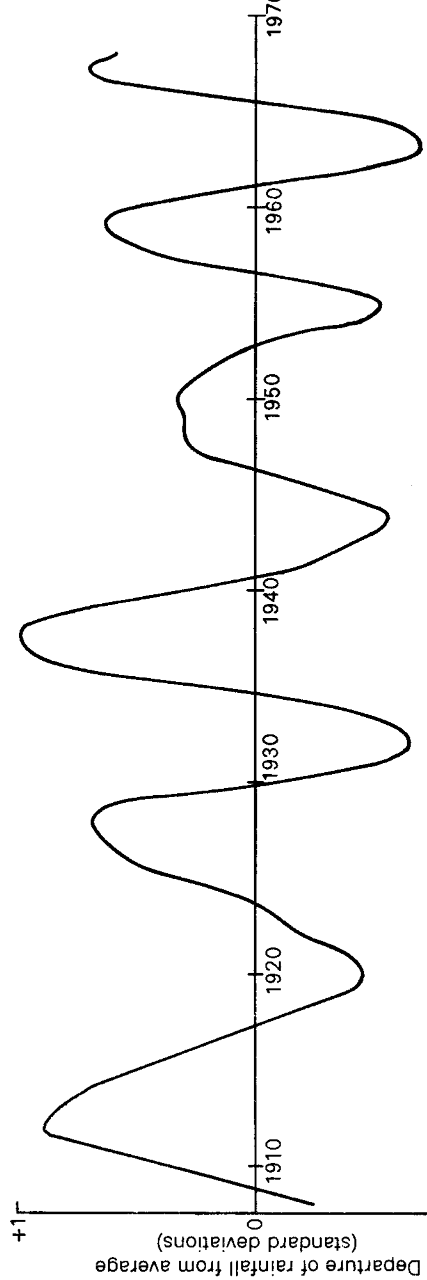

Figure 7. Sixth-order filtered series illustrating 11-year periodicity in winter half-year rainfall over England and Wales.

Table XI. *Significant spectral peaks in Kew rainfall during 80 year epochs*

Results were obtained from the Maximum Entropy Method using 26 coefficients.
T = period (years); *V* = proportion of variance (%); *S* = level of significance (%).

		12 months starting in January				Spring		
1736–1815	*T*			2.40	*T*	5·53		2·42
	V			9·2	*V*	8·6		28·7
	S			3	*S*	1		0·7
1816–1895	*T*		3·33		*T*		3·33	
	V		15·2		*V*		11·9	
	S		0·9		*S*		5	
1896–1975	*T*	11·8		2·40	*T*	5·55		
	V	15·1		6·6	*V*	14·3		
	S	0·9		5	*S*	2		

		Summer								Autumn						
1736–1815	*T*	51·2		7·16		2·63			*T*	6·05		4·77	3·44	2·62		
	V	8·5		10·1		8·8			*V*	10·7		8·4	8·8	7·2		
	S	5		0·5		2			*S*	0·7		4	4	5		
1816–1895	*T*				6·18				*T*		5·40		3·34	2·82		2·15
	V				10·9				*V*		7·3		8·8	10·9		7·2
	S				4				*S*		4		4	2		3
1896–1975	*T*		12·6				2·43	2·10	*T*					2·77	2·38	
	V		9·5				14·4	9·4	*V*					11·1	10·5	
	S		0·8				0·8	0·9	*S*					3	5	

		Winter						Winter half-year			
1736–1815	*T*		17·4		2·65		*T*		8·84		
	V		16·7		13·3		*V*		11·5		
	S		5		2		*S*		2		
1816–1895	*T*	38·4		2·89		2·08	*T*				2·14
	V	10·7		7·4		23·7	*V*				20·0
	S	4		5		0·9	*S*				0·1
1896–1975	*T*		11·2		2·55		*T*	12·2		3·54	
	V		11·2		7·7		*V*	13·3		10·3	
	S		4		2		*S*	0·5		4	

It was found that rainfall fluctuations were largely random, and although some regular periodicities were evident, their use for forecasting was limited because they accounted for only a few per cent of the total variance. Cycles that could be regarded as permanent were located at periods of 2.1 and 2.4 years, of which the latter, associated with the summer half-year, was most important. Cycles that were less prominent, but which attained 5 per cent significance over the complete length of all the series examined, were found at periods of 3.9, 5, and 6 years. The 6 year cycle related mainly to the summer half-year, while the 5 year cycle, which has been well developed this century, is associated with the winter half-year.

Acknowledgements

The author is grateful for useful discussions with Messrs A. F. Jenkinson and G. H. Ross. The work was funded by the Department of the Environment under contract DGR 480/87.

Table XII. *Significant spectral peaks in Pode Hole rainfall during 80 year epochs*

Results were obtained from the Maximum Entropy Method using 26 coefficients.
T = period (years); *V* = proportion of variance (%); *S* = level of significance (%).

12 months starting in January

Epoch			
1736–1815	*T*		2·38
	V		8·5
	S		4
1816–1895	*T*	3·37	2·89
	V	9·3	10·2
	S	3	2
1896–1975	*T*		2·40
	V		10·5
	S		2

Spring

Epoch					
1736–1815	*T*	8·47			2·09
	V	20·9			6·7
	S	4			4
1816–1895	*T*				
1896–1975	*T*	16·5	5·46	3·48	
	V	9·7	14·8	7·8	
	S	2	3	3	

Summer

Epoch						
1736–1815	*T*	7·01	5·44		2·58	
	V	11·1	9·5		10·3	
	S	2	4		4	
1816–1895	*T*			4·61		
	V			10·4		
	S			4		
1896–1975	*T*					2·44
	V					15·5
	S					0·3

Autumn

Epoch								
1736–1815	*T*	37·8					2·38	
	V	17·9					7·2	
	S	4					4	
1816–1895	*T*			5·50	3·34	2·83		2·15
	V			11·4	6·4	9·3		8·4
	S			5	5	2		3
1896–1975	*T*		7·24			2·74		
	V		7·2			11·6		
	S		3			0·5		

Winter

Epoch						
1736–1815	*T*	15·5				2·65
	V	11·6				17·7
	S	4				4
1816–1895	*T*				3·95	
	V				5·9	
	S				5	
1896–1975	*T*	21·3	10·1	5·00		
	V	7·6	16·2	9·4		
	S	5	5	2		

Winter half-year

Epoch				
1736–1815	*T*			3·27
	V			8·8
	S			2
1816–1895	*T*		5·08	
	V		15·0	
	S		3	
1896–1975	*T*	11·4	4·96	
	V	10·5	10·4	
	S	5	3	

Table XIII. *Significant spectral peaks in Manchester rainfall during 80 year epochs*

Results were obtained from the Maximum Entropy Method using 26 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

12 months starting in January

Epoch				
1816–1895	T	6·20	4·88	2·84
	V	6·0	9·3	12·4
	S	5	0·9	4
1896–1975	T	3·81	2·00	
	V	12·6	11·3	
	S	0·9	0·1	

Spring

Epoch			
1816–1895	T		
	V		
	S		
1896–1975	T	3·52	2·46
	V	10·8	11·6
	S	2	3

Summer

Epoch				
1816–1895	T	8·50	6·03	
	V	8·1	12·0	
	S	5	3	
1896–1975	T	2·56	2·42	2·00
	V	12·1	13·7	7·3
	S	4	3	4

Autumn

Epoch		
1816–1895	T	35·0
	V	9·4
	S	4
1896–1975	T	
	V	
	S	

Winter

Epoch				
1816–1895	T	15·1	8·39	2·92
	V	11·1	8·6	10·6
	S	3	5	3
1896–1975	T			2·53
	V			9·3
	S			1

Winter half-year

Epoch				
1816–1895	T	8·47		
	V	9·0		
	S	5		
1896–1975	T		5·10	3·07
	V		10·1	15·0
	S		3	5

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551.578.45(423+429)

The blizzard of 18–19 February 1978 in south-west England and South Wales

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Summary

Heavy falls of snow accompanied by strong to gale force winds affected the south-west of England and South Wales on 15–16 February 1978 and again on 18–19 February 1978. The sudden onset and the severe drifting of the snow caused considerable disruption to communications and damage to property and livestock. Although some hill tops and open fields were scoured of snow cover, drifts of 6 metres were reported in valleys and deep-set roads. A comparison with past snowstorms indicates that not since 1891 has there been so much snow in conjunction with high winds over such a wide area of south-west Britain.

1. Introduction

During the third week of February 1978 snowfalls were considerable in south-west Britain and culminated in the blizzard of 18–19 February when the combination of strong to gale force easterly winds and heavy snowfall practically brought life to a standstill from Hampshire to East Cornwall and north to Avon and Glamorgan. A quick thaw on the 20th and 21st produced some flooding on the south coast but in some areas drifts remained until May.

2. Synoptic situation

The broad pattern remained virtually unchanged over the British Isles from 15 to 21 February 1978. A large depression, centred at about 50°N, dominated the North Atlantic, and a ridge of high pressure extended south from the polar regions into central Europe, which resulted in a south-easterly airstream over much of the United Kingdom.

On the 15th an occluding frontal system approached south-west England, bringing the warm, moist air from the Atlantic into juxtaposition with the established cold air. A small low-pressure centre formed on this front between the Isles of Scilly and Brest by midnight on the 15th and moved into northern France. A further low-pressure centre developed off south-west Ireland late on the 16th and also moved into northern France. Late on the 18th another occlusion moved in from the west with a small wave developing into a centre near Scilly by midnight. This low became stationary in the mouth of the English Channel on the 19th and gradually filled. Figure 1 shows the synoptic situation at 06 GMT on 19 February 1978.

Strong to gale force east to south-easterly winds over the south and west of the country were produced between the ridge which remained over northern and eastern Britain and the succession of lows near south-west England. On the 20th this ridge moved eastwards allowing the weakening fronts to move north-eastwards and the winds to moderate.

3. Data used

The climatological returns received in the Meteorological Office from the network of observing stations were the main source of information for this survey. These returns are from both official meteorological offices and from auxiliary and climatological co-operating stations. Use has also been made of the reports from the contributors to the *Snow Survey of Great Britain* (Meteorological Office, 1978). Figure 2 shows the locations of all the stations in southern England and South Wales

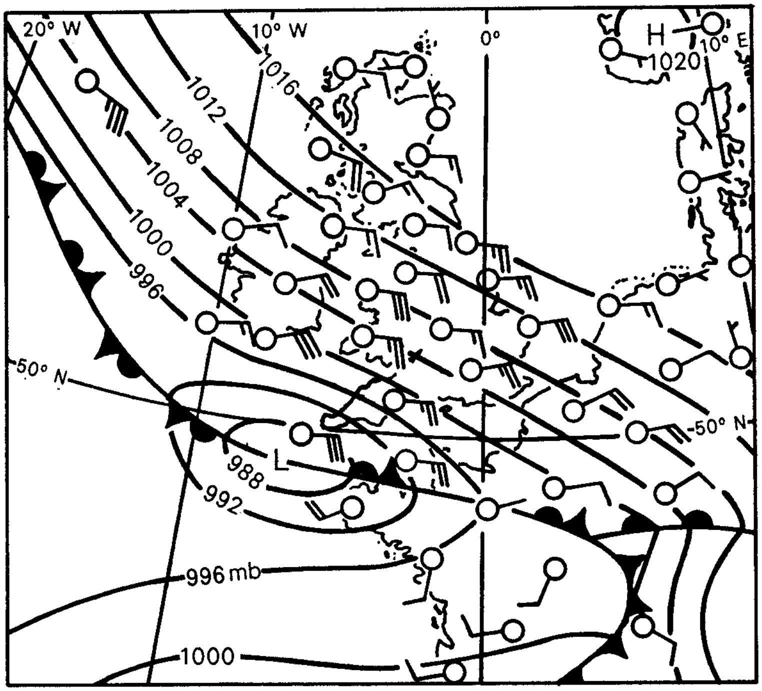

Figure 1. Synoptic situation at 06 GMT on 19 February 1978.

which were used in this report. Supplementary accounts have also been received from the meteorological offices at Mount Batten, Rhoose (Cardiff/Wales Airport) and Upavon, and reports in the national and local newspapers have been consulted.

References to accounts of past snowstorms are given at the end of this paper.

4. Weather

The weather at the beginning of February 1978 was changeable with periods of mild, stormy weather in the south-west. From the 7th it turned gradually colder and during the three days from the 8th to the 10th slight snow showers fell over many parts of the south-west. After a fine, sunny day on 11 February the next few days saw some moderate falls of snow, mainly over the higher ground. More general snow fell on the nights of 15/16 and 16/17 February, giving an appreciable cover over most of southern England, from Surrey and Sussex westward, and South Wales; more than 25 cm were recorded on Exmoor and Dartmoor, and drifts of up to 10 ft (3 metres) quickly formed in the strong easterly winds, blocking many roads.

The winds moderated on 17 February and the weather that day was fine and sunny. As a result of valiant efforts by council workers all main roads in the west were clear of snow by that night. However, after a cold night, Saturday 18 February became cloudy, and rain and sleet in Cornwall turned to snow as it spread further east and north. In the transitional state between rain and snow, generally in south-east Cornwall and south-east Devon, some unusual forms of precipitation were noted, variously described as ice pellets, ice needles, wet icicles or hail. The snow spread into south-west England and by evening had extended to South Wales and central England. The winds increased again to strong to near gale force from an easterly direction, causing severe drifting of the snow especially over the higher

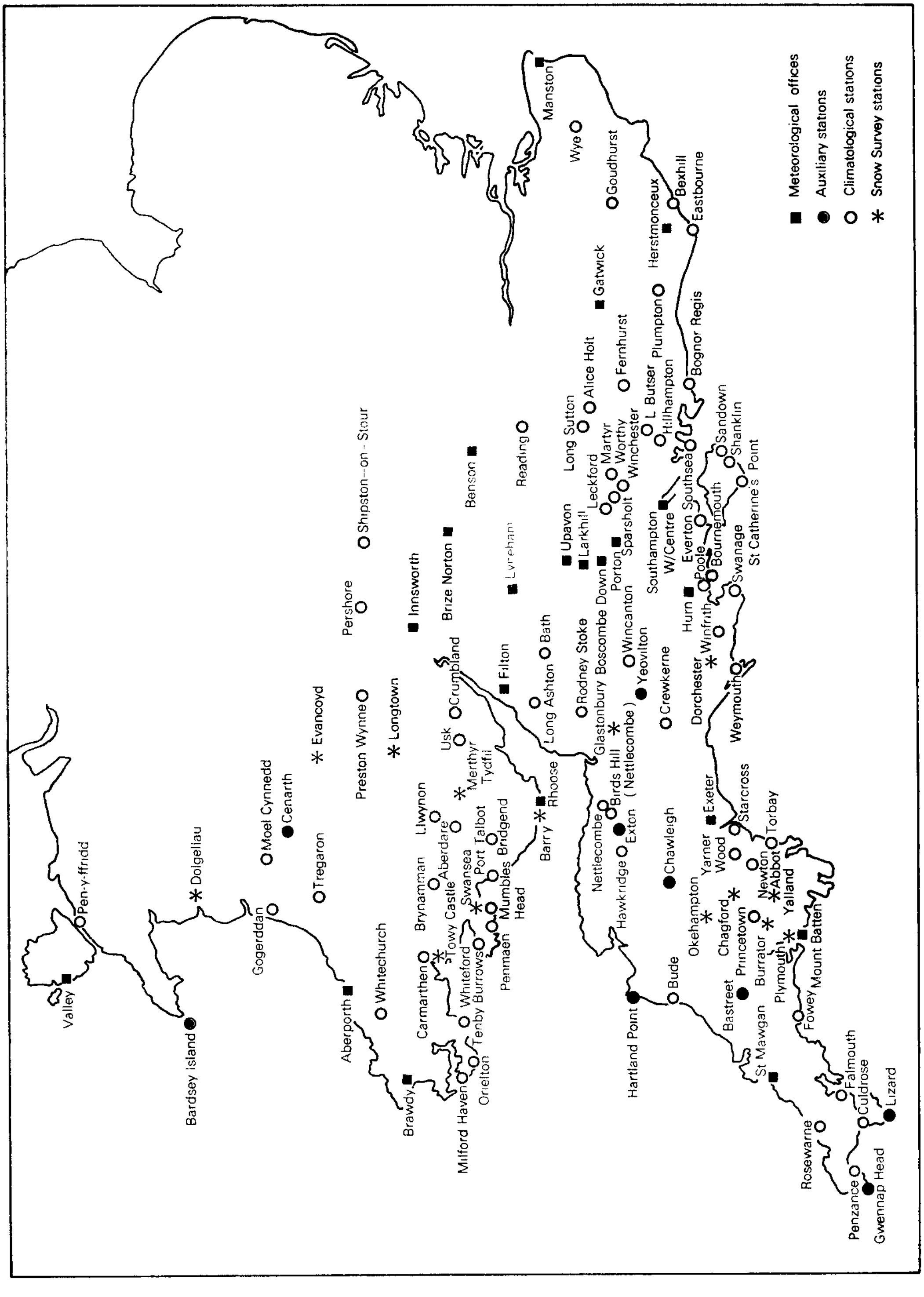

Figure 2. Location of stations reporting to the Meteorological Office during the period 16–20 February 1978 and used in this report.

ground. This blizzard with mean winds of 25–30 knots and blowing snow continued on to 19 February, causing havoc to communications, power supplies and livestock, mainly in Devon, Dorset, Somerset and Glamorgan. Temperatures were low away from the south coast; at Cardiff/Wales Airport, the temperature did not rise above −0.7 °C and on Exmoor the maximum recorded was −1.6 °C. South and west Cornwall, however, had comparatively little snow. The gale force winds continued throughout the 19th and the blown snow prevented accurate assessment of the amounts of snow actually falling. Wind speeds in gusts of 50–60 knots were recorded at a number of places and a maximum gust of 73 knots was recorded at Gwennap Head (Cornwall). Exposed areas such as North Hessary Tor, Dartmoor, were scoured of lying snow while some adjacent areas had drifts of 20 feet (6 metres) or more. Accumulations of level snow to a depth of about 60 cm were recorded in places on Dartmoor and Exmoor and in Glamorgan. The greatest depth recorded was 85 cm at Nettlecombe (Bird Hill) in north-west Somerset.

The area affected by the blizzard stretched from the South Downs west of Beachy Head and including the Isle of Wight, across Dorset, Devon, Somerset and Avon and into Gwent, Glamorgan and parts of Dyfed. Table I gives the snow depths recorded at a selection of places throughout the area between 13

Table I. *Depths of level undrifted snow in centimetres at 09 GMT, 13–23 February 1978*

Place	Altitude *metres*	Date 13	14	15	16	17	18	19	20	21	22	23
South Wales												
Aberporth	134	6	5	4	4	3	3	5	3			
Brawdy	111	7	8	4	4	9	5	18	14	11		
Brynamman	183	2			3	4	3	17	6	3		
Merthyr Tydfil	235			tr	tr	3	2	46	56	48	30	5
Rhoose	67	tr			4	8	7	30	39	30	22	10
Somerset & Avon												
Filton	59					3		12	5	4		
Nettlecombe (Bird Hill)	96	tr			20	29	27	(50)	85	(60)	40	
Hawkridge	314	1	2		23	31	31	62	50	20	10	
Crewkerne	101				13	21	14	25	38	38	8	
Yeovilton	18				6	2	7	29	16	12	7	tr
Devon												
Mount Batten	27	tr						tr				
Exeter	32		tr		3	7	4	21	32	15	9	
Starcross	9					2		14	14	9	2	
Chawleigh	168				15	18	18	40	45	40	28	20
Princetown	414	tr	3	3	29	26	26	45	60	32	8	
Burrator	230	2	8	5	16	10	10	25	30	—	—	—
Dorset												
Dorchester	69	tr			4	13	12	30	30	25	15	5
Winfrith	26				5	9	6	35	40	30	20	
Poole	5					6		25	30	10		
Hurn	10				3	6	6	17	22	14	5	
Wiltshire												
Boscombe Down	126				5	7	4	11	10	9	4	
Hampshire												
Southampton	3				5	2		6	8			
St Catherines I.O.W.	16							15	8			

Figures in brackets are estimated values; tr = trace, i.e. less than 0·5 cm;—indicates no observation; see Figure 2 for location of stations.

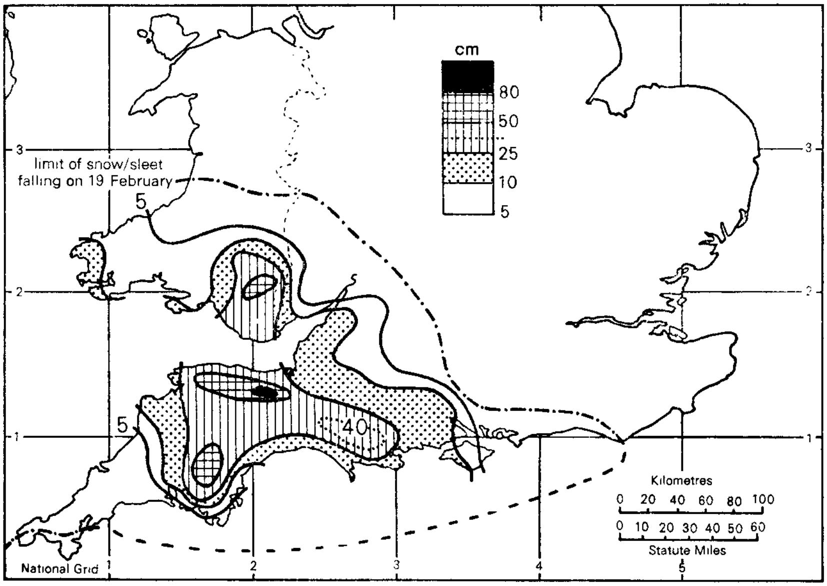

Figure 3. Maximum snow depths (level undrifted snow) measured at 09 GMT on 19 or 20 February 1978.

and 22 February 1978 and Figure 3 shows the greatest depths recorded on the mornings of 19 and 20 February, together with the extent of snowfall on 19 February.

On the 20th the winds slowly moderated and further snowfall in the west turned first to freezing rain and then, as temperatures rose, to rain, which, together with the melting snow, brought further problems with flooding in some areas. Although much of the snow thawed quickly, drifts remained for some time in places in the Glamorgan valleys and on Exmoor and Dartmoor; even as late as 1 May a drift two feet deep still remained on Dartmoor.

The sequence of events as they occurred at Rhoose between 12 and 20 February is given in Figure 4. This shows the rise in wind speeds coinciding with the snow on 15–16 and 18–19 February and also the combination of below-freezing temperatures and strong winds on 18–19 February. In fact at Rhoose there were 15 hours on 18–19 February 1978 when the temperature was below freezing and the associated hourly mean wind speed was 29 knots or more. This is no common occurrence and there have been only 30 such hours during the past 18 years; only one of these occasions was in February (February 1969, also in conjunction with snow.)

5. Some problems caused by the blizzard

Eyewitnesses in some of the worst affected areas spoke of the suddenness with which vehicles became buried in the snow; the drifts were forming much more quickly than they could be cleared. At one stage all inessential transport was prohibited from entering Devon to ease the work of the snow ploughs and rescue workers.

Farmers in Devon and Somerset reported drifts up to the eaves of their houses and on Dartmoor some drifts reached the top of the walls of Princetown Prison. Sheep, which tend to seek shelter in the lee of banks or hedges, were buried in the drifts, though many were rescued after several days. Unfortunately the floods which followed the blizzard drowned some of the sheep before they could be dug

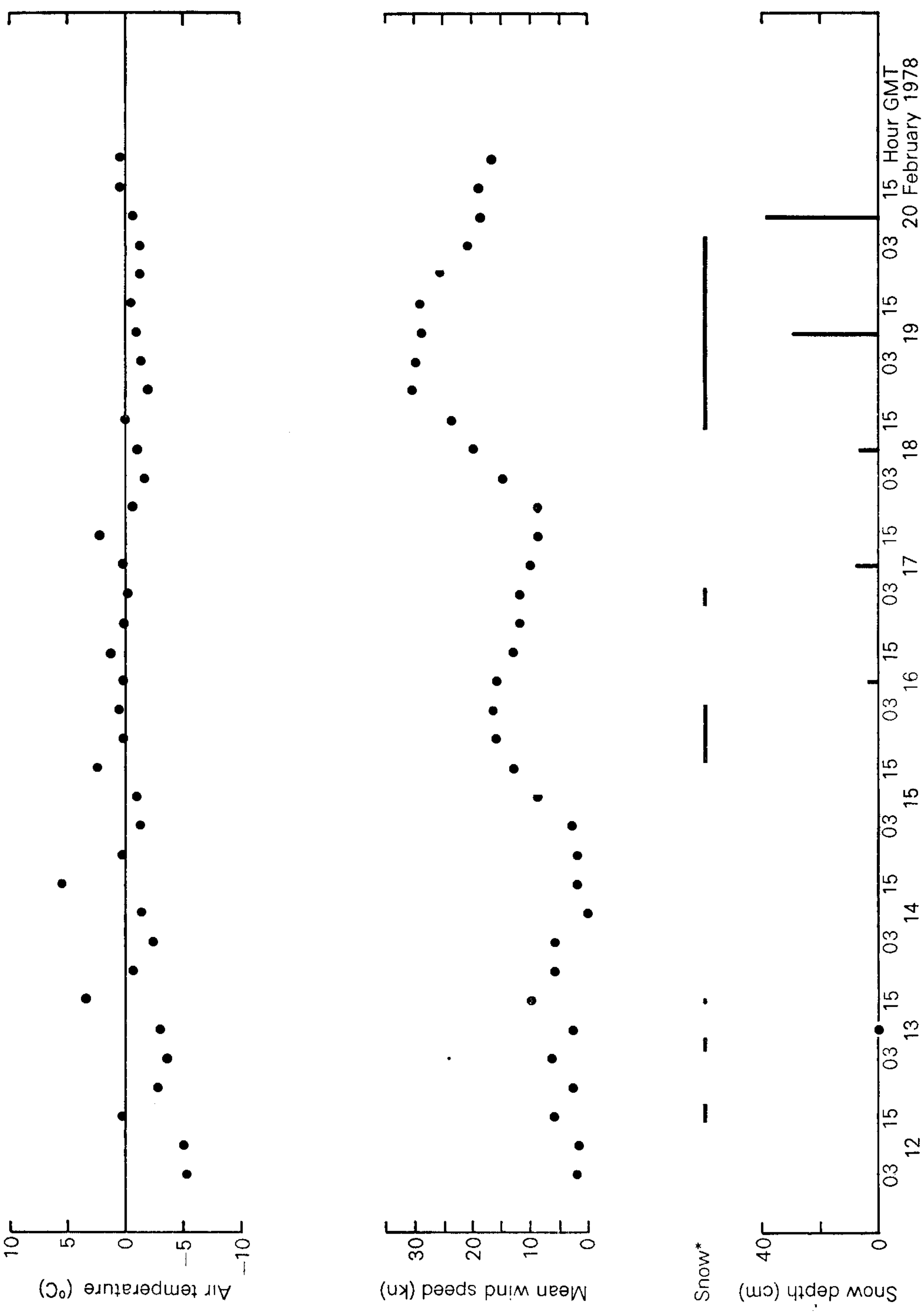

Figure 4. Temperature, wind speed and snow recorded at Cardiff/Wales Airport. Wind speeds are 10-minute means; * indicates duration of snow falling.

out. A farmer near Lynton had so much snow in his yard that he could not find his horses. Later he managed to dig down to them where they were lying on their backs and get them into the barn where they thawed out and revived. In a number of places milk could not be transported from the farms and had to be poured away.

Considerable damage was done to trees and property. Glasshouses suffered greatly as they collapsed under the weight of snow. On the west side of Dartmoor hundreds of trees were brought down by the snow and wind. The Royal Mint, Llantrisant, had to close and the staff were sent home. Electricity lines were damaged and this caused pump failure and lack of water supplies to some areas. In the Cardiff area many people attending the Wales–Scotland rugby match found themselves stranded for several days.

The thaw brought its attendant problems. Dense fog curtailed helicopter flights that were engaged in rescue work and in flying in supplies to stranded communities and fodder for cattle and other livestock. Heavy rain combined with the melting snow coinciding with the high tides brought flooding to Kingsbridge (Devon) where the water rose to seven feet in the town. Fields were flooded in many areas, especially in the Taw and Torridge valleys and around Taunton. Huge slabs of snow drifted down the swollen streams, and lakes formed behind snowdrifts.

The weather observers, both professional and amateur, had an arduous task during these days as instruments became buried in snow and the difficulties of reaching the site became almost insurmountable. At Rhoose the enclosure was inaccessible because of deep snow from the 18th to the 20th. At Hartland Point on the 18th observers were unable to open the screen because of icing and remarks for the 19th–20th state 'station closed down—snowed under'. The climatological observer at Sidmouth turned out although suffering from bronchitis but found the journey to the site too strenuous and had to seek shelter in a nearby house. The following account by the observer at Chawleigh (Devon) gives some idea of the appalling conditions.

'Doing the 2100 ob at Chawleigh on Saturday 18th was very difficult as it was next to impossible to see; however the 40 metre journey to the enclosure was made successfully. The 0900 [observation] on Sunday morning however was done in impossible conditions—great drifts of snow 15 ft high or more had to be climbed with visibility almost non-existent, the temperature was −2.0 °C and the wind near 50 kt—indeed conditions were almost beyond the limit of human endurance and the observation was a nightmare, as was the 2100 the same day.'

6. Past snowstorms in the south-west

The following are some of the more severe snowstorms to which the south-west of England and South Wales have been subjected.

1962/63. Although the total amount of precipitation during this winter was not great there were some heavy falls of snow in the south-west. Tredegar (Gwent) recorded 65 inches (156 cm) of level snow on 8 and 9 February. This weather was caused by troughs of low pressure moving into southern England from France (Shellard, 1968; Meteorological Office, 1963).

1947. A trough moving west from the continent covered virtually all Britain with snow on 27/28 January, and a depression which formed on this trough became centred in the western Channel and prolonged the snow in south-west England, including the Isles of Scilly, where 7 inches (18 cm) were measured (Douglas, 1947; Meteorological Office, 1947).

1945. A complex situation of small secondary lows off the south-west coasts moved east and brought snow to the Bristol Channel areas during the period 22–25 January. Cardiff recorded 30 inches (76 cm) of level snow; Okehampton (Devon) reported a greater depth than at any time since 1895 but remarked that there was little drifting (Bonacina, 1950; Jackson, 1977).

1933. Snowfall, associated with a polar low which developed in St George's Channel and moved southwards, affected a wide area of England and Wales on 23–26 February. In South Wales the general depth of level snow was 1–2 feet (30–60 cm) with deep drifts (Bonacina, 1937).
1929. On 16 February heavy snowstorms occurred in west England and Wales. Cardiff had great difficulty in keeping the streets clear of snow. On Dartmoor it was estimated that up to six feet (180 cm) of snow fell in 15 hours. This is thought to be the deepest fall of snow in a single storm anywhere in the British Isles at so low an elevation as 1000 ft (300 m), but it cannot be classed as a blizzard as there was little wind at the time (Bonacina, 1937).
1927. Heavy snow over the Christmas period was accompanied by gale force north-easterly winds engendered by a depression in the western Channel. Drifts of 20 ft (6 m) were reported on Salisbury Plain and on Dartmoor the prison was unapproachable for days. On the south coast the effects of drifting were most striking; there were reports of snow being blown off the Isle of Wight over the sea. In terms of drifting this storm was comparable with those of 1881 and 1891 (Bonacina, 1937; Jackson, 1977; Douglas, 1928).
1891. From 9 to 13 March the 'great west country blizzard' affected the whole of the south of England and South Wales with areas of great intensity in Kent and in Devon and Cornwall. The average depth of snow in the south-west was reported as about 2 ft (60 cm) with immense drifts, and locally on Dartmoor this amount was doubled by a secondary outbreak of snow on 12 March. Great disruption to transport was caused, with many trains marooned and many ships sunk in the Channel. In those days drifts had to be cleared by manual labour, the railway gangers vying with each other to keep their own lines open. This blizzard was the result of waves developing on a cold front: one such low-pressure centre, on 9–10 March, deepened at Ushant and moved up the Channel, depositing snow in drifts with the strong east to north-east winds (Bonacina, 1928; Jackson, 1977; Symons, 1891; Shellard, 1968).
1881. The great blizzard of 18–21 January mainly affected the Wessex area, that is to say east Devon, Somerset, Dorset, Wiltshire and Hampshire. The Isle of Wight was particularly badly hit: 'the depth of snow which was doubled on 20th was about 3 feet with gigantic drifts'. A depression was centred near the Channel Islands on the 18th and moved steadily up Channel. The blizzard was described at the time as the worst since 1836 (Bonacina, 1928; Symons, 1891).

Figures 5 and 6 show the distribution of the maximum snowfall in 1881 and 1891 (Jackson, 1976).

7. Conclusion

The main features of the blizzard of February 1978 were the comparative shortness of the cold spell, the persistence of the snowfall in one area for two days, the severity of the drifting and the quickness of onset of both the snow and the thaw.

The snowfall was the heaviest to occur in the south-west for many years. The combination of so much snow with gales had not been experienced in Devon since 1927 and in south-west England and South Wales as a whole since 1891.

Of the eight outstanding storms in the south-west since 1850 the visitations of March 1891 and January 1881 seem to have been very similar in extent and severity to those of 1978. All three were the result of low-pressure centres in the western Channel.

Bonacina (1928) remarks that in the storms of 1881, 1891 and 1927 there were two phases to the snowfall with a gap of one or two days between, and although in each phase the depths were substantial it was the combination of the two falls which produced such outstanding conditions. This feature was present also in 1978; the snow on 15 and 16 February was followed by the main blizzard of 18–19 February which more than doubled the depths of snow and drifts in some areas.

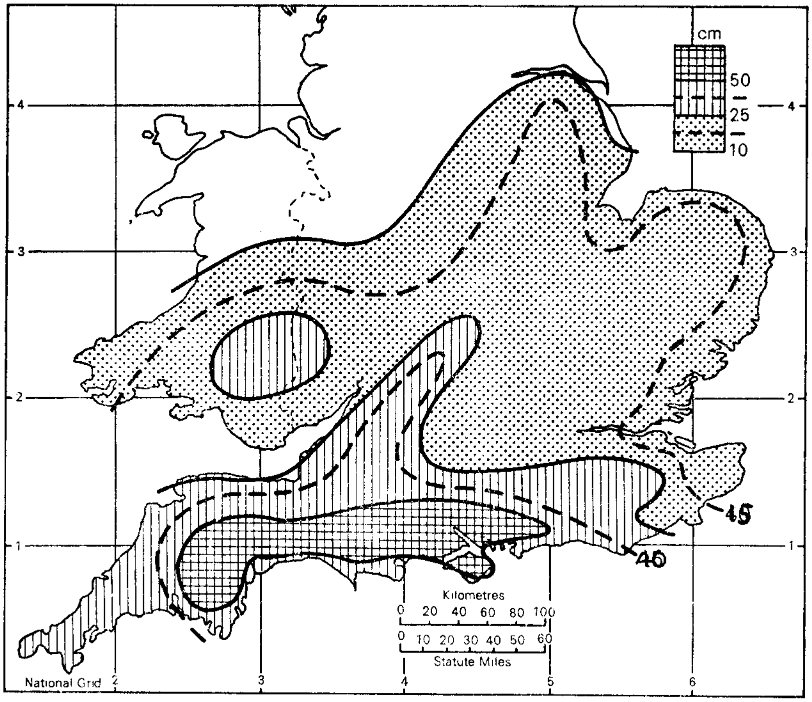

Figure 5. Maximum snow depths 17–21 January 1881.
(N.B. Correction: the '15' and '40' labels should be interchanged.)

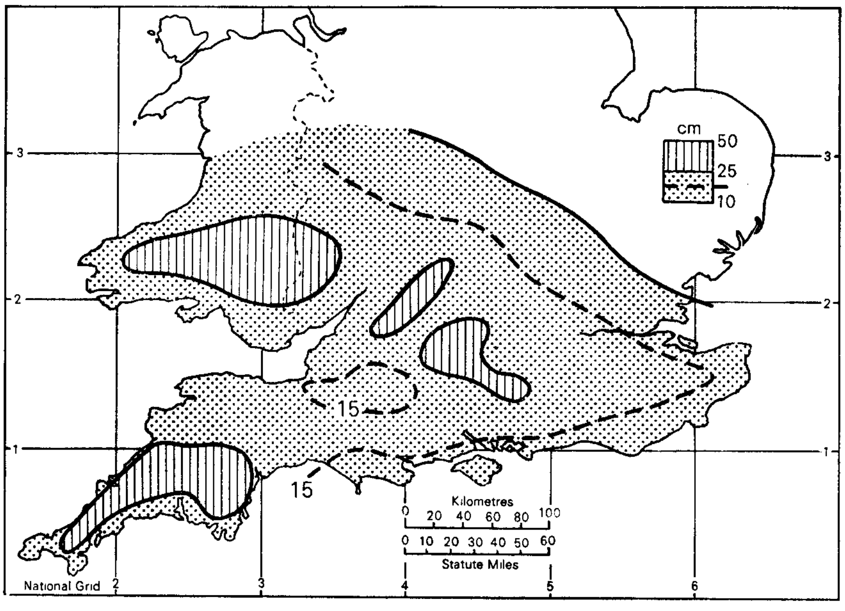

Figure 6. Maximum snow depths 9–13 March 1891.

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Notes and news

Dr P. M. A. Bourke

Dr P. M. Austin Bourke, Director of the Irish Meteorological Service since 1964, retired in May of last year. Apart from a few years as a university lecturer in mathematics, his career was spent entirely in the Irish Meteorological Service. He became well known for his work on agricultural meteorology and had regular close contact with Mr L. P. Smith and the Agricultural Meteorology section of the Meteorological Office; he preceded Mr Smith as president of the WMO Commission for Agricultural Meteorology, serving from 1958 to 1962.

Dr Bourke is highly regarded, not only for his intellectual ability, but also for his humour and charm which have enlivened many international meetings. We wish him well in his doubtless active retirement.

Obituary

We record with regret the death on 12 January 1979 of Miss C. A. Parkhouse, Assistant Scientific Officer, HQ Strike Command, after a brief illness. Miss Parkhouse joined the Office in August 1978.

Corrections

Meteorological Magazine, Volume 107, December 1978; article by J. P. Cowley. The unit used for Figure 5, pp. 366–372, is MJ m^{-2}.

Meteorological Magazine, Volume 108, January 1979; article by C. J. Richards. In the penultimate line of the caption to Figure 2, p. 14, 1970 should read 1976. In equation (10), p. 22, a fraction bar and a figure 2 have been omitted after the second square-root sign.

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NOTICES

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

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The First GARP Global Experiment

By A. Gilchrist

(Deputy Director, Dynamical Research, Meteorological Office, Bracknell)

For a number of years now we have been hearing about GATE, the international experiment conducted in the eastern tropical Atlantic during the summer of 1974. The contents of current scientific journals are evidence of the degree to which the initial aims of the experiment are being achieved for they contain a growing volume of research that is clarifying many of the most significant problems in tropical meteorology. Hard upon the heels of GATE comes a new experiment and a new acronym—this time it is FGGE, the First GARP Global Experiment. What is it all about and what does the Meteorological Office hope to get out of it?

Scientifically, interest in a Global Atmospheric Research Program stemmed from two technological developments—satellites and computers. The former brought the ability to monitor the global atmosphere continuously within grasp, and computers provided the means for digesting the colossal amounts of information involved and for using them for prediction. A global atmospheric program to exploit the scientific possibilities was attractive politically because it called for co-operation between nations for peaceful purposes to achieve worthwhile shared scientific aims. The potential benefits that might accrue from improved forecasts and better understanding of the atmosphere's general circulation were enormous and they would be available to all nations, not merely to those with advanced scientific capabilities.

As early as 1961, the General Assembly of the United Nations adopted the following resolution: 'Noting with gratification the progress for meteorological science and technology opened up by the advances in outer space and convinced of the world-wide benefits to be derived from international co-operation in weather research and analysis recommends . . . the early and comprehensive study of measures: (a) to advance the state of atmospheric science and technology . . . (b) to develop existing weather forecasting capabilities . . .'. In 1962, following a report submitted to it by WMO as a result of this resolution, the General Assembly recommended that the WMO should develop a more detailed plan for an expanded program in consultation with other United Nations Agencies and governmental and non-governmental organizations. In 1964, a WMO Advisory Committee and an ICSU/IUGG

Committee on Atmospheric Sciences were established in response to the UN action and they began the task of marshalling an international scientific effort aimed at solving some of the most pressing problems in meteorology. In 1966, the WMO Commission for Atmospheric Sciences recommended that 1972 should be designated a twelve-month period for intensive international study and analysis of the global circulation of the troposphere. They also proposed a series of supplementary studies aimed at understanding particular parts of the atmospheric system: these included studies in the tropics, the calculation of radiative transfers in the atmosphere and the investigation of air/earth exchange processes. The whole was to be called the Global Atmospheric Research Program or GARP.

It was soon evident that 1972 was a hopelessly optimistic date for a venture as large and novel as a global experiment. It would require careful planning and development of appropriate observing systems over a number of years, and furthermore there were good reasons why some of the supplementary investigations, particularly those concerning the nature of atmospheric developments in the tropics, should be completed before the main experiment. The methodology for preparing for the main FGGE was devolved to a Joint Co-ordinating Committee (JOC) for GARP, which was established in 1967 as a result of a formal agreement between WMO and ICSU. The Global Atmospheric Research Program was to be a program for studying those processes in the troposphere and stratosphere that are essential for an understanding of: (a) the transient behaviour of the atmosphere as manifested in the large-scale fluctuations which control changes of weather . . . and (b) the factors that determine the statistical properties of the general circulation of the atmosphere which would lead to a better understanding of the physical basis of climate. From the outset, the JOC has been active in promoting international co-operation in meteorology and in encouraging large-scale experiments to probe the outstanding problems which limit our understanding of the atmosphere. It saw clearly at an early date that one of its main aims must be the setting up of a global experiment, since so many of the questions concerning the predictability of the atmosphere required an input of observations on the global scale. As early as the second meeting proposals were put forward for a global experiment in 1974–75, but the need for tests of the proposed observing systems and further consideration of the detailed logistics have led to postponements to the present firm dates for the First GARP Global Experiment in 1979.

FGGE will involve the deployment of special observing systems to supplement the normal World Weather Watch. In addition to five geostationary satellites providing continuous cover of the whole of the Earth equatorwards of about 50–55° latitude and four polar orbiting satellites, special efforts are being made to supplement the observational data for a number of areas where the network is otherwise inadequate. Over the tropical oceans for example, ships (Tropical Wind Observing Ships, TWOS) and aircraft will be deployed to try to make good large blank areas in the conventional coverage. They will concentrate on the Special Observing Periods when it is expected that 40 or 50 ships and 5 or 6 aircraft flights will provide substantial additional data each day. In the tropics also, constant level balloons (TCLBs), up to 300 in number, will be released to float at about 46 000 ft. Their positions will be monitored, using satellites for communications, and winds will be derived. In the southern hemisphere, the great need is for observations over the southern oceans that will provide more surface observations to supplement the upper-air data obtained from satellites. In this instance, floating buoys, capable of transmitting surface pressure and temperature values back to satellites will be deployed. About 300 will be launched, and with a reasonable life-time, many may still be operating at the end of FGGE to feed additional data into the World Weather Watch network for some time thereafter. Special emphasis is being given to the program to collect as much information as possible from commercial aircraft flights. For example, arrangements have been made to use the Aircraft Integrated Data Systems (AIDS) in over 80 aircraft.

The opportunity to experiment with enhanced amounts of data on a global scale is one for which the Meteorological Office has been preparing for a number of years. There are, in particular, three questions we shall be endeavouring to answer:

(1) What analysis system should be used to make the optimum use of the data available?

(2) What is the operational benefit of each of the observing systems and, in particular, can we use FGGE to indicate what is the best mixture of observing systems to plan for in the future?

(3) What can we learn about the predictability of the atmosphere, and how can we use the information to improve forecasts for the British Isles?

The analysis procedures now used in CFO were designed a number of years ago and were suited to the observing systems that were then in operation. For analysis of upper-air charts, the methods assumed that the data came primarily from radiosonde observations, which take soundings through the atmosphere at fixed times and places. The number of soundings is comparatively small, and some areas, especially over the oceans, are thinly covered, but the observations are reliable and have rather small errors. An analysis system could therefore concentrate on providing the best possible fit to the synoptic observations for 00 GMT and 12 GMT. Also the system was based on an analysis of contour heights, winds being derived using the geostrophic or similar relation. It was not well suited to the incorporation of wind reports, especially when they were not accompanied by height information, nor did it aim to deal with tropical areas.

The assumptions on which the analysis system were based are becoming less and less valid. Nowadays there are a large number of observations-of-opportunity which are made as and when the particular observing system happens to be available. For example, there are more wind observations from aircraft which, with modern navigation and recording instruments, are more accurate than they were some years ago. Polar orbiting satellites give information about clouds and temperatures as and when they pass over the area concerned. On the other hand the number of radiosonde observations has decreased in some regions. Over and around the North Atlantic they are fewer and there may be difficulties in the future in maintaining even the present network. Both because the Meteorological Office is involved in supplying winds for long flights into or crossing the tropics and because we are aiming to provide forecasts for the British Isles for longer periods ahead our analyses need to cope with tropical conditions. A system that is partly based on geostrophic assumptions is clearly inappropriate for this.

The growing part played by aircraft, satellites and new observing devices in the observational system has led to a larger total volume of information about the atmosphere, but its characteristics are changing from those of a well-ordered, synoptic, rather accurate system to a more continuous but heterogeneous flow which is in general less accurate and less internally consistent. The data show more clustering in space around specific altitudes and geographical locations and can apply with more-or-less equal probability to any time of day. To deal with this situation requires a new approach to analysis, and poses difficult problems of interpretation which for the volume of data concerned can probably only be solved by systematic computer methods.

In the Meteorological Office an objective analysis scheme has been developed for use during FGGE. If it proves sufficiently successful it may indicate how the operational analysis system must also change in the future. Its characteristics can be summarized as follows:

(a) All observations of upper-air parameters, surface pressure and surface wind over the sea from whatever source can be made use of, irrespective of the method of observation or of the time of day at which they are made.

(b) Observations are, however, not treated equally. They are allocated weights depending on their likely statistically determined errors. For example, temperatures from radiosonde ascents are assumed to be more accurate in the troposphere than values derived from the inversion of satellite radiance measurements. The former are therefore given substantially more weight than the latter, but in areas where more accurate information is lacking satellite observations of temperature can nevertheless have a substantial impact.

(c) The observations are inserted into the forecast model during a forward integration, with a weight that starts from a small value $1\frac{1}{2}$ hours before the observation time, increases to a relative value of 1·0 at that time and decreases again to zero after $1\frac{1}{2}$ hours. In this way the model has time to adjust gradually to the data and there are hopes that this will eliminate the need for special initialization procedures such as have to be followed with the present operational model.

(d) The process of inserting observations leads to an immediate alteration in model values at a group of points surrounding the observation both vertically and horizontally. For instance, an observation of wind at one level causes consistent changes determined in a statistically optimum way at other levels and within a specified horizontal radius of influence. During the forward integration the influence of the observation spreads wider afield, and therefore during the three hour period of assimilation it is capable of influencing a substantial surrounding area.

The whole process can be envisaged as one in which at successive time-steps the model is nudged towards the observed values, but at no stage is it forced to fit them precisely. However, if the values are consistent among themselves and with the structures that the model can handle, the resulting analysis will be a good representation of them; if, on the other hand, the observations are in some way inconsistent the model will adjust to the nearest probable state and a certain amount of noise, which the model has to be capable of dealing with, will be created.

A test of this system on a global scale took place in CFO for one week during October 1978. Preliminary results are encouraging, and there is every reason to expect that the analysis scheme will be suitable for carrying out the further experiments that are planned for FGGE. Whether it can be adapted for operational purposes and so become the basis for a future system in CFO depends on the outcome of these experiments.

The availability of an advanced and flexible analysis scheme that can deal with all kinds of observations is a prerequisite for investigating the second main topic. The analysis scheme has been developed from one that was originally produced for the purpose of carrying out a series of Observation System Simulation Experiments (OSSEs) which were asked for by the JOC to help in their planning of FGGE. The idea was that one could use the results of a general circulation integration as though it represented the real atmosphere, and a second different model as though it were a forecasting model. By deriving 'observations' from the first model and feeding them into the second, run in forecast–analysis mode, one could then see how closely the second model could be persuaded to follow the developments in the first. By changing the assumptions about the observations available, a number of possible global observing systems could be simulated, and some idea obtained about what observations are required to reach any specified error level. The advantage in comparison with similar experiments involving the real atmosphere is that for the general circulation model, we know what is happening at every point and are not frustrated in our attempts to determine the adequacy of an observing system by a lack of knowledge. Before FGGE the experiments were carried out using an 11-layer model with a 220 km grid to represent the real atmosphere and a 5-layer model with a 330 km grid to represent the forecasting model. During FGGE itself, the OSSEs will become Observation System Experiments, in which the general principle will be the same but the roles of the 11- and 5-layer models will be taken over by, respectively, the real atmosphere and the 11-layer model. This will enable us to examine the utility of particular kinds of observation. For example, it will be possible to remove temperature soundings from satellites and repeat the analyses and forecasts to determine by how much they are degraded. The question of estimating the importance of weather ships or aircraft in the global observing systems is another that might be usefully looked at in this way. What is proposed therefore is a natural extension of the work that was carried out before FGGE and one of the aims will be to see how well the information that was given to the JOC then stands up to critical evaluation. This in turn will provide us with useful data about the performance of the general circulation models that have been developed over the last decade or so.

The third question is concerned with improving the numerical forecasts used within the Meteorological Office and is of course part of a continuing commitment that occupies a substantial part of the effort of the Operational Computer Analysis and Forecasting section and the Forecasting Research Branch (Met O 2b and Met O 11). The particular questions that one hopes will be helped particularly by the enhanced observing systems available during FGGE are those that arise regarding the area the operational forecast model should cover to serve the Office requirements as well as possible. It is already clear, for example, that the area of the 10-level operational forecasting model is too small for some purposes. With a boundary at around 15°N, it fails to cope with some of the long flights now being undertaken by large aircraft. Also we are aware that there are occasions when the influence of motions near or outside the boundaries substantially influence middle latitudes within a few days and certainly within the period for which we wish to produce numerical forecasts. There is therefore a real need to deal with a larger area, but how large should it be? Experiments have shown that it is not advisable to place the boundary at or near the equator since then the Hadley cell which is driven by low-latitude heating is grossly distorted; also at most times of the year there are substantial cross-equatorial flows which may extend into subtropical latitudes. There are probably good reasons therefore if we wish to have a forecast that is valid over the northern hemisphere why the boundary should be placed well into the southern hemisphere, probably at a latitude which can be considered from a meteorological point of view to be quiet at most times of the year. A global coverage of data will enable us to consider these matters more effectively than in the past, in order to reach a decision taking account both of the scientific advantages of extending the area and of the computational disadvantage of so doing.

In the longer term there are other investigations that will use FGGE data. Concerning predictability, for example, it is well known that the present level of forecast success is well below that indicated as possible by theoretical experiments. Why this is so is undoubtedly a very complex matter involving a number of factors. The shortcomings in the models themselves is certainly one of the most significant. However, it is important to try to find out how the level of forecast achievement is affected by uncertainties in the initial state of the atmosphere, and while FGGE will certainly not resolve this problem completely it will provide the best data yet available for investigating the question.

Two other areas of activity within the Meteorological Office that will greatly benefit from the intense observational activity during FGGE are the study of the general circulation of the atmosphere, and the verification of the simulations of climate. Concerning the first, the data available for describing the atmospheric circulation in the greater part of the northern hemisphere are, despite some shortcomings, reasonably complete, but in the tropics and in the southern hemisphere, they are far from adequate. The possibility of examining the southern hemispheric motions and of comparing the hemispheres in greater detail will be a most valuable opportunity for increasing our understanding of the global atmospheric system.

It is not at first obvious that FGGE has much to do with climate or climatic change. However, considering that within the annual cycle and over the surface of the globe a very wide range of climates is represented and further that what we are most interested in is a physical description of how these climates are created (rather than a descriptive account of what they are, though this of course is a necessary preliminary) it is evident that the potential of FGGE for improving our knowledge of climate and of the factors that might cause climatic change is substantial. Investigations to exploit the FGGE data for this purpose are likely to be an important part of the work on climate in the Dynamical Climatology Branch (Met O 20) for some years.

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The northerly gales of 11–12 January 1978

By E. G. E. King
(Meteorological Office, Bracknell)

Summary
Synoptic reports and anemograph records of the gales were analysed. None of the recorded gust speeds exceeded the values currently used in building design. Mean wind speeds were recorded which are likely to be exceeded only once in 50 years. The strongest northerly winds occurred in eastern England, especially on and near the coast.

Introduction

The storm of 11–12 January 1978 was immediately recognized as a rare event by people in east coast districts whose homes were inundated by the sea. The northerly gale that accompanied the flooding also caused a good deal of structural damage in inland districts, and it was the wind damage that led to this examination of the gales. The main object was to find out how the wind speeds that occurred were related to the existing published values of extreme wind speed which are used by architects and engineers in the design of buildings and other structures.

1. Synoptic situation

A low centred near Lincolnshire in the early morning of 11 January 1978 moved across the North Sea and was over the Continent by midnight (Figure 1). Strong south-westerly winds associated with the deepening of this depression during the night 10th–11th affected Wales, south-west England and the English Channel. By early morning on the 11th these south-westerly winds had decreased, and northerly gales had already started in Shetland. After 03 GMT the surface pressure rose by 7–8 mb each three hours in the Hebrides until 15 GMT, and this large and sustained pressure rise resulted in a very strong geostrophic wind from about 030°, with little curvature of the isobars (Figure 2). East Scotland, north-east England, much of southern England, and south-east England were in turn affected, as the greatest pressure rises migrated south-eastwards across south-west Scotland and the Irish Sea to southern England. Geostrophic winds measured 90–100 knots over north-east England from 15 to 21 GMT, over central southern England at 18 GMT and over south-east England at midnight and 03 GMT on the 12th.

With the continuing rise of pressure in the north-west, the horizontal gradient of surface pressure was increasing quickly, so that the geostrophic approximation was not valid, and the so-called isallobaric wind—the ageostrophic term which quantifies the effect of the changing pressure pattern—could not be ignored. The isallobaric wind was calculated as 30–35 kn from 310–340° over extensive areas south-east of a line Lincoln–Bournemouth from 15 to 21 GMT (Figure 3). While isallobaric winds over 30 kn are not particularly unusual it seems probable that only rarely would they occur over such large areas. If an isallobaric wind of 335° 35 kn is added as a vector to a geostrophic measurement of 030° 100 kn (for example, north of London at 18 GMT) the resultant is 015° 125 kn, and this may be the best estimate of the strongest winds in the free air over south-east England that evening. However, the isallobaric vector as a component of the upper wind has not been confirmed, either in the original work on isallobaric effects (Brunt and Douglas, 1928) or subsequently. In this instance also, the reality of the 125 kn estimate cannot be verified. The only independent evaluation of the free air movement is that obtained by radar-following of balloon-borne reflectors, and these

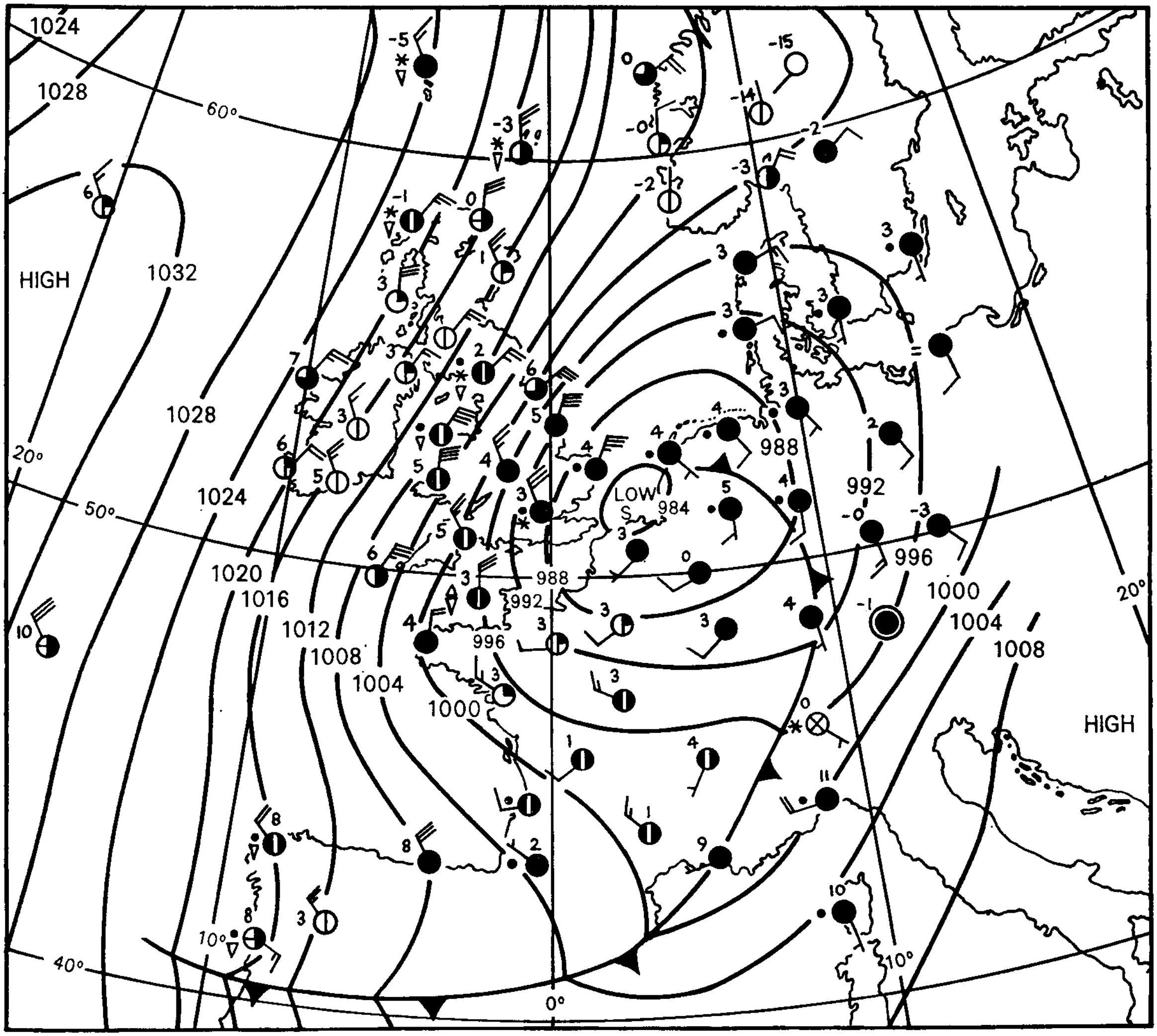

Figure 1. Synoptic situation at 18 GMT on 11 January 1978.

routine radar measurements did not coincide with the strongest geostrophic wind measurements. Disregarding the possible isallobaric contribution, therefore, it is presumed that the free air winds are indicated by the geostrophic measurements, and these were over 100 kn in some places.

2. Synoptic reports

In synoptic reports from hourly charts, very strong northerly winds (nominally 10-minute mean speeds) were reported extensively over the North Sea and the Channel. Mean winds over 57 kn were reported at Ballycastle (Co. Antrim), Gorleston (Norfolk), St Abbs Head (Borders) and The Needles

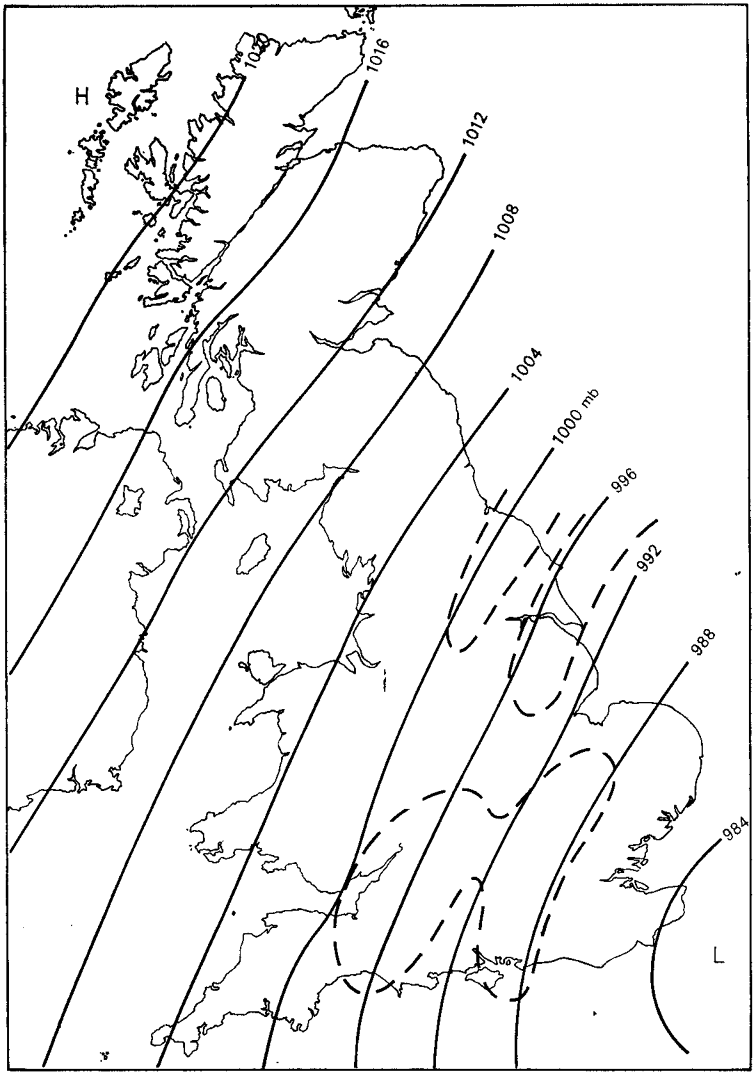

Figure 2. Mean-sea-level pressure at 18 GMT on 11 January 1978. Dashed lines are isotachs of the 90 knot geostrophic wind.

(Isle of Wight). Mean winds over 47 kn were reported for 11 hours at Flamborough Head (Humberside) and 12 hours at St Margaret's (Kent); these two sets of measurements were obtained with hand-held anemometers, the other stations having permanently installed eye-reading cup anemometers or (at Gorleston) an anemograph.

Synoptic reports from inland stations included measurements of 40 kn at Yeovilton (Somerset), Binbrook (Lincs.), Cardington (Beds.), Wyton (Cambs.) and Wattisham (Suffolk). Inland stations reporting 30 kn or more were mostly east of a line Newcastle upon Tyne–Exeter, and these strong winds persisted for 12 hours in some places, especially in the more eastern counties.

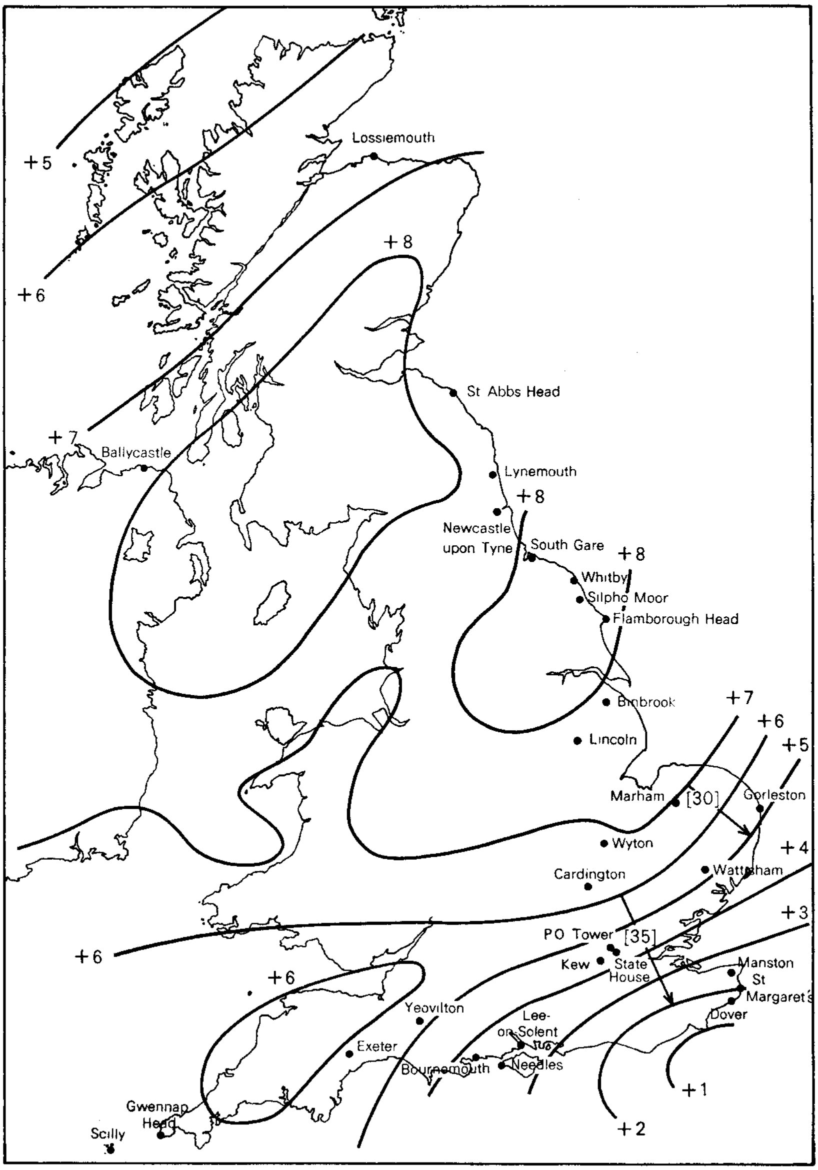

Figure 3. Isallobars at 18 GMT on 11 January 1978. Isopleths show pressure changes in millibars between 15 and 18 GMT. The arrowed lines with figures in square brackets indicate the isallobaric wind in knots.

Too much reliance should not be placed on mean wind speeds in synoptic reports because they are often only eye estimates made from a fluctuating pointer of a wind speed indicator, and tend to err on the high side. A gust speed is often included in the synoptic report and this is usually the highest instantaneous reading of a wind-speed dial; if the dial is not under observation when the highest gust occurs the true maximum gust speed will be higher than the gust speed reported. This does not apply, of course, to a station which has the benefit of an anemograph. Some coastal stations experience wind flows that may be considerably accelerated by a cliff or exposed hill: gusts of 82 kn reported at Whitby and St Abbs Head probably fall into this category. The extreme mean and gust speeds at any station may of course have occurred in the breaks between the synoptic reports. However, even with all these inadequacies it is clear from the synoptic reports that the main impact of the gales was felt in the east and south-east of the country.

3. Anemograph records

The only continuous wind records are from the anemograph charts. Special reports for 11–12 January were received from 136 anemograph stations in the United Kingdom. In north-east Scotland the strongest gusts occurred before midday whereas in central southern England they came about 12 hours later.

Gust speeds of 60 kn or more were recorded at points on the coast (predominantly the east coast) from Lossiemouth to Scilly (Figure 4) and at some places inland in south Scotland, north-east England, Lincolnshire, East Anglia and London. Gusts of 70 kn or more were recorded at Lynemouth (Northumberland), South Gare (Cleveland), Silpho Moor (North Yorks.), Gorleston, Manston (Kent), Dover, and Gwennap Head (near Land's End), all on the coast; the only inland stations to record 70 kn gusts were Kew, London Weather Centre (State House) and the Post Office Tower.

Hourly mean speeds of 40 kn or more were recorded at points on the coast from Orkney to Land's End, again predominantly in the east (Figure 5). The highest hourly mean speed recorded, 53 kn, was at Gorleston.

Even in the areas of strongest winds, however, many places had speeds no greater than would occur in the normal run of winter gales; at Heathrow Airport, only 10 km from Kew, for instance, the highest gust was 54 knots.

4. Return periods

One measure of the severity of a gale is the 'return period' of the wind speed recorded. This is the statistically estimated number of years in which a given speed will be equalled or exceeded only once. In reality it may be equalled or exceeded more than once or not at all, but once is the most probable outcome. The speeds (at 10 m) which have a return period of 10, 20, 50, 100 or 120 years have been calculated (Hardman, Helliwell and Hopkins, 1973) for 142 anemograph stations and are listed in Climatological Memorandum No. 50A (CM 50A). Those stations which on 11–12 January recorded speeds within a few knots of their 50-year-return-period value are shown in Table I, and the return periods of these speeds, inferred from CM 50A, are given. Stations not listed in CM 50A were compared with stations in the same region for which CM 50A does give details. The anemometers are at different effective heights, and for the comparison the recorded speeds were reduced to a common effective height of 10 m, using the usual relationship

$$\frac{V}{V_{10}} = \left(\frac{h}{10}\right)^{\alpha},$$

the exponent α being taken as 0·17 for mean speeds and 0·085 for gust speeds.

The return periods estimated from station data in CM 50A confirm that the gales were more significant on the east and south-east coasts and in the London area than elsewhere. As is emphasized in CM 50A, the computed extremes for individual stations should be used with caution; since the

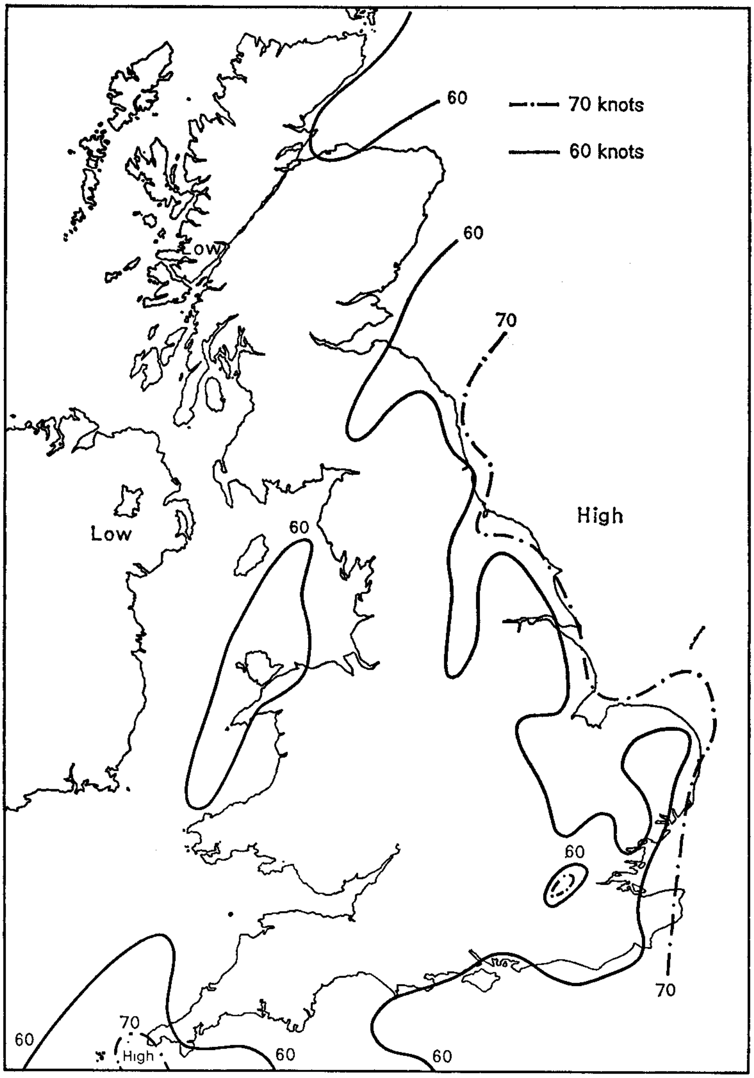

Figure 4. Maximum gust speeds for 11–12 January 1978 deduced from anemograph records.

difference between a once-in-20-years speed and a once-in-50-years speed is often only 2 kn, a rather wide tolerance must be accorded to any return period estimated from an individual station's records.

The outstanding return period for gust speed is that for **Kew**; using CM 50A the 70-kn gust would have been estimated as a once-in-70-years event but it is now estimated to be a once-in-35-years event (see Appendix). In central London a gust of 71 kn was recorded at **State House** (effective height 38 m) and this is estimated as a once-in-30-years event (see Appendix).

At **Gorleston** a gust of 74 kn was recorded. By comparison with CM 50A this would have a return period of 20–50 years. However, a 74 kn gust occurred in 1976 also, after the CM 50A table

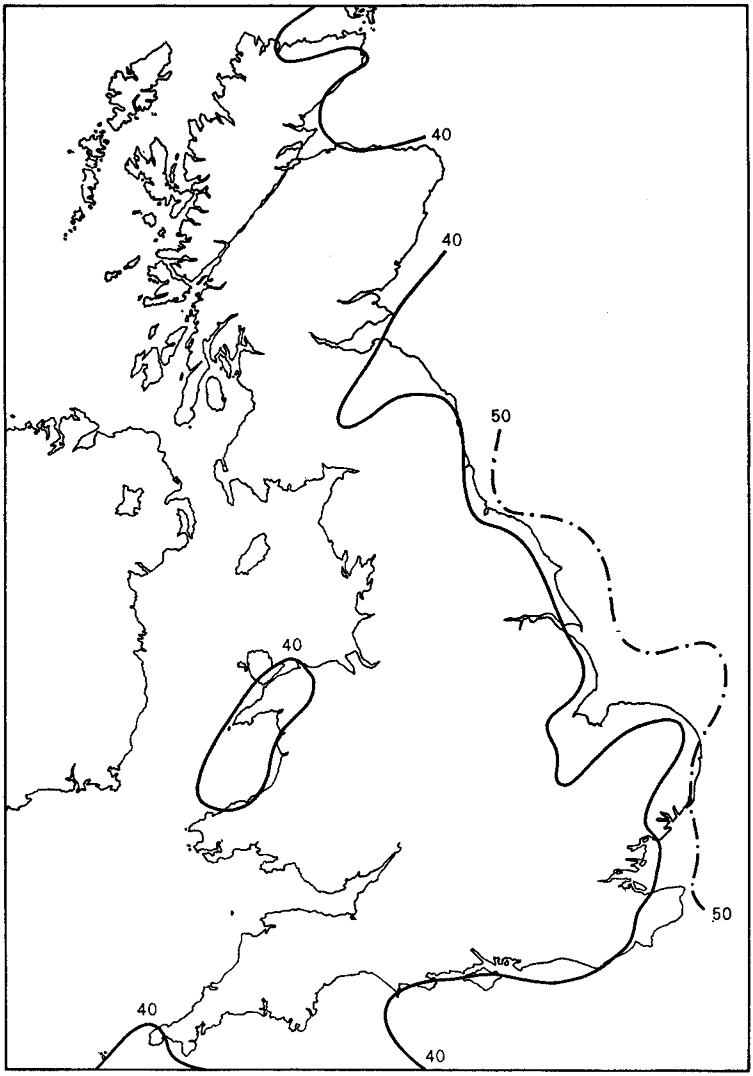

Figure 5. Maximum hourly mean wind speeds (knots) for 11–12 January 1978 deduced from anemograph records.

was compiled. It is not possible to make a reliable new estimate, as was done for Kew, because of numerous breaks in the long-period record, but it would seem prudent to regard this 74 kn event as having a return period close to 20 years.

The sustained very high speeds, rather than the gust speeds, were the main feature of this storm. The outstanding return periods for hourly mean speed were 100 years at State House (estimated from 13 years' annual maxima by comparing them with Kew's long-period record, as described in the Appendix), and 100 years at Gorleston (from records spanning 50 years but with some breaks). Return periods of 50 years were estimated for Marham (Norfolk), Manston and Dover. Furthermore, strong winds from the northerly quadrant are several times less common than strong winds from the south and west. An extreme-value analysis of winds at Kew from different directions based on the 20 years 1957–76 shows a 30 kn hourly wind speed to have a return period of 85 years for northerly winds (Figure 6), 80 years for easterlies, 20 years for westerlies and 10 years for southerlies. This is consistent with the all-directions return period of <10 years obtained from CM 50A.

Table I. *Anemograph stations—high values*

		Maximum gust speed			Maximum hourly mean speed		
	Effective height *metres*	Obs. *knots*	Reduced to 10 m *knots*	Return period *years*	Obs. *knots*	Reduced to 10 m *knots*	Return period *years*
Lynemouth	10	71	71	15	33	33	<10
South Gare	15	72	70	10	51	48	15
Silpho Moor	9	71	71	15	27	27	<10
Marham	10	61	61	<10	38	38	50
Gorleston	13	74	72	20	53	51	100
Wattisham	10	66	66	10	39	39	10
Cardington	41	67	59	<10	46	36	<10
Manston	18	72	68	10	48	43	50
Dover	18	71	68	10	47	43	50
Lee-on-Solent	12	64	63	10	36	35	<10
London							
State House	38	71	63	30	41	33	100
Kew	15	70	68	35	30	28	<10*

* N.B. Return period of *northerly* winds with mean hourly speed 30 kn at Kew is 85 years.

5. Design winds

All the gust speeds recorded on 11–12 January fall below the Basic Wind Speed for design purposes obtained from the map in the British Standards Institution Code of Practice C.P.3; that is to say, all the gusts recorded were less than the 50-year return period values on which the map is based. Hence no change in the design values in the map or in Table I of the Code of Practice is called for by this later knowledge. The map value of 37 m/s (72 kn) for the Kew area, apparently a rather high value when set against the Kew records up to 1971, is justified by the more recent events.

6. Conclusion

The northerly gales of 11–12 January 1978 were not of special significance in the north and west of the United Kingdom; their greatest effect was in the counties bordering the North Sea from Northumberland to Kent and in part of the London area.

Mean winds or gusts of exceptional strength occurred in several places on the east coast and in a narrow belt across the London area. Generally the hourly mean speeds were statistically more significant than the gusts, and at Gorleston and London Weather Centre the hourly mean wind reached speeds likely to be exceeded only once in 100 years. Probably at many more places the speeds recorded were unusually strong for a northerly wind, as was the case at Kew.

The long-term frequency of strong gusts at Kew (all directions) has been reassessed. No amendments are required in the wind-loading Code of Practice, however.

Winds in the free air at times exceeded 100 knots, and may have reached 125 knots in one or two places in south and east England.

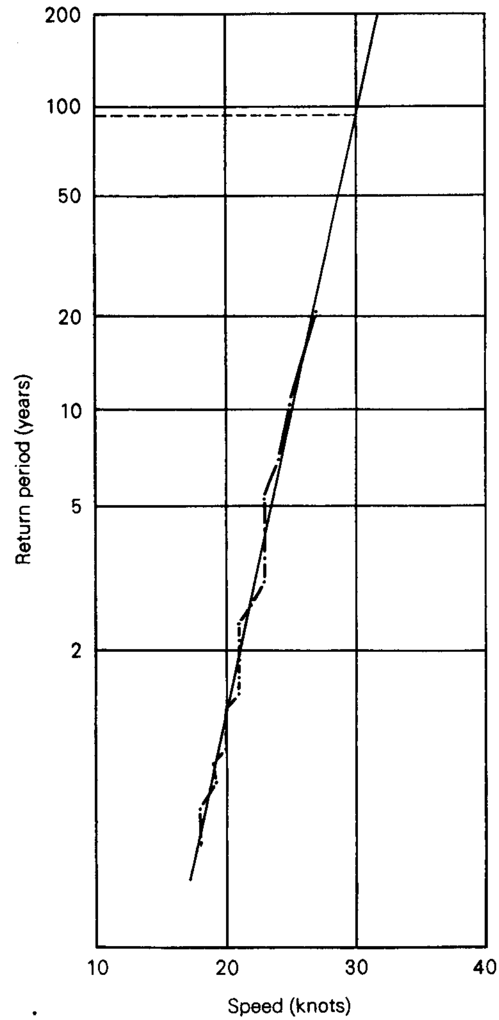

Figure 6. Maximum annual hourly wind speed at Kew (northerly winds, quadrant 320°–040°) at effective height of 15 metres, 1957–76.

Acknowledgements

Thanks are due to the Director of the Building Research Establishment, Department of the Environment (which financed this study) for permission to publish the results. The valuable advice given by Mr R. H. Collingbourne and the co-operation of Mr H. G. Hills and other colleagues is much appreciated.

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Brunt, Sir David and Douglas, C. K. M.	1928	The modification of the strophic balance for changing pressure distribution and its effect on rainfall. *Mem R Meteorol Soc,* **3,** No. 22.
Hardman, Carol E., Helliwell, N. C. and Hopkins, J. S.	1973	Extreme winds over the United Kingdom for periods ending 1971. London, Meteorological Office, *Climatological Memorandum* No. 50A.

APPENDIX

Return periods of strong winds at Kew and State House

The pressure-tube anemograph at Kew Observatory recorded a gust of 70 knots at 1809 GMT on the 11th. This station has now had a continuous high-quality record in a 'suburban' situation with no local changes of exposure or instrument for 47 years. The return periods quoted in Climatological Memorandum No. 50A (when a 41 years' record was to hand) should therefore have been a very close approach to reality, and the strongest gust in the 41 years up to 1971 was 63 kn in 1947 (Figure A1, *A*). Since 1971, however, four large annual maxima have occurred:

1974	78 kn
1976	69 kn
1977	66 kn
and now 1978	70 kn (Figure A2).

This sequence of extreme gust speeds is unique to Kew: no other station in these years experienced so many or such large departures from its historical pattern. With this later information a 70 kn gust (at 15 m effective height) at Kew can no longer be taken as a once-in-70-years event. A new estimate of return period has been made by the Gumbel procedure using all data now available, including the 70 kn gust of 11 January 1978. In the initial analysis the 78 kn value of 1974 produced a distortion in the plot of speed versus probability (Figure A1, *B*), but a very good fit was obtained by excluding this extreme figure and analysing the remaining years (Figure A1, *C*). The 78 kn gust then appeared as a once-in-200-years event. The autographic record and a verbal description of this 78 kn gust suggested a tornado as the cause, and this would in fact be an exceedingly rare occurrence at any one place. In Table A1 are the revised values for Kew reduced to effective height 10 m for comparison with the CM 50A values: the new once-in-50-years gust speed is 69 kn. The revised estimate of return period for a 70 kn gust at 15 m (equivalent to 68 kn at 10 m) is 35 years.

The electrical anemograph at State House in High Holborn recorded a 71 kn gust at 1809 GMT. A Gumbel analysis of the 13 years' data now available gives an estimated return period of 17 years, but these 13 years include the noticeably windier years (at Kew) 1974 and 1976. A preferred alternative approach was to compare the 1965–77 period at State House (38 m) with Kew (15 m), but excluding 1974 as before. The total of annual maximum gust speeds at State House was expressed as a percentage of the total of annual maximum gust speeds at Kew, and this percentage was then applied to the speeds in a revised frequency table for Kew (15 m) to obtain speeds (at 38 m) for State House for various return periods: these are in Table A2. This would give an estimated return period of 30 years for a 71 kn gust. Knowledge of wind flows over cities is scanty, so that these speeds and return periods can only be tentative, and no equivalent speeds for 10 m above ground can be given.

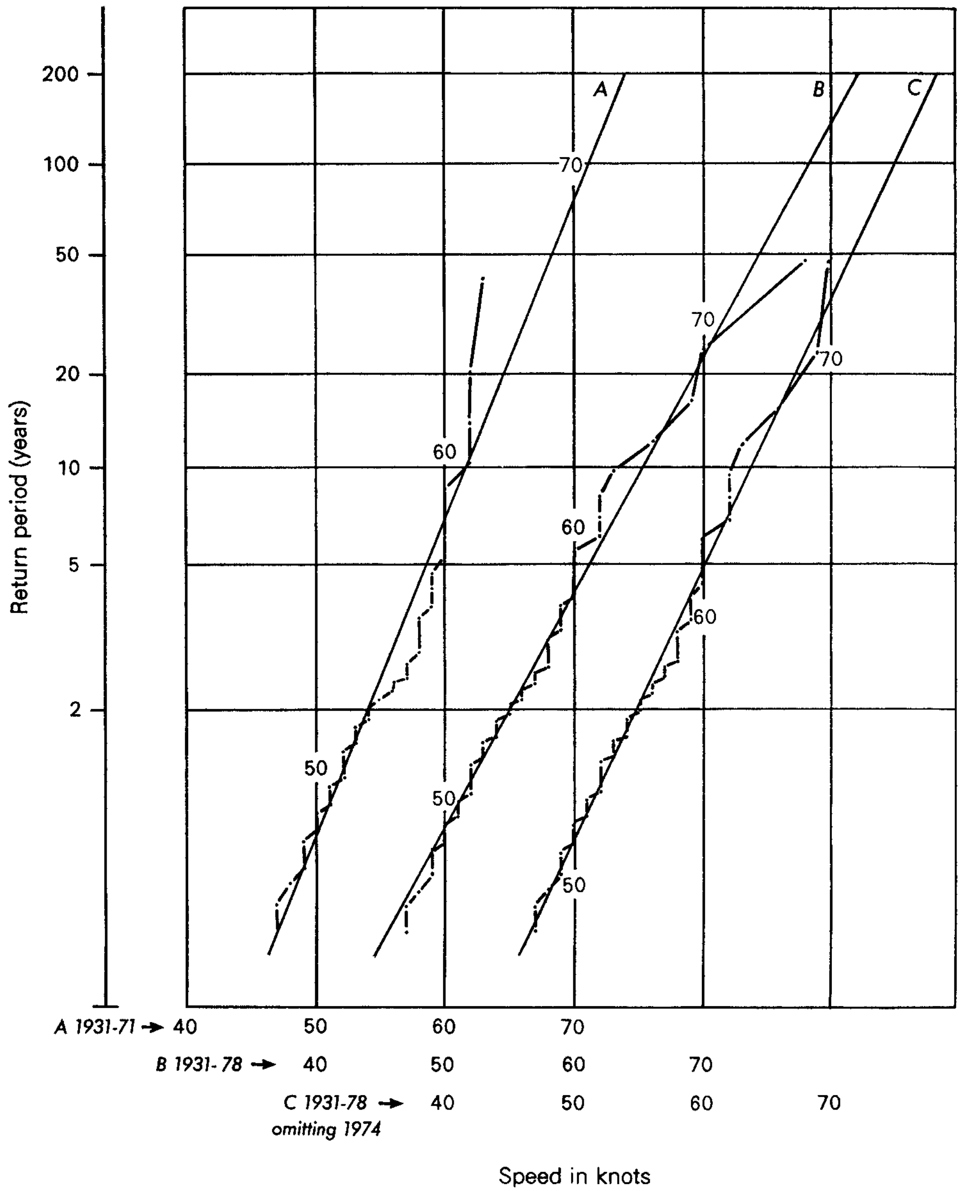

Figure A1. Annual maximum gusts at Kew at effective height of 15 metres.

Table A1. *Variation of gust speed with return period at KEW**

Return period (years)	1†	10	20	50	100	120
			knots			
Gust speed (revised)	53·7	62	65	69	72	73
Gust speed (from CM 50A)	52·8	60	62	66	70	72

* At standardized height of 10 m.
† Corresponds to average annual maximum.

Table A2. *Variation of gust speed with return period at STATE HOUSE, LONDON**

Return period (years)	1†	10	20	50	100	120
Gust speed (knots)	57·4	66	69	74	77	78

* At effective height 38 m: reduction to 10 m standard height not practicable, see Appendix to CM 50A.
† Corresponds to average annual maximum.

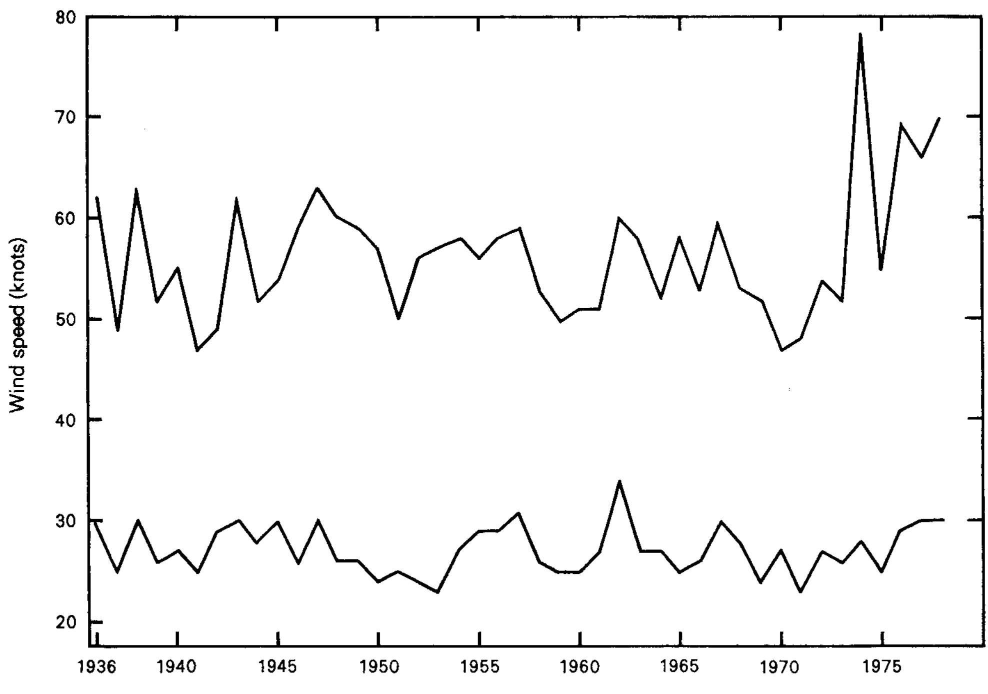

Figure A2. Annual maximum gusts and maximum hourly mean wind speeds at Kew.

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The storm surge of 11–12 January 1978

By Lt Cdr J. Townsend
(Storm Tide Warning Service, Meteorological Office, Bracknell)

Summary

An account is given of the storm surge of 11–12 January 1978, the worst since that of January 1953. The meteorological situation is described and the actual tidal residuals are compared with the forecasts made by the Storm Tide Warning Service. Forecasts were very satisfactory at four of the five 'reference ports'.

Introduction

The storm surge of 11–12 January 1978 has been described as the worst since 1953, and that with some justification: tidal levels on the north-east coast of England near the Humber Estuary were higher than those of 31 January 1953, approximating to the very high levels of 28 September 1969, and while levels in the Thames Estuary were not as great as in 1953, they equalled those of 10 December 1965, the last occasion on which flooding occurred in central London.

The following table compares the levels reached on this occasion at the five East Coast ports used as 'reference ports' for tidal warnings, with the levels reached with other major tides since 1953. Tidal heights are given in metres above Ordnance Datum (Newlyn).

Reference port	31 Jan.–1 Feb. 1953	28–29 Sept. 1969	3 Jan. 1976	11–12 Jan. 1978
North Shields	3·57 m	3·57 m	3·43 m	3·50 m
Immingham	4·51 m	4·69 m	4·60 m	4·67 m
Lowestoft	3·35 m	2·56 m	2·73 m	2·37 m
Walton*	3·99 m (Harwich)	2·96 m (Harwich)	3·08 m	—
Southend	4·60 m	3·60 m	3·50 m	4·18 m

The towns worst affected by the tide of 11–12 January 1978 were Cleethorpes on Humberside, King's Lynn and Wisbech near the Wash, and Deal in Kent.

At Cleethorpes the number of houses affected by flooding was variously reported as 500 to 1000, and 20 families were evacuated from their homes. The railway line from Grimsby to Cleethorpes was damaged. An audience of 150 people, which included aged, disabled, and children, who had been watching a performance of a pantomime in the pier theatre, found that they could not leave because the pedestrian walkway had been damaged, and had to return to the auditorium for three or four hours until rescued.

At King's Lynn, a two-mile belt near the River Ouse was flooded to a depth of up to 4 feet, affecting 400 houses. Twenty-two children had to be evacuated from the children's ward of the hospital. Many parts of the town were affected by electricity failures.

At Wisbech, where the River Nene overflowed its banks, 700 people were evacuated, and 300 houses left empty—subsequently, there were reports of looting from the empty houses. A 70-year old woman was found drowned in her front lounge which was flooded to a depth of 3 feet.

Parts of Boston, Lincs., were flooded to 3 feet; at Wells-Next-the-Sea a 300 ton coaster from the Medway was washed up on the quayside.

(* Up to late 1969, Harwich, not Walton-on-the-Naze, was the reference port for the Essex and Kent coasts.)

At Herne Bay in Kent, boats and the wreckage of beach huts were washed up on to the street. Parts of Sheerness were flooded to 5 feet.

Several piers were badly damaged, the 150-year old pier at Margate being destroyed and the lifeboat station at the pier end left isolated. Much of the piers at Skegness, and at Hunstanton in Norfolk, was washed away, and the piers at Clacton, Walton and Herne Bay also suffered damage. The tide gauges on Margate and Walton piers were put out of action (this accounts for the blank in the table above).

The cause of the surge, which coincided with a Spring Tide, was a depression over the Dutch coast which established a strong north-north-easterly gale in the North Sea.

Meteorological situation

The development of the meteorological situation is shown in the accompanying Figures 1–4.

Figure 1 shows the situation at noon on 10 January. Depressions were centred off the south-east coast of Iceland and off the northern coast of Norway, and to the south of these a westerly airstream covered the British Isles. In this westerly airstream, a small wave depression had formed at 54°N, 15°W, and this moved east, deepening as it came. Meanwhile, the depression off south-east Iceland was moving south-east, to reach 59°N, 12°W by midnight; at this time the wave depression had reached Anglesey, so that an area of low pressure covered north-west Britain (Figure 2). The low-pressure area continued to move eastwards, and at 0600 GMT on 11 January, a deep depression was centred near the Wash (Figure 3). This moved south-east to the Dutch coast during the following 12 hours (Figure 4). As a result a strong north-east gradient (geostrophic winds around 030° 60 knots), affected the western half of the North Sea from about noon on the 11th to 0600 on the 12th.

Storm surge

Figure 5 shows the tidal 'residuals' (difference between actual and predicted* tides for Stornoway and various East Coast ports).

No appreciable positive surge occurred at the Scottish ports—only a small persistent residual of around 0·2 metre throughout 10 January, attributable to the low pressure. As the northerly winds became established on the west coast of Scotland, a marked 'negative' surge (levels below predictions) developed at Stornoway and progressed to Wick.

The north to north-east gradient became established in the northern part of the North Sea early on the 11th, and extended to the remainder of the North Sea coast during the day as the depression moved from the Wash to the Dutch coast. The peak of the resulting surge occurred somewhat after the time of the evening High Water on the 11th.

At North Shields, the surge peak occurred at 2000, with a level 0·75 m above prediction. High Water, 3 hours earlier, had been 0·69 m higher than predicted.

At Immingham the 1930 High Water was 0·96 m above the predicted value, and levels reached a value of 1·37 m above prediction at 0200. At estuarial ports, a fall in the surge is commonly observed at the time of High Water, but on this occasion it was almost absent at Immingham.

Immingham is the 'reference port' for the stretch of coast known as 'Division Two' in tidal warnings, the stretch from the North Yorkshire border to North Norfolk. With the north-east gradient, surge

* The terms 'predicted tide' and 'prediction' are used here and elsewhere in this paper to denote the tides expected from astronomical considerations only, i.e. those given in published tide-tables.

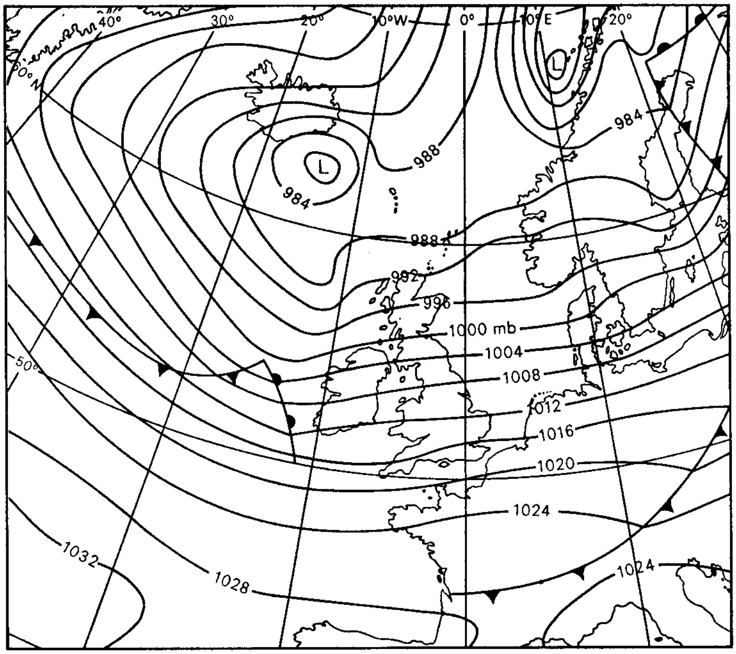

Figure 1. Synoptic situation at 12 GMT on 10 January 1978.

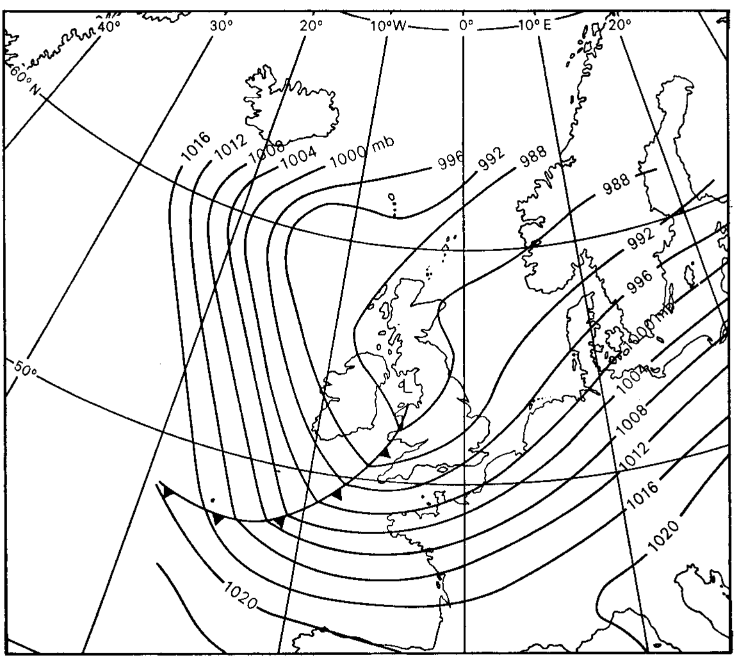

Figure 2. Synoptic situation at 00 GMT on 11 January 1978.

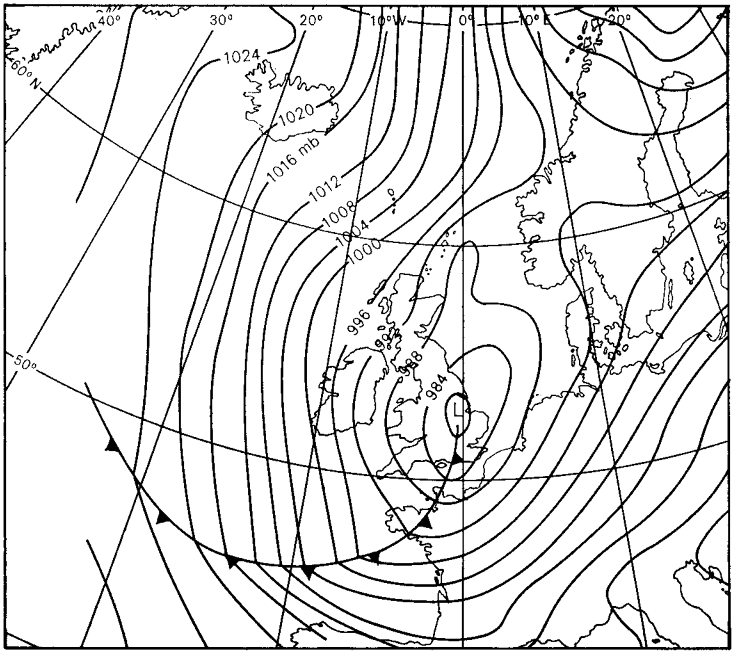

Figure 3. Synoptic situation at 06 GMT on 11 January 1978.

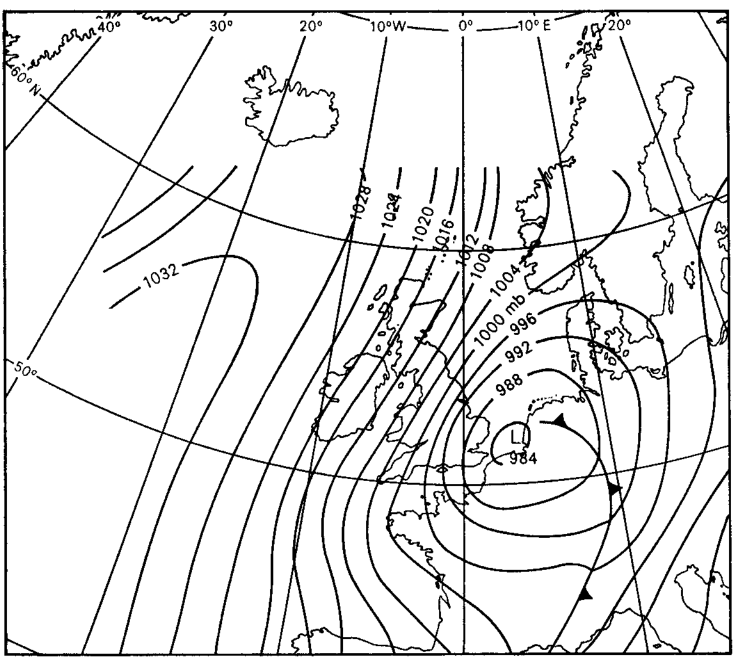

Figure 4. Synoptic situation at 18 GMT on 11 January 1978.

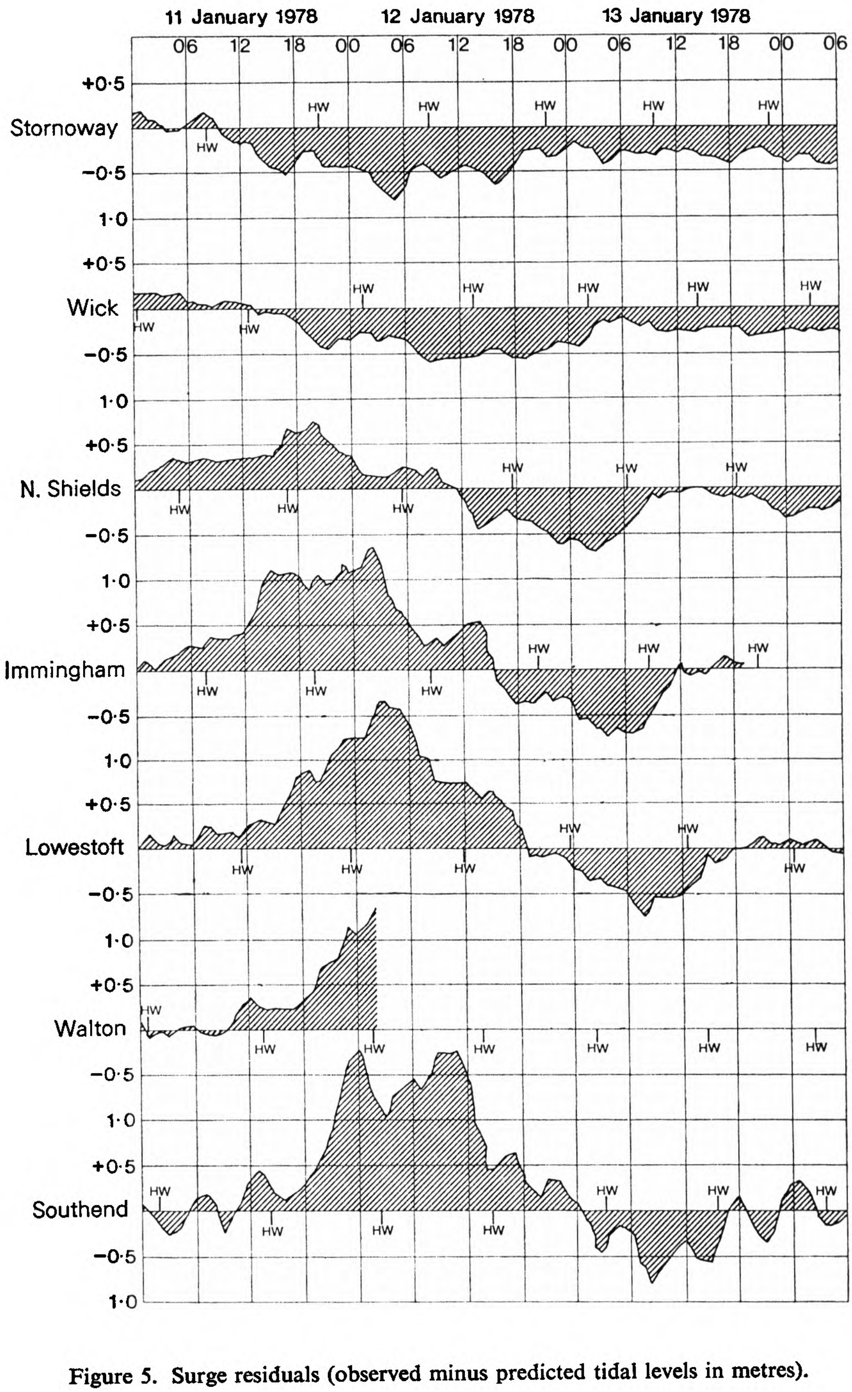

Figure 5. Surge residuals (observed minus predicted tidal levels in metres).

levels in the southern part of the Division were considerably higher than in the northern part: at King's Lynn the High Water was 1·49 m above its predicted value, and at Wells 1·8 m above prediction.

At Lowestoft, High Water was 1·21 m higher than predicted: the greatest difference between observed and predicted levels was 1·63 metres at 0300.

At Walton, where the pier was damaged, the tide gauge went out of action at just about the time of High Water—levels were then about 1·3 m above prediction.

At Southend, the usual drop in residuals at the time of High Water, due to surge–tide interaction, was well marked; the surge rose to a peak of 1·78 m at midnight, fell away to 1·04 m at 0200 (High Water) and rose again to a second peak of 1·76 m at 1000.

As Figure 5 shows, this positive surge was followed by a negative surge. By midday on 12 January, the depression had moved from the Dutch coast into North Germany, and a ridge of high pressure lay across Ireland and Scotland. As this swung south-east across England, winds in the northern part of the North Sea backed round to west. With the relaxation of the north-easterly gradient, the negative surge which had been affecting the Scottish coast advanced down the east coast of England (probably emphasized by an oscillation of the surface following the large positive surge). Tidal levels at North Shields reached 0·7 m below prediction at 0230 on the 13th, at Immingham at 0530, and at Lowestoft at 0800, and at Southend the levels fell to 0·8 m below prediction at 0800.

Forecasting the surge

Issuing flood warnings is the task of the Storm Tide Warning Service, a small unit housed in the main Meteorological Office at Bracknell and staffed by the Hydrographic Department of the Navy. Heights of High Water at the five 'reference ports' are calculated using empirical equations in which the parameters are tidal levels at more northerly ports (where H.W. occurs earlier) and winds in various parts of the North Sea. A first calculation is made 12 hours before High Water, and if the result is close to or above Danger Level, a preliminary 'Alert' is issued. A second calculation is made 4 to 6 hours before High Water and if it still indicates that Danger Level will be passed, a Danger Warning is sent stating by how much the predicted tide will be exceeded. In borderline cases, where the calculated height is close to Danger Level and it cannot be stated with certainty whether the Danger Level will be passed or not, the second warning is worded 'Alert Confirmed'. Root-mean-square errors of the empirical equations used are of the order of 0·2 or 0·3 m (which implies occasional errors of three times as much).

(During the recent (1978–79) winter, trials are being made of a mathematical model technique for forecasting surge heights.)

On this occasion, the calculated heights were very satisfactory except at North Shields, where the final calculation underestimated the height by about 0·4 m. Here, an 'Alert Confirmed' warning was issued; elsewhere 'Danger' warnings were sent. The forecasts are tabulated on the facing page.

At 2300, a further calculation was made of the level expected at Southend, based on the observed level of High Water at Lowestoft. This gave an improved result of 4·12 m, which was passed to the Greater London Council for use in the London Flood Warning System. On the strength of this, the preliminary warnings that they had passed to the local boroughs could be cancelled.

In view of the considerable difference in surge size between Immingham, the reference port of Division Two, and King's Lynn and Wells in the south of that division on this occasion, the practice has since been adopted of quoting High Water heights for King's Lynn and Wells as well as for Immingham in Division Two Danger Warnings.

Port	Predicted H.W.	Observed ht of H.W.	'ALERT' sent	Calculated ht at Alert	Final Warning	Final calc. height
North Shields	11th 1652 2·81 m	3·50 m	0635	3·56 m	1315 ALERT CONFIRMED	3·12 m
Immingham	11th 1928 3·71 m	4·67 m	0625	4·86 m	1318 DANGER 0·84 m above predicted	4·55 m
Lowestoft	11th 2308 1·16 m	2·37 m	1150	2·58 m	1810 DANGER 1·18 m above predicted	2·34 m
Walton	12th 0127 2·25 m	—	1320	3·26 m	2048 DANGER 1·2 m above predicted	3·46 m
Southend	12th 0219 3·14 m	4·18 m	1320	4·46 m	2048 DANGER 1·2 m above predicted	4·33 m

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The International Conference on Meteorology and Oceanography in The Hague

By R. M. Morris
(London Weather Centre)

An international conference on meteorology and oceanography applied to the engineering, installation and operation of offshore structures was held in The Hague on 31 October and 1 November 1978. The conference was organized by the Society for Underwater Technology, the Royal Meteorological Society and the division for underwater technology of the Royal Institution of Engineers in the Netherlands in conjunction with the Netherlands Council for Oceanology. The conference was attended by about 200 people from a wide range of disciplines, including environmental modellers and offshore operators as well as meteorologists and oceanographers; the program was divided into four sessions each concerned with a different aspect of environmental data.

The first session dealt with data requirements and the specific demands of the offshore industry and there were five presentations roughly equally divided between operational and design requirements. The operational aspects included the use of wind, sea state (including wave spectra) and pressure, temperature and ocean current data for activities involving helicopters, supply boats, cranes, tankers, derrick barges, diving and towages. The raw data have to be processed on board using mini-computers which calculate the characteristics and limitations of the equipment under the given weather conditions. The value of and need for accurate forecasts of wind and sea-state parameters was clearly brought out. In particular Captain Mervyn Jones of Noble Denton Associates underlined how important it is during special operations to have a weather forecaster close at hand to give up-to-the-minute advice. The value of weather forecasts to salvage operations was shown dramatically in a film presented by the BV Bureau Wigsmuller who successfully salvaged a tanker in the English Channel over a three-month winter period.

The data requirements for design purposes were presented in some detail by an engineer, Dr J. H. Vugts of Shell International. The engineer is concerned with maximum loads on the foundations, extreme loads on the superstructures and fatigue in relation to the distribution of load. The three major factors influencing design are wind, ocean currents and waves but Dr Vugts pointed out that long-term statistical distributions of these parameters would not necessarily provide sufficient information. The dynamical nature of the environment is very important and so the second-order interrelationships between these parameters may be more significant. A practical example of designing an offshore structure was presented by Dr B. J. J. Van der Pot of Delta Marine Consultants, Rijswijk who described the design of the Dunlin A platform. The problem of resonance associated with a particular wave period and height was especially interesting and in order to determine optimum location of loadings, directional wave data were needed.

In summing up the first session, the Chairman emphasized both the interest in obtaining accurate weather forecasts for offshore operations and the design requirement for sequential analyses of directional wave spectra. The second session was concerned with the gathering of data. The session began with three presentations on different data buoys. EMI described the design and deployment of the U.K. national data buoy DB1 which is located 280 km from Land's End on the south-west edge of the continental shelf in a water depth of 170 m. Under contract to the UKOOA Oceanographic Committee for collection of (initially) one year's data, the buoy had recorded and transmitted data satisfactorily since early summer but it was recognized that it had not yet experienced severe weather conditions. Marex then gave a description of their own data buoy which has been deployed in many world-wide locations. There was some reference to the Marex buoy deployed near Foula west of Shetland where both the original buoy and replacement had suffered damage in these very hostile waters with a considerable loss of data over a period of some two years. Although that performance was clearly unsatisfactory, there was unfortunately no evidence yet to suggest that DB1, for example, would perform any better in such severe weather. A major advantage with DB1, however, is the facility to transmit real-time data every hour to a land station which permits a constant monitoring of the system and the build-up of a secondary data bank. Information on a new lightweight buoy, called DABS 3M, was given by the British Aerospace Dynamics Group from Hatfield, and it was a pity that this presentation was so dull. This buoy appeared to have most of the qualities of DB1, also a capacity for recording and limited processing on board and an ability to transmit to a shore base using HF or VHF radio. The buoy is not expected to be ready for trials until summer 1979 at the earliest but a major attraction will undoubtedly be its cheapness compared to DB1. A presentation by Dr R. E. W. Pettifer described the Meteorological Office involvement with data acquisition offshore including the installation of automatic weather stations on data buoys as well as on remote islands and platforms. These systems include micro-processors and transmit real-time data to a shore base.

Following the presentations on buoys, emphasis switched to the sensors themselves. The basic requirements of the meteorological sensors including robustness and an ability to withstand severe exposure were stressed by Dr D. N. Axford of the Meteorological Office. Display boards, recorders and communications were discussed and also the need for routine maintenance and regular calibrations to ensure quality and reliability. Whilst the requirement for real-time observations was re-emphasized it was also pointed out that offshore observers should be properly trained to observe in accordance with internationally agreed standard procedures.

Oceanographic sensors were described by Mr E. G. Pitt of the Institute of Oceanographic Sciences. After a brief description of the basic wave theory, wave rider buoys were described in great technical detail, mostly without illustration. Several promising projects were outlined including those involving ocean currents. The use of radar to observe waves was described by M. A. Fontanel of the Institut Français du Petrole. The technique is still developmental and uses the Doppler shift principle in the micro-wave region. The radar operates from shore using HF and has 200 km range with a seven degree angular spread. Experiments so far indicate a good correlation between the wind and wave directions. It is planned to experiment next spring off the Atlantic coast of France. The session was completed by a description of the role and purpose of the Meteosat satellite given by Mr P. Berlin of the European Space Operations Centre in Darmstadt. Among the uses of Meteosat is the facility to relay observations from platforms to a land-based receiving station. In view of the length of message transmitted by Meteosat, it appears that the system is ideal for relaying a large network of observations.

Summarizing the second session, the Chairman, Mr G. Larminie of BP Environmental Control Centre said it appeared that the meteorologists and oceanographers knew what they wanted in data collections but he wondered whether the offshore industry knew what it wanted. There was an increasing emphasis on the need for real-time data, particularly as the industry moved from the exploration to the production phase. My own reaction to a long and arduous session was that there was a vast amount of information crammed into a relatively small amount of time. Inevitably there was some overlapping and common ground largely because competitive systems were being described. This may have been the only way the organizers could be fair to the designers but it was rather hard going for the conference as a whole.

The third session, on data management, was chaired by Dr B. J. Mason, Director-General of the Meteorological Office. Mr E. J. English of Meteorological and Plotting Services began by emphasizing the importance of quality control of the observational data and he compared visual observations with automatic observations such as those recorded by data buoys. Several systems of checking were described including internal consistency, time series, ranges and, most important, the operational quality control exercised by the human analyst using his charts in real time. Finally the need to specify the format and content of data files was stressed because the data would in many instances be made available to users other than those who collected and originally processed the data. An example of the use of offshore data collected by a close network was presented by Mr C. Van der Burgt of the Dutch Public Works Deparment. Strictly this exercise is concerned with predicting the onset of flooding in the Netherlands and data gathered from the automatic stations offshore in the southern North Sea are vitally important to the operation of storm surge barriers. The conference was then given an insight into the work of WMO in organizing the first GARP global experiment (FGGE) scheduled for 1979. Unfortunately this presentation was not particularly well done and the visual aids were poor. The question was raised of how quickly improvements could be expected in long-range forecasting after FGGE. The view was that it would take several years.

The importance of establishing an adequate data base was the main theme in a presentation by Mr D. J. Painting of the Meteorological Office. It was argued that there were insufficient data for fixed offshore locations in areas of special interest; these are necessary for example to determine the probability of exceeding certain thresholds or to calculate extreme values. Fortunately there exists another source of data namely the ships of the world's voluntary observing fleets (VOF) whose synoptic observations have been used for weather analysis during the past 100 years. These data have been checked and then stored by the Meteorological Office in a marine data bank, which now contains some 3 million observations from the continental shelf around the U.K. as well as 40 million observations from other parts of the world. Confidence in the reliability of the VOF data was greatly strengthened by a comparison of the measured wind data from OWS 'K' (1962–75) with the VOF data for the same area and period. The profiles of frequency distribution of wind speeds were almost identical. Despite some doubts being expressed concerning the quality of the VOF wind data in more northern waters, Mr Painting resolutely stated his belief that the VOF data are good and represent a very sound data base from which the offshore designers and operators could extract much profitable information. This session concluded with a presentation on extreme wave heights in Norwegian waters by Professor O. G. Houmb from the Division of Port and Ocean Engineering at the University of Trondheim. The longest series of data available were visual observations and hindcast studies based on them; these covered some 30 years, whereas there are less than 10 years of instrumental data. It was therefore concluded that the most reliable estimates of extreme heights are those based upon hindcast data.

The third session was probably the most stimulating and interesting, mainly because of the variety of presentations on different aspects of data management. Certainly Mr Painting's presentation generated much interest and many enquiries long after the conference closed.

The fourth and final session was essentially concerned with the application of data for use in offshore operations. A presentation by Mr H. D. Barnard of Phillips Petroleum purported to show how knowledge of the local site wind and sea state climatology could help an offshore drilling supervisor to interpret his daily weather forecasts. The presentation was handicapped by the fact that the visual aids were virtually invisible to the audience but the gist of the theme seemed to be that if the forecast values approached the extreme values determined by climatology, drilling activity should cease. This was followed by a presentation from Mr D. F. Bertonneau of Ocean-Routes who deviated from his synopsis to deliver a sales talk on the virtues of Ocean-Routes services to offshore operations. There was a useful description of how spectral wave data could be applied to determining the relative response characteristic of barges, ships and semi-submersibles by calculating heave, pitch and roll. This presentation brought comment from the floor to the effect that none of the response characteristics would be adequately determined without calculation of tidal surge. Commander A. Wood of Sea and Storm Service Specialists Ltd, then spoke about uses of satellite data for offshore forecasting, but his talk was considerably shorter than scheduled and bore no relation to the impressive synopsis in print; the presentation consisted almost entirely of a series of satellite cloud pictures and was devoid of explanation as to how meteorologists incorporate satellite data into their routine synoptic analyses. From this presentation the conference could be excused for thinking that weather forecasters had not made any significant advances using this powerful extension to their resources.

The session was completed by two fairly light-hearted presentations. Professor H. O. Mertins of the Seewetteramt of the Deutscher Wetterdienst in Hamburg described the routeing of a delicate cargo across the Baltic and finally Mr D. M. Houghton of the Meteorological Office spoke about the prospects for long-range prediction up to six months ahead. There was a good illustration of the variability of climate over decades, emphasizing the need for long-period samples of data. The importance of the tropical oceans as storehouses of energy was brought out with a striking illustration of the variability of cloud cover from year to year within the tropics. After the presentation of some figures of success rate for seasonal forecasts the talk concluded with a forecast for Europe during the coming November.

To sum up, there is no doubt that the conference as a whole was highly successful in that most people connected with the offshore industry learnt a great deal during the two days. There was a clear invitation for the Meteorological Office to demonstrate to the industry how efficiently it is geared up to support the daily operational activities offshore and increasing interest is being shown in verification of forecast accuracy. The great interest in the marine data bank could precipitate a major increase in the number and complexity of climatological enquiries from the designers and planners. One was also left in no doubt that if the Meteorological Office does not meet the needs of the offshore industry, commercial services will be quick to make the attempt.

Letter to the Editor

Tornadoes and the cold front of 3 January 1978

I was interested by Mr L. G. Chorley's synoptic analysis of the weather in eastern England on 3 January 1978 with its particular reference to the tornado at Newmarket (Chorley 1978). In his last paragraph the author states that 'the only tornadoes reported on 3 January 1978 were those at Hull and Newmarket'. In fact, at least ten damaging tornadoes have been reported to the Tornado and Storm Research Organisation (TORRO) for the same morning in eastern England. From the times of occurrence of these tornadoes and the nature of the eye-witness and press accounts, there is no doubt that these tornadoes were associated with the same line-squall/cold-front system which Chorley described. Full details have been given elsewhere (Meaden 1978). The places affected include the following: Wold Newton, NGR TA 0473, at 0640 GMT; Holme-on-Spalding Moor, SE 8238; Hull, TA 1030 at 0710; Aldbrough, TA 2438; Withernsea, TA 3428, at 0715; Scunthorpe, SE 8911; South Reston, TG 4084; Tattershall, TG 0755, at 0755; Ringsfield, TM 4088 (near Beccles); and Newmarket, TL 6363, at 0920 GMT. The overall path length is known to exceed 50 kilometres. The severest of the tornadoes was the Newmarket one; its strength on the TORRO intensity scale (Meaden 1976) was force 5–6 (Buller 1978, Meaden 1978). The other tornadoes were rated at TORRO force 1–3.

The frequency of occurrence of damaging tornadoes in Britain is much greater than is generally recognized. For the 16-year period 1963–78, over 335 have been listed by the Tornado and Storm Research Organisation; 1974 and 1975 were the peak years with 52 each. Many of the tornadoes were associated with cold fronts, several of the occasions being multiple events, as on 3 January 1978, with tornadoes breaking out at intervals all along the front or nearby squall line.

G. T. Meaden

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Wiltshire.

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Buller, P. S. J. 1978 Damage caused by the Newmarket tornado, 3 January 1978. *J Meteorol, Trowbridge*, 3, 229–231.

Chorley, L. G. 1978 The Newmarket tornado of 3 January 1978. *Meteorol Mag*, **107**, 308–313.

Meaden, G. T. 1976 Tornadoes in Britain: their intensities and distribution in space and time. *J Meteorol, Trowbridge*, 1, 242–251.

Meaden, G. T. 1978 Tornadoes in Eastern England on 3 January 1978. *J Meteorol, Trowbridge*, 3, 225–229.

[Mr Chorley informs us that the tornadoes at Hull and Newmarket were the only ones known to him at the time of writing and the only two widely reported in the national press, although he realized that others might well have occurred in the conditions prevailing at the time. We are grateful to Dr Meaden for drawing our attention to the reports collected by his Tornado and Storm Research Organisation; his conclusions agree well with those of Lamb (1957)*: Editor.]

* Lamb, H. H. 1957 Tornadoes in England, May 21st 1950. *Geophys Mem* No. 99 (Vol. XII).

Reviews

Remote sensing of the atmosphere: inversion methods and applications (*Developments in Atmospheric Science 9*), edited by Alain L. Fymat and Vladimir E. Zuev. 245 mm × 165 mm, pp. xvi + 327, *illus.*, Elsevier Scientific Publishing Company, Amsterdam and New York, 1978. Price US $54.75, Dfl 123.00, £36.70.

This ninth volume in the series 'Developments in Atmospheric Science' is devoted to publishing a selection of papers presented at conference sessions entitled 'Remote sensing of the atmosphere: inversion methods and applications'. These sessions organized by the editors Fymat and Zuev took place in Seattle in late August 1977 as part of the Second Special Assembly of IAMAP (International Association of Meteorology and Atmospheric Physics).

There are three sections each containing eight or nine specialist papers covering temperature sounding, composition sounding and particulate sounding. Each paper is distinct and only loosely related to the other papers in the same section; there is no discussion of the papers. As such the selection of papers represents some details of particular problems of interest to the authors, and airs a sample of current topics in remote sensing. This volume is not, and has no pretensions to be, a definitive review of atmospheric sensing. This book is one that appeals primarily to specialist research workers in the retrieval field, and as such is certainly worthy of inspection.

In a review intended for readers of the *Meteorological Magazine*, I will mention some of the more general papers on applications which have a significant meteorological content. In the temperature sounding section probably two out of the eight papers are of general interest. Halem, Ghil and Atlas describe a four-dimensional assimilation method for including satellite data in a combined analysis and forecast scheme, and demonstrate some improvement in a 48–72 hour forecast as a result. They also include a useful discussion of comparison criteria. McMillin discusses retrieval errors in cloudy situations for the National Environmental Satellite Service temperature retrieval scheme and indicates that 'lack' of effect, on analysis schemes, of satellite data is due to rejection of data in the meteorologically interesting but cloudy areas.

The composition sounding section mainly airs the problems of using 'limb sounding' data, particularly with reference to NIMBUS 6 LRIR (limb radiance inversion radiometer), and the retrieval of ozone and water vapour profiles.

In the particulate sounding section, the major contribution is two papers by Fymat on detailed aspects of Mie scattering and the experimental accuracy required to retrieve the size distribution and the complex refractive index of atmospheric aerosols. Of more direct meteorological interest is McCleese's paper on 'Remote sensing of cloud properties from NIMBUS 5'. He describes with examples the retrieval, from the NIMBUS 5 Selective Chopper Radiometer, of cloud top heights for opaque clouds, and cloud parameters of height, thickness and particle size for cirrus clouds.

An author index, which includes a citation index, and a useful subject index complete the volume.

D. R. Pick

The Australian climatic environment, by E. Linacre and J. Hobbs, 245 mm × 190 mm, pp. x + 354, *illus.*, John Wiley & Sons, Milton, Queensland, Australia, 1977. Price A$15.50.

The title of this book is a little misleading. It is really a well-designed, well-produced, and—on the whole—well written introductory text-book of meteorology and climatology with its illustrative examples drawn from the southern hemisphere in general and Australia in particular. The intended readership consists of 'school teachers, tertiary students who are taking geography or meteorology courses, and . . . the intelligent layman'. The main text is divided into five parts, each with about five chapters, entitled 'Energy Flows in the Atmosphere', 'The Cycle of Water Movement', 'Winds and Weather', 'Climates', and 'Applied Climatology'. There are two more parts: 'Additional Information' and 'Tests'..

The treatment is deliberately non-mathematical and a praiseworthy and largely successful attempt is made to convey the fundamental physical ideas underlying complicated processes. When such processes are not yet fully understood—for example in the separation of electrical charge in a cumulonimbus cloud—the reader is not misled into believing that they are, but plausible explanations get a fair mention.

Now and again, however, particularly in the section dealing with dynamical meteorology ('Meteorological Concepts')—why is the word concept so dreadfully over-used today, by the way?—simplification degenerates into error. For example: 'Wind following a curved path around either a high or a low is called a gradient wind, differing from the geostrophic wind because of the centrifugal effect' (p. 121); 'Winds are driven by pressure differences between various parts of an approximately horizontal layer of the atmosphere. In practice, the two driving forces combine to create the observed wind. The component due to the temperature difference is called the thermal wind and is a hypothetical wind, not measurable.' (p. 123). No mention is made at all of geopotential in the discussion of 'thickness' which is defined purely in terms of geometric height. The English is occasionally slovenly: on page 229 reference is made to 'the dividend of height to mass', meaning the ratio of height to mass, or the quotient of height by mass. These are, however, minor blemishes.

The diagrams are well chosen, clear and informative, and are largely derived from other, duly acknowledged, sources. (The registration of the overlays in Fig. 8.8. has, however, gone sadly awry.)

Part VI—'Additional Information'—contains useful physical constants, tables of data, meteorological symbols, a list of further reading and the bibliography. Part VII—'Tests'—contains essay questions, numerical examples, and a set of self-assessment tests comprising 20 questions for each chapter; these latter showed up several lacunae in the reviewer's knowledge.

At A$15.50 the book is better value than many.

R. P. W. Lewis

Notes and news

Snow Survey of Great Britain

These reports contain monthly descriptions and tables of snowfall in Great Britain, especially in the highland areas during the snow season from October to May, and are normally published in December each year. The Report for 1977/78 is now available from Meteorological Office Met O 3(b), London Road, Bracknell, Berks. RG12 2SZ at a price of £2 (post free), or a three-year advance subscription is offered at £5. Copies of the 1976/77 Report are still available at a price of £2 and limited numbers of the Reports for 1971/72 to 1975/76 are also available at a price of £1 per copy.

Award

The University of Manchester Institute of Science and Technology is to confer its highest honour, Honorary Fellowship, on Dr B. J. Mason, C.B., F.R.S., the Director-General of the Meteorological Office, at a ceremony to be held on 25 July 1979.

Correction

Meteorological Magazine, Volume 108, February 1979; article by A. Gilchrist. The patterns of isobars in Figures 3 and 4 should be transposed.

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NOTICES

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

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The FRONTIERS plan: a strategy for using radar and satellite imagery for very-short-range precipitation forecasting*

By K. A. Browning, F.R.S.

(Meteorological Office Radar Research Laboratory, Royal Signals and Radar Establishment, Malvern)

Summary

The FRONTIERS program described in this article addresses the problem of analysing and forecasting the detailed pattern of precipitation over the period 0–6 hours ahead. The acronym FRONTIERS embodies the following key elements: Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite. In this program we adopt a whole-system design approach, with digital data handling all the way from the observational input to the disseminated forecast product. We also emphasize the crucial role of human judgement which is required to make up for the limitations of the observational data and the incompleteness of our understanding on the mesoscale. In the plan discussed here the data from a network of radars and a geostationary satellite are composited on an interactive video display and the forecaster does his analysis and forecasting by modifying what is on the television screen whilst preserving the basic data in store. The resulting screenful of digital information can then be tailored and disseminated promptly to users without further manual effort. Although the emphasis in this paper is on the accurate analysis of current weather and extrapolation of current trends, these methods must be considered in the context of an eventual forecast system incorporating a mesoscale numerical model.

Introduction

The progress in synoptic-scale weather forecasting brought about during the past two decades by developments in numerical–dynamical methods has not been matched by progress in forecasting for the period from 0 to 6 hours ahead. Nowhere has this lack of improvement been more evident than in the case of precipitation. One of the main difficulties has been the lack of suitable observational data on the mesoscale. However, many meteorologists have for a long time had a vision of radar and satellite data doing for very-short-range forecasts what radiosonde data have enabled numerical–dynamical models to achieve on the larger scales. The time is now ripe for this dream to be turned into a reality, and in this paper we describe a specific strategy for generating very-short-range forecasts of precipitation in the United Kingdom. The strategy will be implemented as part of the Short Period Weather Forecasting Pilot Project which began in 1978 (Browning 1977). The aims of this project are to lay the foundations for improved very-short-range forecasts by setting up new observing and data-handling facilities, developing analysis and forecasting techniques and increasing our fundamental understanding of mesoscale weather systems.

* This article is part of a longer report, *Meteorological Office Radar Research Laboratory Research Report*, No. 11, January 1979, by K. A. Browning, C. G. Collier and P. Menmuir, a copy of which is held in the National Meteorological Library, Bracknell.

Radar and satellite data have already been used semi-operationally for subjective forecasting (nowcasting) 0 to 6 h ahead (e.g. Scofield and Weiss 1977). Objective extrapolation of radar data has been employed semi-operationally by Bellon and Austin (1978). Our plan calls for the use of radar and satellite information as a merged whole, with all-digital data handling from data input through to final dissemination of the forecast product; the plan also calls for the use of objective extrapolation procedures. However, a further crucial ingredient is a large degree of man–computer interaction in both analysis and forecasting, exploiting the video display techniques pioneered by V. Suomi's group at the University of Wisconsin. The name FRONTIERS applied to our plan incorporates the key elements of the program, namely: Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite.

Although the emphasis in the FRONTIERS program is on the accurate analysis of current weather and the extrapolation of current trends as identified by radar and satellite, these methods must be considered as part of a total system such as that depicted in Figure 1 (Kreitzberg 1976). The part of the system dealt with in this paper (see the dashed rectangle in Figure 1) will eventually be linked to a new generation of mesoscale numerical weather prediction models (Carpenter *et al.* 1978). This linkage will need to be a two-way process, with simple very-short-range forecasts generated by extrapolating the radar-cum-satellite data being modified in the light of output from a mesoscale numerical weather prediction (NWP) model, and the model itself using inputs from the radar and satellite (and other) sources. The patterns of precipitation derived in the manner discussed in this paper may not be useful in their own right for initializing the numerical model, but the implied fields of humidity, vertical velocity and latent heat release probably will be (Kreitzberg and Rasmussen 1977).

This paper presents the guiding principles of a plan which will take several years to implement. Almost certainly, the details of the plan will change as it is implemented. However, the underlying strategy is expected to endure and, since it could have a substantial impact on local forecasting practice, the author believes that it is important to expose the strategy to critical discussion by the research and forecasting community while the program is still in its infancy.

The elements of a system for deriving very-short-range forecasts of precipitation in the United Kingdom

In this section we present a check-list of the important elements that constitute the proposed radar-cum-satellite system, but first we stress the need to view the scheme as a *whole system*. There would be little sense, for example, in having an observational capability without adequate means of assimilating and interpreting the data, or in having the means of generating detailed very-short-range forecasts without the capability of disseminating so perishable a product in a speedy fashion to the eventual users.

The elements of the forecasting system are as follows:

(i) *The radars*

Experiments such as the Dee Weather Radar Project (Central Water Planning Unit 1977) have demonstrated that a high degree of quantitativeness can be achieved in the radar measurement of surface precipitation intensity, even in difficult hilly areas, provided that the radars are calibrated using telemetered rain-gauge data. Moreover, modern radars, with the benefit of solid-state technology, are capable of stable and reliable operation for long periods and so they can be operated unattended (Try 1972, Aldcroft 1976). This enables them to be sited optimally and to be run with low labour costs. By using a mini-computer at each radar site preprocessed* rainfall data can be sent in

* Throughout this paper 'preprocessed' is used in the sense 'having been subjected to preliminary processing' rather than 'having been processed in advance'.

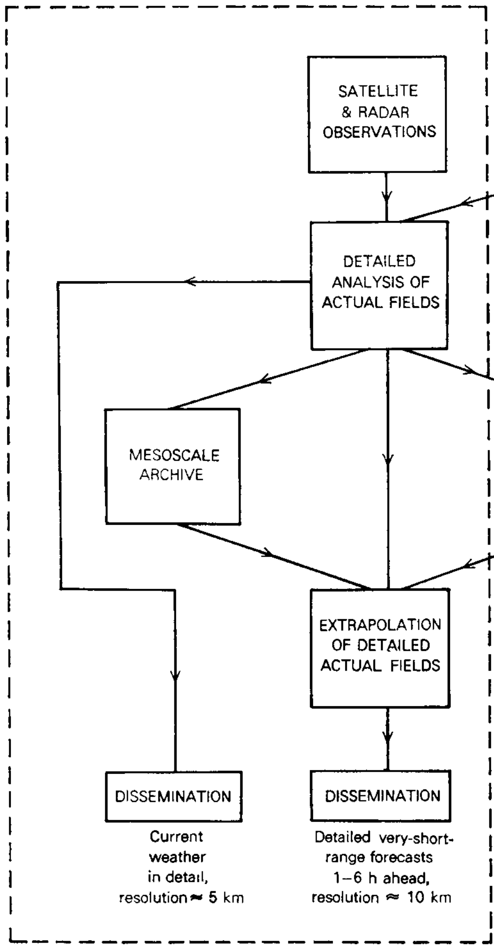

Figure 1. Integrated forecast system (this paper deals with the part enclosed within the dashed rectangle). NWP = Numerical Weather Prediction.

real time by land-line to remote locations (Ball *et al.* 1976, Saffle 1976). One of the requirements for short-range forecasting, especially with fast-moving weather systems, is to have large-area surveillance using a network of radars with overlapping coverage (Hill *et al.* 1977). Thus techniques have been developed to combine automatically on a single television display the digital data being received from a network of radars (Taylor and Browning 1974, Ball *et al.* 1979b).

(ii) *Geostationary satellite imagery*

Satellite-borne microwave techniques are capable of measuring precipitation directly over the oceans (Wilheit *et al.* 1977) but their spatial resolution is poor. Moreover these techniques have as yet been used only on polar-orbiting satellites and these cross any given area too infrequently to be of great value for very-short-range forecasting. The European geostationary satellite Meteosat, on the other hand, although not instrumented to observe precipitation directly, is capable of providing *cloud* imagery with a resolution in time and space which does satisfy the basic needs of very-short-range forecasting. The time resolution of Meteosat is 30 minutes and its spatial resolution at the latitude of England and Wales is 6 km (E–W) and 12 km (N–S) in the infra-red (IR) (3×6 km in the visible (VIS)). Although better resolution is needed for identifying characteristic patterns of cumulus heralding outbreaks of thunderstorms (Purdom 1976) and for tracking individual cumulus to determine low-level winds (Fujita *et al.* 1975), the resolution of Meteosat is nevertheless adequate for keeping track of the important precipitation-producing mesoscale cloud systems, especially if occasional (say, 6-hourly) high-resolution polar-orbiting satellite images are available (e.g. from TIROS-N) to assist in the interpretation of the Meteosat cloud patterns.

(iii) *The marriage of radar and satellite data*

Ground-based radar is superior to satellite methods for measuring surface precipitation intensity, but the coverage of radar is rather limited. In the United Kingdom, even with a network of radars, perhaps linked eventually to a network on the Continent, there would still be large areas over the surrounding sea for which the satellite data would be needed to provide advance warning of approaching precipitation systems. Thus the principle we adopt is that of converting the two sets of data to a common format so that they can be merged on the same television display, the radar data being used where possible and the overall coverage being extended by satellite data.

(iv) *The emphasis on advection*

The role of radar and satellite is to watch for the early signs of mesoscale outbreaks of precipitation and to keep track of their movement and subsequent development. The emphasis in this paper is on forecasting by advection of existing precipitation areas identified by radar and satellite*, together with some assessment of the likely development and decay of these existing areas. The emphasis on advection—which differs from that adopted in the USA (e.g. Scofield and Oliver 1977)—is appropriate for much of the time in places like the United Kingdom where most of the precipitation is associated with frontal disturbances. Hill and Browning (1979) show that in these frontal systems some convective mesoscale precipitation areas show considerable persistence and can be tracked over hundreds of kilometres as resolvable entities despite orographic modulation of the surface rainfall.

(v) *Digital data handling*

A single satellite IR image as considered in the present scheme may consist of 256×256 cells each with up to 256 radiance levels assigned to it, i.e. almost 10^6 bits of data. Such images will need to be compared and combined with other images (e.g. visible satellite or radar data) and parts of the images will need to be rapidly accessed and manipulated in a variety of ways, as well as being displayed and disseminated in different formats. All these procedures have to be completed within 15 to 30 minutes if the forecast is to be issued soon enough to be of value. To handle this volume of data flexibly and rapidly, without degrading it, digital techniques should be employed at every stage from the observational input to the final dissemination of the product. Advances in mini-computer and microprocessor technology, in solid-state fast-refresh memory devices, and in digital communications systems, now make it possible to achieve this at reasonable cost.

* In order to address the problem of forecasting the initial outbreak of deep convection it will of course be especially important to supplement the satellite imagery with mesoscale surface observations (e.g. from automatic weather stations). Moreover, it is to be hoped that later versions of Meteosat will provide higher-resolution cloud imagery for use in thunderstorm situations and will also be capable of providing profiles of temperature, humidity and wind in the manner discussed by Smith *et al.* (1978). Although not addressed in this paper, these other techniques are receiving a lot of attention in the USA where the sudden outbreak of severe tornadic storms is a matter of great concern.

(vi) *Interactive computer-driven video displays*

Video display techniques have recently become available which, when linked to a small computer, provide the capability of recalling the required image almost instantly and of permitting a large amount of human interaction with the television display (Hilyard 1977). These techniques provide the key to the rapid performance of the various analytical and forecasting steps described later. Work on interactive displays in the early 1970s led to the development of a display system known as McIDAS (Chatters and Suomi 1975). Other more recent systems in the USA include AOIPS (Bracken *et al.* 1977), ADVISAR (Smith and Reynolds 1978) and NEDS (Thormeyer 1978). In the United Kingdom there is the IDP-3000 (Balston 1978). The kind of activities that can be carried out using such systems are:

- *Rapid data access*, i.e. almost instantaneous selection of any required image from a set of stored images.
- *Precision navigation*, i.e. *x–y* translation of the image to remove residual registration errors by reference to electronically generated coastline overlays.
- *Enhancement (contrast-stretching and level-slicing)*, i.e. adjusting grey shades or assigning colours at variable thresholds, either to make features of interest stand out or for the purpose of calibrating the intensity levels.
- *Animation*, i.e. replaying a time-lapse sequence of images.
- *Zooming*, i.e. selecting and enlarging an area of interest.
- *Image combination*, i.e. combining or comparing with great precision the images from different sources, e.g. radar and satellite, or satellite IR and VIS.
- *Superposition of graphics*, i.e. capability of superimposing geographical features, labels, numerical data, and line charts.
- *Intervention*, i.e. modification of the image data within areas delineated by means of a movable cursor whilst preserving the original data in store.

These activities can be carried out rapidly by means of simple analogue controls (e.g. a joystick) plus keyed-in instructions. Later on we shall discuss a specific sequence of steps whereby it is planned to generate detailed analyses and very-short-range forecasts of precipitation entirely on the television screen itself.

(vii) *Improved understanding of mesoscale weather systems*

The use of an interactive display can be only as good as the state of meteorological understanding will permit. Thus, for example, a major problem is to convert the radar and satellite data into fields which represent the true pattern of surface precipitation intensity as faithfully as possible. The transfer function is reasonably well established for the radar and much of the analysis of the radar data has to do with improving accuracy and removing unwanted echoes; however, the transfer function for converting satellite cloud data into surface precipitation intensity is not well established, especially in mid-latitudes where much of the precipitation is non-convective and there is abundant cirrus in regions far removed from areas of surface precipitation (Barrett 1973). In this case we need to use a combination of approaches:

- Empirical adjustment of satellite data to correspond to precipitation intensities given by *ground truth* or by *nearby radar data*.
- Exploitation of the *different spectral response* in different satellite channels. For example, Reynolds *et al.* (1978) and Lovejoy and Austin (1979) exploit the fact that whereas the IR radiance is a measure of cloud height, the visible brightness tends to be more a measure of cloud thickness. Consequently low (cold) radiance values together with high brightness is indicative of precipitating cloud while low radiance coupled with low brightness is indicative of cirrus alone.

- Exploitation of the *texture* of high-resolution visible data from occasional passes of a polar-orbiting satellite to reveal the presence of characteristically fibrous cirrus which otherwise might be interpreted as being deep rain-bearing cloud.
- The use of *conceptual models* relating cloud patterns to surface precipitation in different synoptic situations (Kreitzberg 1969). A simple example is the fact that the leading parts of baroclinic disturbances have considerable upper cloud unrelated to surface precipitation, whereas the trailing parts of such disturbances are more convective and the high cloud tops tend to be better related to the occurrence of precipitation. At present most of the conceptual models are biased toward the synoptic scale, the few mesoscale models (Browning 1974, Houze *et al.* 1976) being derived from a limited number of detailed case studies. However, when the kind of analysis described in this paper is carried out on a more regular basis, we shall begin to accumulate the raw material for the derivation of a more systematic classification of mesoscale cloud and precipitation patterns.

Much fundamental research remains to be done to improve all aspects of the analysis of satellite data. More research is also needed to enable us to derive forecasts from the analysed precipitation fields. It is sometimes possible for useful forecasts for a few hours ahead to be obtained simply by linear extrapolation. However, it will be important to develop methods to predict the development or decay of existing precipitation patterns that results from both internal dynamical factors and from external topographical forcing. Approaches to be used will include:

- Incorporation of large-scale trends predicted by synoptic-scale or mesoscale numerical–dynamical models.
- Incorporation of topographical enhancement factors derived from mesoscale climatological statistics and from simple diagnostic models.

It will be possible to implement these approaches in a fully satisfactory way only when a substantial body of experience has been amassed concerning the way in which mesoscale precipitation patterns evolve. In particular, a precipitation archive* needs to be established on the basis of detailed radar and satellite data which have been carefully combined and quality-controlled to remove obvious errors and unwanted echoes.

(viii) *Optimizing the man–machine mix*

Many of the steps in the analysis and forecasting procedure (described later in this paper) can easily be automated and, in time, more of the steps will become amenable to automation; however, it is difficult to foresee a time when the observational data on the mesoscale will be good enough to eliminate the need for considerable human judgement. The use of an interactive video display will permit the man–machine mix to be optimized by automating the repetitive tasks whilst enabling the forecaster to retain and indeed expedite the use of his judgement. As discussed by Woodroffe (1976), use is already made of a visual display unit interactively connected to a computer for the purpose of manually intervening in the objectively analysed fields used as input to the Meteorological Office 10-level model. The approach advocated in this paper involves a considerable extension in the degree of interaction. Instead of using satellite and other information to adjust values at a limited number of widely spaced grid points, the approach here is to use the detailed radar-cum-satellite information

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* In addition to the importance of a mesoscale precipitation archive for forecasting, such an archive would also be valuable for off-line hydrometeorological applications. According to Bussell *et al.* (1978), considerable savings could be made by reducing the UK network of rain-gauges if a reliable radar-rainfall archive could be maintained. However, to achieve the accuracy required for many hydrometeorological applications, data from a radar-rainfall archive (consisting of data analysed as described later in this paper) would need to be combined off-line with data from a rationalized network of autographic gauges so as to generate what Harrold *et al.* (1974) refer to as an 'optimum rainfall field'.

itself as the primary material and to adjust it to bring it into conformity with other constraints so as to achieve the best possible representation of the mesoscale field of precipitation. This requires repeated modification of a dense matrix of data points and implies a far larger amount of interaction than is currently regarded as normal.

(ix) *Dissemination of the forecast product*

Existing methods of disseminating forecasts are inadequate to do justice to the wealth of perishable information likely to be contained in the forecasts generated using radar and satellite data. One approach in the future will be to transmit automatically a limited amount of digital data precisely tailored to individual users' needs. As Carpenter *et al.* (1978) point out, the increasing use of on-site microprocessor control systems and of dial-up computer access will make automatic response to such forecast information more feasible. It will also be necessary to make more use of local radio, especially techniques for providing flash messages to travellers (e.g. 'Carfax'). Another approach will be to send out picture information from which the user can select for himself the information which interests him. The information should be frequently updated, the most recent data being accessible continuously on demand rather than intermittently at scheduled times. A number of options exist for this approach; they include:

- *Special-purpose equipment* capable of receiving and storing digital data transmitted by standard lines and of replaying one picture or a sequence of pictures on a television set. Simple devices of this kind are commercially available and are coming into use in the Meteorological Office and in some Water Authority offices (Taylor 1975, Ball *et al.* 1979a).
- *Teletext ('Ceefax' and 'Oracle')*. In this scheme the data would be sent in a spatially degraded format to a television broadcast company via a computer-to-computer link and could be displayed on demand on domestic television sets equipped to receive teletext.
- *Viewdata (e.g. the 'Prestel' system described by Parker 1978)*. This is similar to teletext except that the data would be sent to regional computers operated by the telephone company and would then be called up on a domestic television set by telephoning the computer data bank. In addition to providing a larger bank of data specially tailored to the needs of the area served by the regional data bank, the viewdata system has the advantage over teletext that it could generate revenue for the data provider in direct proportion to the demand for the product (Meteorological Office 1978). The viewdata system could also permit the monitoring of the demand for individual forecast products, which is an important requirement for the development of a sound marketing plan.

A specific scheme for deriving very-short-range forecasts of precipitation in the United Kingdom

(a) *General survey of the scheme*

The FRONTIERS system concept outlined above is being implemented within the Short Period Forecasting Pilot Project at the Meteorological Office Radar Research Laboratory. As part of this program a pilot network of, initially, four radars* is being established in England and we shall be combining the data from these radars with Meteosat data reduced to a radar-compatible format. We are proceeding on the assumption that there will be a continuing service of geostationary imaging for north-west Europe. In this section we shall be describing a sequence of steps forming a systematic work flow pattern for the derivation of current weather and forecast products from the radar and

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* The radars are a mixture of C- and S-band sets with 1- and 2-degree beams, respectively. One of the radars is new; the other three radars in this interim network are not so up to date. The new radar is being funded by a consortium of government agencies as part of the North West Radar Project.

satellite data. Some of the steps are straightforward and have already been implemented. Others are more complex and will require several years of experience or the accumulation of an archive of data before they can be implemented satisfactorily. Yet others may turn out to be too time-consuming or costly in relation to their effectiveness to justify inclusion in the final scheme. Only practical experience will indicate what operational compromises will be required. Clearly the system must be designed with a view to evolutionary robustness. Although it will be several years before the precise form of the forecasting procedures will emerge, we consider it worth while at this stage to describe our present plans in some detail as a means of clarifying the problems that have to be addressed.

The principal stages in the proposed forecasting scheme are shown in Figure 2. The four main stages—preprocessing, meteorological analysis (including quality control), forecasting, and dissemination—will be elaborated upon in Figures 3 to 6. The two other areas of activity shown in Figure 2—archiving and forecast validation—will be automated and carried out in parallel with the Stage 2 and Stage 3 activities. Although the hardware facilities will be the subject of a later paper, it is appropriate to mention here that a mini-computer is required at each of the radar sites to perform the Stage 1 preprocessing (we are using the PDP–11 series of computers). Similar computers are needed to process the satellite data and to receive and combine the data from the network of radars. A further mini-computer is required to drive an interactive video display system. The radar data available at the network centre are in 8-bit format. At the moment we are making the best possible use of redigitized analogue data from Meteosat together with a very simple interactive display, but the scheme outlined here is based on the use of 8-bit digital data from both satellite and radar together with a versatile interactive video display.

(b) *Preprocessing of the satellite and radar data*

A breakdown of the activities involved in the preprocessing stage is shown in Figure 3. The on-site radar data processing is essentially as described by Taylor and Browning (1974). Two categories of data are available at the network centre. One category—areal integrations—is for hydrological use and is not used subsequently for meteorological forecasting. The other, meteorologically important, category of data is a radar composite map available every 15 minutes on a 256×256 grid with 5 km* resolution. This map is displayed on a television screen (and is also available as hard copy). The radar rainfall patterns are stored and can be manipulated in 8-bit form, i.e. 256 levels of intensity, although for ease of interpretation only eight levels are likely to be displayed at any one time. The standard display system, for example, has a different colour for each of the following precipitation categories: L, 1, 4, 8, 16, T, H, where L = light rain, T = probable thunder shower, H = probable hailstorm, and the numbers refer to rainfall intensity thresholds in millimetres per hour averaged over each 5 km square. The reason for storing the data as 256 levels is to reduce quantizing errors during the subsequent Stage 2 and 3 processing when a whole series of correction factors has to be applied.

As far as the satellite data are concerned, Figure 3 shows that we intend to concentrate on the use of the frequent imagery available from Meteosat. There are three channels of interest: infra-red (IR), visible, and perhaps water vapour. These data are available at 30-min intervals for the IR, and also for the visible during daylight hours, but less frequently for the water vapour channel. The IR channel, representing approximately the temperature of the cloud top, is available around the clock and so is treated as the primary satellite data for precipitation forecasting; however, the facility will be provided for automatically combining the IR data with the other channels, at times when they are available, according to empirical rules developed by off-line research, in order to improve the delineation of the probable extent of surface precipitation.

* Data over limited areas with a resolution of 2 km and 5 min are also available for off-line research.

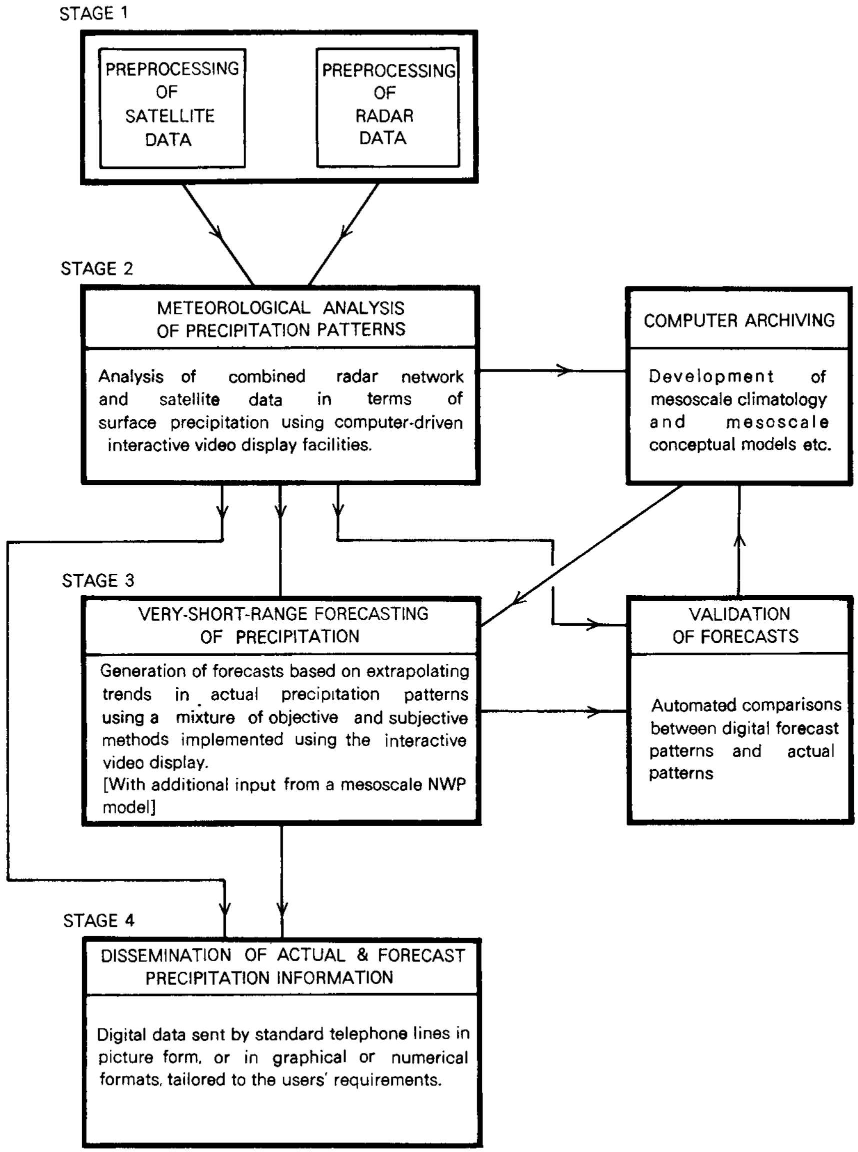

Figure 2. Outline of scheme for very-short-range precipitation forecasting (showing major stages only).

One of the first tasks with the satellite imagery is to convert it automatically to the same projection as the radar data. The next step is to use the coastlines to locate the images with the high degree of precision required for local forecasting purposes. This is the registration or so-called navigation procedure. The 256 radiance levels available from Meteosat give ample scope for colour enhancement to make the coastlines stand out clearly. The interactive display is used to position the image on a

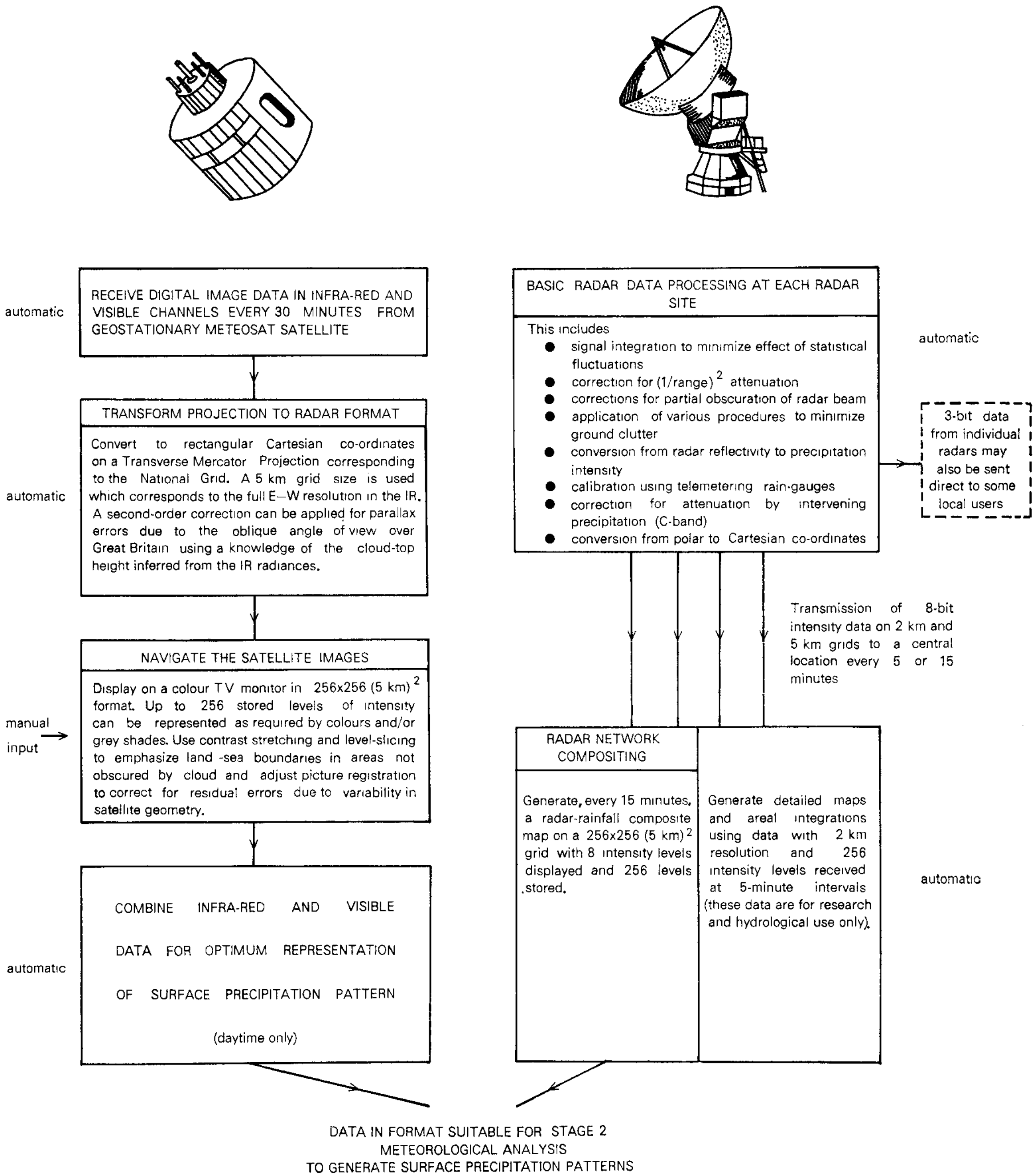

Figure 3. Stage 1: Preprocessing of satellite and radar data.

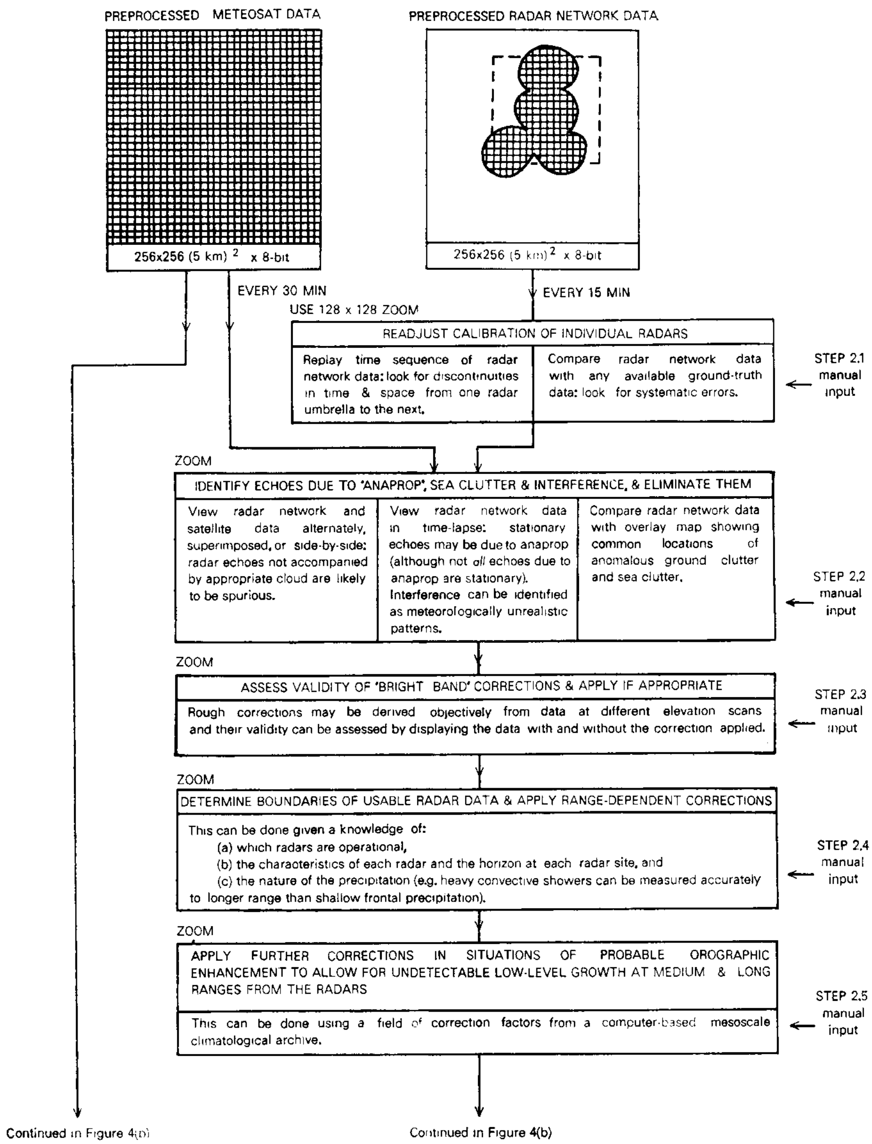

Figure 4(a). Stage 2: Meteorological analysis of precipitation patterns (a) Corrections to the radar network data.

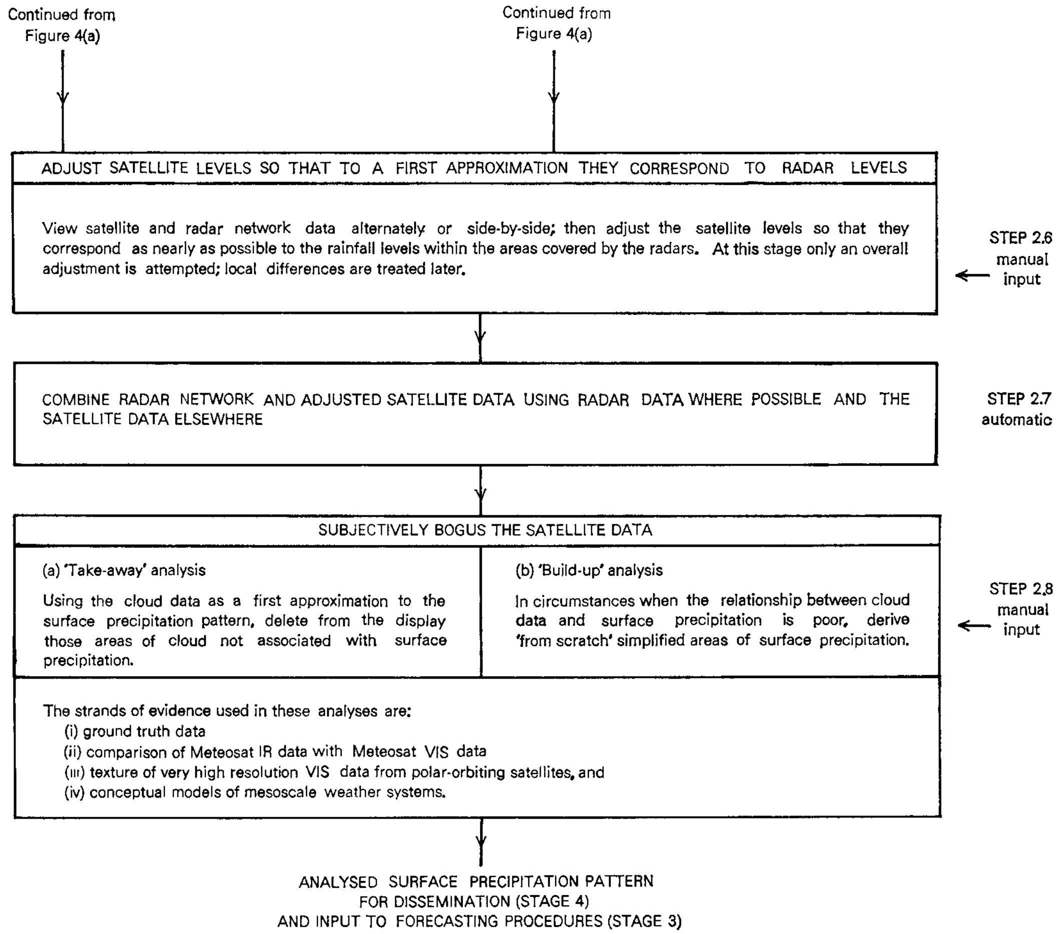

Figure 4(b). Stage 2: Meteorological analysis of precipitation patterns (*continued*) (b) Analysis of satellite data and merging with radar data.

256 × 256 grid against an electronic overlay of the coastline. This image usually covers a large enough area to ensure that at least some coastlines are unobscured by cloud. The navigation is the only task in Stage 1 that may require a manual input.

(c) *Meteorological analysis of precipitation patterns*

Figures 4(a) and 4(b) show the sequence of tasks involved in merging the radar and satellite data sets and in analysing them in terms of surface precipitation intensity. The input data sets at the top of Figure 4(a) are preprocessed data in common formats, with the entire 256×256 (5 km)^2 array filled with Meteosat data but only a part of the array filled with data from the limited-area UK radar network.

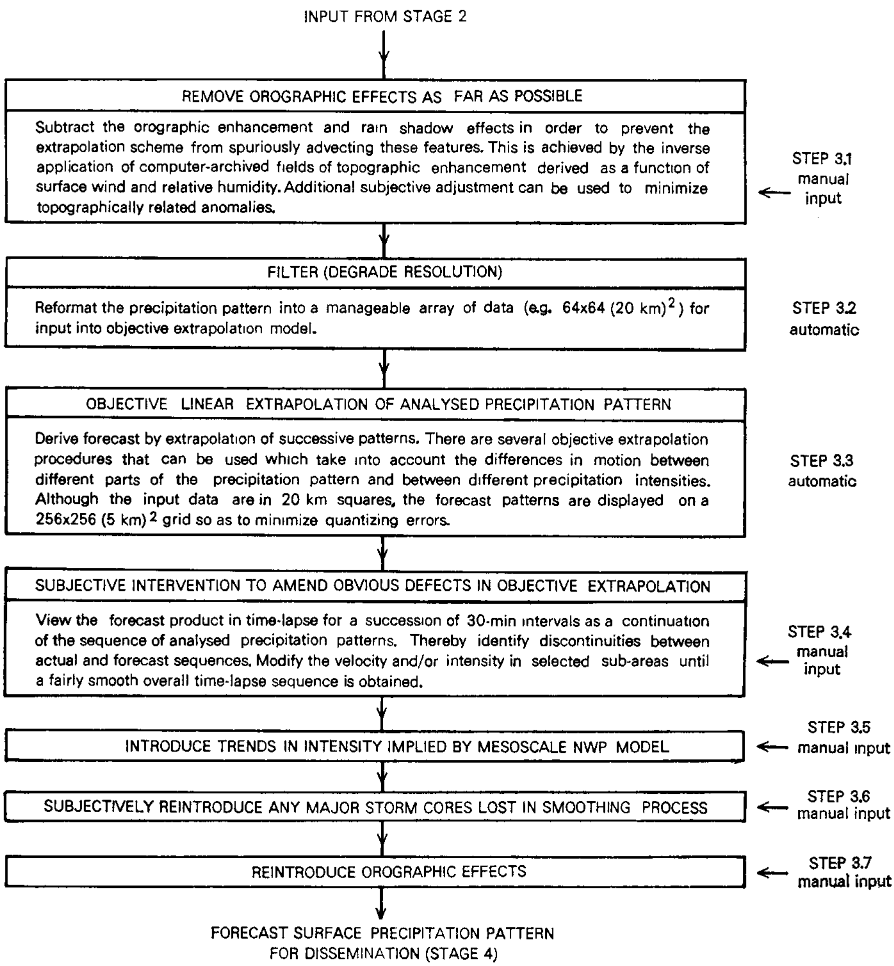

Figure 5. Stage 3: Very-short-range forecasting of precipitation patterns.

The first five tasks (Figure (4a)) all have to do with refining the quality of the radar rainfall data on the basis of manual inputs to cope with problems that cannot be fully dealt with objectively in the radar-site preprocessing:

Step 2.1: Readjustment of the calibration of individual radars. Although it is planned that individual radars will normally be calibrated at the radar sites and in real time by means of telemetered rain-gauge data, there will be occasions when such calibrations will either be unavailable (e.g. because of lack of rain over the calibration gauges) or unreliable (e.g. because of contamination of the radar beam by the strong echo from melting snow at the range of the calibration gauges). Any overall radar calibration errors arising from such effects can be identified in one of the ways indicated in Figure 4(a) and then appropriate adjustments can be made using the interactive display facilities.

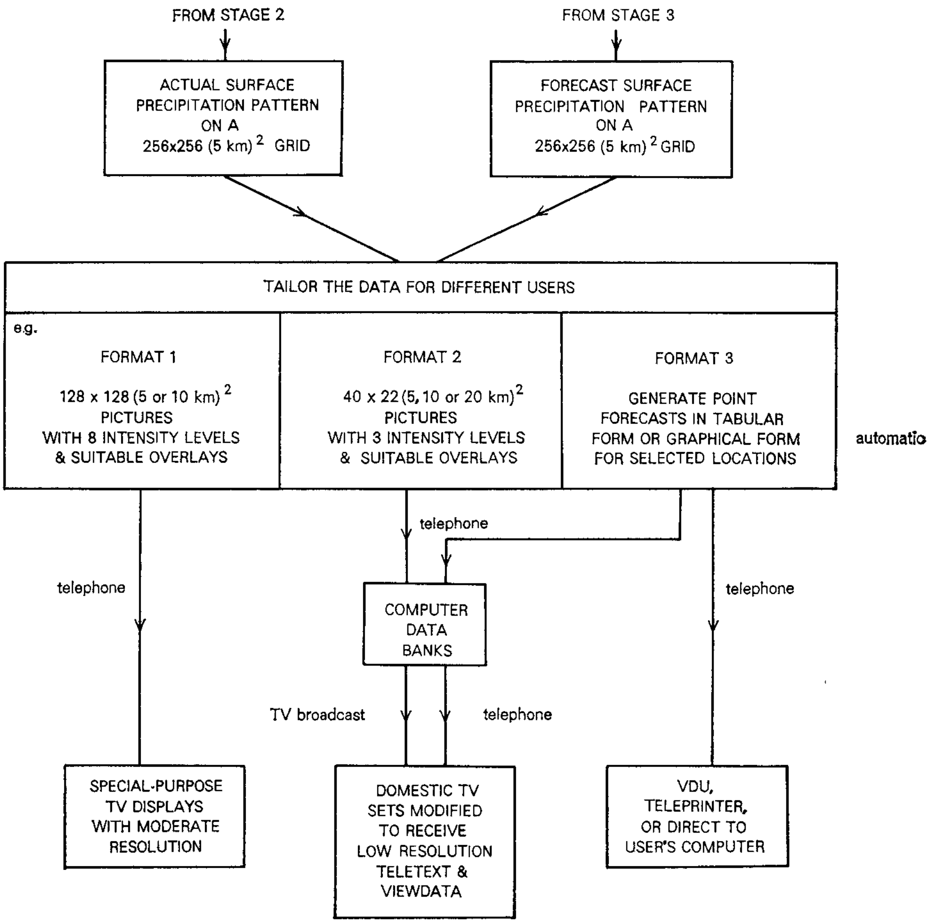

Figure 6. Stage 4: Dissemination to the users.

Step 2.2: Identification and eradication of spurious echoes due to anomalous propagation, sea clutter and radar interference. Techniques have been developed which make use of the fluctuating characteristics of the radar signal to enable precipitation targets to be distinguished from ground echoes, including those associated with anomalous propagation (Johnson *et al.* 1975). These techniques have yet to be implemented operationally and, if they do not provide a complete solution, the additional procedures shown in Figure 4(a) can be applied subjectively to reject any remaining echoes of this kind. Before applying any correction the analyst should of course ascertain whether the atmospheric conditions are conducive to the production of anomalous propagation. Sea clutter probably cannot be distinguished from precipitation on the basis of its fluctuation characteristics and its presence will have to be inferred from the expected sea state or, in ideal circumstances, from the absence of satellite-observed cloud in the area. Radar interference can generally be recognized by its characteristic configuration, e.g. radial spokes and spirals. Once identified, these unwanted echoes can be removed from the video display by means of manual inputs.

Step 2.3: Assessment of the validity of bright-band corrections and their implementation if appropriate. The radar bright band is the name given to a shallow layer of intense echo associated with melting snow which, at ranges where it is intersected by the radar beam, can lead to an overestimate in the precipitation intensity. An objective method for minimizing the effect of the bright band using data from radar scans at different elevation angles has been proposed by Harrold and Kitchingman (1975). Subsequent tests by Clarke and Collier (1977) have indicated difficulties in applying it in practice. More work is required to develop this procedure and it is not clear at present whether it will be better to apply the correction at the radar sites for individual radars or centrally on the radar composite. In either case, however, there are likely to be occasions when, perhaps because of the inhomogeneous character of the precipitation, the resulting objective corrections will be unreliable. Thus there will be a need to display the radar rainfall patterns with and without corrections applied and to use subjective judgement to exploit man's superior pattern recognition capability to assess what corrections if any should be applied.

Step 2.4: Determination of the boundaries of usable radar data and the application of range-dependent correction factors. The horizontal boundary of usable radar data depends on the radar horizon and on the vertical extent of precipitation and its intensity profile. For each radar, a set of boundaries can be defined for a few broad categories of precipitation type. Within these boundaries at the longer ranges correction factors will need to be applied over and above the standard $(1/\text{range})^2$ correction applied at the radar sites. This is to allow for the fact that the radar beam may not be filled with precipitation or may be sampling precipitation echo aloft which is less intense than that close to the ground. Fields of statistical correction factors can be derived by comparing daily-integrated radar rainfall patterns with corresponding patterns of daily rain-gauge data and these should be computer-archived in broad categories related to the nature and probable vertical extent of the precipitation.

Step 2.5: Application of orographic enhancement factors. This step is rather similar to Step 2.4 except that the corrections will be confined to exposed hilly areas and will be a strong function of the conditions at low levels, especially the wind velocity and relative humidity. According to Browning (1979), substantial orographic enhancement can occur in the lowest 1 or 2 km in certain circumstances, and the correction factor may be significant even at ranges as close as 50 km. The correction factors due to low-level enhancement can be derived climatologically as in Step 2.4 or by using diagnostic fine-scale numerical models such as that of Bell (1978).

Step 2.6: Adjustment of the satellite levels so that to a first approximation they correspond to radar levels. Having bogused the radar network data in Steps 2.1 to 2.5, the next step is to compare the satellite IR data (or some automatically derived combination of IR and VIS data) with the by-now optimized radar data and to adjust the satellite level-slicing scheme for the display as a whole to correspond as nearly as possible to the rainfall levels used in the radar scheme (Figure 4(b)).

Then, as Step 2.7, the radar and adjusted satellite data are composited on the same display using the radar data where available and filling in the gaps with the satellite data.

Step 2.8: Subjective bogusing of the satellite data. We then come to one of the most challenging tasks, namely modifying the parts of the display that are based upon the satellite data* in order to remove

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* Step 2.8 is described assuming that the satellite data are based upon IR information only, as for example during the night. The combined use of IR and VIS data, as described by Lovejoy and Austin (1979), may by itself provide a fairly good indication of the extent of precipitation. Even then, however, an abbreviated application of Step 2.8 should significantly improve the analysis.

areas of high cloud not associated with precipitation and to introduce any areas of precipitation associated with rather shallow cloud. Two approaches can be used depending on how close the correspondence is between the satellite cloud pattern and the precipitation pattern. We shall refer to these as the 'take-away' and 'build-up' methods, respectively. In cases where there appears to be a reasonable overall correspondence between the areas of high cloud and precipitation, the satellite radiance patterns are used as a first approximation to the detailed precipitation pattern outside the areas of radar cover and the main analysis task is to 'take-away' areas of high cloud which are believed not to be associated with surface precipitation. In regions dominated by convection it is relatively easy to relate high cloud-tops to precipitation cores but in areas of extensive high layer cloud (e.g. at warm fronts) it may not be obvious where the precipitation areas at the surface begin and end. Deciding what cloud to take away then requires the skilful weighing of diverse strands of evidence such as may be gleaned from surface observations, and the texture of the visible cloud observed by polar-orbiting satellites. These pieces of evidence must be reconciled by the human analyst with his knowledge of conceptual models of precipitation systems.

The other method of analysis, referred to as the 'build-up' method, is applied when the overall correspondence between cloud radiance and surface precipitation is so poor that it is necessary in effect to 'wipe the slate clean' outside radar range and to build up the main features of the precipitation pattern from scratch. In this case one would not use the detailed pattern of Meteosat imagery as a direct indication of the detailed pattern of precipitation but, instead, one would recall it on to the screen for use as just one strand along with the other strands of evidence to delineate a rather crude outline of the probable extent of surface precipitation. With this approach the tendency would be to look for characteristic cloud patterns thought to be associated with specific categories of mesoscale organization. A case in point would be the heavy precipitation that often occurs in association with the 3 km tops of convective line-elements at sharp ana-cold fronts (Browning and Harrold 1970, James and Browning 1979). Sometimes, too, it is possible for the human analyst to discern bands of medium-level cloud associated with surface precipitation lying beneath upper cloud bands of different orientation associated with non-precipitating cirrus.

Implementation of the changes to the display called for in Step 2.8 can be achieved using a joystick-controlled movable cursor to define the corners of polygons within which the required modifications can be effected by means of simple keyboard instructions. Different modifications may be required in different geographical sub-areas; in some of these areas 'take-away' analysis may be possible whilst in others the cruder 'build-up' analysis may be needed. Having finished Step 2.8, one has on the screen a fully analysed precipitation pattern on a 256×256 $(5\ \mathrm{km})^2$ grid which is ready for immediate transmission to users interested in current weather or for input to the Stage 3 forecasting procedures. Too much accuracy must not be expected from the analysis in Step 2.8; in some situations one will have done well even if one succeeds in delineating the major areas of rain/no rain. In any case we must remember that the critical land areas will be covered more quantitatively by radar and that the primary role of the satellite is to provide a larger-scale context and some advance warning of approaching areas of precipitation.

(d) *Very-short-range forecasting of precipitation patterns*

The analysis of precipitation patterns in Stage 2 was carried out using 256 levels of intensity in order to retain the contrast enhancement facility for the satellite data and to avoid quantizing errors during the application of successive correction factors to the radar data. Further corrections will need to be applied during the forecast procedure but the level of precision justified at this stage is less; thus the number of intensity levels stored can be reduced.

Figure 5 suggests that the sequence of steps in the forecasting of precipitation patterns should be as follows:

Step 3.1: Removal of orographic effects. The principal step in the forecast procedure is the objective extrapolation of the analysed precipitation pattern (Step 3.3). In order to avoid the mistaken impression that the entire pattern of precipitation is almost stationary, or the possibility of the extrapolation procedure spuriously advecting orographic maxima or rain shadows, it is first necessary to minimize the topographical effects as far as possible. This is achieved by cancelling the enhancement factors applied in Step 2.5, followed by the inverse application of a computer-archived field of topographical radar echo enhancement factors derived climatologically as a function of wind velocity and relative humidity. The objective corrections will be only a first approximation and further subjective tuning may be required to diminish probable topographically related anomalies.

Step 3.2: Filtering of the data. The previous corrections in Step 3.1 do not have to be applied too painstakingly since we may next need to smooth the 256×256 $(5\ \text{km})^2$ array to one of, say, 64×64 $(20\ \text{km}^2)$* before applying the objective extrapolation procedure. This smoothing would be done to enable the objective extrapolation to be carried out in a reasonably short time and to get rid of the more evanescent small-scale features of the precipitation pattern. Indeed, Tatehira *et al.* (1976) found that a significant improvement in predictability in the case of forecasts up to 4 h ahead could be achieved by degrading the resolution even further, from 20 to 40 km. In either event, Tatehira *et al.* found that more accuracy could be achieved by using extrapolation procedures than by advecting precipitation patterns with the wind at some level.

Step 3.3: Objective linear extrapolation of analysed precipitation fields. There are several objective extrapolation procedures that can be used; they may be summarized as follows:

(i) A cross-correlation technique similar to that used by Austin and Bellon (1974) and Bellon and Austin (1978). In this scheme portions of one radar or satellite picture are matched with portions of a subsequent picture. This procedure has the advantage of taking into account the detailed shape of the radar echo or cloud being tracked, and therefore decreases the chance of mismatches. If there are large differential motions from one part of an area to another, then the pattern of precipitation or cloud must be split into several sub-areas in order to produce useful forecasts.

(ii) Tracking of individual radar echo centroids or clouds using a linear least squares extrapolation (Barclay and Wilk 1970, Wilk and Gray 1970). This method has the advantage of coping well with differential motion, but unless echo or cloud clustering techniques are applied (Endlich *et al.* 1971, Wolf *et al.* 1977) there may be difficulty in matching echoes or clouds that change their shape significantly from one picture to the next.

(iii) Tracking of individual echoes or clouds using parameters describing the shape and intensity profile of the entire echo or cloud complex, instead of taking a single intensity threshold as in (i) and (ii) above (see Duda and Blackmer 1972, Blackmer *et al.* 1973). This type of procedure is complex but it does describe the movement of individual clouds or radar echoes.

The overall forecasting scheme specified in this section calls for a high degree of man–computer interaction in order to optimize the forecast. It is therefore unnecessary to strive for the unattainable goal of an objective technique which produces perfect results in all weather conditions.

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* The figure of 20 km is somewhat arbitrary; the choice of the most suitable grid size for forecasting will be made in the light of experience.

Step 3.4: Subjective intervention to amend obvious defects in the previous objective extrapolation. The previous step is capable of generating a sequence of forecast patterns over a series of 30-min intervals. This sequence can then be replayed in time-lapse as a continuation of the earlier sequence of analysed precipitation patterns. Shortcomings in the objective extrapolation will show up as discontinuities in the time-lapse sequence which can be ameliorated by subjective modification of the velocity and/or intensity of the precipitation pattern within selected sub-areas.

Step 3.5: Introduction of trends in intensity predicted by a mesoscale numerical dynamical model. The forecasts generated so far are merely linear extrapolations of the most recently observed precipitation pattern. Any broad trends in intensity predicted on the basis of a NWP model can now be introduced provided that they are not inconsistent with the observed trends.

Step 3.6: Subjective reintroduction of major storm cores lost in the earlier filtering process. Thunderstorm cores may have been smoothed out during Step 3.2. Although it is probably appropriate that this should have been done, in view of the lack of persistence of individual convective cells (Wilson 1966), compact clusters of thunderstorm cells sometimes persist much longer than the component cells. If this appears to be happening on a given occasion it may be helpful to reintroduce a few of the major storm centres at appropriate locations perhaps on the basis of a subjective interpretation of the previous time-lapse sequence.

Step 3.7: Reintroduction of orographic effects. At the beginning of the forecast sequence (Step 3.1) we were at pains to rid the precipitation pattern of orographic effects to enable the advective forecasting scheme to function properly. The final step in the forecast procedure is to reintroduce the orographic effects with 5 km resolution. The knowledge of the 'disenhancement' carried out in Step 3.1 should help in applying an appropriate 're-enhancement', assuming that changes in orographic effects occur only slowly, or in a predictable manner as, for example, at the passage of well-defined cold fronts (Browning *et al.* 1975). Having completed this step, one then has a complete set of very-short-range forecasts consisting of a sequence of identically displaced precipitation patterns subjected to varying topographical modification as the precipitation areas pass across different locations over a period of several hours. These forecast patterns are on a 256×256 $(5\text{ km})^2$ grid and are now ready for dissemination.

(e) *Dissemination of the actual and forecast precipitation information*

The crucial aspects of dissemination are that the information should reach the users quickly, should be frequently updated, and should be in sufficient detail and in an appropriate format. Three dissemination formats are indicated in Figure 6. All the formats shown in Figure 6 involve some form of visual display* for clarity and ease of assimilation or, alternatively, the data can go straight into the user's computer system. All the formats can be disseminated automatically via standard land-lines. Very frequent updating is possible.

One of the obstacles to speedy dissemination is the amount of prior data processing required in Stages 2 and 3. Nevertheless, as a result of the degree of automation and the ease with which the manual interaction can be achieved using interactive video display techniques, these steps are not expected to be as time-consuming as might appear at first sight. It must also be remembered that only a rather small fraction of the display is likely to be filled by precipitation at any given time and, once the data have been processed for a few consecutive times, the processing of subsequent data is made easier by

* Verbal dissemination will of course continue to be used for communicating limited amounts of information.

continuity considerations. We anticipate that the time delay between receipt of the raw data and dissemination of the forecast will be between 15 and 30 minutes. Unfortunately the basic Meteosat data are not received until about 45 minutes after real time. Thus it seems that we should aim to get the forecast product to the users within just over an hour of the time of the latest data used in the derivation of that product. If there is a risk of it taking longer than this, then it will be necessary to bypass or abbreviate some of the less important steps.

Throughout the development of these procedures we shall constantly need to be balancing the benefits of introducing additional steps against the penalties of the extra time and labour involved. In view of the rather long delay in receipt of Meteosat data from source compared with the almost real-time receipt of radar network data, there is, for example, a strong case for also disseminating actual data, based upon an abbreviated analysis of the radars alone, to some users requiring very up-to-date information on current weather.

Conclusions

The plan for very-short-range precipitation forecasting in the United Kingdom, as outlined in this paper contains the following key elements:

- The primary requirement is to *observe the mesoscale field of precipitation* on an almost continuous basis. Sequences of such fields can form the basis of simple *forecasts by extrapolation* in the 1–6 h time frame, and can also be used to help *initialize mesoscale NWP models* for predictions in the 6–24 h time frame.
- It is not an easy matter to observe mesoscale precipitation fields, and data from several sources need to be *carefully analysed and then combined.*
- The most effective tool for the quantitative determination of precipitation fields is *radar*; to get sufficient coverage for forecasting a few hours ahead an *integrated network* of radars is needed.
- To obtain more warning of approaching precipitation systems, especially from data-sparse sea areas in the case of the UK, it is possible to extend the coverage using satellite cloud imagery; only a *geostationary* satellite is capable of providing data frequently enough for very-short-range forecasting. To facilitate the combined analysis of radar and satellite data the two sets of data need to be *reduced to a common format.*
- Vast amounts of data are generated by radar and satellite and this calls for a high degree of automation in the handling of the data; at the same time, however, the imperfections in the observational data and objective forecasting procedures, as well as the ill-defined nature of the transfer function between cloud imagery and surface precipitation intensity, are such that for the foreseeable future *a combination of objective procedures and subjective judgement* will be required in the analysis and forecasting.
- The new technology of *interactive computer-driven video displays* can be exploited to enable the human forecaster to exercise his judgement effectively within the framework of an otherwise highly automated procedure; the degree of interaction required is far greater than that employed in present intervention schemes. All-digital processing is required for flexibility and quantitativeness.
- Detailed forecasts for a few hours ahead are a perishable commodity whose value depends on the ability to distribute them widely and promptly, and in an easily understood format: *new dissemination techniques* such as teletext and viewdata offer this capability.
- Obvious errors and artefacts will be removed during the analysis of the radar data using the interactive video display; this provides the kind of preliminary *quality control* that is necessary if the radar data in addition to being used for real-time forecasting are also to constitute a reliable *mesoscale precipitation archive.*

• The systematic archive of data and the analytical experience gained by regular use of these facilities will provide the means for *improving fundamental understanding* of the structure and mechanisms of mesoscale precipitation systems; this will in turn contribute to further improvement in forecasting techniques.

A pilot forecasting program based on the above plan has been initiated at the Meteorological Office Radar Research Laboratory. Small teams will be working side by side to develop technical facilities, to do basic mesometeorological research and to develop operational forecasting techniques. There will be a combination of real-time operational research and off-line analysis on a case study basis. It is hoped thereby to tailor the technical developments to suit both the operational and research demands and to enable forecasters to take quick advantage of improved understanding. The scheme will be built up in stages and will be operated in a real-time mode over a period of years to establish cost-effectiveness. Although we have focused in this paper on the integration of radar and satellite data, an important extension will be to incorporate other data from the synoptic data bank as a series of overlays to the radar-cum-satellite display.

The man–computer interactive analysis and forecasting will be a centralized activity at first. However, with the decreasing costs being brought about by advances in solid-state technology one can foresee a time when some interactive procedures could be extended to outstations. Such a distributed computer weather-analysis and forecasting network would lead to perhaps the biggest change in meteorological operations since the advent of the large computer: outstation meteorologists would then have a real opportunity to produce significant improvement in their forecast products on the small scales relevant to local needs.

A major change in the mode of operation at regional forecast offices is already under way in the USA with the introduction of the AFOS (Automation of Field Operations and Services) system in which visual display units are replacing hard-copy facsimile charts for the display of synoptic data (Klein 1976). The use of AFOS, along with Model Output Statistics (Glahn and Lowry 1972) and computer-worded forecasts (Glahn 1978; Wickham 1976), will allow forecasts to be produced with fewer outstation staff and less reliance on subjective forecasting skills. However, these same developments have been accompanied by fears that forecasters may give up using their skills altogether, to the detriment of the quality of the operational product (e.g. Snellman 1977). Although the AFOS system provides for interaction in the limited sense of allowing flexible access to different data formats, the FRONTIERS type of concept carries the interaction a stage further and actively encourages the subjective element in very-short-range forecasting. The aim is to seek the right blend of modern technology and the forecasters' skill and understanding. We consider that the FRONTIERS approach will motivate the forecaster to contribute effectively whilst leading to a local forecast product which has a degree of detail and accuracy that has previously been unattainable.

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Noctilucent clouds over western Europe during 1978

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Table I summarizes the observations of noctilucent clouds (NLC) over western Europe during 1978 which have been reported to the Department of Meteorology, University of Edinburgh. The co-operation of the Swedish meteorological authorities is welcomed. The information they provide enlarges the area of coverage previously watched over by voluntary observers in Denmark and Norway.

A grant from the Meteorological Office finances the collection, collation and publication of the written and photographic data.

Observers are asked to report for the period May–August (inclusive), mid-May to mid-August encompassing the main observing 'season' in the northern hemisphere. The immediate effect of the Swedish observations is to show an increase in number and in depth of observations of the clouds during the first two weeks of August. It will be a matter of interest to see if the data from the higher latitude stations make this a regular feature of the collection.

The reader is asked to note that the times given in the second column of the Table are not necessarily the total duration of the NLC display, though appearance and disappearance times are referred to in the notes, where known. Observers from widely different areas reported worse than usual tropospheric cloud obstruction to viewing during 1978, and cloud-free regions were at times too restricted to allow of a sure assessment of longitudinal extent of the cloud field.

In the third column of Table I brief notes of the displays enlarge on the facts listed in the remaining columns, referring to photographs and sketches available. Further information will be provided wherever possible, if requested.

Positive reports of NLC were received from 16 stations of the Meteorological Office network of Great Britain, one station of the Irish Meteorological Service and 11 stations of the Swedish Meteorological & Hydrological Institute and from a special NLC observing aircraft operating over Sweden. Positive reports from voluntary observers included those from the Fair Isle lighthousekeeper, Whitby coastguard and experienced contributors of many years from Newton Stewart, Milngavie, Fort Augustus, Enfield, Rønne and Fiane. Photographs and sketches of great detail and artistry were a welcome addition whenever provided.

Routine hourly observations for hours of darkness were received from 16 meteorological stations and form an important part of the data collection, particularly where conditions are sufficiently clear to allow an observer to state confidently 'No NLC'. These records are supplemented by voluntary observers, in many instances, who are providing lists of negative observing periods. The Swedish data summary lists the prevailing tropospheric conditions with details as to the degree of possibility of ascertaining the presence or absence of the clouds. 'Negative' nights are significant, particularly during a possibly unbroken series of appearances of NLC. They are also a helpful point of reference when NLC is suspected by a single observer in the vicinity.

During 1978 NLC sightings were listed on 50 nights; no details are available for a few of these, and others are recorded as 'suspected' only. There seem to have been few outstanding displays; the brightest, most widely viewed and most extensive occurred during July, that of 10/11 July being seen as 'brilliant' from western Scotland, and observers in Gotland were favoured with some bright displays.

More displays were recorded for July than for June, the fortnightly periods of the former showing 12:11 against 6:8 for June. Eight were recorded in the first fortnight of August. The starting date for positive observations, 25–26 May for 1978, is 11 days and some 5 displays later than in 1977, and compares rather with 1973, 1974, and 1976. There were no displays reported outside the expected end-of-season dates.

In Edinburgh time-lapse photography was carried out throughout the observing season; on occasions there NLC was detected by eye, but conditions for protracted filming were unfavourable. Photographs were received from Fort Augustus (0030 h 18/19 June) and from Rønne (2255 h 18/19 June) and Alrö (2205–2230 27/28 June).

We are grateful for all the information received to enable the compilation of this list and congratulate observers on the quality of their reports.

Table I. *Displays of noctilucent clouds over western Europe during 1978*

Date—night of	Times UT	Notes	Station position*	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
25/26 May	2300–0100	Low elevation veil to N and band in NNE, fading to veil only in NNE.	56.5°N 03°W	2300	10	350–040
				2400	7	010–030
26/27	0300	Wispy NLC 'plumes' in NNE; veil NE–E.	55.5°N 01.5°W	0300	11	020–090
28/29	0100–0300+	All stations agreeing on high elevation of NLC, with consequent more tenuous appearance; seen finally as strands against blue dawn sky, fading as sun rose.	59°N 03°W	0100	25	350
			57°N 02°W	0100–0200	80	
			55.5°N 04.5°W	0200	24+	300–030
				0300	45	
29/30	2200, 2300 0100, 0200	Suspected NLC, though 'nil' report at 2400 h.	57°N 02°W	2300	9	360
2/3 June	2400, 0100	Faint veil with wisps spreading to higher elevation.	55.5°N 01.5°W	0100	30	340–030
			55°N 04.5°W			
4/5	0100	Broken band of NLC—not visible at 0200 h.	54.5°N 06°W	0100	25	340–030
8/9	0010	Faint NLC visible through broken tropospheric cloud to N.	56°N 03°W		10	330
10/11	2340, 0100	Faint NLC to N.	55.5°N 05.5°W	0100	7	360
			55°N 04.5°W			
12/13	2300–0100	NLC visible through breaks in tropospheric clouds—later complete coverage of low cloud. Indications of extensive azimuth spread of NLC.	57.5°N 03.5°W	0100	25	350–090
			57.5°N 07.5°W	2300	—	350–020
			56°N 03°W	2355	8	360
			55°N 04.5°W			
13/14	2315–0300	Extensive display, carefully sketched at Kinloss and Fort Augustus, with all the various forms visible; brightest 2400–0030 h.	57.5°N 03.5°W	2400	46	330–070
				0100	46	330–070
			57°N 04·5°W	2315	20	360
				2345	60	305
					25	308-360
					35	004
				0030	60	315
					30	350–050
			56·5°N 07°W	0100	12	340–030
				0300	7	045
			55·5°N 03°W	2400	11	020
			55·5°N 04·5°W			
16/17	2350	Probable NLC (conditions of very good visibility, but moonlight).	55·5°N 04·5°W			
18/19	2145–0245	Earliest report from Sweden, latest sighting from Newcastle, most southerly from Bedford. At Fort Augustus display brightest 0030 h when a vivid blue striated band stretched in N–S direction (photograph). Display seen from Leeming (0040 h) as 3 bright bands radiating fanwise, with cross billows developing in centre of the 'fan'. From Bedford 5 or 6 bands visible, angled at 45° NNE towards SW. Photographs taken serially 2330–2400 at Milngavie.	57·5°N 18·5°E	2200	15	350–020
				2350	30	350–020
				0020	25	340–010
			57°N 04·5°W	0015	28	044
				0030	32	360–045
			56°N 04·5°W		40	
			56°N 03°W			
			55·5°N 04·5°W			
			55°N 01·5°W	0145	15	340–040
				0245	20	330–020
			55·5°N 01·5°W			
			55°N 04·5°W	0040	15	360
			54·5°N 01·5°W	0040	12	330–045
			52°N 0·5°W	0200	45	340–020

* to nearest 0·5 degree.

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths
					degrees	
19/20	2200–0200	No details.	56°N 03°W			
			55·5°N 01·5°W			
20/21	0245	At 0200 h 'No NLC' in almost clear skies. At 0245 h very faint patch of NLC visible—faded 0308 into sunrise.	59°N 03°W	0245	18	030
23/24	2200	No details of early sighting. Extensive formation of billows and band visible to high elevation from Visby.	59·5°N 18°E			
	2340–0040		57·5°N 18·5°E	2340	45	360–090
				0015	30	340–360
					50	030–100
24/25	2230–0100	Banded veil formation to high elevation remaining constant, brightest 2300 h.	57·5°N 18·5°E	2230	50	330–030
				2300	60	340–030
26/27	2330	NLC visible through breaks in tropospheric cloud—photographs.	56°N 03°W			
28/29	2255–2345+	Faintly at first, but with increasing brightness, NLC (thin bands and billows) reached max. elevation at 2325 h. New formations appeared NNE horizon and moved in westerly direction.	55°N 14·5°E	2315	15	315–020
				2325	25	
30 June/1 July	2350	Probable NLC to N.	56°N 03°W			
1/2 July	2230	Faint patch of NLC with single bright band, above tropospheric clouds to 8°.	55°N 14·5°E	2230	12	360
2/3	2250	Presence of NLC strongly suspected visible through breaks in tropospheric cloud.	56°N 03°W			
4/5	2330, 0100	Low elevation, short-lived appearance of NLC seen central and SW Scotland, partially obscured to N by tropospheric clouds.	56·5°N 03°W	0100	5	340–020
			55·5°N 05·5°W			
			55°N 04·5°W			
5/6 July	2300, 0300	NLC visible in gaps in 7/8 tropospheric cloud cover.	57·5°N 07·5°W			
			56°N 03°W			
6/7	2315–0045	Sufficiently clear conditions before 2300 h to decide NLC not visible. After 2315 h medium brightness formation of veil, bands, billows and whirls to high elevation; varying brightness (very bright at Visby 0015 h). After 0045 h increasing tropospheric cloud.	58°N 14°E	2330	90	300–070
				2400	80	300–070
				0200	80	300–050
			57·5°N 18·5°E	2315	25	350
				0015	35	330–020
7/8	2155–2330	Medium brightness NLC showing whirl formation at high elevation.	59·5°N 18°E			
			58°N 14°E	2300	80	320–060
8/9	2045–0100	A bright display of NLC as viewed Gotland with all forms visible, increasing to cover most of N sky. Faded quickly after 0045; no longer visible at 0115 h though viewing conditions still good. Seen through breaks in tropospheric clouds from Northumbria, and suspected at Edinburgh. (Photographs—Paviken)	57·5°N 18·5°E	2045	30	350–030
				2145	40	340–030
				2300	90	300–090
				0015	75	280–070
				0045	30	280–350
			56°N 03°W			
			55·5°N 01·5°W	0100	10½	
9/10	2300, 2320	Possibly small patch of NLC at high elevation.	57·5°N 03·5°W	2300	80	360
			55°N 04·5°W			
10/11	2115–0215	Widely observed display, brilliant as seen W Scotland. At Jönköping NLC spread to 45° max. elevation; seen as bands to elevation 3° from N Yorkshire.	58°N 14°E	2230	30	340–030
				2345	45	330–020
				0015	45	340–020
			57·5°N 07·5°W	2400	12	340–020
			56·5°N 07°W	0100	4	330–030
				0200	9	040
			55·5°N 10°E	2115	30	315–045
				2130	35	290–045
			55·5°N 05·5°W	2400	15	315
			55·5°N 01·5°W	2300	12	300–020
				0100	11	360–030
				0145	13	360–010
			54·5°N 01·5°W	2330	3	310–320
				2400	2	340–040
			54·5°N 00·5°W			
12/13	2153–2400	No details.	59·5°N 18°E			
13/14	2030–0045	First noted as bright amorphous spread of NLC: bands and billows developed and were discernible to end of display. At 0045 h no NLC visible in clear observing conditions.	59·5°N 18°E			
			57·5°N 18·5°E	2115	30	300–030
				2215	60	310–020
				2315	30	330–030
				0015	45	320–070
			55°N 04·5°W	2350		

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths
					degrees	
14/15	2200–2400	No details.	59·5°N 18°E			
			55°N 04·5°W			
17/18	2125–0245	Earliest sighting Alrø (Denmark) when banded structure to 4° elevation discerned through binoculars. Noted soon after at Visby (Gotland) when bright bands and whirls visible to 40° elevation. No further NLC visible there at 2345 h, though viewing conditions good. At 2220 h bright bands and whirls to 70° elevation seen at Jönköping. There, too, an hour later no NLC visible in clear conditions. In E Scotland NLC suspected 0050 h and at 0140 h clearing of tropospheric clouds to E revealed very bright bands to 37° elevation. At 0225 h azimuthal spread to 130°, with many forms parallel to horizon and more tenuous filaments in N–S direction. NLC mainly obscured by tropospheric cloud at 0245 h though billows still visible in cloud breaks to 20° elevation ENE (sketches). Bands and billows seen briefly but bright in NE England to approx. 10° elevation at 0150 h. No details of farthest N sighting at Arlanda/Bromma.	59·5°N 18°E			
			58°N 14°E	2220	70	350–360
			57·5°N 18·5°E	2145	40	340–020
				2315	30	
			56·5°N 03°W	0140	37	020
				0215	40	340–060
				0225	22	?–130
				0235	35	040
			56°N 10°E	2125	4	045
				2200	10	045
			55·5°N 01·5°W	0150	8	355–005
			54·5°N 01·5°W	0145	10	340–020
18/19	2140–2345 0150–0215	NLC visible through breaks in tropospheric clouds from Edinburgh and Bedford. Seen as veil with brighter patches; whirl formation suspected by more southerly observer.	56°N 03°W		15	320–040
			52°N 00·5°W	0200	5	355–030
19/20	2400	Probable NLC seen from Edinburgh.	56°N 03°W			
20/21	2215–0020	No details.	59·5°N 18°E			
22/23	2100–0100	NLC to high elevation over mid and southern Scandinavia—bands, billows and whirl formation: brightness no more than moderate.	64°N 10·5°E	2130	30	340–020
				2230	40	320–020
				2330	50	310–020
			61°N 14°E	2215	90	360
			59°N 09°E	2205	60	345–070
			57·5°N 18·5°E	2200	15	330–020
			57·5°N 12·5°E	0100	30	340–010
			56°N 12·5°E	2215	6	350–010
23/24	2225–2400 0140–0300	Earlier sighting from Sundsvall limited by tropospheric clouds though viewing conditions still 'possible' when NLC no longer visible at 2205 h. Later sightings from Dyce and Kinloss both sketched to show compacted area of bands with firm E edge. At latest sighting, from Rosslare, banded veil spread to high elevation N–ENE.	62·5°N 17·5°E	2225	30	330–040
			61°N 14°E			360
			57·5°N 03·5°W	0200	15	040–050
				0220	18	360
			57°N 02°W	0140	18	340–040
				0235	25	325–360
			56°N 03°W			
			52·5°N 06·5°W	0200	6	360–060
				0300	30	360–070
24/25	2250	Probable NLC to N.	56°N 03°W			
26/27	2300 2340–0230	Scottish stations reported striated veil with multiple 'bolder' bands. From more northerly station wisps of NLC also seen to higher elevation.	59·5°N 18°E			
			57·5°N 03·5°W	2400	35	360–030
				0100	35	360–030
			57°N 02°W	2400	15	005–012
			56°N 03°W			
27/28	2140–2300 0200–0230	NLC seen at Alrø through breaks in tropospheric cloud: photographed there 2205–2230 h during peak brightness. From Scotland east part of display obscured. Sketched visible area shows fine ripples, multiple parallel bands and denser patches of NLC. Positive report from Swedish NLC observing aircraft 2140–2230.	63°N 17–20°E			
			57·5°N 03·5°W	0200	20	340–010
			56°N 10°E	2155	13	290–345
			56°N 03°W			
28/29	2300–0230	Display at peak brightness and extent 0100–0200 h; viewed mainly between tropospheric clouds but in clear conditions from Dyce: sketches show multiple bands and whirls against veil background; weak veil noted to 50° elevation at 0145 h. Faded into brightening sky around 0215 h.	61°N 14°E	2400		290–360
			60°N 01°W			
			59·5°N 01·5°W			
			59°N 03°W			
			57·5°N 03·5°W	0200	12	360–020
			57°N 02°W	0030	25	330–015
				0130	30+	315–030
				0145	50	
			55·5°N 01·5°W	2400	2	340–010
				0100	4	350–010
				0200	8	340–030
30/31	2130–2200	No details.	63°N 17–20°E	2130		
			61°N 14°E	2145		315–360

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
2/3 Aug.	2220–2400+	Medium brightness herring-bone formation to high elevation. Fog obscured observations at 0020 h.	62·5°N 17·5°E	2220	30	010–040
6/7	2200–0100	Billows against veil background—medium brightness, decreasing towards end of sighting.	63°N 17–20°E			
			62·5°N 17·5°E	2330	20	360–030
				0030	15	360–030
8/9	2150–2350	Display visible N Sweden—SE Norway—mainly seen as extensive veil, though billow formation noted Umeå. No NLC visible by midnight GMT in clear sky conditions.	65·5°N 22°E	2200		345
			64°N 20·5°E	2230	20	310–360
				2320	15	300–330
			62·5°N 17·5°E	2330	15	330–030
			59°N 09°E	2215	90	345–090
9/10	2235–2345	Faint NLC noted for short periods from NLC observing aircraft and later from Sundsvall—billow formation seen NNE.	63°N 17–20°E			
			62·5°N 17·5°E	0200	10	020–030
10/11	2150–2205	Short-lived veil and band of NLC; medium brightness seen at Sundsvall in clear sky conditions. No details of more southerly sighting.	62·5°N 17·5°E	2200	80	360–040
	2230–0130		55·5°N 13·5°E			
12/13	2215–0100	Faint NLC seen from NLC observing aircraft.	63°N 17–20°E			
13/14	2240–0014	Veil of NLC, extensive but faint. Earlier sighting from aircraft.	63°N 17–20°E			
	0100–0200		62·5°N 17·5°E	0100	30	300–010
				0200	30	300–010
14/15	2330–0230	Faint NLC veil observed constantly over 3 hours.	62·5°N 17·5°E	2340–0230	15	340–060
			61°N 14°E			
			59·5°N 18°E			

Reviews

Microphysics of cloud and precipitation, by H. R. Pruppacher and J. D. Klett. 180 mm × 245 mm, pp. xiv + 714, *illus.* D. Reidel Publishing Co., Dordrecht, Holland, 1978. Price Dfl 85.00.

The title of this scholarly and useful book is rather misleading in that it contains much that is only marginally relevant to clouds and precipitation and does not attempt to get to the heart of cloud physics which is concerned with the evolution of populations of hydrometeors within a framework of cloud dynamics.

Some idea of the content and balance of the book may be given by noting that after a chapter of only 35 pages describing the microstructure of clouds and precipitation, nearly 100 pages are devoted to the thermodynamics of aqueous phase changes and to the structure and surface properties of the water substance. Fifty pages are allocated to the mechanics of aerosols, much in the spirit of Fuchs's classical text, and 45 pages to the effects of electrical forces on the evolution of clouds and precipitation which, in the reviewer's judgement, could have been omitted as being of very little importance. Two of the most valuable and relevant chapters for cloud physicists are those given to the collision and coalescence of cloud particles but one might question whether the present state of knowledge of these topics merits 80 pages of text.

The treatment of all topics is detailed and thorough with more emphasis on formal mathematical presentation than on experiment and physical insight. The reader's patience is often tested by having to follow the authors through a long mathematical argument which leads to no useful physical result until they make a crucial, simplifying assumption or an appeal to experiment which they could have done much earlier. The text is well and clearly written but is not helped by the heavy, mathematical symbolism and type, the small diagrams relieved by very few photographs and hardly a single diagram of experimental apparatus. Even Dr Pruppacher's own beautiful experiments on the aerodynamics and growth of single hydrometeors receive much less than their due.

However, it is perhaps not quite fair to criticize the authors for not writing a different kind of book. They have obviously tried to produce a text quite different from the standard works on cloud physics but their restricted view of the subject hardly merits a book of this length. In following all the mathematical detail (not to mention the 18 mathematical appendices) the student will find it difficult to see the wood for the trees, for there is little attempt to set the individual topics in their wider context and link them in a manner that gives a feeling for the subject as a whole. This book contains much that is admirable and useful but there is no whiff of the atmosphere, no glimpse of real clouds, and few hints of the most important of the unsolved problems in cloud physics. For me, it fails to convey the fun and the excitement of the subject; it impresses but does not inspire.

B. J. Mason

Scientific aspects of the 1975–76 drought in England and Wales (A Royal Society discussion organized by Sir Charles Pereira, F.R.S., O. Gibbs, H. L. Penman, F.R.S. and R. A. S. Ratcliffe on behalf of the British National Committee on Hydrological Sciences, held on 28 October 1977). The Royal Society of London. 240 mm × 170 mm, pp. vii + 133, *illus.* The Royal Society, 6 Carlton House Terrace, London SW1Y 5AG, 1978. Price £6.50 (United Kingdom addresses, including packing and postage) and £6.70 (overseas addresses, including packing and postage).

The 1975–76 drought was discussed at the Royal Society in London on 28 October 1977. This book is the official account of the meeting; all papers except the first deal with hydrological aspects of the drought and its effects on the water supply industry and on agriculture in England and Wales.

The paper by Ratcliffe on 'Meteorological aspects of the 1975–76 drought' covers and extends material contained in papers published in the *Meteorological Magazine* dated May 1977. The description of features of the broad-scale atmospheric circulation, the anomalous rainfall distribution, the unusually cold sea surface over the Pacific etc., is excellent. Several interesting synchronous interrelationships between atmospheric circulation, sea temperature anomalies and large-scale weather are presented with clarity. The 'explanations' of the drought in terms of feed-back between ocean and atmosphere and persistence effect of the dry soil produced by the drought are suggestive and plausible although not objectively convincing. There is a surprising statement on p. 9 that 'All the statistical evidence . . . suggested a breakdown to a normal unsettled summer pattern' (in 1976). In fact, the pressure anomaly rules for predicting seasonal rainfall over England and Wales, published by the reviewer in the *Meteorological Magazine*, correctly indicated not only the dry summer of 1976 but also the dry winter 1975–76, the dry spring 1976 and the wet autumn 1976 (see *Weather* **32**, 1977, p. 325).

Carter gives a straightforward account of 'The effect of the drought on British agriculture'. Lack of water and weather-related diseases and pests seriously restricted crop yields and affected quality, but livestock survived the drought fairly well. The long-term effects on agriculture seem to have been small.

The rest of the book is concerned with hydrological aspects. Clarke and Newson analyse hydrological observations at several experimental catchments. The marked variations in the severity of the drought on stream flow are largely explained by differences in catchment characteristics, in underground water storage and in land-use. The authors stress the importance to water management of future changes in land-use from pasture to forest in upland areas where many major reservoirs are sited.

Day and Rodda deal with 'The effects of the 1975–76 drought on groundwater and aquifers' by discussing well hydrographs covering four years to 1977 for several places and by comparing the observations with long-period data. Well levels had fallen below previous records in many places by late summer 1976, but no adverse long-term effects on aquifers seem to have occurred.

A long paper by Hamlin and Wright gives much information on the low flows in many river systems. River-flows are related to catchment rainfall and soil moisture deficit and the low flows in 1975–76 are put in historical perspective. The severity of the 1975–76 drought in different river systems was extremely variable: for durations of a month or two in some rivers (for instance the Severn) the return period exceeded 200 years but for durations of many months in most rivers it was much less.

As pointed out by Davies, the chemical and biological effects on the quality of surface- and ground-water arising from the drought are evidently complex and varied.

Apart from a short summing-up by Pereira, the last paper is by Gibb and Richards and deals with 'Planning for development of ground water and surface water resources'. After assessing the water resources of England and Wales, they describe the build-up to serious water shortages in the summer of 1976. The authors outline long-term plans for developing water resources, based to some extent on the experience of the drought.

This book puts on record many facts and shows that progress has been made in scientific understanding, especially regarding hydrological aspects of drought. Many thought-provoking ideas are presented, but the root-causes of the abnormal atmospheric behaviour which resulted in the drought and ultimately in its breakdown are still unknown.

R. Murray

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	1973	Forecasting seasonal rainfall and temperature for England and Wales in spring and autumn from anomalous atmospheric circulation over the northern hemisphere. *Meteorol Mag*, **102**, 15–26.
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Ratcliffe, R. A. S.	1977	A synoptic climatologist's viewpoint of the 1975–76 drought. *Meteorol Mag*, **106**, 145–154.

Letter to the Editor

Forecasting for the escape of Scharnhorst and Gneisenau

I read the article which appeared in the *Meteorological Magazine*, 107, 1978, pp. 321–338, 'Forecasting for the escape of Scharnhorst and Gneisenau' with great interest and found it fascinating reading. I believe, however, that there may have been some errors in the translation. The Editor assumes (page 323) that Island (Iceland) must be a typing error and translates it as Ireland. The text states that there were four regular daily flights, two of which covered Ireland and the Irish Sea. The 'important gap' referred to must surely be Iceland and the 500 km wide zone between Iceland and Scotland.

Secondly the Editor expresses doubt over the translation of the following passage (page 329): Die Basis würde in gleichem Maße schlechter, als der Kampfraum wieder aufklart. I believe that die Basis should be translated as the Base and not the Bases (German, die Basen) which makes the sentence read:

'The weather over the base (Brest) would be deteriorating as it again improved over the battle area (Dover Strait). In the afternoon the base would again have favourable weather'.

R. F. Lovett,
Lieutenant Commander,
Royal Navy.

*RN School of Meteorology
and Oceanography,
RNAS Culdrose*

[The translation of Dr Stöbe's text was carried out by several people in consultation, using the first English version as a basis. The original German of the first passage to which Commander Lovett refers is as follows:

Da die Flüge nur einmal am Tage stattfanden, jeweilig also 24 Stunden zwischen den einzelnen Beobachtungen lagen, bildeten sie doch nur einen notdürftigen Ersatz für die sonst üblichen laufenden Wettermeldungen normaler Zeiten. Die sehr fühlbare Lücke Island und ein durch die Flüge nicht erfaßter Raum zwischen Irland und Schottland von fast 500 km Breite blieben immer bestehen. Ganz vereinzelte Meldungen von England und Irland, teils aufgefangene Wettermeldungen von Flugplätzen, teils Agentmeldungen, waren wohl wichtig, aber durchaus unzureichend.

As regards Iceland versus Ireland, the bother is that Iceland is nearly 800 km from Scotland, not 500; however, the stretch St George's Channel–Irish Sea–North Channel *is* about 500 km long. Hence our perplexity. Editor.]

Notes and news

Appointment of the Director-General as Pro-Chancellor of the University of Surrey

At the annual meeting of the Court of the University of Surrey held on Friday, 19 January 1979, it was agreed unanimously to approve the appointment of Dr B. J. Mason, CB, FRS, Director-General of the Meteorological Office, as Pro-Chancellor from 9 September 1979. He will succeed Sir George Edwards, OM, CBE, FRS, who will retire from office on that date.

Dr Mason has been associated with the University for ten years. He is currently Vice-Chairman of Council, having been a member since 1969, and Chairman from 1971 to 1975.

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NOTICES

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

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Forecasting for the construction and tow of the Ninian Field Platform

By O. M. Hull

(London Weather Centre)

Summary

The weather forecasting problems involved in the construction of a massive concrete drilling platform off north-west Scotland and its towing to its operational position in the North Sea oilfield are described, as is the successful overcoming of these problems by the establishment of a special local forecasting office.

A new task for the London Weather Centre

For many years now the London Weather Centre has been involved in forecasting for the North Sea Oil industry, but in 1977 we first became involved in the tow-out and positioning of production platforms. After exploratory drilling has established the existence of an undersea oil field, and the exact position from which it can best be tapped, the test well-heads are sealed off and the sea bed is cleared for the construction of a production platform. From the production platform a number of new wells will be sunk into the oil-bearing strata, and a pipe-line or loading buoy will be attached to get the crude oil ashore.

In the deep water of the northern North Sea there are two types of production platforms in use. Steel platforms consisting of a framework of huge steel girders taller than the water depth, say 200 metres, are floated over the field and stood upright over the spot chosen for drilling. The difficult and weather-sensitive task of pinning the platform to the sea bed with huge piles must then be completed before the superstructure of pump rooms, drill equipment, accommodation and helicopter deck, is lifted and built into position—a very slow job in a rough stretch of water. Concrete platforms, on the other hand, consist of vast and complicated concrete towers, which are floated in sheltered bays during the construction phase, then towed out to the chosen locations and sunk. Their own weight and vast base area make piling unnecessary and, since the superstructure is in position when they leave harbour, these platforms are almost ready to start drilling and be coupled to the pipe-line as soon as they hit the sea bed. Positioning on the drilling site is a much less weather-sensitive operation than for steel platforms, but calm conditions are necessary for the critical operation of fitting the superstructure into position on the platform.

Most concrete platforms for the North Sea have been built in the deep but sheltered waters of the Norwegian fjords; however, Chevron Petroleum had their Ninian Field platform built by Howard Doris Ltd at Loch Kishorn on the west coast of Scotland, just east of the Isle of Skye (see Figures 1 and 2). The base of the platform, about the area of Trafalgar Square, was built like a huge washing-up bowl in a specially constructed dry dock and then floated into Loch Kishorn. As the construction continued, the structure sank deeper in the water and for the final stages of the work it was moored in very deep water at the southern end of the Inner Sound of Raasay.

Howard Doris had set up a forecasting office to assist in the construction phase, using a French forecaster and two assistants. The office was equipped with radio-teleprinters and radio-facsimile receiver.

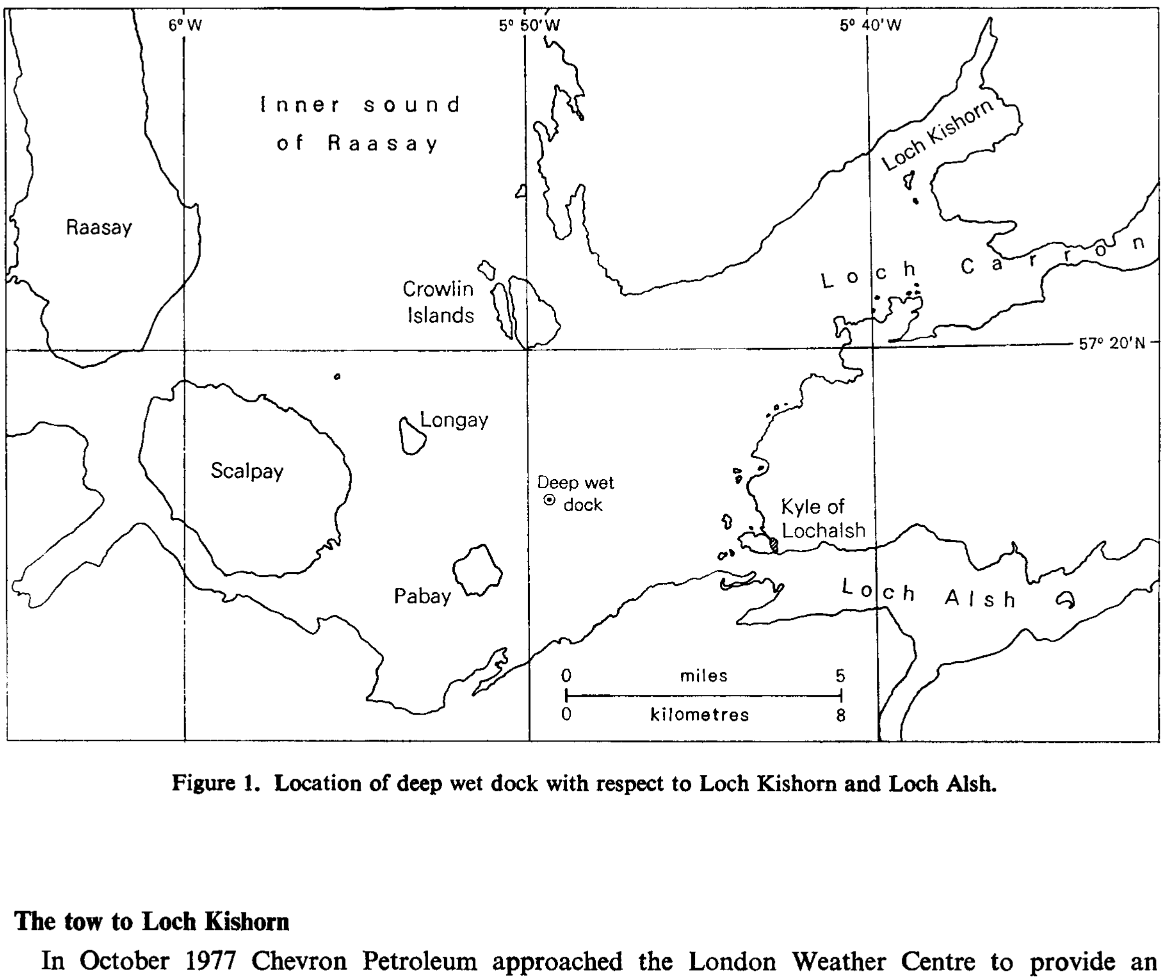

Figure 1. Location of deep wet dock with respect to Loch Kishorn and Loch Alsh.

The tow to Loch Kishorn

In October 1977 Chevron Petroleum approached the London Weather Centre to provide an 'on-site' forecasting service for the mating of the concrete base and the steel superstructure, which would hold most of the engineering and accommodation. The first task was towing the superstructure from its construction site at Ardersier, near Inverness, through the Fair Isle channel to Loch Toscaig

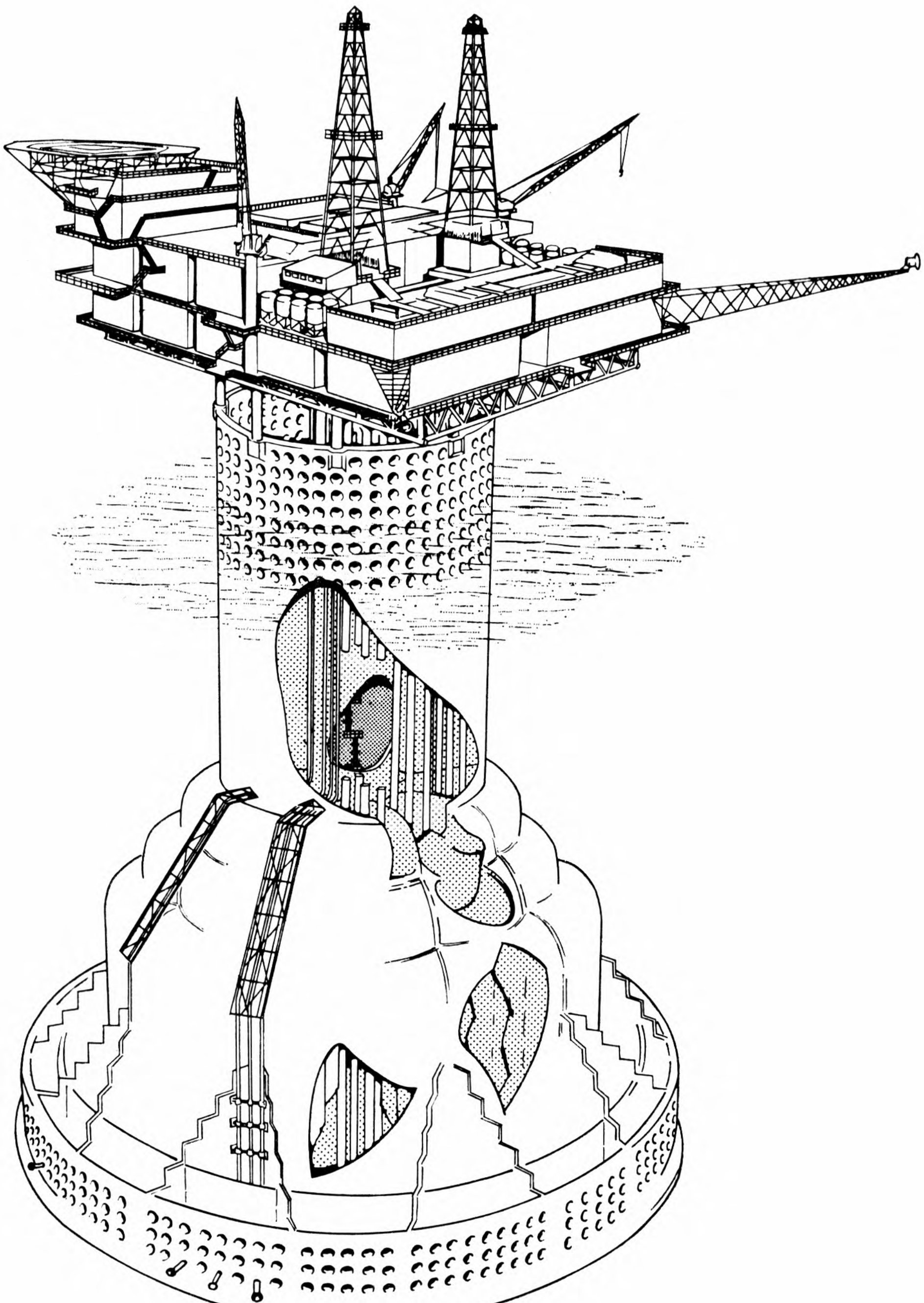

Figure 2. The Ninian Field Central Platform (reproduc d by permission of Howard Doris Ltd).

near Kishorn. The forecast for this operation was provided by the London Weather Centre and started on 19 October 1977. The two-and-a-half-day tow was completed during a short 'weather window' between two autumnal depressions, and the tow arrived off Loch Toscaig on 9 November.

Transfer from barge to catamaran

Two forecasters from the Weather Centre were at Kishorn when the tow arrived, and by snatching every moment when fair weather was forecast the engineers jacked the huge superstructure off the towing barge and secured it on a catamaran barge whose pontoons were wide enough to straddle the top of the concrete base. This work was completed on 11 November and the catamaran was moored in the sheltered waters of tiny Loch Toscaig.

A new forecasting office

For the mating of the base and superstructure a flat calm was required for 48 hours and about five days' warning of the calm was needed to mobilize all the necessary staff and facilities into this remote part of Scotland. A forecasting office had been set up at the Chevron office. Chevron provided a barometer, and an anemometer which was very badly sited at the top of a cliff and on the south side of a 2500 ft hill; but in that wild country there are few good anemometer sites, and the readings from Loch Kishorn bore little relation to the readings from the anemometers on the structure floating in the Inner Sound. There was a wave recorder buoy anchored to the north of the platform with read-out in the forecasting office of the construction company, Howard Doris Ltd. A teleprinter link from Inverness Airport, a radio-facsimile receiver and best of all a telecopier completed the forecast office equipment. The forecasters were provided with extended forecast charts covering a period up to five days ahead. They also had copies of the unique surface wind output from the fine-mesh numerical forecast model run twice a day on the COSMOS computer system at Bracknell together with guidance forecasts issued by London Weather Centre to Chevron Petroleum. Formal briefings were given twice a day to the Chevron site manager and any of his staff who were involved in planning the next day's work.

The first submerging

For a few days after the transfer of the superstructure to the catamaran, the engineers were busy putting the final touches to the platform, removing the scaffolding from it and dismantling the cranes which had been used to build it. This gave the forecasters a few days to sort out their communication problems and to assess the problem of forecasting for a huge structure floating in a narrow bay between the mountains of Skye and the mountains of mainland Scotland.

In order to float the superstructure over the concrete base, the platform had to be ballasted deep into the water; at this stage the outer skin was being used for flotation and this was constructed with a honeycomb of holes, to act as a breakwater for the inner skin when the platform was in position. These holes had been plugged and it was decided to test the plugs by ballasting the structure down to the depth it would have to reach when the superstructure was floated over it. The task was fairly delicate since the collapse of one plug would probably mean the loss of the £30 million structure. At first a 15 knot weather window was required but as time went by and pressure increased the job was done in winds of nearly 25 knots and seas of 1 to 1·5 metres.

A weather window opens

On the morning of 21 November the forecast for late that week showed a col over the west of

Scotland, and the Chevron site manager called for a special briefing at 2200, after the issue of the extended forecast charts. These charts indicated a weather window on Friday the 26th, and the mobilization of manpower was started.

Count-down to the mating

During the next few days the platform was stripped of the remaining huts, cranes, aerials and of course the anemometer. Much of this work was carried out in atrocious weather. Thursday the 25th was a stormy day with violent showers and the crew aboard the concrete platform reported waves of 1·5 metres. At noon on Thursday the senior staff from Chevron's London Office were briefed. The weather forecast was good but the amount of swell forecast was not acceptable. A strong northerly wind had generated swell about 400 miles north of Kishorn, the wind in the generating area had moderated, and a swell of 30 cm with a period of 11 seconds was forecast for Friday morning, falling to nil by 1800 on Friday. At noon on Thursday the wave recorder was giving 80 to 100 cm waves with a maximum wave of 160 cm and a period of 5 seconds. There was no noticeable swell on the trace of the wave rider, but it was probably masked by the wind waves. During Thursday afternoon, reports available at the London Weather Centre indicated that the swell might have a shorter period, about 10 seconds, and observations by the light-keeper at Rudh Re 50 miles to the north of Kishorn indicated that the seas were moderating.

At 1800 on Thursday a meeting was held of all the senior engineers, marine superintendents, the senior tug skipper, and the representatives of the insurance companies covering the operation. The meteorological briefing came first, and very light winds and a rippled sea could be forecast with confidence but the exact figure of 30 cm of swell at dawn falling to nil by 1800 had to be qualified; however, since the calm was now certain to last until Saturday and the swell at worst would cause a delay, it was decided to start the operation at first light on Friday, provided that a weather check at 0500 proved satisfactory.

The first part of the job completed

At 0300 on Friday the wave rider buoy gave 20 cm, with a maximum wave of 25 cm and a period of 10 seconds; a hand anemometer on the concrete platform gave 15 knots. At 0500 the necessary insurance certificate was issued and by 0730 the tow out of Toscaig started. A report from the catamaran when clear of the harbour indicated a swell of 12 cm, and this agreed with the maximum wave given by the wave rider buoy. The wind fell to calm, no technical snags developed and the work was soon running ahead of schedule. By 1400 the final mating took place and at that time there was about 2·5 cm of vertical movement between the two structures; 'Just enough to jiggle the guide pins into place', said the engineer in charge. This implied a swell of about 6 cm.

Life on the North-west Frontier

Although three out of four of the forecasters involved in the work at Loch Kishorn were Scots, we were all city dwellers and found the north-west of Scotland in winter a strange but beautiful place. The snow fell and stayed white, the deer moved down from the hills and foraged each night between the cranes and the scrap iron for what bits of grass were left on the construction site. The early morning drive to work was always interesting, and sometimes impossible; then we would come in by boat, which was far more pleasant.

At first we were accommodated in a magnificent but unheated shooting lodge at Strathcarron. The walls were thick with the heads of ten-point stags but there was not a radiator in the place. The local ladies who cleaned, and made the beds, were fresh-air fiends and always opened the windows wide; the night duty forecaster often returned to find inches of snow on the bedroom carpet. Later we moved into an hotel which was nearer to Loch Kishorn and was heated!

Fitting out the superstructure

After the critical mating operation there was a pause of a few days in the weather-sensitive activity at Loch Kishorn, but on 6 December a forecaster returned to the site to provide forecasts during the lifting of the prefabricated units containing workshops, generators and living accommodation. These lifts were up to 700 tons and were carried out by the derrick barge *Odin*.

The individual lifts only took a couple of hours, but between lifts the huge barge had to be manœuvred round the concrete tower to a new position and each move was a slow and delicate process; a snapped cable in a 25 knot wind could swing the barge on to the platform with shattering force. As the *Odin*'s charter time ran out it was necessary to use every minute of fair weather. The barge crew worked round the clock and the forecaster was needed from early in the morning until late at night. On 27 December the *Odin* sailed and the duty forecaster returned to the Weather Centre. In the New Year a further array of prefabricated modules was assembled at Loch Kishorn and a forecaster returned for a short period to help with their positioning. These lifts were generally much heavier, some of them over 1000 tons, but the derrick barge moved around the rig less often.

Getting ready for sea

Towards the end of April the platform was nearly ready to be towed into the North Sea. On the 24th a forecaster arrived at Loch Kishorn to find a hive of activity which made the earlier busy periods seem tame. The forecast office at the Chevron site was reopened and regular meteorological briefings were provided. The meteorological thresholds which were needed varied with the section of the route.

The tow could not be started in the confined waters of Raasay Inner Sound if the wind was force 5 or more, but in the open sea, winds of 40 knots and seas of 5 metres could be handled. However, over the relatively shallow water of Shiant Bank in the Minches the wind had to be less than force 5 and tides, currents, salinity and adverse weather all had to be considered before the tow started so that the platform would pass over the Bank with three metres' clearance from the sea bed.

The tow starts

On the morning of Wednesday 3 May the platform was ready to go but the forecast, which indicated a low moving across Ireland and Northern England, was not completely favourable and the tug skippers and insurers were reluctant to let the tow start, but later in the morning the next issue of 48 and 72 hour forecast charts suggested that the low would keep further south and at the afternoon briefing the decision to go was taken.

On Thursday 4 May the London Weather Centre forecaster moved aboard the tug *Smit London*. At 1800 on Friday the tow started and with apparent ease the 600 000 ton platform became the heaviest man-made object ever to move (see Figure 3). At 0500 on 8 May the platform crossed the Shiant Bank and the decision to shelter or move on had to be made. After receiving a favourable forecast from London Weather Centre the tow continued into the open sea.

A slight snag

During the afternoon the speed was increased to slightly over one knot and the platform developed a marked list. The list was thought to be due to the drag effect of the base which was still close to the sea bed so the tow was slowed until deeper water was reached.

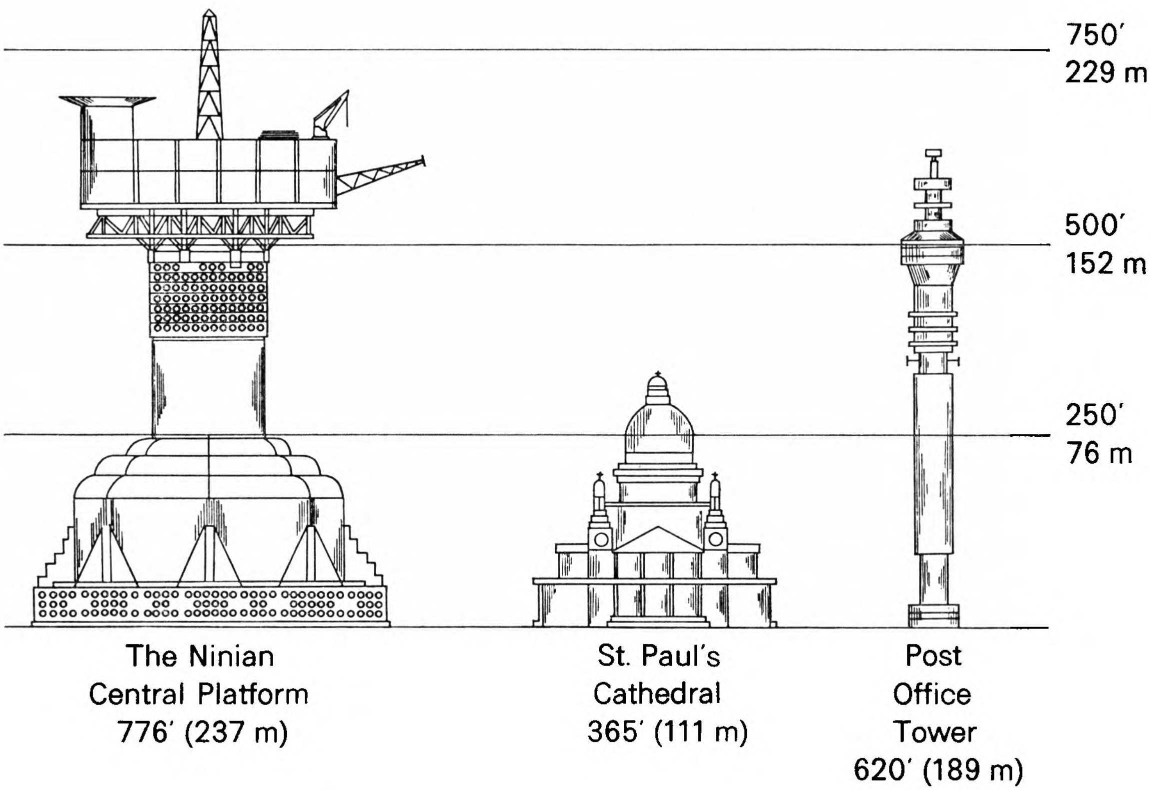

Figure 3. Pictorial comparison of the Ninian Field Central Platform and other well-known structures.

The job completed

From the 9th to the 15th the tow continued at nearly two knots until the shallower water near the Ninian Oilfield was reached. On the 16th, a forecast for the Ninian Field was issued, giving winds of 5 to 10 knots and significant waves of ½ to 1 metre consisting mainly of a confused swell. After that forecast the tow moved straight to the Ninian Field.

On the 17th, a slow approach was made to the site, at 8 metres per minute, in almost perfect conditions with a smooth sea and a long, low westerly swell. The platform was slowly ballasted down and at 1800 it came to rest on the sea bed, perfectly aligned and only 10 metres off the chosen position.

Thick fog drifted over the Ninian Field that night and the forecaster had to decide whether to return to Shetland by helicopter or on one of the tugs. He chose the tug and received the supreme accolade as the Chevron staff all said, 'If the Met. man is going ashore by tug so are we'.

Appendix—The logistics of the operation

By R. M. Morris

(Principal Meteorological Officer, London Weather Centre)

The background leading up to the establishment of a forecasting office at Loch Kishorn is worth recording. Chevron had experienced a series of delays and occasional disasters during the previous winter and spring during the construction of the circular concrete platform at Kishorn, and the deck at Ardersier. The result was that the schedule fell too far behind time to allow for the critical mating with the deck to take place during the 'climatologically' favourable weather of summer. Chevron were thus faced with having to wait until the following summer before completing the mating. As a result of a preliminary contact by our offshore consultant in Aberdeen, Chevron approached London Weather Centre (LWC) about the possibility of carrying out the work during the winter by making maximum use of the expertise and skilful forecasting of weather windows by the offshore forecasters at LWC.

On Thursday 29 October 1977 Sam Murphy of Chevron flew down to London from Inverness to discuss the project with P.Met.O., LWC. By the early afternoon Murphy confirmed that Chevron would give LWC the contract for the forecast service. This service included the establishment of a local forecast office at Loch Kishorn with full back-up support from LWC. Just to show that we could move fast too, on the following Saturday P.Met.O. and a senior offshore forecaster (P. Deeks) flew up to Inverness to inspect the superstructure at Ardersier prior to its tow round to Kishorn. At the crack of dawn on the Sunday we flew by helicopter to Kishorn to see the site of the proposed forecast office and also inspect the floating concrete platform. The weather decided to put on a special show for us that day and the wind increased to 70 knots, straight up the Loch. We made a brave—one might almost say foolhardy—attempt to visit the platform (6 miles away, in deep wet dock) by tug but we were forced to return to base as the vessel could make no headway into the storm. Later we flew back to Inverness by helicopter (a truly remarkable experience in those conditions). I think the fact that we undertook the boat and the helicopter trips impressed Chevron more than anything else that day. By Monday lunchtime (2 November) we were back in London and the organization was set in motion.

A forecaster was detached from LWC to Kishorn within 72 hours. A radio-facsimile receiver and recorder were taken from the radiosonde station at Leuchars to Kishorn, and a document facsimile from Interscandex in Inverness quickly followed to establish a direct documentation link between LWC and the site. There was already a telex line available but the most impressive action was the establishment of a land-line by the Post Office within 14 days to enable the meteorological teleprinter broadcast from Bracknell to be received at the site office. In all there were four forecasters deployed on the site, three from LWC (Messrs M. McColm, O. M. Hull and J. G. Allardice) and J. R. Hill from Glasgow Weather Centre. At any one time there were two forecasters at Kishorn covering the 24 hours and each tour of duty lasted about two weeks.

There is no doubt that the whole operation was a major success and an excellent tribute to the co-operation between all the sections of the Meteorological Office that were involved, i.e. Supply and Finance (Met O 4), Telecommunications (Met O 5), Public Services (Met O 7), the Central Forecasting Office, and the London Weather Centre.

551.575.1(420)

The clearance of persistent fog

By A. A. Brown

(Meteorological Office, Birmingham Airport)

Summary

An investigation was made into the behaviour of fogs which had already persisted from 09 to 17 GMT. It had been noticed that such fogs often seemed to clear during the following night. This is confirmed by the results of the investigation.

Introduction

In radiation conditions the usual expectation is for fog to form rather than disperse at night. However, some fogs do disperse during night-time, and the purpose of this investigation was to examine the behaviour during the subsequent night of fogs which had persisted throughout the day.

It should be emphasized at this stage that no attempt has been made to explain why a fog persists all day, nor yet to find specific reasons for individual fog clearances. Rather the point of the exercise is to highlight the facts that

(a) persistent day-long fogs are perhaps more common than is generally realized, and that

(b) clearances at night are also quite common.

Records for 20 inland stations* in England (shown in Figure 1) were examined from 1975 back to 1967. Earlier than this, it was felt that smoke pollution prior to implementation of the Clean Air Act would distort the results. The choice of stations was restricted to those whose data were available on the computer 'climat' tapes. Where data were missing from the tapes, they were obtained directly from the observation registers of the stations concerned. Hill stations (more than 150 metres above mean sea level) and coastal stations were excluded. Liverpool, however, was included as an inland station because in radiation conditions the wind drift over Liverpool is invariably from the south-east owing to the terrain, and the effect of the adjacent Mersey is largely negated. This was supported by the Meteorological Office staff at Liverpool Airport. The data obtained during this investigation confirmed this point and there was reasonably good agreement between the figures for Liverpool and those from some of the other inland stations.

Only the four winter months from November to February were examined because a pilot survey showed that the occurrence of persistent fog (excluding sea fog) is rare in other months.

The figure of 600 metres was taken as the upper limit in this investigation. This is the halfway point between the upper limits of 'public' fog at 200 m and 'aviation' fog at 1000 m. Also a visibility of 600 m on Runway Visual Range is the limit above which many civil aviation operators can legally make an approach to an airfield.

In general terms it can be argued that a 'normal' fog is one which forms during the night or around dawn and then clears during the following morning, often in the period between 10 and 12 GMT in these winter months. For this investigation a 'normal' fog is so defined. The incidence of fog (using the same 600 m criterion) for each station at 09 GMT gives an indication of the complete winter fog picture, that is to say, 'normal' plus 'persistent' (defined below) fogs. By relating this incidence to that of the 'persistent' fog, a reasonable comparison can be obtained between these two types of fog.

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* Following closure of two of the stations, Mildenhall in 1969 and Abingdon in 1974, the series was continued using Honington and Benson respectively.

Figure 1. The 20 stations concerned in this investigation.

Extraction of data

Table I column (b) shows the number of days in the four winter months November–February over the eight and a half winters in the period from November 1967 to December 1975 when the visibility remained below 600 m from 09 to 17 GMT with no more than a one-hour 'break' of visibility above this limit. Such days were defined as 'persistent' fog days.

Two hundred and sixty-one such days (events) were identified and these occurred on 90 actual dates. Visibility is recognized as being a most variable meteorological element in time and space for any given synoptic situation. In other words, visibility changes at one station are not necessarily connected with those at another station under the influence of the same synoptic system. As there was often a wide disparity of fog-clearance times for these 90 dates, it was decided to treat each event separately.

Table I. *Number of days with fog in the four winter months November–February over 8½ winters from November* 1967 *to December* 1975

	(a) Height of station in metres above mean sea level	(b) Number of persistent fog days	(c) Number of days with fog at 09 GMT	(d) = (c) − (b) giving number of normal fog days
Wattisham*	87	18	102	84
Stansted*	106	18	113	95
Mildenhall*/Honington*	9/53	14	70	56
Marham*	24	16	96	80
Waddington*	70	21	99	78
Wittering*	84	26	97	71
Watnall*	107	23	118	95
Coltishall*	19	9	71	62
Finningley*	17	13	77	64
Leeming*	40	21	94	73
Manchester	78	17	51	34
Shawbury	76	8	53	45
Birmingham	99	9	65	56
Pershore	40	9	81	72
Boscombe Down	124	9	73	64
Gloucester	27	5	43	38
Abingdon/Benson	82/70	8	70	62
Heathrow	24	5	42	37
Gatwick	62	5	58	53
Liverpool	26	7	61	54

For the 20 stations the average number of persistent fog days per station per winter was 1·5. The stations marked with an asterisk can be broadly regarded as being situated in East Anglia together with Yorkshire. For the 10 stations in this eastern area the average per station per winter was 2·1 and for the other 10 stations it was 1·0.

Table I, column (c) shows the number of occasions when the visibility was 600 m or less at 09 GMT for the same stations in this period from November 1967 to December 1975. The figures shown are in good agreement with the generally accepted characteristics of the stations concerned.

Subtracting the number of persistent fog days from the number of occasions at 09 GMT gives the number of 'normal' fogs in this period (Table I, column (d)).

For the 20 stations the average number of normal fog days per station per winter was 7·5. For the 10 stations in the eastern area the average was 8·9 and for the other 10 stations it was 6·1.

It is interesting that for persistent fogs the 10 eastern area stations have 2·1/1·0 = 2·1 times the average for the other 10 stations, and for normal fogs the 10 eastern area stations have 8·9/6·1 = 1·5 times the average for the other 10 stations. These ratios, especially the higher one for the persistent fogs, are a good indication of the influence of the North Sea in providing a supply of moist cool air both on producing and also maintaining fog at this time of year.

In order to demonstrate that persistent fogs are not rare events, consideration of the ratio of persistent fog to normal fog for all 20 stations, when expressed as a percentage, shows that 16 per cent of all fogs reported at 09 GMT persist until 17 GMT in these winter months.

Analysis of the occasions of persistent fog

The occasions were tabulated month by month thus:

November	December	January	February	Total
49	87	88	37	261

It was found that any number of stations could be affected at any one time. This distribution is not unexpected in view of the radiation balance for this time of year. It is clear that the stronger higher-level flows are not reflected at the surface with more wind and less fog.

The numbers of days in each month on which a persistent fog occurred (regardless of the number of stations affected) in the eight and a half winters were also tabulated thus:

November	December	January	February	Total
15	31	31	13	90

Again this distribution shows no abnormal pattern and is consistent with the previous table.

The height in metres of each station above mean sea level is shown in Table I, column (c) and a comparison of column (a) with column (b) does not reveal any simple association between these heights and the incidence of persistent fogs.

Clearance of persistent fog

The 261 persistent fog events in this period having been identified, the time of clearance of the fog was noted. A clearance was defined as the time at which the visibility improved to more than 600 m and remained so subsequently for at least three hours. Three hours was thought to be the minimum period which could be operationally useful, for example, for recovering a squadron of military aircraft or permitting the movement of a significant number of passengers from a civil airport. When a clearance as defined above did not take place throughout the next 18 hours following persistent fog, it was defined as a NIL clearance.

Figure 2 shows a graph of the number of occasions each hour when persistent fog clears, plotted against the clearance times. From the graph it can be seen that there are marked peaks at 19, 00, 03, 06 and 10 GMT. It was found from statistical tests—see Appendix—that these peaks, as a departure from the mean curve, could occur by chance except for the one at 10 GMT. This latter is almost certainly due to the normal diurnal clearing agents finally working to clear the fog on day 2.

The peaks at 19 and 06 GMT, approximately dusk and dawn in the period under investigation, fall within the limits of chance, but, as discussed in the Appendix, there is some statistical evidence to suggest that the large number of clearances at 06 GMT is a real phenomenon.

Where a clearance occurred around these times (18–20 and 05–07 GMT), the observations were checked to see if the clearance had been caused by a small change, possibly due to the change in lighting conditions from day to night and vice versa, but it was found that in all cases the changes were real ones, often by a factor of more than 50 per cent. The corresponding transmissometer records for the events at Birmingham Airport were analysed and they confirmed this point.

Figure 3(a) shows the cumulative percentages of clearances by a given hour for the two areas—east and west. It is interesting to note that in the western area half the clearances occur within seven hours of the end of the persistent fog day (17 GMT), that is to say before midnight GMT, whereas in the east the halfway point is not reached until after 02 GMT. This probably reflects the fact that, in general, synoptic effects progress from west to east.

By 08 GMT, 87 per cent and 70 per cent of the persistent fogs have cleared from the western and eastern areas respectively so that the odds are greater than 6 to 1 and 2 to 1 respectively that a persistent fog will clear before dawn.

Of the 261 total events, 31 occasions (approximately 12 per cent) were NIL clearances as defined previously, and 28 of these were in the eastern area. The only stations in the western area to record a single NIL clearance apiece were Abingdon, Liverpool and Pershore. Of these 31 events, about half

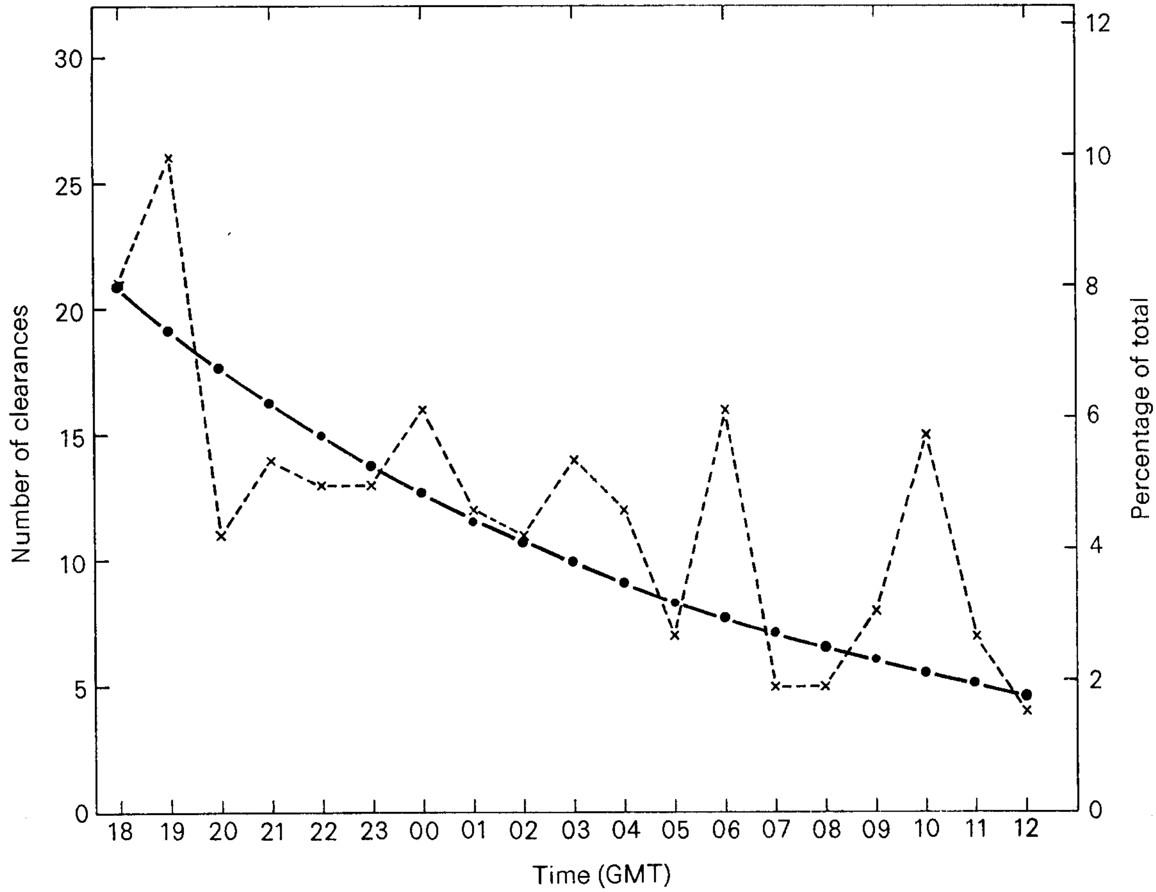

Figure 2. Numbers of clearances each hour plotted against clearance times (x – – – x) and hypothetical 8 per cent clearance rate (· —— ·). Total number of clearances = 261. Number of NIL clearances = 31.

(15) led to a second persistent fog day with the clearance occurring late on day 2 or during day 3. In this period under investigation, fog did not persist at any of these stations for more than three days, in contrast to the six-day fog over south-east England in November 1962.

Reasons for clearance of the persistent fogs

Although the scope of this investigation was not intended to cover the reasons for clearance of persistent fogs, it was felt that a brief examination of the causes might be useful. A subjective analysis of these occasions was therefore made, mainly using the relevant *Daily Weather Reports.* These clearances were categorized in terms of well-known causes as follows:

(a) Frontal: an organized frontal system was present, usually within 200 km.

(b) Wind: mostly a straightforward increase in wind strength; on occasions it was possible to identify from the station's observations that the clearance was due to the advection of drier air. Sometimes, from a personal knowledge of the local geography, the clearance could be identified as due to a change in wind direction.

(c) Cloud: including all types of cloud, but with no frontal system in evidence.

(d) Miscellaneous or unknown reasons: this group was necessary because the dividing line between (a), (b) and (c) was in some cases marginal. This emphasizes the subjective nature of the analysis and the difficulty of using DWRs for such micrometeorological events. It was not possible to examine these occasions in greater detail.

However, these 261 events break down as shown in Table II.

Table II. *Number of clearances by type*

(a) Frontal	(b) Wind	(c) Cloud	(d) Miscellaneous	NIL clearances	Total
81	90	48	11	31	261
Expressed as a percentage for each category					
31%	35%	18%	4%	12%	100%

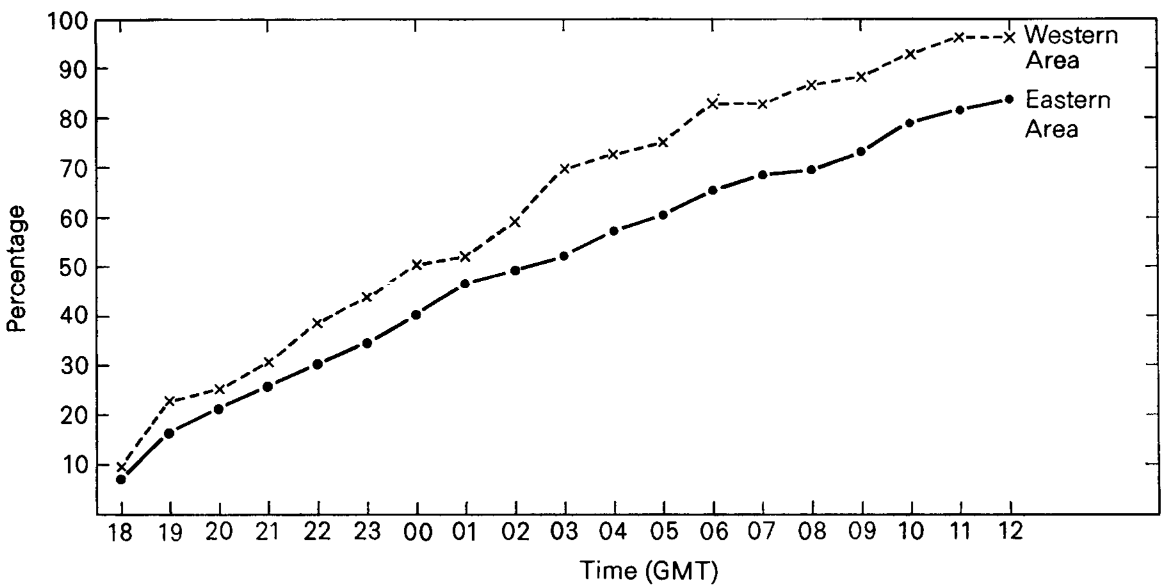

Figure 3(a). Cumulative percentages of persistent fogs that clear by given hour. Western area (84 events) x – – – x; Eastern area (177 events) • —— •.

Figure 3(b) shows a graph of cumulative percentages of clearances with the cause of clearance shown.

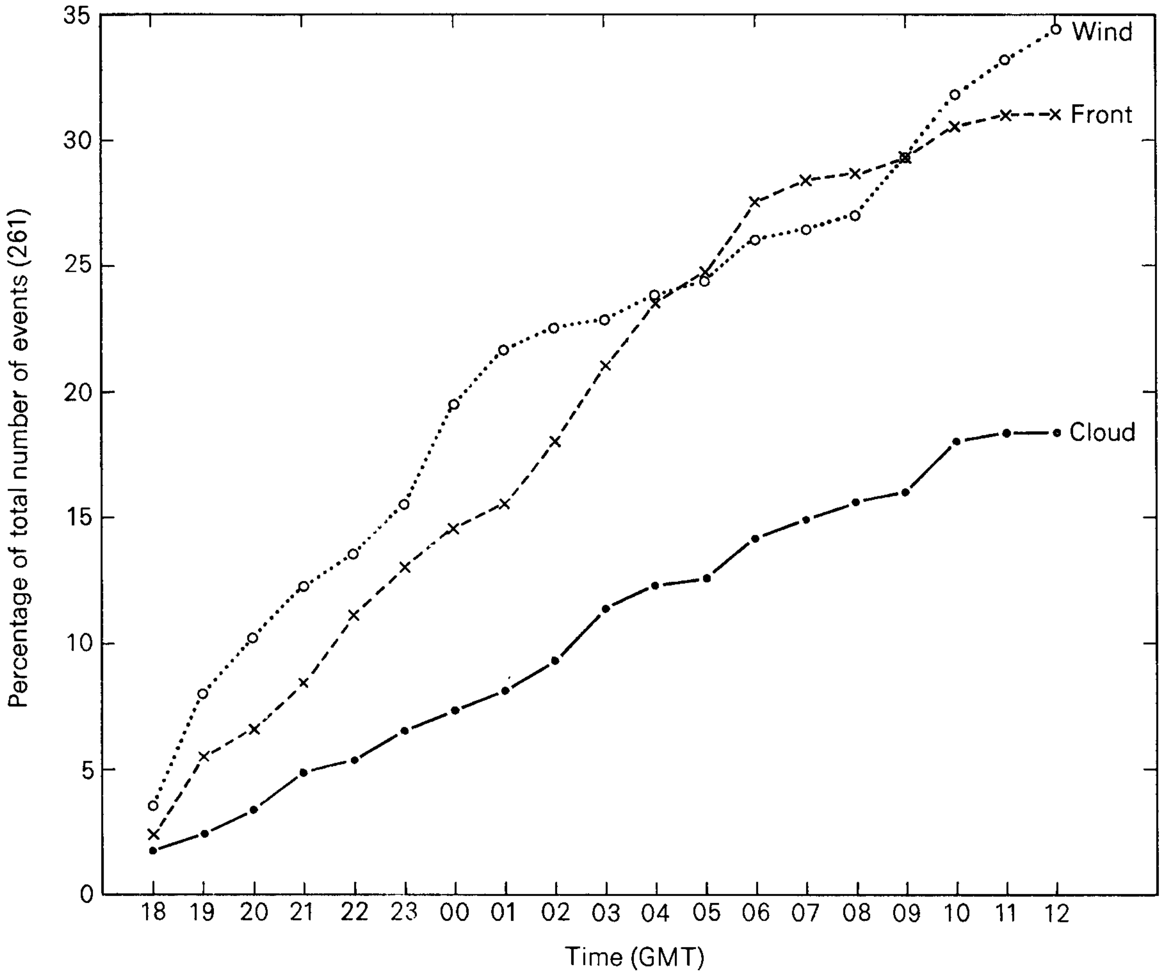

Figure 3(b). Cumulative percentages of persistent fogs clearing in each hour with cause of clearance.

Verification of the frequency of persistent fog days

The period January 1976 to February 1977 was used to verify the frequency of persistent fog events. The average number of persistent fog events was 1·7. For the eastern area it was 2·3 and for the other 10 stations it was 1·1. These figures are in close accord with those obtained previously.

Conclusions

A persistent fog was defined as one which lasted from 09 to 17 GMT; it is not a rare phenomenon. Records for 20 inland stations in England show that 10 of the stations, which are situated in an area roughly to the east of the M1 motorway, had on average two occurrences per winter and the remaining 10 stations averaged one occurrence per winter. It was rare for there to be more than four such occurrences per winter at a station.

Some 18 per cent of clearances of all persistent fogs occurred by 19 GMT and 44 per cent by midnight GMT. It is suggested that this latter percentage could be represented in a TAF, say by TEMPO 0104 or PROB 30 for example*, with an even chance of getting it right; in the case of public service forecasting, one could suggest the fog becoming patchy as opposed to remaining widespread.

On 12 per cent of occasions the fog persisted for at least a further 18 hours from 17 GMT and on nearly 6 per cent of occasions the fog persisted until at least 17 GMT on the second consecutive day.

On 35 per cent of occasions the clearance appeared to be associated with a change in the wind, on 31 per cent with a front and on 18 per cent with a change in the cloud cover. On the remaining 4 per cent of occasions the reason for the clearance was not easy to define. It appears that with any sort of front approaching the area or with any marked change of either wind speed or direction indicated, clearance of a persistent fog during the evening or early night could fairly confidently be forecast.

In other words, although at the time, say between 17 and 23 GMT, there may be virtually no indication on the hourly charts of any major change taking place, this is the time to look for some hint of even a small change, for example the appearance at certain stations of slightly bigger pressure tendencies than one would expect in such a flat situation. At a particular station, perhaps it will be a change in the direction of the wind drift that is the clue. A diligent search by the duty forecaster may turn up enough evidence to suggest a particular occasion as likely to be one of those where, on the basis of long-term statistics, a clearance is to be expected: the TAF can then be refined accordingly.

On a day of persistent fog, the duty forecaster at any station is always under a lot of pressure, due not least to the sheer volume of enquiries. Towards the end of such duties and once the psychologically important time of 16 GMT (the sun is going down, temperatures are falling etc.) has passed, the author recalls that on occasions he had assumed, almost without thought, that in the apparent absence of any marked clearance agents the fog would persist overnight. In the light of subsequent personal experience and also from the results of this investigation, it would seem that such an assumption is not necessarily likely to be true.

Acknowledgements

The author would like to thank the many colleagues who helped to extract data from the observation registers and also Mr C. L. Hawson of the Special Investigations Branch of the Meteorological Office for his assistance in the preparation of the final draft.

* These technical terms of aviation forecasting are defined in *Handbook of Weather Messages, Part III.*

Appendix

From Figure 2 it can be seen that there are marked peaks in the number of clearances of persistent fog at 19, 06 and 10 GMT and a marked trough at 20 GMT. To determine the significance of these peaks and troughs a null hypothesis was assumed and a chi-square (χ^2) test applied to the whole series.

The null hypothesis. Assume initially that there is no preferred hour for the dispersion of a persistent fog, the time of arrival of the clearing agent being random. Under these circumstances it is reasonable to expect that the clearances in any one hour will be proportional to the number of outstanding events and give an exponential type of distribution for the clearances. As a corollary to this hypothesis, since the onset of diurnal clearing factors is not random then a significant departure from this assumed hypothetical clearance rate can be expected some time after dawn. This is consistent with general meteorological experience of non-persistent fogs which tend to clear preferentially about mid-morning.

Now, 261 events exist at 17 GMT and 21 of these (i.e. 8%) clear by 18 GMT. Applying the null hypothesis, 8% of the outstanding (92%) events will clear in the next hour. Thus 7·4% of the total clear in the hour ending 19 GMT, and 6·8% of the total clear between 19 and 20 GMT. Continuing this calculation throughout the night provides the results which are plotted on Figure 2 to make up the curve labelled '8% reduction rate'.

Table A1 shows the χ^2 totals derived from the difference between the observed fog clearances after 17 GMT and expected clearances at a reduction rate of 8% of the outstanding events.

Table A1. *Chi-square test for observed fog clearances after* 17 *GMT and expected clearances at a reduction rate of* 8 *per cent*

Hour (GMT)	Observed clearances	Expected clearances	Cumulative total chi-square
18	21	21	0·00
19	26	19·5	1·85
20	11	18	4·20
21	14	16·5	4·44
22	13	15	4·59
23	13	14	4·61
00	16	13	5·09
01	12	11·5	5·09
02	11	11	5·09
03	14	10	6·32
04	12	9	7·01
05	7	8·5	7·13
06	16	7·5	15·66
07	5	7	15·98
08	5	6·5	16·13
09	8	6	16·51
10	15	5·5	31·24
11	7	5 }	31·35
12	4	4·5 }	
13 or later	31	52	39·43
10 or later	57	67	17·86

Note. Yates's correction has been made to the value of O–E (Observed minus Expected) for continuity because the data relate to a discontinuous variable.

Consider the values of χ^2 calculated from the departures from expectation of the numbers of clearances when these are taken hourly up to 09 GMT but are combined into one class for 10 GMT or later.

$\chi^2 = 17{\cdot}9$ for 16 degrees of freedom. There is approximately a 35 per cent chance of getting values as big as or bigger than this by accident. The conclusion is that the data are consistent with the null hypothesis holding up to 09 GMT.

Now consider χ^2 when the clearances are taken hourly up to 12 GMT and combined for 13 GMT or later.

$\chi^2 = 39{\cdot}5$ for 18 degrees of freedom. There is a less than 0·5 per cent chance of getting values of this order by accident, and the conclusion is that the working hypothesis does not hold to 12 GMT. It can be seen from the detail of the calculation that it is the excessive number of clearances between 09 and 10 GMT which causes the conflict with the hypothesis. This is as expected from the corollary to the hypothesis as stated previously.

To test the individual hourly totals, a 'Student's' t-test was applied, using the calculations set out in Table A2.

Table A2. *'Student's' t-test based on percentage differences of observed and expected fog clearances in each hour for the sample of* 261 *events* (*Figure* 2)

Hour (GMT)	x (Observed−Expected) *per cent*	t value	Equivalent probability for single-sided test
18	0	0	
19	2·55	1·63	6%
20	−2·6	−1·67	6%
21	−0·9	−0·58	
22	−0·8	−0·51	
23	−0·3	−0·19	
00	1·2	0·77	
01	0·1	0·06	
02	0	0	
03	1·5	0·96	
04	1·0	0·64	
05	0·6	0·38	
06	3·0	1·92	4%
07	−0·8	−0·51	
08	−0·6	−0·38	
09	0·7	0·45	
10	3·6	2·31	2%
11	0·7	0·45	
12	−0·3	−0·19	

Parameters of this distribution: $\bar{x}$ = 0·392; standard deviation = 1·509; root-mean-square = 1·559; $t = x$/r.m.s.

If, for reasons unconnected with these data, the departure is expected to be positive and a maximum at 10 GMT, then testing 1000 as though it were a single one-sided trial, there is only a 2% chance of getting a positive t as large as or larger than this by accident in a random sample. The conclusion is that the 10 GMT results are incompatible with the null hypothesis but in line with the corollary. Similarly, the equivalent probabilities for 06 and 19 GMT are 4% and 6% respectively. These values, on the basis of the null working hypothesis, are on the borderline of the generally accepted significance level of those expected by chance in a random sample of 19 values.

It is possible that an observer is more able to assess actual visibility at 06 GMT—given the advantage of a little actual light—than would be possible earlier when in view of the persistence of the fog there could be a tendency to underestimate visibility. Similarly at 19 GMT when it is fully dark, the transition from natural lighting may be having an effect. The fact that clearances in the next hour (20 GMT) are apparently excessively low relative to the null hypothesis conforms to what might happen if the peak at 19 GMT is a lighting effect. This peak at 19 GMT shows up primarily at the western stations. The fact that there are no excessively low frequencies of clearances leading up to 06 GMT or immediately afterwards tends to support the suggestion that this 0600 peak is a real phenomenon. There are no sound physical reasons why this should be so, but it is worthy of note that nearly 6% of the total clearances occur at this time (06 GMT), i.e. about twice as many as would be inferred from the general run of the graph.

To sum up:

(1) Observed departures from the expected hypothetical 8% reduction curve of fog clearance could readily occur by chance up to 09 GMT.

(2) Clearances between 09 and 10 GMT are significantly more frequent than such a curve indicates—consistent with increasing diurnal factors.

(3) The peak in clearances around 'first light' and 'first darkness' may be artifically induced, may be accidents of the sample, but could be real phenomena.

551.58:001

The distinction between weather and climate

By B. J. Mason, C.B., F.R.S.

(Director-General, Meteorological Office)

Summary

It is necessary to distinguish clearly between weather and climate, and definitions suitable for this purpose are proposed. The definitions are useful for the rational discussion of the concepts of climatic variability and climatic change. These definitions were adopted by the recent World Climate Conference.

Present interest in climate and climatic change would appear to require definitions of both weather and climate leading to a clear distinction between the two concepts. Such definitions, if they are to be useful and gain acceptance, should conform as far as possible to common understanding and practice and not depend on the results from a particular model or on a theoretical criterion which cannot be tested by observations. It is in this spirit that the following definitions are proposed.

Weather is associated with the complete state of the atmosphere at a particular instant of time and with the evolution of this state through the generation, growth and decay of individual atmospheric disturbances.

Climate is the synthesis of weather over a period long enough to *establish* its statistical properties (mean values, variances, probabilities of extreme events etc.) and is largely independent of any instantaneous (weather) state.

Because weather systems range in scale from small shower clouds to the planetary waves, with life-times ranging from less than one hour to several weeks, this concept of weather embraces all these time scales but with no sharply defined upper limit. Rapid atmospheric fluctuations with periods of up to a few days, originating largely within the atmosphere itself, are naturally ascribed to weather, and it is sensible to extend the concept to cover stable, large-scale features of the atmospheric circulation, such as blocking situations, that may persist and dominate the weather for several weeks. Alternatively it may be more useful, especially in retrospect and when the daily sequence of events is not of great interest, to characterize the atmospheric state over a month or season by a statistical description in terms of averages, standard deviations and frequency distributions of daily values. Such a statistical summary of the weather of, say, a particular January could not sensibly be described as the *climate* of that particular month although we can speak of a January climate based on the statistics of a long series of Januarys. Furthermore the statistical description of a particular January may be described in terms of its departure from the 'average' or 'climatological' January or the January climate.

For example, in the following statement: 'The mean daily temperature at Kew during February 1947 was −1·1 °C with a standard deviation of 1·76 °C. This was the lowest such February temperature since 1895, being 6·0 °C lower than the corresponding average for the 30-year period 1906–35', the first sentence is a statistical description of one weather parameter, temperature, for the month of February 1947, whereas the second sentence sets this in its climatological context.

As the period of the sample is extended from months to seasons to years . . ., synoptic descriptions in terms of day-by-day fluctuations become less and less useful and are replaced by statistical descriptions so that the concept of weather is eventually displaced by that of climate. However, the inter-annual variations are usually such that, say, a January or a spring climate can be established only if the record spans a sufficiently long sequence of Januarys or springs for the statistics to be treated as if they were stationary. Since this usually requires a record of at least 30 years' duration, it seems inappropriate to apply the term climate in any of the above contexts unless the statistics cover at least a decade. The fact that the statistics of many global circulation and so-called climate models achieve a steady state more rapidly than the real atmosphere is to be regarded as a deficiency of the models rather than a good reason to change the definition of climate.

There have been attempts to draw a sharp distinction between weather and climate, for example, by defining weather in terms of the longest period over which an initial state continues to exert a detectable influence on future developments and for which it is possible to make deterministic predictions. At present, such a definition would set the upper time limit for weather at about one week. This seems an unrealistic and unnecessarily restrictive definition imposed by the limitations of current prediction models and, even so, cannot set a well-defined time limit because the periods over which developments can be followed or predicted depend on the initial state. Nor does it seem possible to separate the two concepts according to mechanism or to the components of the geophysical system involved. Although short-range weather forecasts are concerned largely with atmospheric fluctuations while climate involves also the more slowly changing oceans, land surface and ice sheets, for periods beyond 1–2 weeks it is not possible to ignore the cumulative effects on the atmosphere of changes in ocean surface temperatures, or of widespread even if temporary changes in snow-cover, vegetation, soil moisture, etc., some of which may be induced by the atmospheric fluctuations themselves.

In general, however, we are not so much concerned with the definition of climate *per se* as with *climatic variability* and *climatic change.* These terms imply departures from a normal regime, the definition of which must be to some extent arbitrary and based on the statistics of a limited past record. We could, for example, specify limits within which mean values, variances or the frequency of values within stated ranges may be regarded as 'normal'. Events outside these limits would then be regarded as anomalous at a certain level of significance and if the statistical properties of a succession of years, decades, centuries, etc. differed consistently and significantly from those of the 'normal' population, we could speak of a *climate change* on the appropriate time scale. Small, gradual changes may not be detected above the normal variability (noise) until long after they have commenced but larger changes will show up sooner. 'No change' would imply that all the observed fluctuations lie within expectation based on the statistics of the long-term record.

The term *climatic variability* may be used to denote variability *within* climate, i.e. fluctuations in the statistical properties over periods of weeks, months or years to cover such events as persistent blocking situations, Sahelian droughts and interannual variations. If a particular month, season or year were to show marked differences from the corresponding long-term (e.g. 30-year) average then it could be regarded as a *variation or an anomaly within* the climate of that period.

Given that there is no natural or precise time scale distinguishing weather from climate, the difference becomes largely one of viewpoint, method and utility. Weather is concerned with the evolution of a succession of atmospheric states or individual disturbances; climate with the long-term average behaviour of the atmosphere expressed in statistical terms. Weather forecasts are usually presented as being deterministic in nature; predictions of climatic variability (in the sense defined above) will, for the foreseeable future, be probabilistic statements based largely on the statistics of past records. In an operational context, weather is largely of tactical significance whereas climate is a strategic concept of value in forward planning, risk-assessment and decision-making.

551.5:06(b):061.4

Meteorological Office participation in exhibitions

By R. D. Hunt

(Meteorological Office, Bracknell)

Summary

The market for highly specialized weather information is potentially lucrative and for many years the Meteorological Office has been attempting to increase the revenue earned from the sale of tailor-made services. This can only be carried out successfully if the approach is wholehearted, and one of the fields which it has been necessary to enter is that of publicity. In particular, appearances at exhibitions have become an important means of displaying our services. Both from a commercial and a public relations point of view they have been found to be of great value.

Introduction

Traditionally the major role of the Meteorological Office was to provide essentially free services to meet the needs of Defence, the Merchant Navy and the general public; as far as was possible free services were also extended to any person or organization who asked for meteorological advice. However, in the 1950s it became clear that there were many highly weather-sensitive activities which required specialized services and that these services had a commercial value. Many public and other organizations either required forecasts of a far more detailed nature than could be obtained through the news media or needed detailed climatological information that was expensive to produce. In the late 1960s, the explosive growth of the offshore industry led to a rapid development in specialized meteorological services, particularly at London Weather Centre. Quite apart from the obvious safety aspects, operating companies found that meteorological services could make a substantial and cost-effective contribution to their work. With such a potentially large market for meteorological advice, not surprisingly several private firms of meteorological consultants entered the field, and for the first time the Office found itself with commercial rivals and the need to sell its services in the market-place.

The importance of publicity and exhibitions in particular became apparent in 1975. At the highly influential Offshore International '75 Exhibition in Aberdeen, stands were mounted by some of our commercial competitors and even by other government departments but a Meteorological Office stand was conspicuous by its absence. If a more commercial approach was to be successful it seemed vital for the Office to display its services at trade exhibitions where useful contacts could be made. At the next Aberdeen exhibition in 1977 therefore, the Meteorological Office was represented by a stand produced within the Office, largely by the Cartographic Section. This was successful in many ways although with the limited resources available the stand was not as impressive as many of the others. However, contacts were made at the time with the MOD Directorate of Promotions and Facilities (MOD (DPF)) who are able to sponsor activities in the field of publicity and who have since been of great assistance to the Office; with the aid also of the Central Office of Information (COI) we now have access to professional exhibition design services and during 1978 these were used at three important exhibitions.

Apart from the commercial advantages of appearing at exhibitions there is also a very important public relations aspect. Indeed at some of the more popular events (such as boat shows) having an opportunity to explain the work of the Office to large numbers of the general public is both useful and rewarding. With this in mind, displays have been mounted at a number of locations close to Weather Centres, for example at Manchester and Middlesbrough. For these the Cartographic Section produced some fine displays and the results were highly successful in bringing the work of the Weather Centres to the attention of the public.

Exhibitions sponsored by MOD (DPF) during 1978

The largest and probably most impressive stand during the year was at the Oceanology International Exhibition in Brighton during March. Several branches of the Office were actively involved in the preparation of the exhibits for the stand. A working forecast office was set up equipped with a teleprinter and facsimile machines to receive a wide range of current meteorological data. Forecasters from London and Southampton Weather Centres were able to prepare up-to-date forecasts and to discuss with visitors the various aspects of forecast production. The very good satellite pictures received on the stand were of particular interest to visitors, and the relation between these and the current analyses was explained. The pictures, together with forecast charts for 24, 48 and 72 hours ahead, were attractively displayed on a board illuminated from behind and with a coloured underlay making it easy to distinguish geographical features. Staff from the Weather Centres were able to talk in detail about the specialized services for the offshore industry which were offered mainly from London but also from other forecast offices including the newly formed public service cells at Lerwick, Kirkwall and Aberdeen. A telecopier machine was also installed to demonstrate how charts and other material could be passed between these outstations and directly to customers.

Although current forecast information is vital for day-to-day offshore operations, climatological data are of great importance to operators, engineers and designers; the Marine Climatology section of the Climatological Services Branch therefore featured prominently in the display. By means of a special terminal on the stand, direct access was obtained to a marine data bank held on-line in the COSMOS computer at Bracknell; it was thus possible to demonstrate the wide range of processed and unprocessed data that are readily available and the speed with which they can be obtained. A great deal of work had been necessary before the Exhibition to prepare the data bank and the access programs, but the demonstrations using the terminal were very successful and the output was impressive.

A wide variety of instruments suitable for a marine environment was demonstrated by the Operational Instrumentation Branch whose contribution included a working automatic weather station with provision for 'call up' so that current data could be displayed. This and other instruments including humidity sensors and anemometers attracted an encouraging number of enquiries which were dealt with by staff from this Branch. The final contribution was from the Marine Division; this consisted of a plinth displaying a marine screen and precision aneroid barometer with a static pressure head as well as a display detailing the ship routeing service, a model of an observing ship and the ship's log book. As well as staff from the ship routeing service, specialist staff who advise on siting of instruments on rigs and platforms and on the making of weather observations, were also available to discuss these services.

All the contributions mentioned above were accompanied by professionally designed and produced boards containing scripts and diagrams prepared by the respective branches in conjunction with the Public Services Branch, and brochures illustrating the services offered by the Meteorological Office were available on the stand. The Telecommunications Branch also made a key contribution by arranging for the Post Office to install the many lines without which neither the computer terminal nor the forecast office could have operated. The net result of all this work was a stand which impressed participants and visitors to the exhibition alike.

The second MOD (DPF) sponsored exhibition during the year was the Southampton Boat Show in September. The stand here was modest by comparison with that at Brighton and was rather a long way from the main show area. The emphasis of the display was on the services which are available to yachtsmen and owners of small boats and the facilities that can be provided for them by Southampton

Weather Centre. At the front of the stand, the up-to-date charts were displayed in much the same way as at Brighton, facsimile machines having been installed to enable current material including satellite pictures to be received. These proved to be a most successful way of attracting people to the stand and the staff from London and Southampton Weather Centres who manned the exhibit spent a lot of their time explaining the charts and leading those interested to the other parts of the display.

The rest of the stand showed how observations were received from all parts of the world; satellite pictures were displayed together with enlarged photographs of various sources of data including radiosondes, ocean weather ships and lighthouses. Some attempt was also made to described diagrammatically the operation of the global telecommunications network.

Many yachtsmen's plotting charts were sold during the exhibition, and although the amount of business accruing from the Show was probably somewhat limited, this display was intended primarily as a public relations exercise, attracted large numbers of visitors and undoubtedly achieved its object. The importance of this aspect of exhibitions and indeed of other forms of publicity should not be underestimated.

The other main exhibition of the year was the European Offshore Petroleum Exhibition and Conference (EUROPEC) at Earls Court in October. The Meteorological Office contribution here was very much along the lines of that at Brighton although owing to the smaller amount of space allocated to the Office at Earls Court certain features prominent at Brighton had to be left out. These included the terminal to the marine data bank and the satellite facsimile machine. Although the number of visitors to the exhibition was relatively small, those who were present were actively involved in the offshore industry. This led to many useful contacts being made with staff from all the branches represented.

Other 1978 exhibitions

Apart from these exhibitions, display boards produced within the Meteorological Office, mainly in the Cartographic Section, also appeared at various other shows. These included the Royal Agricultural Show at Stoneleigh (where a video-cassette made by the BBC showing how the TV Farming Forecast is produced was shown), a 'Climate and Weather' exhibition on the Isle of Wight, and the special exhibition arranged by the Royal Meteorological Society to mark the visit to Bracknell of HM The Queen. On a different theme and with the valued assistance of the High Atmosphere Branch, a contribution was also made to a 'Physics at Work' exhibition organized for schoolchildren by the Institute of Physics and shown at the University of Surrey.

Conclusions

There is little doubt that displaying Meteorological Office services at specialized exhibitions can lead to important contacts being made and subsequently to new requests for our commercial services. Although it is impossible to state precisely what the financial benefits are—no contracts are actually signed on the stand—it is clear that all the branches represented at Brighton gained new business. For London Weather Centre services at least, Earls Court was perhaps even more rewarding. From a public relations viewpoint, contributions at boat shows or the Royal Agricultural Show provide an extremely valuable opportunity for staff to explain to members of the public some of the problems involved in producing forecasts and other services and more especially in having sufficient outlets for them. Such exchanges can only be of benefit.

As the Office gains more experience in arranging and staffing exhibitions many of the earlier mistakes are being rectified. The need to book space very early in order to have a good site is vital, but this was only appreciated after obtaining a poor position at Aberdeen in 1977. It is also important to order the required telecommunication lines from the Post Office several months in advance and to have as much contact as possible with MOD (DPF) and COI during the planning and construction stage to ensure that all details are considered. Even the choice of colours for the stand furniture can have a considerable effect on the general appeal of the display. The importance of having all the material ready well in advance and of having suitable standby material was underlined at Earls Court in 1978 when a model of Meteosat which was to have been the highlight of the stand failed to arrive from Switzerland where it was being displayed beforehand. This resulted in a hasty and not altogether satisfactory reorganization. Another lesson learned from experience has been the necessity for someone to arrive at the exhibition a day or so in advance to make contact with the engineers, the Post Office, the electricians and others, and to sort out the state of complete chaos that normally prevails at this stage. Problems such as the stand number being incorrect in the Exhibition Directory (as happened at Earls Court), or the wrong number of telephone lines having been installed can then be dealt with.

Exhibitions and other forms of advertising are essential parts of a commercial approach to the provision of services. This is particularly important in the offshore area where the Office is in direct competition with commercial firms who freely make use of material the Office issues to meet international obligations. There are other areas, for instance in the field of energy saving, where the services that the Office can provide are not as widely known as they should be. Exhibitions are a shop window to interest, inform and attract potential customers. Having done so, the business will continue at its present level and indeed expand only if the services provided are of the necessary quality, and meet the required specifications. This is the real challenge.

Reviews

Climate and man's environment, an introduction to applied climatology, by J. E. Oliver. 255 mm × 180 mm, pp. vii + 517, *illus*. John Wiley and Sons Inc., New York, 1973. Price £10.

Climatology has traditionally been the most popular part of meteorological science among geographers. The main reason for this no doubt lies in the deterministic thinking of such practitioners as Herbertson, Semple and Taylor, who suggested in the earliest years of this century that climate does indeed help to 'determine' the nature of human activity in any given place. Whilst deterministic thinking no longer occupies a major place in geographical study, the effects of climate upon human activity do appear to be taking on renewed importance in the corridors of power of both meteorological science and international politics. In the above context it is perhaps not surprising that at least half the books on applied climatology within the last decade have been written by geographers. The subject of this review is one such book. At this stage it is worth noting that the long delay since publication means that one is essentially reviewing the author's thoughts of nearly a decade ago.

The book comprises fourteen chapters grouped into three sections as follows: climate and environment; climate, man and man's activities; climates of the past and climatic change. In the first section the author essentially attempts to show the role of climate in the workings of other parts of the natural environment. Thus we have chapters on, for example: climate and geomorphology; climate and soils; climate, plants and natural vegetation. The section concludes with a review of climatic classifications. In section two the emphasis is on the more traditional aspects of applied climatology, concentrating upon physiological responses to climate, architecture, urban climates, agriculture, industry and transport. Section three is a brisk run through the evidence for, and theories of climatic change.

The tremendously wide scope of the book, a point stressed by the author in his introduction, may of course be, at one and the same time, a strength and a weakness. To the geographer much of the material will have been familiar since his schooldays and the treatment will seem to be rather superficial, particularly at any level above that of a first-year undergraduate. This criticism is more appropriate to section one than to the other two. To the professional meteorologist the material (particularly that in section one) may be less familiar and thus its superficiality may be less obvious. Indeed he may consider the breadth of the coverage to be the chief merit of the book. But both geographer and meteorologist would probably quibble with the inclusion in a book on applied climatology of a chapter entitled 'Theories of climatic change'.

Putting aside consumer preferences one or two general points should be made. Within the book the treatment tends to jump quite sharply from particular to general, from the didactic to the critical, and from exposition of technique to presentation of results. There appears to be a heavy dependence upon material that has already appeared in book, and even text-book form. A few of the diagrams (e.g. Figure 1.6) have no units on them and, as the publication date and place would suggest, units, where used, are non-SI. The main market for this book must be the geography students in North America. It may be success in that market that has persuaded the publishers finally to release the book in Britain. It faces stiff competition from the more limited and coherent books by Smith (1975) and Mather (1974).

B. W. Atkinson

References

Mather, J. R. 1974 Climatology: Fundamentals and applications. McGraw-Hill. 412 pp.

Smith, K. 1975 Principles of applied climatology. McGraw-Hill. 233 pp.

Water Data 1977, by the Department of the Environment, Water Data Unit, Reading, Berkshire. 295 mm × 210 mm, pp. iv + 88, *illus.*, 1978. Price £2.20.

Water Data 1977 is the fourth in an annual series bringing together data from many sections of the Water Industry into a single volume. The layout is similar to previous editions of *Water Data,* one of which was reviewed in *Meteorological Magazine* (1979) Volume 108, p. 95.

The standard of presentation has been improved in the 1977 edition, with fewer clerical errors, and in some cases clearer diagrams. For example, some tables have been replaced by figures, which are more easily assimilated by the reader, and a greater number of the figures are now printed in blue as well as black and white for greater clarity and impact. In particular the graphs of groundwater fluctuations have been clarified by the use of a blue trace for the 'actual' water level, and by the use of larger lettering.

The major criticism of the 1976 edition was that the data were presented with inadequate explanations, thus preventing the average reader from fully appreciating the importance of the various sets of information. This criticism is valid for the 1977 edition as well.

The photographs are well reproduced, but lack explanations. This detracts somewhat from their value, although they make a pleasant interlude between the many tables and figures, which are the essential part of the volume.

As a reference work, it is of a high standard, providing a comprehensive and clearly presented catalogue of data from the various branches of the Water Industry. The series should be a valuable addition to the libraries of many organizations with direct or indirect links with water resources, hydrometeorology and hydrology.

C. A. Nicholass

Notes and news

Solar-cell experiments

Following a visit to Cyprus by a member of the Space Department, Royal Aircraft Establishment, Farnborough, arrangements have been made to carry out an annual two-week solar-cell experiment at RAF Akrotiri starting in July this year. A site has also been selected on Mount Olympus, Cyprus for a long-term environmental exposure test of solar-cell panels. The site has the advantages of high solar intensity with a strong ultra-violet content and a wide thermal variation between summer and winter.

Meteorological services in Malta

United Kingdom responsibility for meteorological services in Malta ceased on 31 March 1979. The first UK office with British staff was opened at Pieta in 1922, subsequently moving to Valetta in 1927. An observing office was opened at Luqa airfield in 1942 and forecasters were added to the complement in 1943. The Main Meteorological Office moved from Valetta to Luqa in 1946. The radiosonde station was established on the old Qrendi airfield in 1946 and was closed at the end of 1978. The last British staff left Malta on 28 March.

Reopening of forecasting office for the Royal Air Force

The observing and forecasting office was reopened at RAF Church Fenton on 28 March 1979, after having been closed in December 1974. A full operational program began on 2 April.

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NOTICES

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Studies of residence times of chlorofluorocarbons using a two-dimensional model

By Mavis K. Hinds

(Meteorological Office, Bracknell)

Summary

In order to predict the possible effects of chlorofluorocarbons (CFCs) on stratospheric ozone, it is necessary first to gain an understanding of the movement of these substances in the atmosphere and their likely speed of removal. It is this preliminary project which is reported in this paper. The computations covered several decades of model-time up to the present, and were continued in order to estimate the lifetimes of CFCs in the atmosphere under differing conditions.

1. Introduction

There has been considerable discussion in recent years about the possible effects of chlorofluorocarbons (CFCs) on the ozone layer in the stratosphere (Lovelock *et al.* 1973, Molina and Rowland 1974, IMOS 1975, Department of the Environment 1976, National Academy of Sciences 1976). An important aspect of the problem is that the CFCs released into the troposphere are apparently not greatly depleted in this region of the atmosphere. Their major sink if this hypothesis is correct is photolysis by solar ultra-violet radiation after transport upwards into the stratosphere. Studies using one-dimensional models have indicated that this is a very slow process, and even if releases at the surface were stopped, CFCs accumulated in the tropospheric reservoir would continue to diffuse upwards and continue to cause ozone depletion for many decades or even centuries. Questions of the distribution with latitude and the transfer between hemispheres are of considerable importance because the major source of these substances is in the northern hemisphere and any sinks will be more widely distributed over the globe.

In order to gain further understanding of the spread of these substances in the atmosphere, computations were performed with a two-dimensional model to simulate the transport and photochemical destruction of chlorofluorocarbons F11 ($CFCl_3$) and F12 (CF_2Cl_2). The computations covered several decades of model-time up to the present, and were continued in order to estimate the lifetime of CFCs in the atmosphere under differing conditions of surface release. Calculations were made with and without the effects of chemical and photolytic destruction for both F11 and F12, and also with and without a simulation of surface deposition or removal. This particular study was confined to the CFCs themselves; the resultant effects on other atmospheric constituents (particularly ozone) were not included at this stage.

2. Description of the model and the chlorofluorocarbon injection

The two-dimensional model has a latitude–pressure grid. In the horizontal there are 12 intervals with a spacing of 15 degrees of latitude (82·5°N to 82·5°S), and in the vertical there are 23 levels with an interval of 0·3 in $\log_e$ pressure (1 mb to 735·1 mb) corresponding to a spacing of about 2 km, above a lowest layer centred at 930·2 mb with a surface pressure of 1013·2 mb. The effects of photochemistry were ignored in the lowest four layers, which were assumed to be entirely within the troposphere.

The annual releases of CFCs F11 and F12 for the years 1931–75 were taken from figures published by the Manufacturing Chemists Association (1976) and are shown in Table I. It was assumed that the 1975 values applied also to 1976–78 and thereafter experiments were run with differing conditions of surface release. The releases for the United States of America were assigned to 37·5°N and those for the rest of the world to 52·5°N, the relative proportions being derived from Table VI–7 of IMOS (1975).

The model is based on the two-dimensional continuity equation for each chemical (described in section 3) integrated for both the dynamics and the chemistry. A forward time-step of two hours was used in the dynamics, the transport parameters being altered every 24 hours. Injections at the surface were also made every two hours. The chemical destruction rates were computed separately every 10 minutes, 12 chemical time-steps being performed between each dynamical time-step. Centred differences were used for computing derivatives in space.

3. The dynamics and the redistribution by transport

From continuity we can write the equation for the rate of change of volume mixing ratio, χ, of an atmospheric constituent as

$$\frac{\partial \chi}{\partial t} = -\frac{1}{E\cos\phi}\frac{\partial}{\partial \lambda}(u\chi) - \frac{1}{E\cos\phi}\frac{\partial}{\partial \phi}(v\chi\cos\phi) - \frac{\partial}{\partial p}(\omega\chi) + S, \qquad (1)$$

where E is the radius of the earth

ϕ, λ are latitude, longitude

u,v are zonal, meridional velocity

p is pressure

ω is $\mathrm{d}p/\mathrm{d}t$

S is net source and sink term.

For any variable, x, we take the average, $\bar{x}$, round a latitude circle to be given by

$$\bar{x} = \frac{1}{2\pi}\int_0^{2\pi} x \, \mathrm{d}\lambda \qquad (2)$$

and x', the deviation of x with longitude, as $x' = x - \bar{x}$.

Equation (1) thus reduces to

$$\frac{\partial \bar{\chi}}{\partial t} + \frac{1}{E\cos\phi}\frac{\partial}{\partial \phi}(\overline{v\chi}\cos\phi) + \frac{\partial}{\partial p}(\overline{\omega\chi}) = \bar{S} \qquad (3)$$

But $\overline{v\chi} = \bar{v}\bar{\chi} + \overline{v'\chi'}$ and $\overline{\omega\chi} = \bar{\omega}\bar{\chi} + \overline{\omega'\chi'}$.

Reed and German (1965) give the eddy fluxes in terms of eddy diffusion coefficients in the form

$$\overline{v'\chi'} = -\left(K_{yy}\frac{\partial \chi}{\partial y} + K_{yz}\frac{\partial \bar{\chi}}{\partial z}\right) \qquad (4)$$

$$\overline{w'\chi'} = -\left(K_{zy}\frac{\partial \bar{\chi}}{\partial y} + K_{zz}\frac{\partial \bar{\chi}}{\partial z}\right), \qquad (5)$$

Table I. *Releases of* F11 *and* F12 *in millions of pounds**

Year	F11 US sources	F11 Other sources	F12 US sources	F12 Other sources
1931	0·0	0·0	0·1	0·0
1932	0·0	0·0	0·1	0·0
1933	0·0	0·0	0·2	0·0
1934	0·0	0·0	0·3	0·0
1935	0·0	0·0	0·5	0·0
1936	0·0	0·0	0·8	0·0
1937	0·1	0·0	1·3	0·0
1938	0·1	0·0	1·9	0·0
1939	0·1	0·0	2·8	0·0
1940	0·2	0·0	3·8	0·0
1941	0·2	0·0	5·1	0·0
1942	0·3	0·0	6·3	0·0
1943	0·4	0·0	7·8	0·0
1944	0·5	0·0	10·4	0·0
1945	0·6	0·0	13·6	0·0
1946	1·4	0·0	26·3	0·0
1947	2·7	0·0	41·9	0·0
1948	5·0	0·0	49·0	0·0
1949	8·2	0·0	53·3	0·0
1950	11·9	0·0	59·7	0·0
1951	16·5	0·0	66·5	0·0
1952	23·8	0·0	69·5	0·0
1953	32·4	0·0	78·3	0·0
1954	40·2	0·0	88·8	0·0
1955	49·9	0·0	100·5	0·0
1956	62·3	0·0	116·4	0·0
1957	69·8	0·0	132·5	0·0
1958	65·7	0·0	138·7	0·0
1959	67·2	0·0	154·8	0·0
1960	71·3	16·8	161·1	24·3
1961	90·4	22·8	173·3	35·1
1962	111·6	30·6	192·9	47·5
1963	132·7	41·7	216·6	66·9
1964	148·6	58·2	240·2	91·6
1965	163·8	73·2	265·0	111·5
1966	167·1	96·4	282·2	144·1
1967	180·5	123·9	303·7	183·2
1968	193·9	152·1	307·2	225·2
1969	221·7	181·9	333·7	265·7
1970	235·2	225·5	337·6	315·0
1971	248·1	263·4	339·9	358·2
1972	275·1	300·7	363·1	406·9
1973	313·6	352·2	397·3	446·2
1974	353·9	397·5	439·9	494·1
1975	353·6	397·2	428·9	481·7

* One million pounds = 453·6 tonnes.

where w is vertical velocity and z is height. Changing to pressure co-ordinates and using the approximations $K_{yz} = K_{zy}$, $K_{yp} = -g\rho K_{yz}$ and $K_{pp} = g^2\rho^2 K_{zz}$, where ρ is density, equations (4) and (5) are then replaced by

$$\overline{v'\chi'} = -\left(K_{yy}\frac{\partial\bar{\chi}}{\partial y} + K_{yp}\frac{\partial\bar{\chi}}{\partial p}\right) \quad \text{(6)}$$

$$\overline{\omega'\chi'} = -\left(K_{yp}\frac{\partial\bar{\chi}}{\partial y} + K_{pp}\frac{\partial\bar{\chi}}{\partial p}\right) \quad \text{(7)}$$

where $\delta y = E\delta\phi$.

Values of $\bar{v}$ for each season were estimated using the values of Newell *et al.* (1972) up to 10 mb in the northern hemisphere and 100 mb in the southern hemisphere. These were extended upwards subjectively using as guidance mean cross-sections of $\bar{v}$ from the COMESA (1975) three-dimensional model and also output from the two-dimensional model of Harwood and Pyle (1975). Mean vertical velocities, $\bar{\omega}$, were calculated from $\bar{v}$ using the continuity equation

$$\frac{1}{E\cos\phi}\frac{\partial}{\partial\phi}(\bar{v}\cos\phi) + \frac{\partial}{\partial p}\bar{\omega} = 0 \quad \text{(8)}$$

with $\bar{\omega} = 0$ at the top of the model. In order to ensure that $\bar{\omega} = 0$ also at the surface, a small correction was applied to $\bar{v}$ at all levels, to make the integral of $\bar{v}dp$ zero at the junction between each latitudinal column. Also $\bar{v}$ was zero above each pole. Schematic diagrams of the corresponding stream functions are shown in Figures 1(a)–(d).

Values given by Luther (1974) were taken as a basis for the eddy diffusion coefficients, those for the southern hemisphere being obtained by using northern hemisphere values for the corresponding season. However, a study of the COMESA three-dimensional model indicated that during stratospheric sudden warmings the variances of the meridional velocity may greatly exceed those given by Newell *et al.* (1966) which were used by Luther in obtaining his results. (Reed and German (1965) suggest that eddy diffusion coefficients K_{yy} are proportional to the variance of the meridional velocity.) Also the three-dimensional model results indicated that in the southern hemisphere winter the variance of the meridional velocity is less at high latitudes than in the northern hemisphere winter. Subjective changes were made to Luther's coefficients, in the light of available information, and then tested on the version with full chemistry of the two-dimensional model. The improved simulation of natural ozone was taken as confirmation that these changes should be incorporated. In the northern hemisphere climatological temperatures were used, those for the southern hemisphere being taken from the northern hemisphere at the corresponding season.

In order to obtain daily values a sinusoidal variation between solstices was assumed for the eddy diffusion coefficients and the temperatures, the phase of the former being delayed by one month. For the mean velocity components, a piecewise smooth quadratic function was interpolated between seasonal values.

4. The destruction mechanisms

The only source of CFCs in the model is the injection into the lowest layer, whereas three possible destruction mechanisms have been included, namely 'surface deposition', photochemical dissociation by solar ultra-violet radiation in the stratosphere, and chemical reaction with $O(^1D)$* in the stratosphere.

* $O(^1D)$ indicates the relevant excited state of the oxygen atom in the usual spectroscopic notation; this notation is explained in standard modern texts on spectroscopy.

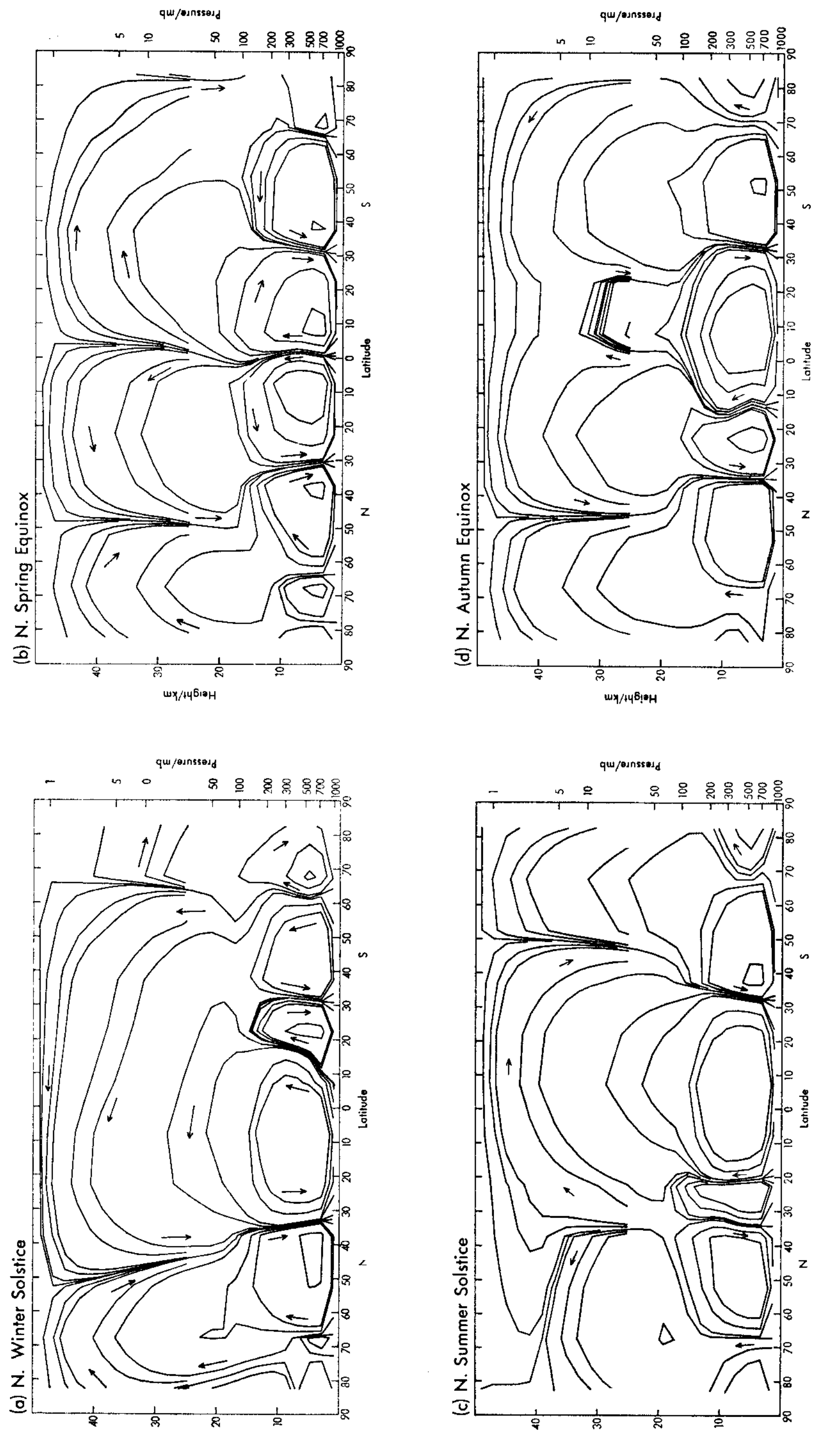

Figure 1. Stream function (arbitrary units) illustrating mean meridional flow for the four seasons.

(a) *'Surface deposition'*. The National Academy of Sciences (1976) gives a summary of various studies (Liss and Slater 1974, Parmalee 1953, DuPont 1971) of the solubility and removal of CFCs by the oceans. They estimate from the limited data available that the mean global removal time for F11 is about 270 years. The considerable uncertainty about the rate of removal by 'surface deposition' is illustrated by the fact that Junge (1976) concludes that the most likely removal time is 800 years. Another possibly important removal mechanism is by dissociation after adsorption on to Saharan dust (Ausloos *et al.* 1977). In view of the general uncertainty about these and other possible loss mechanisms it was decided to represent this by a removal of F11 from the lowest layer of the model at a rate of 1·8 per cent per year at all latitudes. This is a somewhat arbitrary figure, but since in this study experiments were run both with and without this mechanism, it should be possible to adjust the results in the light of future discoveries. There is even greater uncertainty about the removal rate of F12, but since its solubility is estimated to be just under half of that of F11, a removal rate of half that for F11 was taken in this model.

(b) *Dissociation and chemical reactions.* The CFCs are dissociated directly by ultra-violet light in the 200 nm region of the spectrum and are also destroyed by chemical reaction with the excited oxygen atom $O(^1D)$ which is in turn formed during the dissociation of ozone by ultra-violet radiation of wavelengths below 310 nm. Thus for both these processes it was necessary first to calculate photodissociation coefficients, J, in the relevant wavelengths, using the equations

$$J(z) = \sum_l Q(l)\,\sigma(l)\,I(z,l) \qquad (9)$$

$$I(z) = I_0 \exp(-\sum_i \sigma_i \sum_z n_i(z) m(z) \Delta z) \qquad (10)$$

$$m = (1 + z/E)(\cos^2\alpha + 2z/E)^{-\frac{1}{2}} \qquad (11)$$

$$\cos\alpha = \cos\lambda\cos\delta\cos\theta + \sin\lambda\sin\delta, \qquad (12)$$

where Q is the quantum efficiency
σ is the photon absorption cross-section
I is the photon flux at height z and I_0 is its extraterrestrial value
l is the wavelength
n is number density and i the absorbing species (O_2, O_3)
α is the zenith angle
m is the path length magnification factor
δ is solar declination
θ is local hour angle.

In order to reduce the computation time of the model, ozone profiles were extracted once per month from an early version of the full two-dimensional chemical–kinetic model, although these were modified slightly in the highest levels so that they were in closer agreement with measured values.

The absorption cross-sections for F11 and F12 were taken from Huebner *et al.* (1975) and for O_3 from Ackermann (1971). Mattingly (personal communication) derived the cross-section for O_2 and Tuck and Clough (personal communication) compiled the solar intensities from data of Thekaekara, Broadfoot, Simon and Ackermann. The quantum yields are as in COMESA (1975). The computed photodissociation rate coefficients for latitude 22·5°N for 1 March are shown in Figures 2(a)–(c).

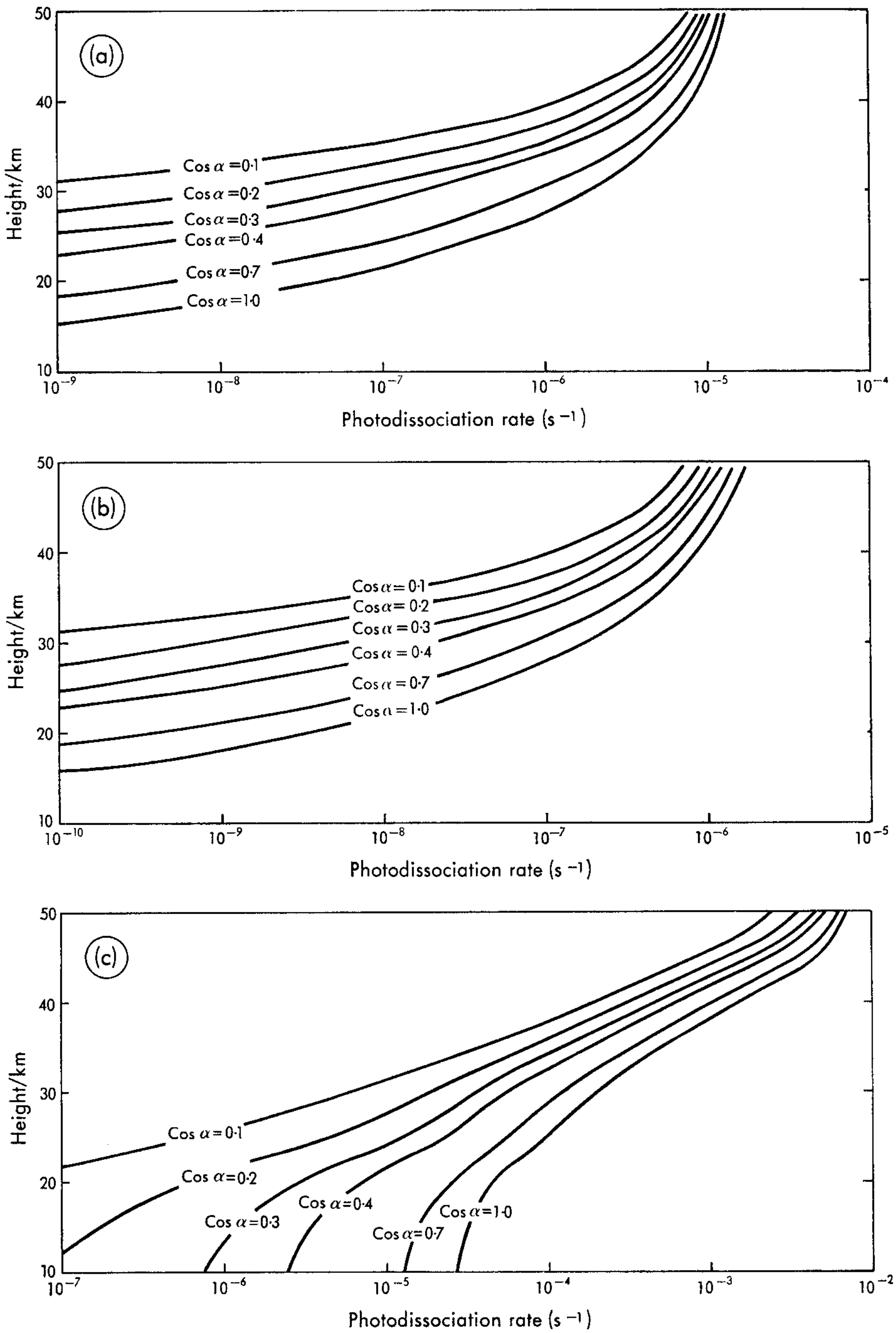

Figure 2. Computed photodissociation rates for 1 March at 22·5°N at stratospheric levels for different solar zenith angles: (a) F11, (b) F12, (c) $O_3 \rightarrow O(^1D)$.

Values of J coefficients were computed for each month, for each latitude, for six values of $\cos\alpha$, for photodissociation of F11 and F12, and also for the dissociation of O_3 to $O(^1D)$. Within the model run linear interpolation was used to obtain values of J for the required time and the value of $\cos\alpha$.

In the calculation of the number densities $[O(^1D)]$ of excited oxygen atoms it was, for simplicity, assumed that the two reactions

$$O_3 + h\nu \rightarrow O_2 + O(^1D) \text{ (wavelengths less than 310 nm)} \quad \text{.. .. ..} \quad (13)$$

$$O(^1D) + M \rightarrow O + M \quad (k = 7{\cdot}0 \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}) \quad \text{.. .. ..} \quad (14)$$

(where M represents some appropriate molecular constituent) were in equilibrium, so that the number density could be obtained using

$$[O(^1D)] = \frac{[O_3] \times J_3}{7{\cdot}0 \times 10^{-11} \times [M]} \quad \text{.. .. ..} \quad (15)$$

where $[M]$ is the number density of air, and J_3 the photodissociation coefficient of O_3 to $O(^1D)$.

The reactions used in this model are

$$CF_2Cl_2 + h\nu \rightarrow \text{products} \quad \text{.. .. ..} \quad (16)$$

$$CFCl_3 + h\nu \rightarrow \text{products} \quad \text{.. .. ..} \quad (17)$$

$$CF_2Cl_2 + O(^1D) \rightarrow \text{products} \quad (k = 5{\cdot}3 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}) \quad \text{.. ..} \quad (18)$$

$$CFCl_3 + O(^1D) \rightarrow \text{products} \quad (k = 5{\cdot}8 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}). \quad \text{.. ..} \quad (19)$$

If J_1 and J_2 are the dissociation coefficients for F11 and F12 then the total coefficients R_1 and R_2 of destruction of F11 and F12 are given by

$$R_1 = J_1 + 5{\cdot}8 \times 10^{-10} \times [O(^1D)] \text{ s}^{-1} \quad \text{.. .. ..} \quad (20)$$

$$R_2 = J_2 + 5{\cdot}3 \times 10^{-10} \times [O(^1D)] \text{ s}^{-1}. \quad \text{.. .. ..} \quad (21)$$

The rate for reaction (14) was taken from Husain and co-workers (see Davidson *et al.* (1976)) and those for reactions (18) and (19) from Pitts *et al.* (1974). Davidson *et al.* (1976) indicate that Husain's value is probably too high by a factor of about two, and since Pitts's values were not absolute but relative to that of Husain for reaction (14), all the reaction rates used here for $O(^1D)$ should probably be halved. However, it is to be noted that although this change would double the amount of $O(^1D)$ present in the model (see equation (15)), it would not in fact alter its effect on F11 or F12 in any way, since the two factors cancel out in equations (20) and (21).

Since in this study we are considering non-interactive chemistry, with predetermined ozone profiles, and are not concerned with the products of F11 and F12 destruction, the computation of chemical changes takes on a much simplified form. If n_i is the number density of a species i, and R_i the total rate of destruction, then in these circumstances

$$dn_i/dt = -R_i n_i$$

and hence $n_i = n_{i,0} \exp(-R_i \Delta t)$, where $n_{i,0}$ is the value of n_i at the beginning of the chemical time-step Δt, which was taken as 10 minutes. Thus, if n_1 and n_2 are the number densities of F11 and F12 at the end of this time-step

$$n_1 = n_{1,0} \exp(-\Delta t \times R_1)$$

$$n_2 = n_{2,0} \exp(-\Delta t \times R_2).$$

It will be noted that a major weakness of the above approach is that the changes in ozone resulting from the effects of the chemistry involving CFCs are not specifically considered. In order to investigate this aspect an additional model run was carried out with reduced ozone amounts (see condition (c) in section 5).

5. The experiments

The experimental program covered the model-years 1931–98 and is summarized in Table II.

Table II. *Experimental details*

Experiment	1(a)	2(a)	3(a)	4(a)	5(a)	1(b)	2(b)	3(b)	4(b)	5(b)	2(c)	3(c)	4(c)
Destruction by photodissociation		X	X	X			X	X	X		X	X	X
Destruction by reaction with $O(^1D)$			X	X				X	X			X	X
'Surface deposition'				X	X				X	X			X
With injections before end of 1978	X	X	X	X	X	X	X	X	X	X	X	X	X
With injections after end of 1978	X	X	X	X	X								
With reduced ozone after end of 1988											X	X	X

The integrations were repeated for both F11 and F12 for a number of different conditions

(1) with no destruction mechanisms

(2) with stratospheric dissociation by solar ultra-violet radiation

$$CF_2Cl_2 + h\nu \rightarrow \text{products}$$
$$CFCl_3 + h\nu \rightarrow \text{products}$$

(3) with (2) and loss reactions by $O(^1D)$

$$O_3 + h\nu \rightarrow O_2 + O(^1D)$$
$$O(^1D) + M \rightarrow O + M$$
$$CF_2Cl_2 + O(^1D) \rightarrow \text{products}$$
$$CFCl_3 + O(^1D) \rightarrow \text{products}$$

(4) with (3) and an assumed rate of 'surface deposition'

(5) with (1) and an assumed rate of 'surface deposition'

The experiments were repeated with the following varying release conditions:

(a) to the end of 1998 with CFC releases at 1975 rates for 1976–98;

(b) to the end of 1998 with no further releases after the end of 1978;

(c) as (b) but assuming that in the years 1989–98 stratospheric ozone amounts were reduced as shown in Table III which is based on data given in Figure 8.6 (without $ClONO_2$) on pp. 8–25 of the National Academy of Sciences (1976) report.

Table III. *Percentage reduction in ozone for years* 1989 *to* 1998

Level (km)	Percentage ozone reduction	Level (km)	Percentage ozone reduction
48	25	27	29
46	37	25	28
43	47	23	24
41	53	21	15
39	51	19	11
37	46	17	11
35	40	15	11
33	35	13	11
31	31	11	9
29	30	9	5

6. The results

To provide a general assessment of the model a comparison is shown in Figure 3 of a model-produced latitude–height cross-section of F11 volume mixing ratio for 1 November 1974 obtained in Experiment 4(a) with observed values for mid-October 1974 given by Krey and Lagomarsino (1975). Model values appear to be rather too high in Arctic latitudes but the general agreement is considered satisfactory.

An illustration of the manner in which solar radiation and transport mechanisms affect the stratospheric distributions throughout the year is given in Figures 4(a)–(d) which show the F12 distributions simulated in Experiment 3(a) for the four seasons of 1978. In the upper stratosphere the values are lowest in autumn at high latitudes owing to dissociation during continuous sunlight with the minimum transferring with season between the hemispheres. In the lower stratosphere the principal feature is the maximum at low latitudes apparently associated with the upward branch of the Hadley cell. The mean motions at higher latitudes do not appear to have a major effect on the stratospheric patterns.

The above diagrams, however, do not illustrate the detailed role of the motions in determining the final distributions of the constituents. In order to study this more closely calculations were made of the fields of the horizontal and vertical fluxes together with their convergences. Typical results for the four seasons are illustrated in Figure 5 for Experiment 4(b) for F12 in the model year 1992 (that is to say, after the termination of injections).

It may be seen that during the northern hemisphere spring the main transfer by the atmospheric circulation of the CFCs into the stratosphere is upwards through the equatorial tropopause. Polewards transport then takes place in the stratosphere in both hemispheres with descent in middle latitudes. There is also a predominance of flux from northern hemisphere to southern hemisphere in the troposphere. The effect of these transports is to produce divergence in the upper tropical troposphere and convergence in the low-latitude stratosphere but also divergence in the southern mid-latitude stratosphere. Thus although the motions apparently made the CFCs available for photochemical destruction (convergence) over most of the stratosphere there are regions where they in fact remove (divergence) the CFCs from the stratosphere.

At the summer solstice in the northern hemisphere the main region of upward flux through the tropopause is in low latitudes and transfer to the southern hemisphere now takes place across the equator at stratospheric as well as upper tropospheric levels. There is a major region of downward flux through the tropopause in southern mid-latitudes. The general effect is to produce flux divergence in the lower stratosphere in the southern hemisphere which is roughly a mirror image of the convergence caused by the ascent in the northern hemisphere. However, convergence occurs at the highest levels at all latitudes (and in all seasons), presumably feeding the photochemical sink. In the troposphere there is also a 'mirror-image' effect with the main convergence to the south of the equator in upper levels, and to the north nearer the surface.

By the northern autumnal equinox the area of main upward flux has returned to equatorial latitudes and the flux patterns are broadly similar to those of the northern spring. The convergence patterns, however, are considerably more asymmetrical, particularly in the stratosphere. Here there is general

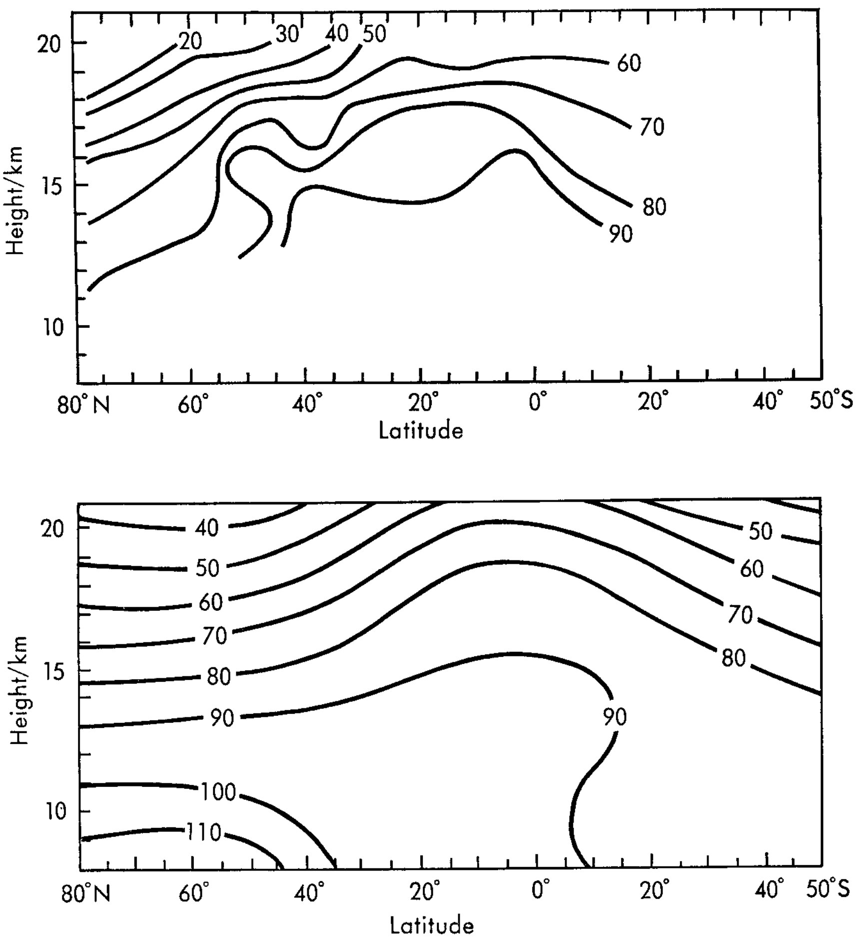

Figure 3. Comparison of latitude–height cross-sections of F11 volume mixing ratio. Upper diagram shows observed values for mid-October 1974, after Krey and Lagomarsino (1975). Lower diagram shows model values for 1 November 1974. For units see caption to Figure 4.

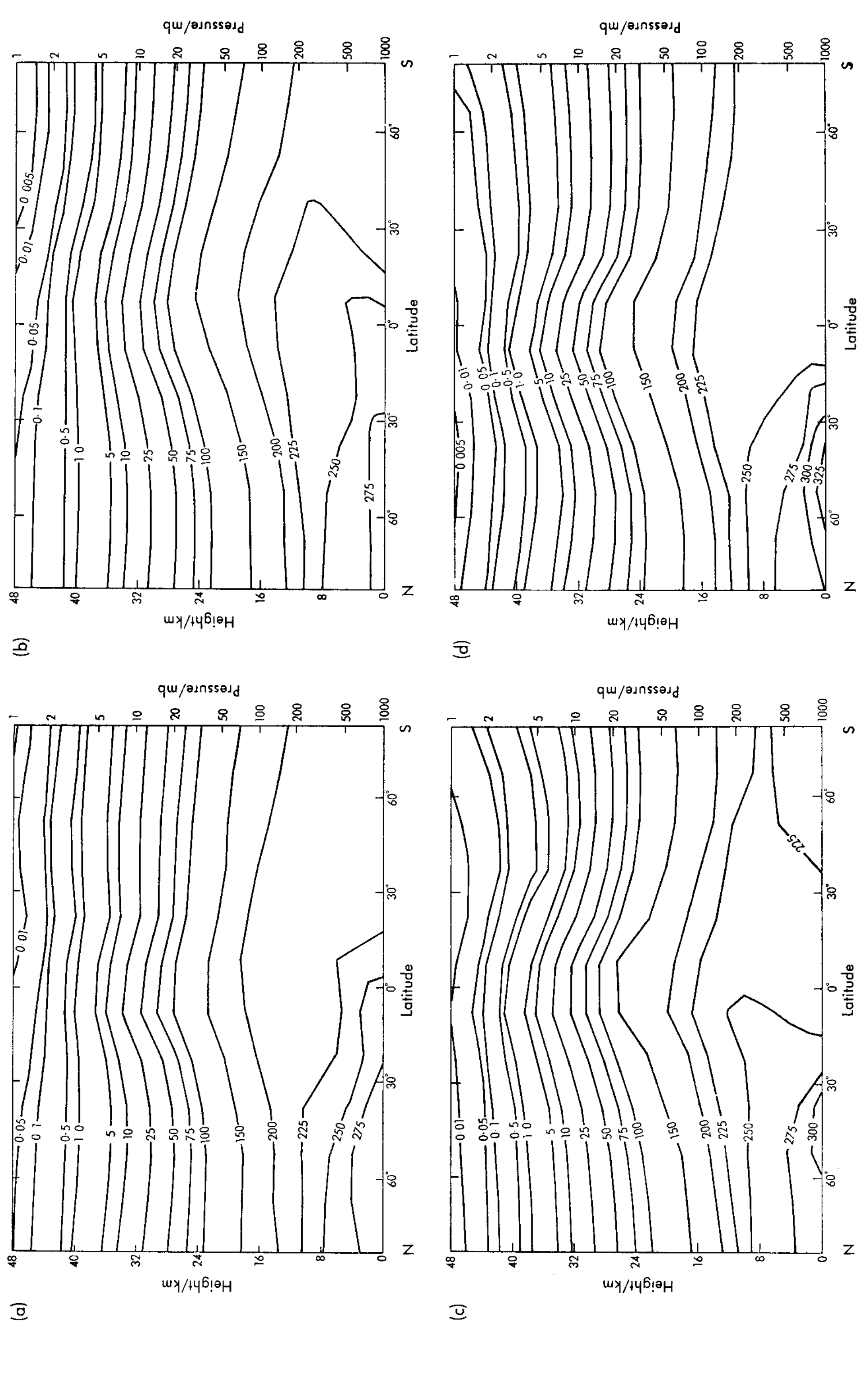

Figure 4. Latitude–height cross-sections of F12 volume mixing ratio (ppt) computed in Experiment 3(a). (a) January 1978, (b) April 1978, (c) July 1978, (d) October 1978. [ppt = parts per American trillion (10^{12}).]

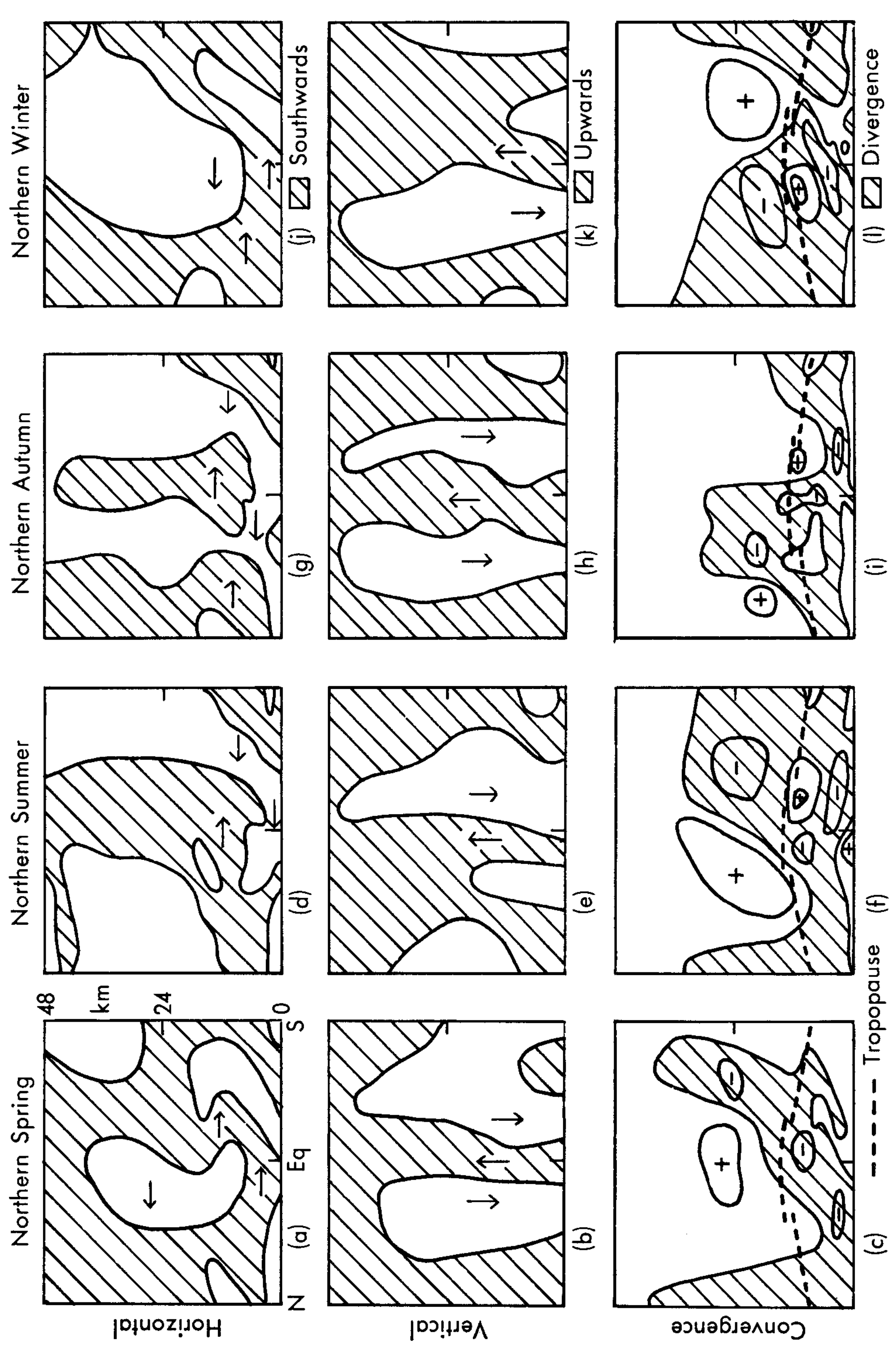

Figure 5. Flux patterns for F12 for Experiment 4(b) for the year 1992.

convergence everywhere except in the tropical and northern middle latitudes of the lower stratosphere. The motions in the latter regions do not act as a supply for the photochemical sink at this time of year.

Finally at the northern winter solstice there is rather general upward motion through the tropopause in the southern hemisphere and large downward fluxes occur in the lower and middle latitudes of the northern hemisphere. Transfers in the stratosphere are generally from the southern to the northern hemisphere. The main flux convergence takes place in the southern hemisphere lower stratosphere at middle latitudes with divergence in most of the lower stratosphere of the northern hemisphere. In the troposphere there is mainly divergence but regions of convergence occur in the upper troposphere at northern mid-latitudes, and in mid-latitudes of the southern hemisphere.

In the main, the flux transfers appear to be dominated by the mean meridional cells, especially the Hadley cell at low latitudes. The convergence–divergence patterns, however, are more complex and in particular there is divergence in the winter hemisphere in the lower stratosphere.

Variations of F11 global averages with time at different levels of the atmosphere are shown in Figure 6(a) for the years 1967 to 1978, in Figure 6(b) for 1979 to 1990 with continued injections, in Figure 6(c) for 1979 to 1990 assuming that injections have terminated in 1978, and in Figure 6(d) for 1989 to 1998 with no injections and lower ozone amounts. Figures 6(a) and 6(b) show that as the injections continue the volume mixing ratio increases at all levels as would be expected. However, the rate of long-term increase at the highest levels is very slow, with the photodissociation almost keeping pace with the upward transport from lower levels. The rate of increase in the troposphere is comparatively rapid and takes place unevenly as the mean circulation patterns change with the seasons. When the injections are discontinued (Figure 6(c)) the increase in the lower stratosphere continues for a few years and is then followed by a slow decrease. If the ozone amounts are reduced, increased penetration of the solar beam and consequently increased destruction of F11 and F12 by photodissociation at lower stratospheric levels will take place. This effect is illustrated in Figure 6(d) where the rates of decrease are appreciably larger than those shown in Figure 6(c).

The F11 mixing ratios in the two hemispheres are shown separately in Figures 7(a) and 7(b). The phase changes between the hemispheres with solar zenith angle and seasonal variations of transport are well illustrated and vary from level to level. Considering first the higher stratospheric levels, both hemispheres show a well-marked seasonal variation with a minimum in the summer due to the change of solar angle. However, the two hemispheres are not exactly in antiphase and this leads to a marked annual cycle in the global values (Figure 6(b)). In the northern hemisphere, where the penetration appears to be greater, the minimum lasts from summer into early autumn, and in the southern hemisphere it extends into late autumn. In the lower stratosphere the hemispheric variations are out of phase with those of higher levels and this must be due to the effects of transport, as illustrated by the convergence zones in Figure 5(f) and (l). There is little annual variation in global amounts in this region. At tropospheric levels there is a marked difference between the two hemispheres and Figure 7(b) suggests that southward cross-equatorial flux is strong in the upper troposphere. The nature of interhemispheric transport, which is expected to be mainly by the mean motions, can be inferred from Figures 1(a)–(d), which suggest that the injected chemicals are carried to the upper troposphere in the upward branch of the Hadley cell and then spread southwards at these levels. This is largely confirmed by fluxes shown in Figure 5 and by the tropospheric configuration in Figure 4. In the experiment in which injections were discontinued at the end of 1978 (Experiment 3(b)), it was found that southern hemisphere totals (Figure 8) continued to increase for over a year after the cessation of injections as interhemispheric transport continued. Surprisingly, after this time the southern hemisphere burden was on average slightly greater than that of the northern hemisphere.

It should be noted that there is a net seasonal movement across the equator of just over 1 per cent of the atmospheric burden.

Finally, Figures 9(a)–(d) show the best estimates currently available from this work of likely F11 and F12 distributions near the end of the century, Figures 9(a) and 9(b) on the assumption that injections continue at 1975 rates and Figures 9(c) and 9(d) on the assumption that they have stopped at the end of 1978.

Turco and Whitten (1975) give F12 mixing ratios in the lower stratosphere for different CFC production histories and tropospheric lifetimes and it is noted that their experiments I_∞ and III_∞ give similar values for 1998 to those shown in Figures 9(b) and 9(d) respectively. Values in Figures 9(a) and 9(b) are about half those given by Derwent and Eggleton (1978) for 'a date in the future when considerable CFC release has occurred' and about one-quarter of the stationary state values given by Rowland and Molina (1975).

7. Conclusions

These studies have provided a means of estimating effects of the various mechanisms on the total residence times of F11 and F12 in the atmosphere and these are summarized in Table IV. These estimates were calculated from global totals one year apart and the separate implied contributions found assuming that the removal rates (reciprocal residence times) are additive.

Table IV. *Calculated residence times*

Destruction mechanism	Using original O_3 values		Using reduced O_3 values	
	F11	F12	F11	F12
	years		*years*	
Photodissociation only	82	193	60	151
Photodissociation and $O(^1D)$ reaction	81	182	59	143
Photodissociation, $O(^1D)$ reaction and 'surface deposition'	65	143	50	118
Separate implied contributions				
'Surface deposition' only	332	675	329	672
$O(^1D)$ reaction only	>6000	>3000	>5000	>2000

The National Academy of Sciences (1976) report concludes that the residence time for F11 is about 50 years and for F12 about 100 years and this is in agreement with the values found in this study when photodissociation, $O(^1D)$ reaction and 'surface deposition' are taken into account and reduced ozone values are used. The removal rate due to the $O(^1D)$ reaction is about 1 per cent of that due to photodissociation for F11 and 10 per cent for F12. These figures are in agreement with those of Rowland and Molina (1975). The 'feedback' effects of the decrease of ozone amounts due to the destruction by the chlorine species are, however, considerable, and of the same order as the effects of 'surface deposition'.

In addition to its broad confirmation of the numerical results of the one-dimensional models this two-dimensional study has provided additional information on the role of transport, and in particular it has illustrated the importance of cross-equatorial transfer by the Hadley cell. This appears to be a more important factor in the CFC problem than with supersonic aircraft effluents because in the latter case the injections were in the lower stratosphere on the poleward side of the jet, where mean motions are downwards in winter. In addition this study has indicated that the effect of the motions

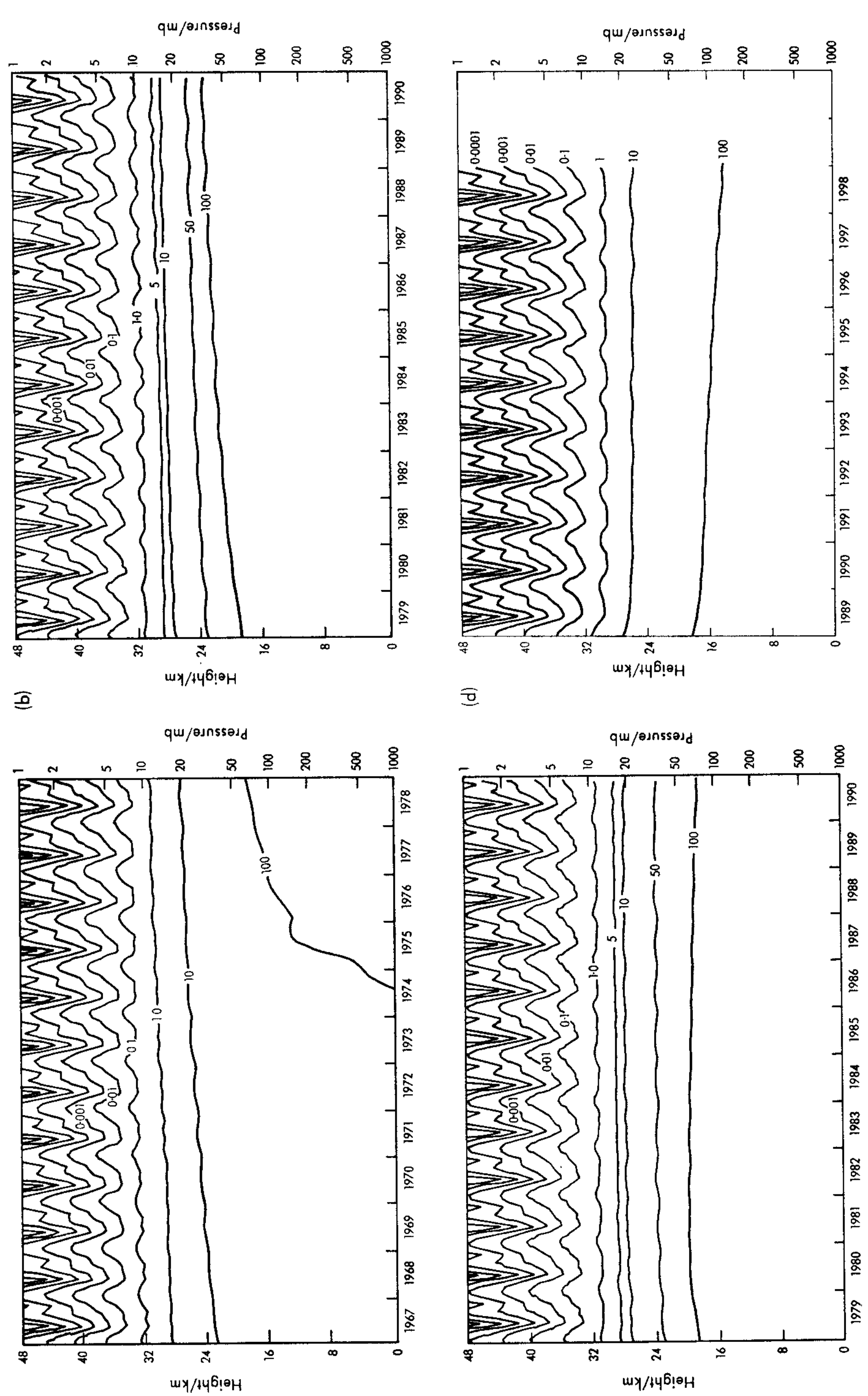

Figure 6. Computed height–time cross-sections of globally averaged F11 volume mixing ratio (ppt). (a) January 1967 to December 1978, Experiment 4(a). (b) January 1979 to December 1990, Experiment 4(a). (c) January 1979 to December 1990, Experiment 4(b). (d) January 1989 to December 1998, Experiment 4(c).

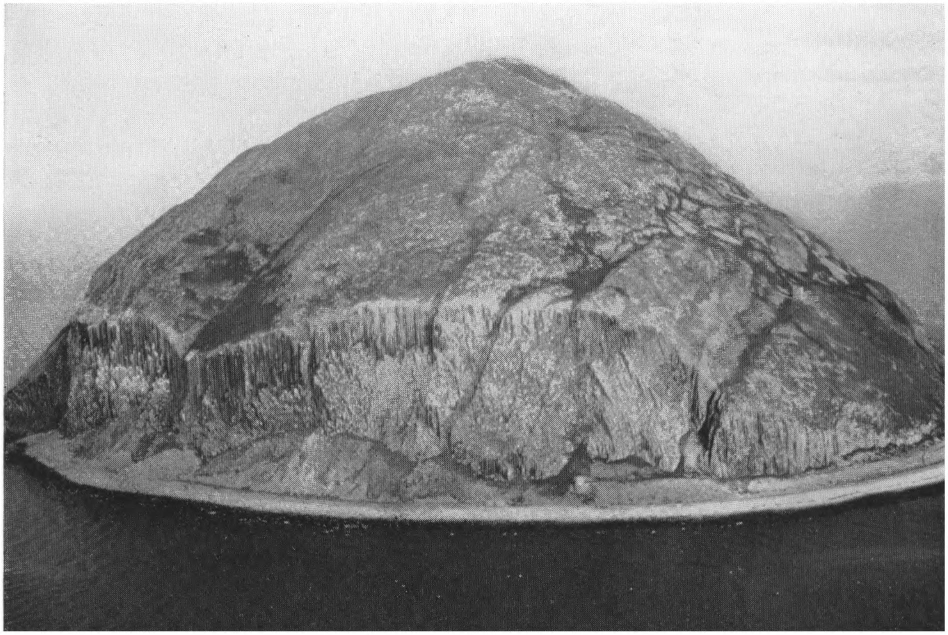

Plate I. Ailsa Craig viewed from the south (see page 250).

Plate II. Ailsa Craig viewed from the east.

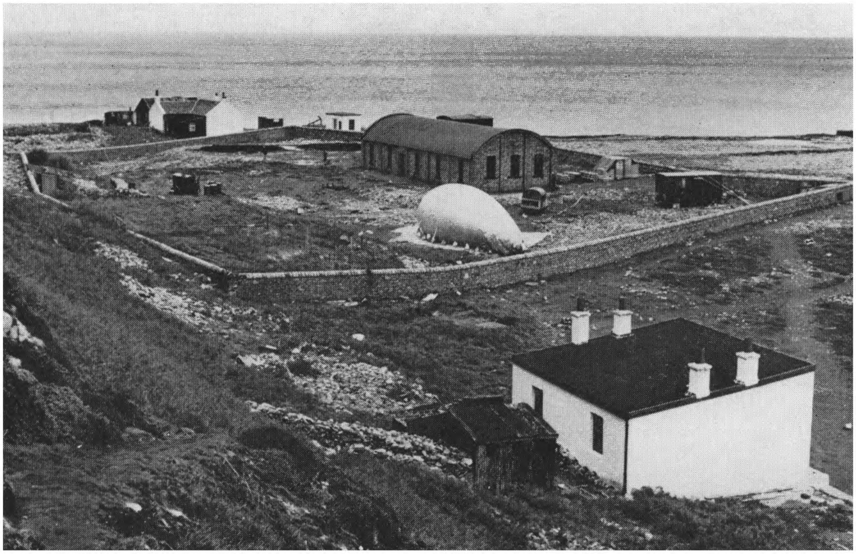

Plate III. RAE balloon lying in the grounds of the old gasworks on Ailsa Craig.

Plate IV. Northern Lighthouse Board buildings and light on Ailsa Craig. The RAE balloon is visible at the bottom left-hand corner.

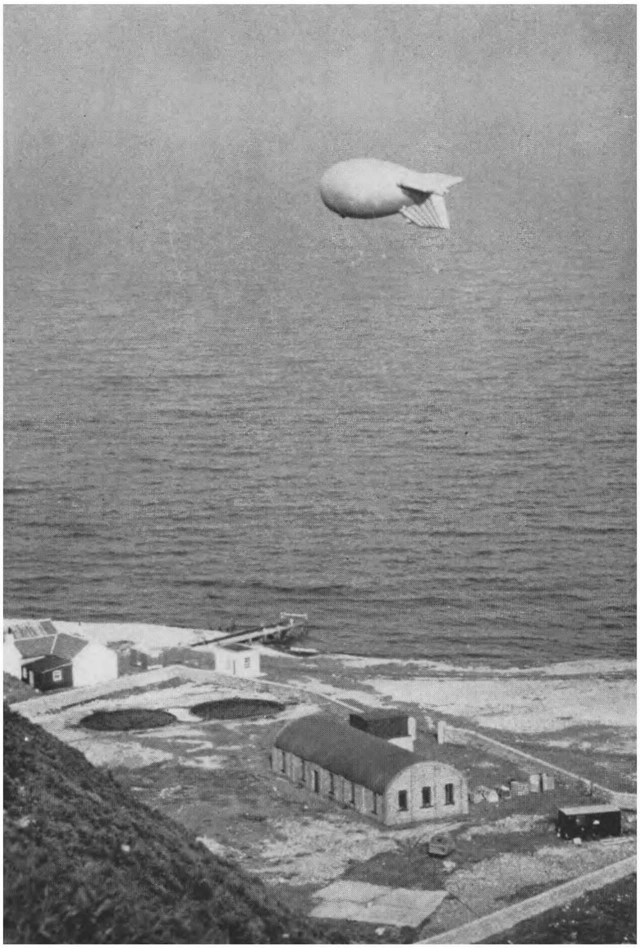

Plate V. RAE balloon flying over the old gasworks on Ailsa Craig.

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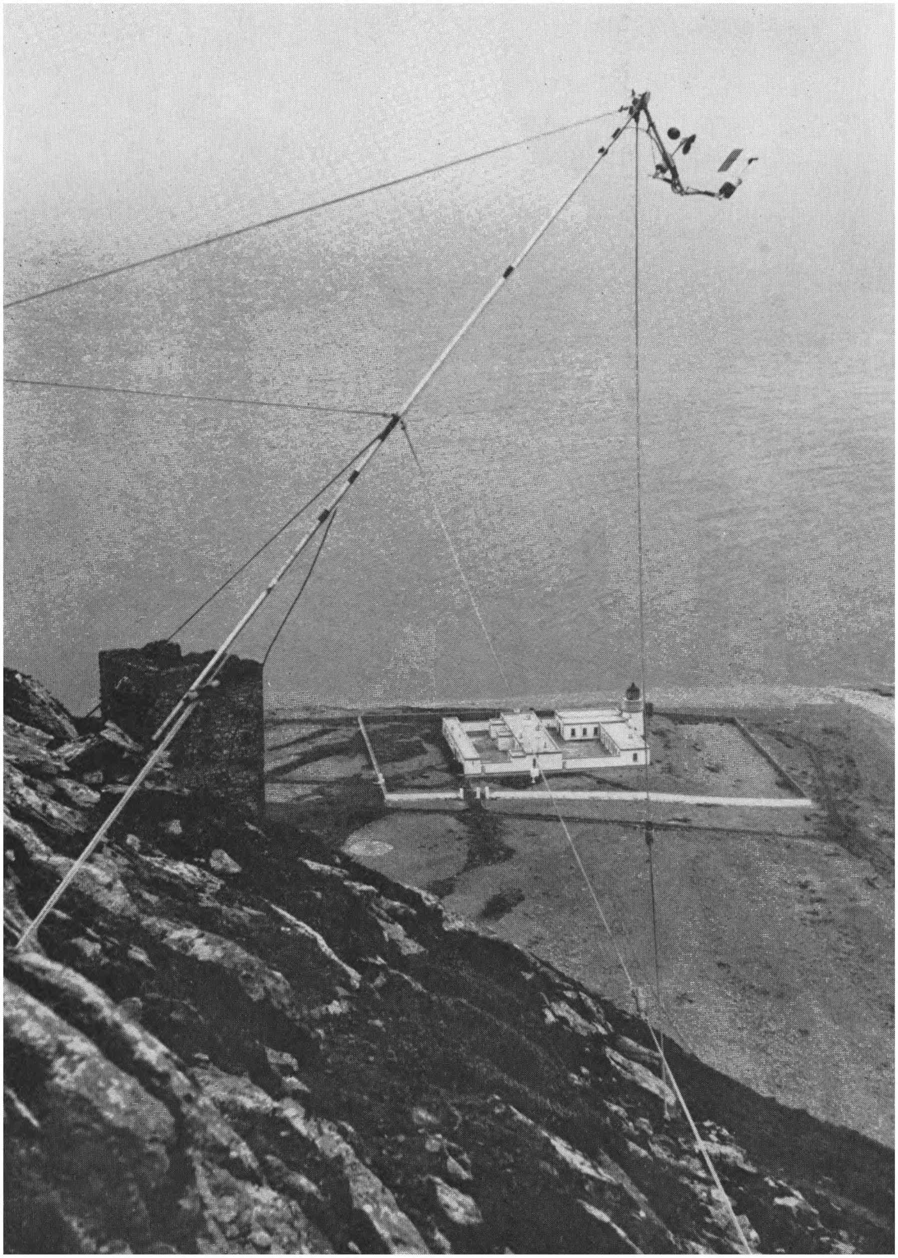

Plate VI. Vector-averaging wind recorder mounted on the hillside overlooking the lighthouse on Ailsa Craig. The ruins of the old castle are visible.

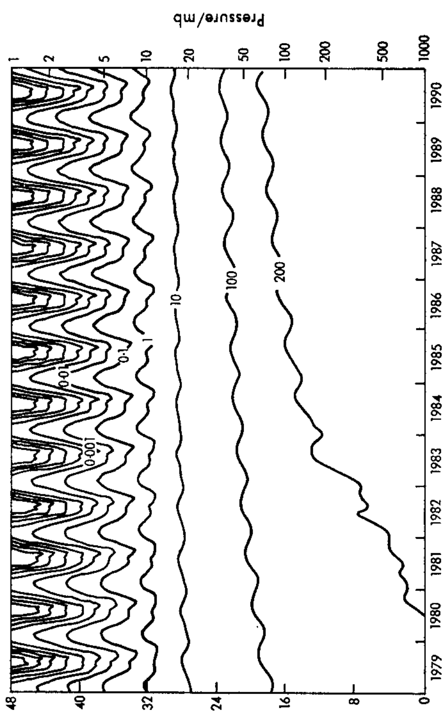

Figure 7(a). Values of F11 volume mixing ratio (ppt) for the northern hemisphere corresponding to the global total of Figure 6(b).

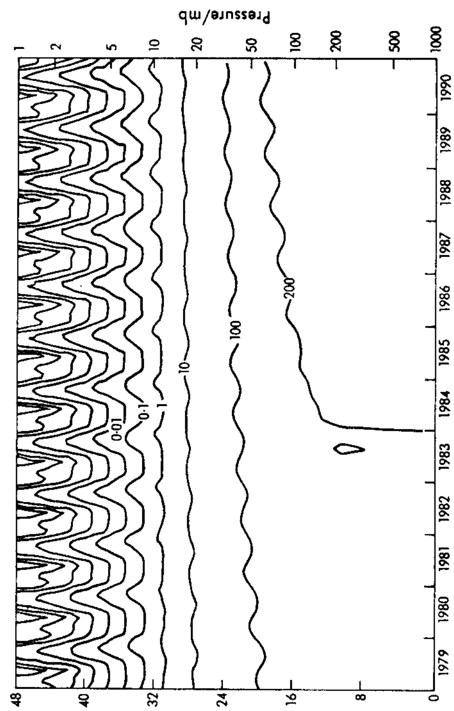

Figure 7(b). Values of F11 volume mixing ratio (ppt) for the southern hemisphere corresponding to the global totals of Figure 6(b).

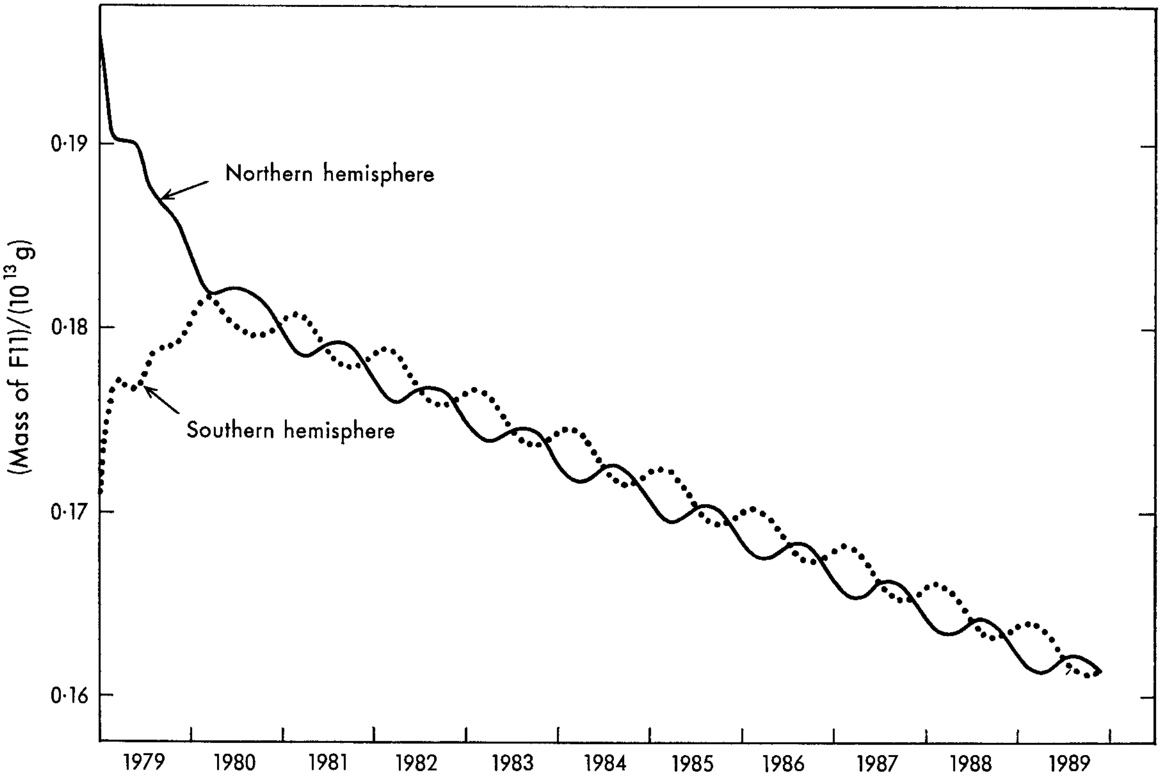

Figure 8. Hemispheric total masses of F11 during the period January 1979 to December 1989 obtained in Experiment 3(b).

is to remove CFCs from the stratosphere in some periods and locations (for example mid-stratosphere in winter—see Figure 5) as well as generally providing the means whereby CFCs are transferred from the source regions in the lower atmosphere to the sink regions in the upper stratosphere, thus illustrating the complications of the total dynamical-chemical problem.

Acknowledgement

The author wishes to thank Dr R. J. Murgatroyd and Dr S. A. Clough for their very considerable advice and help.

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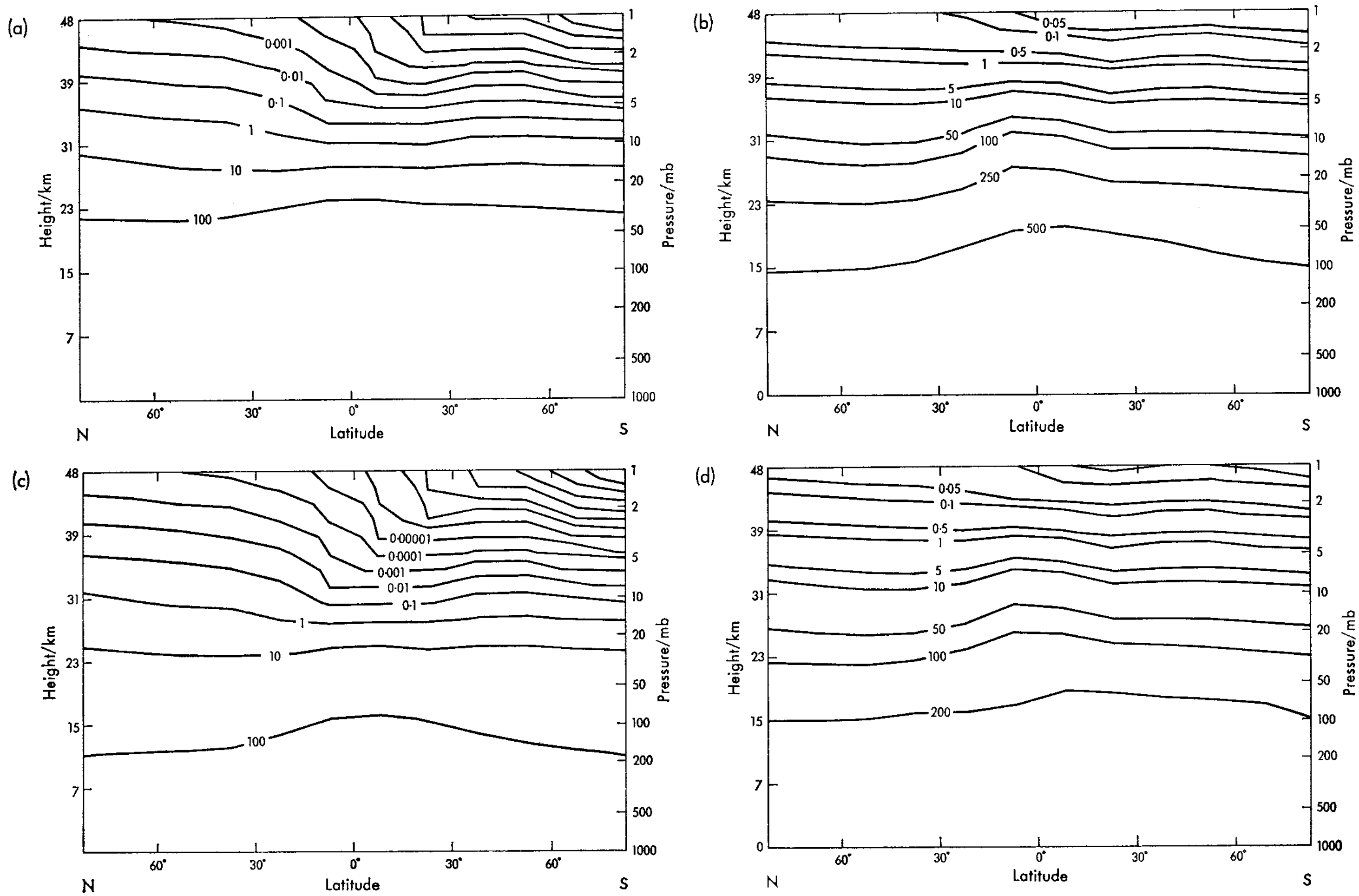

Figure 9. Predicted cross-sections of volume mixing ratio (ppt) at the end of 1998. (a) F11, Experiment 4(a). (b) F12, Experiment 4(a). (c) F11, Experiment 4(c). (d) F12, Experiment 4(c).

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Memoirs of an Army Meteorologist

By H. Cotton, M.B.E., D.Sc.

Part 1

We print this month the first of a series of extracts from the unpublished memoirs of Dr H. Cotton who, until his retirement in 1954, was Professor of Electrical Engineering at Nottingham University. He has sent us a copy of his memoirs—which contain many details of his childhood, early education, and personal reminiscences as well as his account of his experiences in 'Meteor'—and has kindly granted us permission to make extracts from them for publication in the *Meteorological Magazine*.
Dr Cotton spent his childhood in Hanley in the Potteries, and won scholarships to Manchester University where he studied under Rutherford. As a boy he became a skilled amateur player of the cello.
The Meteorological Section of the Royal Engineers, or 'Meteor' as it was generally known, was commanded by Captain (later Lt.-Col.) E. Gold, F.R.S., who described its work in the special issue of the *Meteorological Magazine* celebrating the centenary of the Office.* Except for that of Col. Gold himself, all names used by Dr Cotton are fictitious.

At the commencement of my final year at the university I tried to join the O.T.C.; only tried, because besides being left-handed, I was almost completely left-sided. I was therefore very clumsy at rifle drill but was a fairly good shot provided that I could hold the butt at the left shoulder and manipulate the breach bolt with the left hand. This of course would not do; if I was to shoot an enemy it must be right-handed or not at all. But for this I might have been one of the sixty thousand casualties of the first day of the Battle of the Somme, for the regiment I would have joined, the Fifth North Staffs., was almost completely wiped out. It is curious to realize that, if I had been right-handed, these memoirs might not have been written, or, if they had been written, would have been entirely different.

At the time of the outbreak of war in 1914 I was a lecturer at the Technical College, St Helens, Lancashire. I was responsible for the whole of the instruction in Electrical Engineering, in Advanced Machine Drawing and Design, and in Advanced Practical Mathematics. I had classes every week-night from seven to ten, every Saturday afternoon from two to five, and part-time day classes on two days a week. It was a formidable program which could not have been sustained if the evening and Saturday classes had been continued beyond Easter. Fortunately, after Easter, there was, apart from day classes, only light administrative work; without this rest I doubt if I, or anyone else, could have continued.

[Soon after the outbreak of war, Dr Cotton attempted to join the motor-cycle machine-gun corps, but the Education Authorities would not release him.]

On September 25th of that year, 1915, the British launched their first major offensive of the war. It was named the Battle of Loos after the town of that name situated in the middle of a vast mining complex. Characteristic of this industry, the terrain was broken land, littered by ramshackle buildings of all kinds, crossed by roads and lanes and railway lines, hopeless for attack but ideal for defence

* Gold, E.; The Meteorological Office and the first world war. *Meteorol Mag*, **84**, 1955, 173–178.

since almost every feature could be converted into a strong-point. Perhaps most important of all, the enemy had possession of every one of the spoil heaps, these giving them such perfect observation that they could note every move made by the British, see the position of every gun, see everything in fact.

Apart from the almost lunatic choice of terrain for an offensive battle and the stationing of the reserve twenty miles away so that when they were needed they had to make a long forced march, the special feature of the battle was that the British used gas for the first time. It was supposed to be a profound secret known only to the Higher Command, but the gas was made at Widnes, and many of the soldiers whose homes were in or near Widnes knew from letters from home that 'Roger' was coming out, 'Roger' meaning chlorine. There are always those who are unable to keep a secret and soon everybody knew this supposed secret, the local population knew it, and through local spies the Germans also knew. So from their ideal observation position they watched the gas cylinders being placed in position in a trench and informed their gunners just where the cylinders were.

Now gas released from cylinders is a very treacherous weapon since to be effective the surface wind must be about three or four miles an hour and must be steady in direction as well as in velocity. But light winds are very fickle, liable to sudden changes in direction, and that is what happened. At first it appeared that the gas would be a great success, but suddenly the wind changed direction and the gas was blown back. This is what the Germans were waiting for; their meteorological service, very much superior to ours at the time, had anticipated such a change. Immediately their guns opened fire on the gas cylinders which, when broken, poured out an almost solid cloud of chlorine. The reserves, tired after their forced march, ran straight into it. The battle was described by the press as a great victory because a few yards of useless territory were captured. In fact it was a tragedy of lessons not learned and courage wasted. In his book 'Fifth Army' Gough wrote 'Both Sir John French and Sir Douglas Haig made energetic protests against launching this attack at Loos . . . the fighting was for "the cause", *a stern necessity which weighed more heavily on us every year as the war continued*' (my italics).

To all intents and purposes the sacrifices in men and material had been in vain, but one important lesson had been learned. It was that the vagaries of purely local winds cannot be forecast from a synoptic chart covering Europe and much of the Atlantic Ocean. It is necessary to have observers covering the whole of the area for which such information is required. So, a few weeks later, I received a letter from the War Office asking if I would volunteer for service in a Meteorological Section R. E. to be stationed in France. This time my request for release by the Education Authorities was granted, and I was to become that *rara avis* a peg in a hole of the right shape and I dropped all ideas about serving with the motor-cycle machine-guns. I immediately wrote an acceptance, and a few days later I received a second communication instructing me to sign on at any convenient Recruiting Station and then await further instructions. I went once more to J.J. [as the Principal was colloquially referred to] and asked if I might have a day off so that I might see my parents; 'you never know' I said. He agreed. 'That will mean someone taking one of your evening classes' he said 'and that someone will have to be me'. He settled for the evening of the Lancashire and Cheshire examination in electrical engineering. I was very doubtful but said nothing beyond thanking him for his help.

I said goodbye to my parents and signed on at the Hanley Recruiting Office as I knew the Recruiting Officer there. I received the King's shilling, which I still have somewhere. When I saw the class the following week I asked what J.J. had taught them and they all laughed. 'Was it very amusing?' I asked. 'It certainly was' said one; 'he said that a line of force was like a string of sausages'. 'Yes' said another 'he worked out a numerical problem and couldn't get the right answer'. 'I think you had better forget all that he told you' I said, and then continued with a proper lesson.

At the very beginning of the New Year of 1916 I received instructions to report at the Queen Mary R.E. Barracks at Chatham. Army barracks are pretty much the same wherever they are and there is little point in describing this one except to say that it was not made for physical comfort. I gave my particulars, name, age, address, religion. That was United Methodist, but if I had said that I had no religion I should have been put down as Church of England. It seemed that I was joining a very religious army. This interrogation over and my pedigree duly recorded I turned away and a sergeant who was standing by said in a sneering voice 'And where have you been all this time my little man?' I wasn't having any, having already sensed the contempt of the old army for us mere civilians. So I said nothing, gave him a weak smile and passed on. The next man was made of sterner stuff and to the same silly question he replied 'Helping my bloody country while you lot were losing the bloody war'. I thought that the sergeant was about to drop dead, and hoped he would. Instead, he recovered himself after visible effort and marched off. 'That was brave of you' I said, 'but I am afraid you will be for it' and I was right. My fatigues were not so bad, peeling spuds one day and acting as housemaid in married quarters on another. The brave man seemed to spend most of his time cleaning latrines and I hoped he would be able to get his own back although I could not imagine how it would be possible. As far as I was concerned the worst bit was the CSM injection which made one feel decidedly miserable for a day, after which it wore off.

I joined a sizable bunch of men about my own age and I heard one of them say that there was a rumour to the effect that they would be going overseas in a day or two.

'Do you all belong to Meteor?' I said.
'Meteor, what's that?'
'It's the unit I have been instructed to join'.
'Never heard of it'.
'What are you then?'
'A gas company, we are the blokes who will turn on the bloody gas taps. Some bloke at the War Office decided that to turn on the taps properly one must have an honours degree in Chemistry, so here we are, a bunch of Chemistry teachers'.

Turning gas taps was not my idea of serving King and Country and I realized that it was time I saw the Commanding Officer and explained the situation. Trying to see the C.O. was almost as difficult as trying to see God, but by working upwards from lance-corporal up the ladder of rank to the adjutant I at last gained permission to see this august personage. I was ushered into the presence, escorted by an enormous sergeant, and explained the position. I handed to him my original letter from the War Office. He was very pleasant and not at all fearsome, not to me anyway, and he started things moving straight away. I was issued with a railway warrant to Newark and instructed to report to the R.E. Barracks there. I travelled by the midnight train from King's Cross and arrived in the early hours.

One thing I brought with me from the barracks at Chatham was a red fibre identity disc stamped H. COTTON, UM, R.E. 160163. The UM stood for United Methodist. I discovered that everyone entering the Army, no matter which service, had to possess an identity disc, and he had to have a religion even if he had never belonged to any religious denomination. If he declared that he had no religion, then, automatically, he became a member of the Church of England. It would appear that the Army authorities could not possibly allow a man to attend a compulsory religious service unless he belonged, if only in an Army record, to some religious denomination. I had already found out that one could not be allowed to handle a rifle left-handed—I happen to be left-handed—but I doubt if there were any troops who, like Cromwell's Ironsides, went into battle on a prayer and a bible. I spent what remained of the night on a sloping board in the guardroom and, after breakfast at the barracks, recited once again all my particulars. I also underwent a medical test once again, a test which at that stage of the war I should have passed even if I needed propping up. Having already had a CSM injection at Chatham, I was spared a repetition, for which I was thankful, as the after-effects were unpleasant.

I was directed to a civilian billet and instructed to report each morning after breakfast, and that was all.

Newark is a very pleasant town, and apart from the necessity to report each morning after breakfast, and before I was provided with Army uniform, I was, to all intents and purposes, a holiday-maker whose expenses were paid by the State. I have always been content with my own company and I went on long walks into the pleasant countryside or along the river banks, watched the express trains at the level crossing on the Lincoln road—I retained my love of railway engines until the sad ending of the steam era—and practised on the violin so that I became quite proficient in my unorthodox manner of playing it. [The violin referred to by Dr Cotton belonged to the owners of his billet, and he played it as though it were a miniature cello.] I also browsed in the town library. Newark, especially in former years, was an extremely important town because it was at a river crossing. I therefore read the history of the town with very great interest.

The day came when I was provided with Army uniform complete with corporal's stripes. For a time I was still free to do what I liked but there was now the irritation of having to salute, which was a nuisance as there were always plenty of commissioned officers about. So I largely avoided the town—I had thoroughly explored it by then—and spent most of my time walking.

Early in 1916 I received information that I was to proceed to France. I was given a railway warrant to King's Cross and told to report to the Railway Transport Officer there, who would give me further instructions. I received no military training whatever, no square bashing, no small arms drill, nothing but the ability to salute, and this I always did badly. Still, I had my corporal's stripes. I presumed that if by any mischance I should meet the enemy I should have to use my initiative. This was my preparation to 'fight the foreign foe'.

The troopship left Southampton in the early hours of the morning. Because I left Newark before breakfast time and there was no chance of a snack at Waterloo even if I could have pushed my way through the crush in the refreshment room I was feeling decidedly peckish. I and all the other troops who were waiting to embark were served with strong sweet tea and two of those army biscuits which look exactly like large dog biscuits. After eating them, whatever they were, I was still feeling hungry. Fortunately the sea was calm, so we were told, for there are few things worse than being seasick on an empty stomach.

We landed at Le Havre and we again were served with tea and dog biscuits. There was one lot of men belonging to Strathcona's Horse, obviously cavalry by their uniform and equipment; I had never heard of the regiment before. Naturally, at that time I knew nothing of the conditions at the fighting fronts but I wondered what use cavalry could be on broken terrain, riddled by shell holes, with a continuous belt of trenches two and three deep, with communication trenches and iron pickets and barbed wire all over the place. The High Command retained their obsession with cavalry far too long. There could be no repetition of Omdurman with such terrain and against an enemy equipped with every conceivable device for killing at a distance.

We stayed at a so-called rest camp near Le Havre and went by train the following morning to Rouen where we stayed another day and night. I managed to get into the town which was of double interest, first its great historical importance and second its beauty. Of course, I visited the spot where Joan of Arc was burned, surely one of the greatest crimes in British history, and I looked up and round at all the buildings in the square so as to see the last things that she would have seen. Then train again, a long slow journey to Abbeville. I had to change there and this gave me a chance to examine a monster of a locomotive with a square funnel, and, by the look of it, all its pipes on the outside. I couldn't imagine a more ugly engine, especially in comparison with the sleek beauty and clean lines of so many British locomotives. It looked a powerful brute. We were all longing for a drink so I borrowed two dixies and took them, along with my own, to the driver, who filled them with boiling water straight from the boiler. Someone in the carriage had candles so that most of the heat lost on the walk back, but not all, was made up and with plenty of tea from the iron rations there was tea for everybody. It was slightly oily but we didn't mind that.

The new train seemed to wander all over the north of France. At every crossing there were hoards of children shouting 'Bully beef, souvenirs', demonstrating the generosity, so often misplaced, of the British Tommy. It was said that many of the peasants had their cottages lined with tins of bully beef, and although this was a gross exaggeration it was a pointer to the extent of this foolish giving away of things which the donor might need for himself later on.

After what seemed an eternity the train arrived at St Omer station, some distance from the town. I had been ordered to report at a place called Helfant and I had to walk. So I asked a man on the platform 'Combien de kilomètres y-a-t-il d'ici à Helfant?', airing my sixth form French. I forget how many kilometres it was, but it was a long walk uphill all the way, and my burden, heavy pack and greatcoat, seemed to become heavier with each step. Helfant is a small village on a high plateau and the first thing I noticed was a cup anemometer rotating merrily. As there were no Meteor personnel there I assumed that there had once been a meteorological observation station, and that it was now abandoned. I heard the sound of gunfire for the first time. There was a mess where I had the first good meal since I left England. My billet was a barn, comfortable enough, as there was plenty of dry hay. I intended to go for a long walk but the plateau was so bare and uninviting, so I thought I might as well go into an estaminet which seemed to be doing a roaring business. I was still hungry. The man in front of me ordered 'doos oofs, pomme de terre fritz, pain et beurre, café avec'. It looked very good so I ordered the same. It was good, in fact it is still, after all these years, a favourite dish of mine. As there was no point in going for a walk I stayed for quite a while talking to anyone who wanted to talk. The war was not even mentioned. When I turned in, the guns were still rumbling but when I awoke they were silent. After breakfast I trudged back to St Omer station, not so tiring this time as it was downhill all the way. I caught a train which also seemed to wander over the whole of northern France. It took me back to Abbeville where I caught another train and reached Hesdin, Second Echelon G.H.Q. in the late afternoon.

I reported immediately to Meteor and after the Sergeant Major had made sure that there were no buttons undone and that my cap was on straight I was ushered into the presence. Colonel Gold had a slightly saturnine appearance which belied his nature although, as was his right, he could be very angry if things went wrong. He questioned me about my university career; was I any good at Mathematics and Physics? He wrote me a differential equation and asked how I would solve it, also a number of questions about certain aspects of Physics, particularly those pertaining to the science of Meteorology. He seemed quite satisfied and after a while I was dismissed and told to report again to the S.M. who would give me further instructions. These were to find my billet, which was in the infantry barracks, leave my kit there and be back in time for dinner. The prospect of dinner was cheering but the billet was the reverse.

The barracks were a plain stone building, uglier I think than any building I had ever seen before. It was old at the time of the 1870 war with Germany. The rooms were large enough to take, I should say, twenty men. Instead of a door there was a wide open archway, and directly opposite, high up in the wall, a window, small for the size of the room. The floor was of stone and there was nothing to give protection against its cold hardness; no straw, no blankets, nothing. I wondered what kind of a night I was going to have. I found a tap, cold water of course, one could not expect even the simplest of luxuries in such a place, and was thus able to wash off the grime of the long hot railway journey. I had this bare room to myself; in fact, vast as the building was there seemed to be very few people in it. As I anticipated I had a very uncomfortable night, not having had time to become accustomed to the absence of luxuries. I was very thankful when morning came, after what seemed an interminable night. I washed and shaved at the cold tap and made my way back to Meteor.

The organization of Meteor was as follows:

(1). *The headquarters staff.* The O.C., the adjutant and a junior officer, all professional meteorologists in civil life. A staff of clerks from S.M. to corporal; there was no rank below corporal in the whole of Meteor, apart from officers' batmen who were privates seconded from infantry regiments.

The work consisted of the collection of data from as much of the world as possible so that the synoptic charts could be drawn. All over the world, in enemy territory as well, observations were made at what were called the fundamental hours, namely in GMT 7 a.m., 1 p.m., 6 p.m. and 1 a.m. The data were sent by priority telegram so that the chart could be drawn up as soon as possible and consisted of barometric pressure corrected to mean sea level; barometric tendency, i.e. whether up or down and the rate of change; wind direction and force; temperature; precipitation, i.e. rain, hail or snow; thunder if any.

From the 7 a.m. chart the O.C. drew up the forecast for the next twenty-four hours and this was supplied to the Commander in Chief whose headquarters were at Montreuil, First Echelon G.H.Q. Later on Meteor moved to Montreuil so as to be immediately available to the C in C when required. Data were also received from all Meteor observation stations in France, also by priority telegram. Thus the current weather conditions for the whole of the fighting area were known at Meteor headquarters.

(2). *Army Headquarters.* The staff consisted of a Meteorological Officer and two observers, both corporals. Data for the construction of the 7 a.m. chart were received by priority telegram and the chart when completed was taken by the officer to the General of that particular army. The weather and its probable tendencies were discussed. The two observers made local observations of all the phenomena required for the synoptic chart, also wet- and dry-bulb thermometer readings, from which the humidity could be calculated, the amount of rain and the amount of sunshine on the previous day. Also the kinds of cloud and their amounts and an estimation of their directions, velocities and heights. A vitally important observation was that of wind velocity and direction in the upper air to as great a height as possible.

For this purpose small balloons were filled with hydrogen so that they could just lift a certain weight; when freed from this weight and when released they rose at a rate of five hundred feet per minute. Actually, this only applied if there were no vertical air currents. The balloon was followed by means of a special theodolite whose telescope tube had a right-angled bend so that, no matter what the position of the balloon, the eyepiece half was always horizontal. Observations of azimuth and elevation were made after one minute, the balloon then having ascended vertically 500 feet; after another minute at 1000 feet and then after two-minute intervals at 2000, 3000 feet and so on for as long as the balloon could be kept in sight. Occasionally, on a clear day with little wind, observations were made up to 20 000 feet.

These observations were made at the fundamental hours including 1 a.m. For this purpose it was necessary for the balloon to carry a suspended light and many experiments were made to find the most suitable. A flare, a large version of children's fireworks, was the most convenient but it was not only heavy, but as it burned away its weight was progressively reduced thus affecting the rate of vertical climb. The final solution was a Chinese lantern made from tracing paper and carrying a toy candle. It was ironical that a toy which could give delight to children was used to facilitate the slaughter of fellow human beings. The possibility of error due to vertical components of the total wind had to be accepted since, to avoid this error, it was necessary to have two theodolites situated a long way apart following the balloon. Under war conditions this was not possible (a) because of the inconvenience and the necessity for two more observers, and also (b) because the complex computations would have taken too long.

The chief function of these pilot-balloon ascents was the determination of wind corrections for the artillery, for times of flight ranging from those of field guns with ranges of a few thousand yards, up to the heaviest guns with ranges up to ten miles or more.

These corrections were deduced as follows: for each time of flight the trajectory was known, this being a departure from the parabola of elementary mechanics because of air resistance. Also the height of climb was known and this was divided into horizontal zones, the time spent in each zone being calculated. Also the mean wind velocity and direction for each zone was known from the results of the pilot-balloon ascent. For each zone the mean wind velocity was weighted by the time spent in the zone. All these weighted velocities were treated like forces and the mean obtained by giving each its appropriate velocity. Actually the calculation was reduced, for practical purposes, to a series of factors so that the wind corrections for half a dozen times of flight could be calculated in a few minutes, reduced to a code, and sent by priority telegram to the battery commands.

(3). *Two-observer posts.* As the name indicates there were two observers and they were attached to an important command such as a Divisional Headquarters. The observations made were the same as those at Army Headquarters except that there were no pilot-balloon ascents. Observations were made at the fundamental hours and at the intermediate times of 4 a.m., 10 a.m., 4 p.m. and 9 p.m.

(4). *Single-observer posts.* These were distributed along the whole of the battle area and as close to the front as possible, the site for the observations post being obviously chosen in accordance with its meteorological suitability. Observations were made only of wind velocity and direction, the instrument used being a delicate portable anemometer. Priority telegrams were sent to G.H.Q. and Army H.Q. at the four fundamental hours, these including the data for the preceding intermediate observations. The observer also compiled a weather diary giving day-to-day information such as wind, weather in general, cloud amounts and kinds.

The most important duty of these observers was the sending of gas alerts if the wind approached within two points of the danger direction for his particular sector of the line, and gas warnings if it moved to only one point. The telegrams giving this information were sent to Corps and Divisions as well as G.H.Q. and Army H.Q. They were first priority which meant that the signaller had to deal with them immediately even to the putting off of other telegrams no matter who the sender might be. Thus when the wind was in a dangerous quarter it was essential that the observer must be vigilant in the lookout for changes towards the dangerous direction. These changes could be very sudden and could not therefore be forecast from the synoptic chart.

From the personal point of view the advantage of being a single observer was the great freedom apart from the necessity of vigilance when the wind was moving towards the dangerous direction.

(*To be continued*)

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Brief historical note on the formulation of Buys Ballot's Law

The name of Buys Ballot is to be found in almost every textbook of meteorology and his law of the relation of wind direction and pressure distribution is taught in the many schools which nowadays include elementary meteorology in their curriculum. It may therefore be of some interest to trace briefly the formulation of this law. Professor Buys Ballot, Director of the Dutch Meteorological Institute and Professor of Physics at Utrecht was amongst the pioneers in the use of synoptic meteorology for the issue of forecasts and storm warnings. In dealing with observations of pressure and temperature he made use of deviations from average values and in a paper presented to the Paris Academy of Sciences in 1857* he discussed the results obtained from observations at three stations in Holland. After showing that strong winds are indicated by large differences between the deviations, he proceeded to explain that if pressure was higher at Den Helder than at Maastricht (that is to say, higher in the north than in the south) then the wind was from the east while if pressure was higher at Maastricht the wind was from west or north-west. In the *Jaarboek* of the Meteorological Institute of the Netherlands for the same year (published in 1858) p. 347, this conclusion is stated in more general terms. Translated into English it reads 'great barometric differences, within the limits of our country, are followed by stronger winds, and the wind is in general perpendicular, or nearly so, to the direction of the greatest barometric slope in such a way that a decrease of pressure from north to south is followed by an east wind, and a decrease from south to north by a west wind'. In 1860 he published a paper entitled 'Eenige regelen voor aanstaande weersveranderingen in Nederland' (Some rules for approaching changes in the weather in the Netherlands), in which the law appears in its well-known form (pp. 50ff). 'Thus the rule for wind direction is this: if one places oneself in the direction of the wind with one's back to the place from which it is coming, then one has the lowest place (i.e. pressure) on the left-hand just as in the case of hurricanes'. (These storms had long been known to have a whirling motion and the distinction between the anti-clockwise rotation in the northern hemisphere and the clockwise rotation in the southern hemisphere had been expounded by Dove in 1828.)

[The above text, authorship unknown, is to be found in a pamphlet held in the National Meteorological Library and dated 1930.]

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* Note sur le rapport de l'intensité et de la direction du vent avec les écarts simultanés du baromètre. *CR Acad Sci, Paris*, **45**, 1857, 765–768.

Review

Turbulent fluxes through the sea surface, wave dynamics, and prediction, edited by A. Favre and K. Hasselmann. 260 mm × 150 mm, pp. xiii + 677, *illus*. Plenum Publishing Corporation, New York, 1978. Price US $59.40.

This large volume contains the papers and discussions from a conference held in 1977 under the auspices of the NATO Air–Sea Interaction Program. The book has been prepared from the original papers by photographic means, so the standards of presentation are variable. The stated aim of both the conference and this book is to bring together specialist papers in the fields of air–sea interaction, wave dynamics, and wave prediction so that a cross-fertilization of ideas can take place. I should have liked to see more review papers in a publication with such an aim. However, for those with the necessary background, the quality of many of these papers is first class. The book is divided into four main sections dealing with: Fluxes through the air–sea interface; Non-linear dynamics of surface waves; Wind–wave interaction; and Numerical wave prediction models.

The first section deals mostly with the atmospheric boundary layer, describing a number of experiments both in the laboratory and in the field. The field experiments include a number from towers and some results from GATE. Of particular interest is a comparison of results from three methods of estimating surface fluxes.

The second section is the most comprehensive collection of papers on a variety of non-linear phenomena in surface waves known to the reviewer. It starts with an excellent review by Professor Longuet-Higgins of instabilities in steep waves. There are several other very good contributions on both weak and strong instabilities. Readers should, however, be warned of the complexity of much of the algebra. The review of bottom interaction which concludes this section is a particularly useful paper.

The third section deals mainly with observations of wave growth by wind action. However, it opens with a very interesting paper by Professor Phillips pointing out some of the dangers of extending laboratory results to the open sea. The papers that follow are nicely balanced between laboratory and field experiments along with two theoretical papers.

The final section on wave prediction models forms a useful survey of current work in this field, including papers on both the classical source function and parametric methods. The section opens with a very illuminating paper by Professor Hasselmann on the energy balance concept used in wave models.

B. W. Golding

Honour

The following honour was announced in the Birthday Honours List, 1979:

KNIGHT BACHELOR

Dr B. J. Mason, C.B., F.R.S., Director-General of the Meteorological Office.

Notes and news

The Ailsa Craig Experiment

Hearken, thou craggy ocean pyramid!
Give answer from thy voice, the sea-fowls' screams!

KEATS, *To Ailsa Rock*

Measurements of the airflow round the island of Ailsa Craig off the Ayrshire coast were obtained by members of the Boundary Layer Research Branch (Met O 14) from Porton, Cardington and Bracknell during a five week period in the autumn of 1978. Ailsa Craig was chosen because of its uniformly smooth shape and its relative isolation from any other features which could disturb the flow. Meteorological and domestic equipment was transported to the island by the Sea King helicopters of 819 Squadron, HMS *Gannet*. For most of the period a staff of four people was maintained on the island, with a VHF radio link to two further staff based at the meteorological office at Prestwick Airport.

The mean wind was measured by an array of anemographs mounted 4 metres above ground. The performance of the normal anemographs had been expected to be inadequate in areas of extreme turbulence and so three vector-averaging wind recorders, specially built at Porton, were used instead. Turbulence data were gathered by instruments supported by a tethered balloon which was launched from a small spit of flat land on the eastern side of the island by a balloon crew from RAE, Cardington. Unfortunately, severe turbulence in the lee of the island often made it impossible to fly the balloon, limiting the number of data collected.

In addition, the Hercules aircraft of the Meteorological Research Flight flew round the area on seven occasions during the experiment in order to measure relevant parameters—in particular the three components of the small-scale wind fluctuation—both upstream of the island (to obtain the 'undisturbed' flow) and also downstream to measure the horizontal and vertical extent of the turbulent wake. Flights were made along and across the wake at heights from about 30 m (very bumpy close to the island—patterns of disturbance could be seen on the sea) to about 1000 m, well above the island where the flow was usually quite smooth. It had been hoped that over the operating period a variety of wind directions and strengths would occur, but unfortunately the moist south-westerly type predominated and most of the flights were therefore in similar conditions.

Analysis of the data is still in progress, but a couple of preliminary results have emerged. The aircraft data consistently show a pronounced vortex downstream of the island with its axis of rotation pointing downwind. The vortex is very powerful, with vertical velocities of up to half the geostrophic wind, so that values of about ± 8 m s^{-1} were measured on occasions. The turbulence data from the tethered balloon show very large changes in the structure of the turbulence as it is distorted in passing round the sides of the island; in particular, the ratio of the turbulent energy components in the downstream and transverse directions is changed by a factor of about 10 from the usual boundary layer value.

(See Plates I–VI.)

Dr Aksel C. Wiin-Nielsen (Denmark) appointed Secretary-General of the World Meteorological Organization

The Eighth World Meteorological Congress, meeting in Geneva in May of this year, appointed Dr Aksel C. Wiin-Nielsen (Denmark) as Secretary-General of the World Meteorological Organization (WMO) for a period of four years commencing on 1 January 1980.

Dr Wiin-Nielsen, who is a graduate of the University of Copenhagen and holds a doctorate in meteorology from the University of Stockholm, was born in Denmark in 1924. In 1952 he joined the Danish Meteorological Institute. He was a member of the International Meteorological Institute in Stockholm (1955–58) and of the Joint Numerical Weather Prediction Unit in Suitland (USA) (1959–61).

From 1961 to 1963 he was the Assistant Director of the Laboratory for Atmospheric Sciences, National Center for Atmospheric Research in Boulder, Colorado (USA). Professor at the University of Michigan (1963–71) and later at the University of Bergen (1971–72), he was nominated Head of the Department of Atmospheric and Oceanic Science of the University of Michigan in 1972. In 1974 he was appointed Director of the European Centre for Medium-range Weather Forecasts near Reading (England). Dr Wiin-Nielsen is the author of numerous scientific papers on subjects in atmospheric dynamics, numerical weather prediction, atmospheric energetics and the general circulation of the atmosphere. He is also the author and the editor of several of the WMO training publications.

Dr Wiin-Nielsen is married and has three daughters.

Dr Wiin-Nielsen succeeds Dr David Arthur Davies, the present Secretary-General of WMO. Dr Davies was appointed to the office of Secretary-General in 1955 and has thus served in that capacity for 24 years, the longest period of service as Executive Head of any organization within the United Nations system.

Climatic variations: facts and causes, Erice, Sicily, 9–21 March 1980

The First International School of Climatology (Director, Professor A. Longhetto) will be held at the Ettore Majorana Centre for Scientific Culture, Erice, Trapani, Sicily from 9 to 21 March 1980. It will deal with Climatic Changes and Variations: Facts, Causes and Geophysical Background.

The main purpose of this course is to present a full review of palaeoclimatology, lectures being essentially oriented towards the physical basis of climatic changes and climatic variations.

This interdisciplinary course will provide an up-to-date survey of the most recent reconstructions of past climates and of the results of theoretical models simulating climatic changes and variations. Some lectures will also be devoted to man's impact on climate and a panel will discuss probabilities of climatic evolution in the next century.

This course is designed for people having a background in physical, mathematical, and geophysical or meteorological aspects of phenomena occurring in the climatic system. The program has been designed to provide information for researchers already working in this field as well as to stimulate and motivate all geophysicists engaged in developments related to climatic variations. Lectures will be delivered by 25 specialists who will review the following subjects: Mathematical and Physical Basis of Climate, Reconstruction of Past Climates, Causes of Climatic Variations, Modelling Techniques and Man's Impact on Climate.

Some fellowships available for travel and/or living expenses will be awarded on a competitive basis. The number of participants will be limited. For further information and applications, contact the Director of this course:

Professor A. Berger,
Institute of Astronomy and Geophysics,
Catholic University of Louvain,
Chemin du Cyclotron 2,
B-1348 Louvain-la-Neuve,
Belgium.

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NOTICES

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The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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Aspects of tropospheric structure over the Bay of Bengal during active and break monsoon over India in August 1977

By M. G. Hamilton

(University of Birmingham)

Summary

Details are given of tropospheric conditions over the Bay of Bengal which were associated with break and active monsoon spells over eastern India during August 1977.

1. Introduction

During summer in most years the fully-developed monsoon circulation over India exhibits at least three synoptic patterns, namely, 'moderate', 'active' and 'break' phases. The relative duration of these three phases directly influences human activity because patterns of rainfall associated with these phases differ considerably.

The moderate phase is typified by weak, short-lived and slow-moving cyclones and ridges in the middle and lower troposphere and by an absence of monsoon depressions. A low-pressure (monsoon) trough spans the sub-continent between central Pakistan and Bangladesh. During an active phase, at least one monsoon depression develops over the north Bay of Bengal at the eastern end of the monsoon trough and moves west-north-westwards for 3–10 days. When a break occurs, the axis of the monsoon trough over a wide longitudinal belt either shifts polewards to the Himalayan foothills or disappears below 500 mb as a ridge develops near 20°N. No monsoon depressions develop during this phase. Breaks usually persist for 3–7 days. Therefore, the active and break phases represent synoptic extremes.

Patterns of circulation and cloudiness associated with active and break phases have been compared before (see, for example, Srinivasan and Sadasivan, 1975; Rao, 1976; Hamilton, 1977; Ramaswamy and Pareek, 1978) but aerological data from the Bay of Bengal have laways been sparse.

During August 1977 an array of ships operating within the MONSOON-77 Experiment provided observational coverage of this region for a short period. Fortunately, this observational effort documented a spell of active monsoon and a spell of break monsoon activity. The following account compares aspects of the dynamical and thermodynamic structure of the troposphere over the Bay of Bengal and Asia near 92°E on one occasion during each of these two spells.

2. Data sources

Radiosonde ascents for 00 GMT were available from stations in India, China, Burma, Thailand and Indonesia, and from the MONSOON-77 polygon formation of four USSR ships centred near 89°E in the Bay of Bengal. Data from seven land stations and the northernmost and southernmost members of the ship array for 16 and 20 August, days when conditions were representative of break and active phases respectively, were used to construct latitude cross-sections of temperature, relative humidity and wind velocity components.

In order to compare tropospheric structure over the Bay of Bengal during each of the three phases the ships' observations were averaged in an attempt to reduce random errors which can occur within a single sounding and to minimize the influence of local phenomena at each ship.

As an aid to analysis and interpretation, daily scene-corrected mosaics of digitized infra-red and visible imagery for 03 GMT (approximately) from the NOAA 5 meteorological satellite were compared with 03 GMT surface charts and synoptic summaries which are published in the *Indian Daily Weather Report*. Further information was available in the form of analysed charts for standard levels from the surface to 100 mb for 00 GMT which were received daily by radio-facsimile from the Regional Meteorological Centre at New Delhi. Charts published by a number of meteorological services also were used.

Since data from organizations which employ different radiosonde systems and different schemes of correction for lag and radiation effects are used there is likely to be a problem of data incompatibility, especially in the upper troposphere (Finger and McInturff, 1978). Additionally, station-based errors of measurement and calculation of an ascent as well as errors arising during communication of the coded message can occur. To produce a reasonably consistent analysis, gross errors which would produce misleading and unrepresentative observations at a station were removed by comparing each observation (a) with preceding and subsequent 00 GMT observations at that station, and (b) with simultaneous observations from nearby stations. Missing data were replaced by the mean of the 00 GMT observations for the previous and succeeding day, if these were available.

This scheme does not eliminate all sources of error. Systematic errors and small, but possibly significant, random errors could remain. However, it is considered that the analyses discussed in this account provide a reasonably accurate description of tropospheric phenomena.

3. Break monsoon, 16 August 1977

During 15–17 August the monsoon trough at the surface lay close to the Himalayan foothills. It extended up to 500 mb with its axis almost vertical. A shallow trough extended along the east coast of India from 22°N to 10°N.

In the lower troposphere a trough between 900 mb and 800 mb moved slowly east across Bangladesh and Assam. Between 700 mb and 400 mb a strong ridge spanned the Bay of Bengal between 5°N and 15°N.

Above 300 mb, a zonally aligned ridge with its axis inclined slightly northwards with increasing height moved steadily from 28°N to 24°N.

On 16 August strong horizontal shear of zonal wind occurred above 250 mb between a westerly speed maximum at 200 mb near 40°N and an easterly maximum at 150 mb and above between 15°N and 20°N (Figure 1). Below 400 mb a westerly current was deepest just south of the monsoon trough near 27°N. A westerly speed maximum occurred at low levels over the ship array near 17°N. The westerly zonal flow was strongest at the ship array on most days between 11 and 21 August. Farther south, weak easterlies flowed along the equatorial side of the ridge near 10°N.

South of the Himalayas the meridional wind below 700 mb was mainly southerly. In the middle

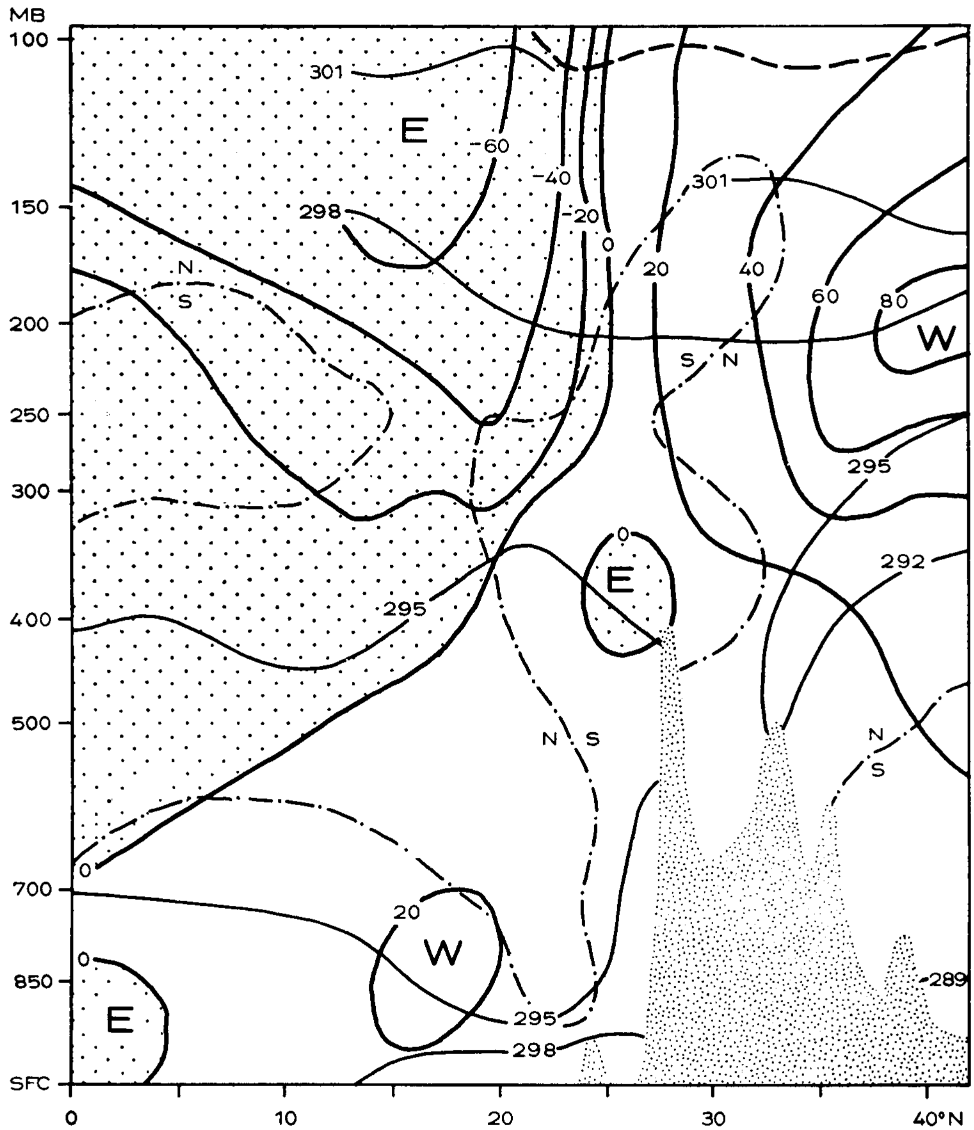

Figure 1. Zonal wind component (knots) and wet-bulb potential temperature (K) for a latitude cross-section near 92°E, 00 GMT 16 August 1977.

Regions of easterly zonal components are shaded. Thin solid lines denote isotherms. Dash–dot line separates regions with northerly (N) and southerly (S) meridional wind components. Tropopause is indicated by dashed line.

troposphere winds were light and variable. Between 300 mb and 200 mb confluence between an east-south-easterly flow south of 15°N and east-north-easterlies over north Bay of Bengal is indicated.

The vertical profile of wet-bulb potential temperature (WBPT) north of 35°N was typically extra-tropical. Tropical conditions south of Tibet are indicated by a minimum in the middle troposphere. Evidently, convective instability was well marked over north Bay of Bengal and north-east India. The meridional gradient of WBPT was small, except over north Tibet below 300 mb.

4. Active monsoon, 20 August 1977

During 18–20 August the monsoon trough west of 85°E extended from the surface to 500 mb and lay close to the Himalyan foothills. Farther east, it moved well south of 25° as a depression formed off the coast of Burma near 19°N early on 19 August within another trough which had developed on the previous day. This depression tracked west near 19°N to the coast of Orissa during the next two days. At the surface, the depression centre was located near 19°N, 90°E at 00 GMT on 20 August. Meanwhile, the shallow trough along the east coast of India persisted but weakened slowly.

In the lower troposphere a cyclonic vortex developed on 18 August near 850 mb at 18°N off the coast of Burma within a deepening trough which was extending west across the Bay of Bengal and east across Vietnam to the China Sea. This vortex was the precursor of the depression. On 20 August this cyclonic (depression) circulation extended from the surface to 400 mb with a trough aloft.

Above 300 mb, the ridge which had moved south to 24°N by 17 August migrated polewards to 28°N as another ridge developed behind an amplifying trough which was moving east across north Tibet.

Figure 2 indicates that, below 500 mb, the depression's circulation was well marked and extended from 10°N to 25°N. The depression axis tilted southwards with increasing height. A strong westerly speed maximum occurred in the lower troposphere near 12°N. A deep easterly current flowed around the poleward side of the depression. This current was strongest near 22°N, where there was weak zonal vertical shear. North of 20°N the vertical shear had begun to decrease before the depression developed (data not shown), partly because the lower tropospheric westerlies veered substantially as the low-level trough extended west ahead of the developing low (cf. Raman *et al.*, 1978).

Above 300 mb, the zonal flow south of Tibet was weaker than it was on 16 August (cf. Ramamurthi *et al.*, 1969) because winds were lighter and had veered to south-easterly below 150 mb behind the trough, which was amplifying as it moved slowly westwards. Farther north, horizontal shear across the ridge over Tibet was weaker than before because the circumpolar westerlies had also weakened and veered slightly as the other ridge moved eastwards.

In the lower troposphere south of Tibet a northerly component developed in the winds to the north of the depression centre. Over much of the Bay of Bengal, flow with a southerly component extended from the surface to 400 mb.

The vertical distribution of WBPT polewards of 25°N differed little from that of 16 August. But in the middle and lower troposphere between 10°N and 15°N convective instability had increased within the south-westerlies equatorwards of the depression centre. It had decreased within the north-easterlies north of 20°N. Above 400 mb, the meridional gradient of WBPT was again small. It was strongest within the circulation envelope of the depression and over Tibet near 35°N.

The differences between the circulation patterns in Figures 1 and 2 are indicated by contrasting patterns of cloudiness (Plates I and II).

On 16 August synoptic-scale deep convection was confined to India east of 85°E and the equatorial Indian Ocean. The extensive cloudiness over north-western India did not show up brightly on simultaneous infra-red imagery (not shown) because it was shallow and broken.

Four days later, the distribution of relatively clear skies and deep convection over the Bay of Bengal and neighbourhood was very different. Convective activity was weaker in the low-level easterlies polewards of the monsoon trough and embedded depression whereas it had strengthened within the low-level westerly current to the south (cf. Srinivasan *et al.*, 1971; Keshavamurty, 1972). Over much of Tibet synoptic-scale convection had diminished but clusters now covered southern India, Malaysia and the Gulf of Thailand.

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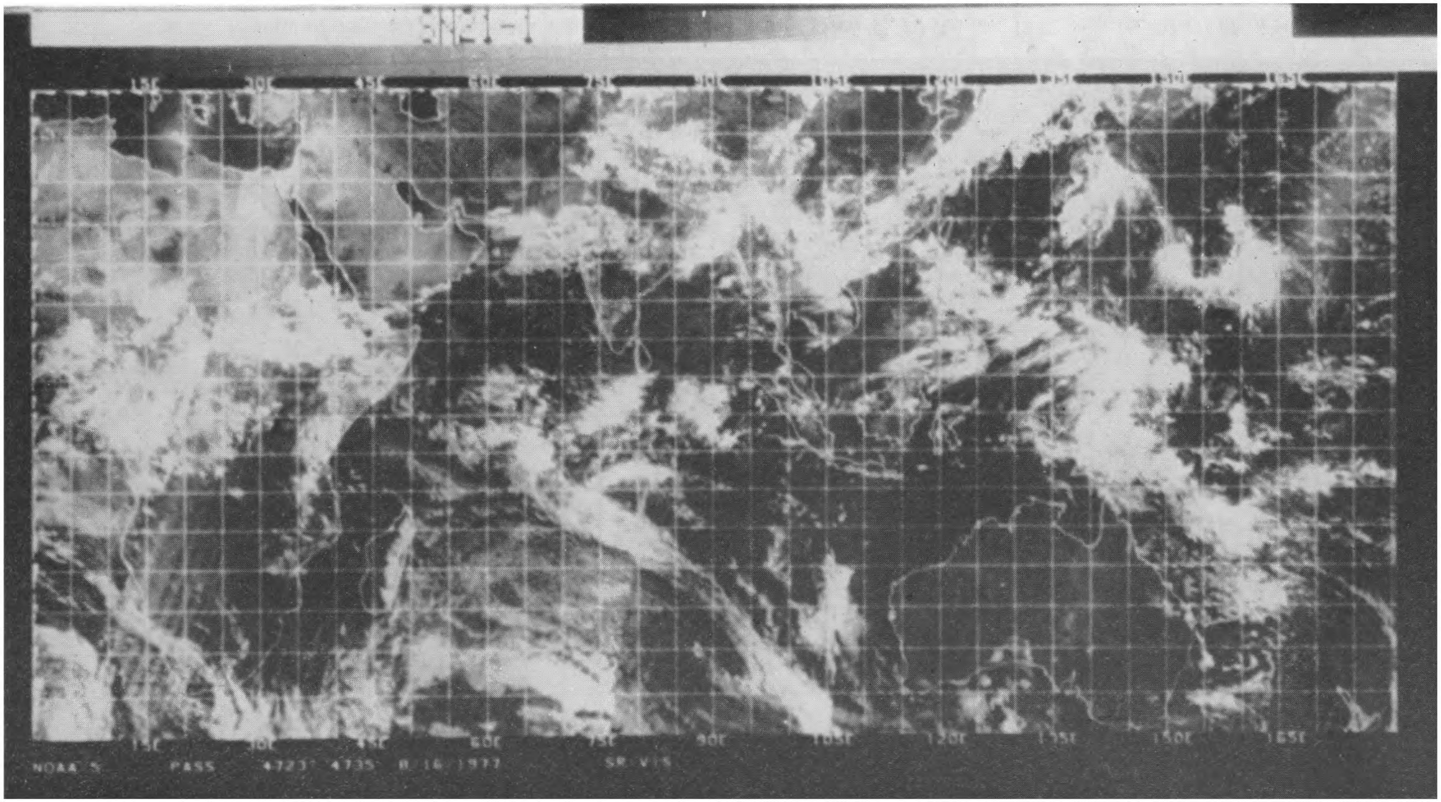

Plate I. Mosaic of digitized scanning radiometer visible imagery (NOAA 5), 16 August 1977 (approx. 03 GMT at 90°E).

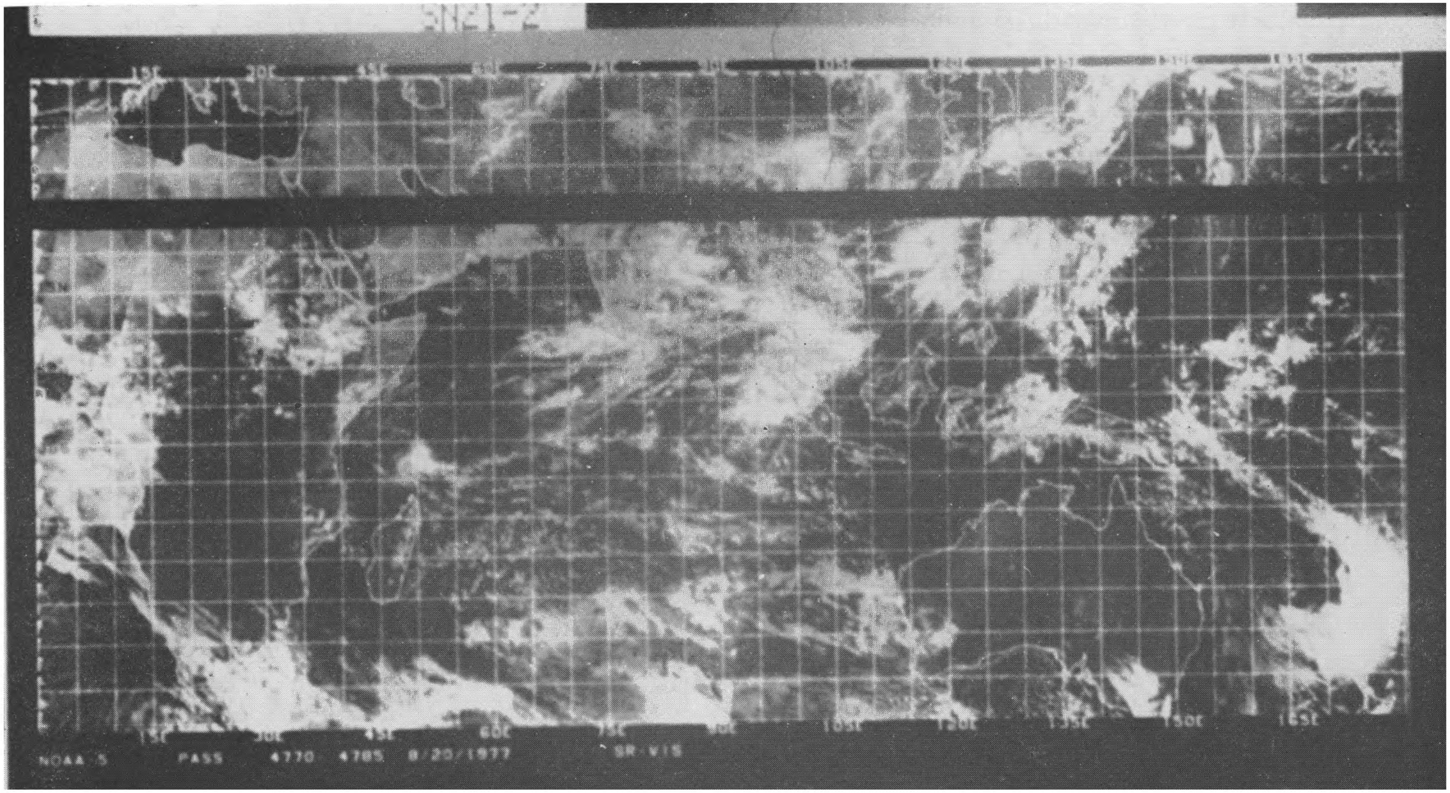

Plate II. Mosaic of digitized scanning radiometer visible imagery (NOAA 5), 20 August 1977 (approx. 03 GMT at 90°E). Horizontal dark band near 25°N is an artefact.

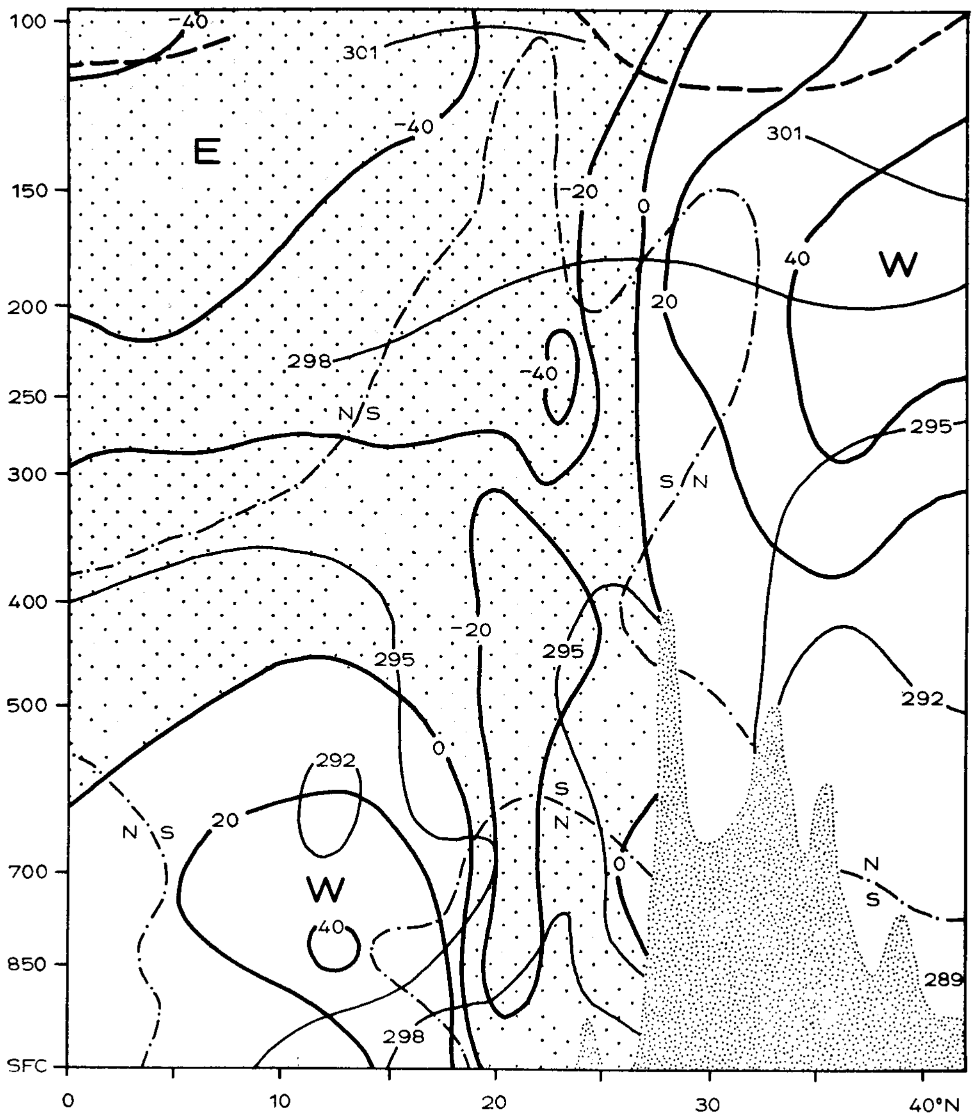

Figure 2. Zonal wind component (knots) and wet-bulb potential temperature (K) for a latitude cross-section near 92°E, 00 GMT 20 August 1977. Legend as for Figure 1.

5. Thermodynamic structure of the troposphere at the MONSOON-77 ship array

After remaining nearly stationary for several days the ship array moved from near 17°N to 19°N between 16 and 20 August.

Figure 3 shows that the lower troposphere was less convectively unstable when the depression was close to the array than it was during either of the break or moderate (12 August) phases (cf. Saha and Singh, 1972). The greatest contrast occurred between 850 mb and 400 mb. Differences between the profiles of dew-point depression for each phase follow a less regular pattern.

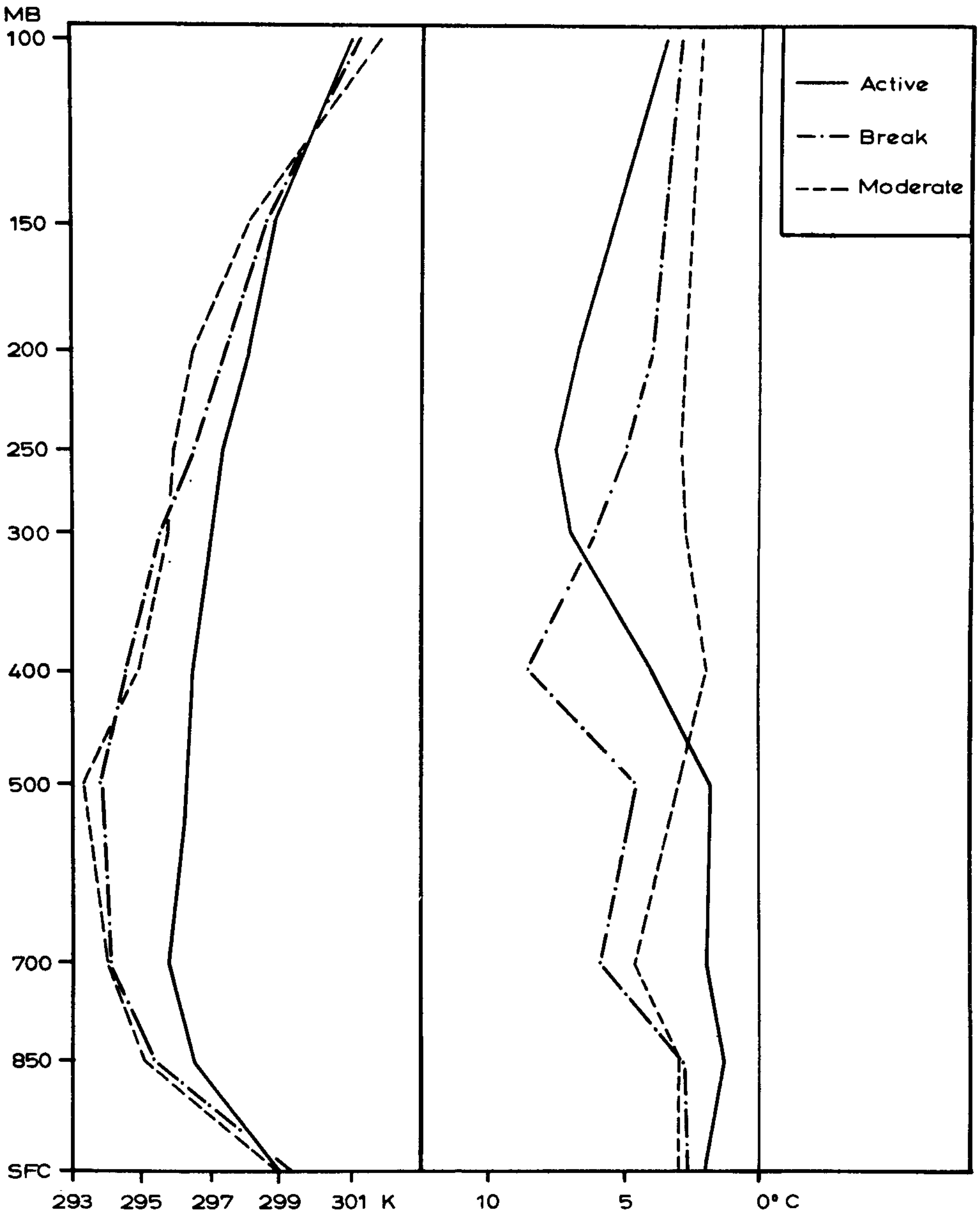

Figure 3. Mean profiles of wet-bulb potential temperature (left) and dew-point depression (right) at MONSOON-77 ship array in the Bay of Bengal at 00 GMT 12 August (moderate phase), 16 August (break phase) and 20 August 1977 (active phase).

During the active phase the 700–400 mb layer was more humid than it was during break but it was noticeably drier near 200 mb. Driest conditions occurred near 400 mb during the break phase. Probably this was due to subsidence within the ridge that covered the Bay of Bengal. During the moderate phase dew-point depression was small and varied little above 500 mb. Vertically averaged dew-point depression was smallest during this phase.

6. Conclusions

In the troposphere over the Bay of Bengal dynamical and thermodynamic features associated with active and break monsoon spells over eastern India during August 1977 exhibited marked differences, despite the short time interval between spells.

The zonal component of the lower tropospheric westerly current south of the monsoon trough was strongest near 15°N, where surface frictional drag is small and contour gradients are likely to be largest. Other observations from the ship array suggest that this maximum is a persistent feature.

When the depression moved near to 19°N the meridional shear of the zonal wind strengthened considerably in the middle and lower troposphere south of Tibet. Simultaneously, zonal vertical shear south of the depression centre increased but polewards of the centre the shear decreased as a deep easterly current was established (cf. Raman *et al.*, 1978). Below 500 mb, convective instability was enhanced near 15°N but was weaker near 22°N. The geographical location and extent of cloudiness associated with each phase were typical (Hamilton, 1977). These differences are attributable to enhanced cyclonic vorticity, convergence and uplift at low levels within a very moist layer during cyclogenesis (Ramage, 1971; Rao, 1976).

Differences above 400 mb are less significant because there is considerable day-to-day variation of the latitudinal and vertical distribution of wind speed within the easterly current (Krishnamurti and Rodgers, 1970). Additionally, estimates of WBPT for the upper troposphere can be unreliable because humidity measurements are liable to systematic errors in very dry or very moist conditions at these levels (Hooper, 1975). However, it is clear that changes in tropospheric structure over India during the summer monsoon are accompanied by well-defined synoptic variations within a deep layer over the Bay of Bengal.

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551.508.5:681.3

Quality control of anemograph data

By G. W. Bryant

(Meteorological Office, Bracknell)

Summary

The detection of instrumental errors in anemograph data presents special problems because of the variability of wind measurements in time and space in response to the synoptic situation and local topography. A successful technique has now been devised and a description of its application to the detection of errors in measurements of wind direction is presented, together with an account of some of the results.

1. Introduction

Every month, the Meteorological Office receives hourly values of wind and gust speed and direction for the whole of the previous month, from about 160 anemograph stations throughout the United Kingdom. This very large quantity of data must of necessity contain a significant number of errors which, until recently, could be corrected only by laborious and time-consuming hand-and-eye methods. In recent years, however, the problem has been greatly simplified by the introduction of computers which permit a wide range of checks and comparisons to be carried out in a very short time. A great deal of effort has consequently been applied to the development of suitable computer programs and by means of range, time sequence and internal consistency checks, it is now possible to ensure that very few significant errors which arise during transcription or keying of the data escape detection.

These techniques are not effective, however, in detecting errors which arise from an incorrectly adjusted anemograph or from such changes in exposure as might occur in the intervals between site inspections. Either event would cause errors to occur throughout the data rather than in a few isolated values. For other climatological data, such a situation could be detected by areal quality control methods which compare the data from each station with those from one or more nearby stations but this is less straightforward in the case of wind data.

However, a quality control technique has now been developed at the Meteorological Office which can detect the presence of errors in anemograph data and estimate both the type of error and its magnitude. The following report describes the technique as it is used in the detection of errors in wind direction measurements, and presents some of the results of its operational use.

2. The anemograph network

The stations in the anemograph network are of high standard and provide, on the whole, very good coverage over the United Kingdom. Most of these stations are equipped with either the Mk 4 or Mk 5 anemograph; thirteen still use a Dines pressure-tube anemometer but these instruments are very carefully maintained. Automatic anemographs are being introduced but these are still very much in the minority. Many of the anemographs belong to organizations outside the Meteorological Office which have an immediate need for wind measurements and provide monthly returns either as a service or in exchange for instrument maintenance. Typically, the instruments are set up at military or civilian airfields, coastguard stations, universities and research stations. The sites tend to have an irregular geographical distribution and to be rather sparse in highlands and other less populated areas.

Every site is carefully inspected for satisfactory exposure before the station is accepted into the Meteorological Office network but since the original choice of site may not have been dictated primarily by climatological considerations, it is almost inevitable that few of them will be free of the effects of local obstruction and topography. In fact, the winds at almost every site are affected to some degree by exposure problems such as the proximity of the site to built-up areas, hills or the coast. This may not be a serious problem because unless the variations are very localized this is precisely the type of information that a climatological station is intended to provide. As already mentioned, though, it makes quality control quite difficult.

3. The first stage of quality control

Anemograph data for each station are sent at monthly intervals to the Meteorological Office where they are keyed to an annual data set on magnetic disc. This stage generates a significant number of keying errors and so the archiving process is accompanied by quite detailed quality control. The tests used, which are listed in Table I, consist basically of range, time sequence and internal consistency checks. The value of each item in the data is confirmed to be within an acceptable range and then compared with the previous and subsequent hourly values, to check for unrealistic time variations. The difference in wind and gust directions and the ratio of wind to gust speed are both checked against fixed limits. This is accompanied by other tests which relate to the particular way in which the manuscript form is completed. For example, zero wind direction is associated only with zero wind speed and no gust speed. Also, the maximum and total hourly wind speed for each day are entered on the form and so may be compared with the results computed from the keyed hourly values.

Errors detected in this way occur at an average rate of about four per thousand items. These are distributed fairly randomly throughout the data with some clustering when a missing digit, for example, corrupts all subsequent data in that line. Correction is fairly simple, though time-consuming, and is usually carried out within a day or two. This process thus proceeds routinely throughout the month and, at the end of that time, the only significant errors remaining in the data should be associated with instrumental faults.

4. Quality control of systematic errors

It is difficult to detect errors in anemograph data by areal quality control methods because, unless the errors are very large, they are easily masked by variations characteristic of the station or its environment. For example, Gunn and Furmage (1976)* have described cases where the wind speed and direction are very strongly influenced by local topography and similar, though smaller, effects must occur at

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* Gunn, D. M. and Furmage, D. F. 1976 The effect of topography on surface wind. *Meteorol Mag*, **105**, 8–23.

Table I. *Quality control tests used on anemograph data (first stage)*

Parameter	Reason for query
Wind speed	Greater than 55 knots
	More than 10 knots from values at adjacent hours
	Zero but gust speed listed for same hour
	Zero but non-zero direction listed
	Total for day not equal to listed value
	Maximum for day not equal to listed value
	Computed number of occasions of equal highest mean speed is not equal to listed value
Wind direction	More than 30° from values at adjacent hours
	Not in range 0–360° or equal to 990 (variable)
Gust speed	Greater than 90 knots
	Ratio to mean speed not in range 1.066 to 3.0
	Maximum value not equal to listed value
	No direction given
	No time given
	Computed number of occasions of equal maximum gust is not equal to listed value
Gust direction	More than 30° from mean direction
	Not in range 0–360°
	Time missing

most stations. In addition, the effective height of anemographs in the United Kingdom varies from the standard value of 10 m up to 18 m, with anemographs at a few stations set even higher. As a result, many stations will show a systematic difference in speed and direction throughout the entire 360° when compared with their nearest neighbours. When the large variations in both space and time associated with the passage of various synoptic features are superimposed then it becomes extremely difficult to detect errors by interstation comparison.

It is important to overcome these problems because faults have been developing in up to ten of the instruments each year. This is, perhaps, not surprising in view of the fact that the anemograph is unique among meteorological instruments in being a mechanical device which is subjected to sudden and violent accelerations. The majority of errors, in fact, occur in measurements of wind direction and can often be related to the occurrence of an unusually strong gust. Instrumental faults should be detected, of course, on inspection of the instrument but the number of stations in the United Kingdom is so large that routine inspections can only be carried out at intervals of 1–2 years. It is necessary, therefore, to devise a method of detecting this type of fault from the hourly data submitted by the station.

Despite the objections, clearly the only method of detecting instrumental errors that seemed likely to be successful was to compare the data from two or more neighbouring stations. Some way had to be found to overcome these problems. There was the advantage, however, that the technique was intended to detect instrumental errors which would be present to the same degree in all data generated while the fault persisted. Variations from hour to hour could be removed by averaging so that if local effects could also be eliminated then any remaining difference between the averaged data at any two stations would indicate a fault in one of the instruments. The problem then resolved itself into one of identifying local influences so that they could be removed in the analysis.

5. Quality control—second level

The method which has been devised is to divide the anemograph stations into sets of three nearest neighbours, with some stations possibly belonging to more than one set, and to calibrate each station by comparison with the other two. Ideally, the technique requires two years of recent data for each station;

only one year is really necessary but since any past errors will have been found and corrected only after a site inspection, data for the most recent year are not always reliable.

If we call the three stations A, B and C then the calibration of A against B involves the computation of the average value of the difference in wind direction at the two stations for all occasions throughout the one or two year period when the wind direction at B is in each of 18 sectors and the wind speed is above 3 knots. Since wind direction is tabulated to the nearest 10°, each sector contains two possible wind directions (0° and 10°, 20° and 30° etc.). If both anemographs have been correctly adjusted then the 18 values which result from this process may be regarded as largely a measure of the steering effect of topography at the two stations. For the quality control program, it is necessary to choose two comparisons (A–C and B–C, for example) in which the second station, common to both, is the one least subject to the effects of topography. Selection of the appropriate comparisons is a fairly subjective process and the comparisons finally chosen tend to be those which contain the lowest values.

An example of the result of this process is shown graphically in Figure 1, where the two stations involved are Leuchars, in Fife, and Bell Rock which is a small islet to the east of Leuchars about 30 km from the coast. The divergences from zero are almost entirely due to the effects of topography at Leuchars. The comparison in Figure 1 shows a bias towards negative values because the two anemographs have different effective heights and because Bell Rock is surrounded by the sea so that the wind will, in general, be veered relative to the wind at Leuchars. In most other cases, the 18 values are fairly evenly distributed about zero and values above 20° are uncommon.

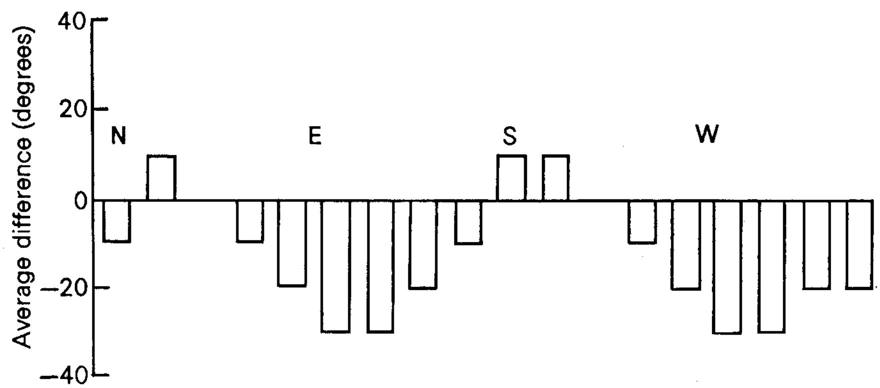

Figure 1. Mean difference in wind direction for each of eighteen 20° sectors for a comparison of Leuchars with Bell Rock.

This fact has been used to detect errors in the archived data before the system is used operationally; Figure 2, for example, shows the effect of an anemograph fault on the values produced by the comparison. The two stations are compared for the first and last six months respectively of the year and the presence of the fault and its approximate magnitude are obvious. The significant feature is that the value for each of the 18 sectors had changed by about the same amount. Except in special circumstances, this type of bias towards positive or negative values usually indicates a fault in one of the instruments and warrants further investigation. Moreover, since each of the three stations is compared with the other two, there should be no difficulty in identifying the faulty station.

When satisfactory comparisons have been found, they are used to 'correct' the differences in hourly mean wind direction at the two stations so that when the average difference is calculated for all sectors

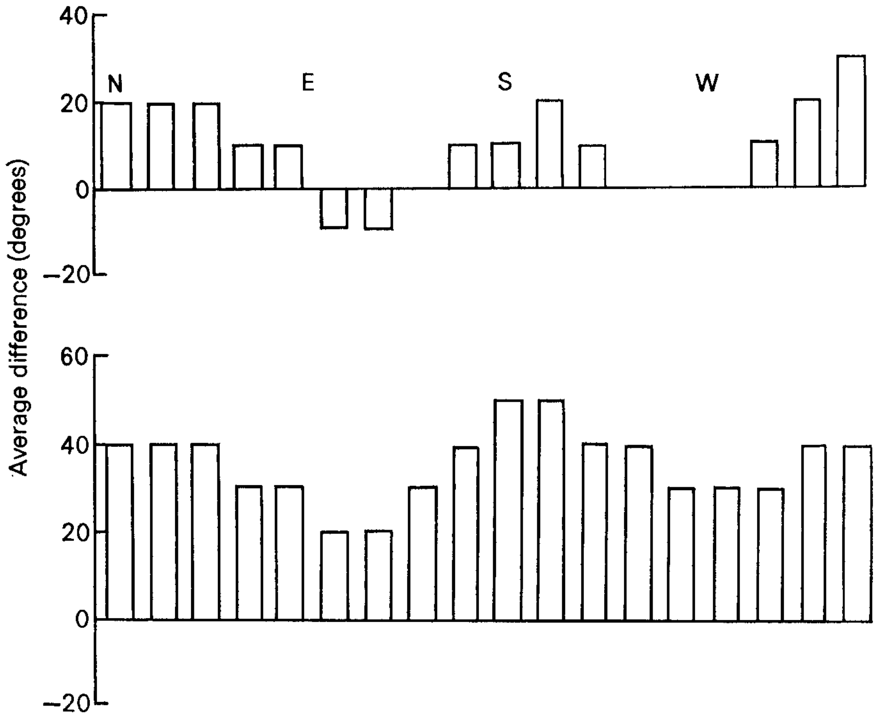

Figure 2. Mean differences in wind direction for each 20° sector for the first and last six months of a year in which a 30° error developed at the second (reference) station.

combined, it should be close to zero with any deviation being ascribed to instrumental error. There is a problem, though, in that in operational use data are analysed for one month at a time and that this is often too short a period to make the averaging technique totally effective. Some measure is therefore needed of the amount of variation to be expected in the monthly averaged difference. For this reason the technique is first applied to the data which were used in the original comparisons and the average difference in wind direction for each pair of stations is calculated for all sectors combined for each month using the corrected values. From the results, which should vary fairly randomly about zero, a value is selected which is exceeded no more than once a year and this is used in the quality control program as a limit to be exceeded before a query is raised. Typical values are 10° to 15°, rising occasionally to 20° for sites where the topography is more complex.

This stage, too, is useful for the detection of errors in the archived data. The case just described, where an error occurred in the middle of the year, produced the monthly mean differences shown in Figure 3. Once again, this type of result indicates a need for investigation.

6. Operational technique

The remaining step is to create the data set which will be used by the operational program. This consists of an entry for each station pair consisting of the two station numbers, their site numbers, the 18 calibration values, the limiting value and two markers, which are initially set to zero.

The comparison program, which requires a different response from the scrutineer than the quality control methods just described, is delayed until the last few days of the month. This program examines

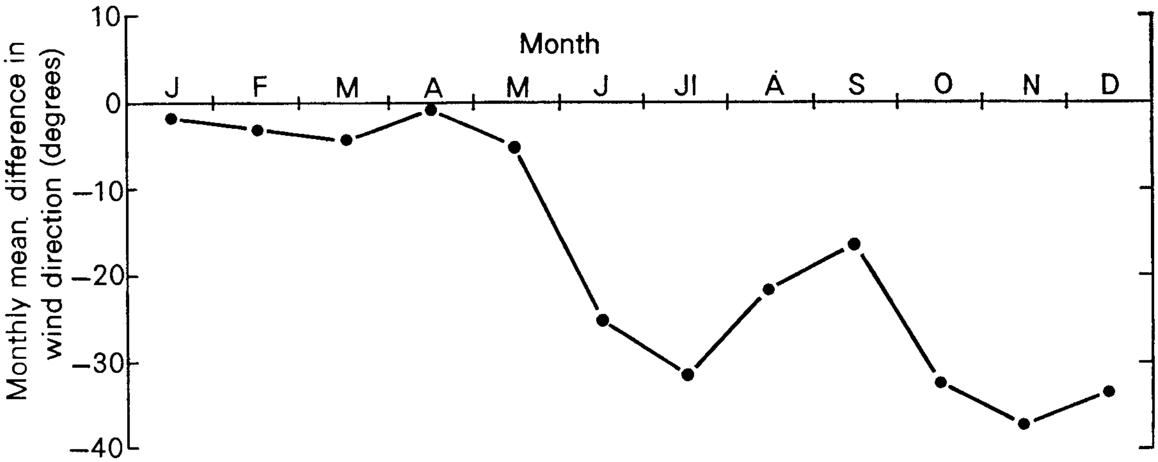

Figure 3. Monthly mean differences in wind direction for the two stations compared in Figure 2.

stations in the groups of three listed in the data set described in the previous section. If we again call the three stations A, B and C in which C is the reference station, then station A is first compared to C. The computer checks all the hourly mean wind directions for the month for the two stations and uses the direction measured at station C to decide which of the 18 adjustments should be applied to the direction measured at A. The adjusted difference for each hour is then computed and the mean and standard deviation of the resultant values calculated. If the mean exceeds the assigned limit or the standard deviation exceeds 30° (a value based on the use of past data), then a query is printed out and a histogram is plotted to show the frequency distribution of the adjusted differences. The process is then repeated for stations B and C.

The histogram is probably the most important part of the program because it contains more information than the basic statistics of mean and standard deviation and it is, in many ways, more convincing. The examples shown in Figures 4 and 5 illustrate this for the two types of direction fault likely to be developed by anemographs. Figure 4 shows the result of a zero shift of 30° in one of the two instruments and the abrupt sideways shift of the distribution, whose shape is otherwise unchanged, is quite characteristic of this particular fault and shows approximately when it developed. Figure 5, on the other hand, shows the effect of a less common situation where the anemograph head has become loose so that considerable backlash had developed. The transition from the fairly narrow Gaussian distribution of the February to April data to the flat, rather distorted distribution of the next three months makes the fault quite obvious.

There is generally no difficulty in identifying the station submitting the suspect data because of the way in which the stations are compared. A fault at station C, for example, will give rise to two queries while faults at either A or B will cause a query to be printed only for the comparison in which they take part.

The limits have been set low enough to be exceeded occasionally by the mean difference in direction even for correctly adjusted anemographs and, in borderline cases, it may be decided to delay any action until the same query has been raised on two or more successive months. To make this easier, the two

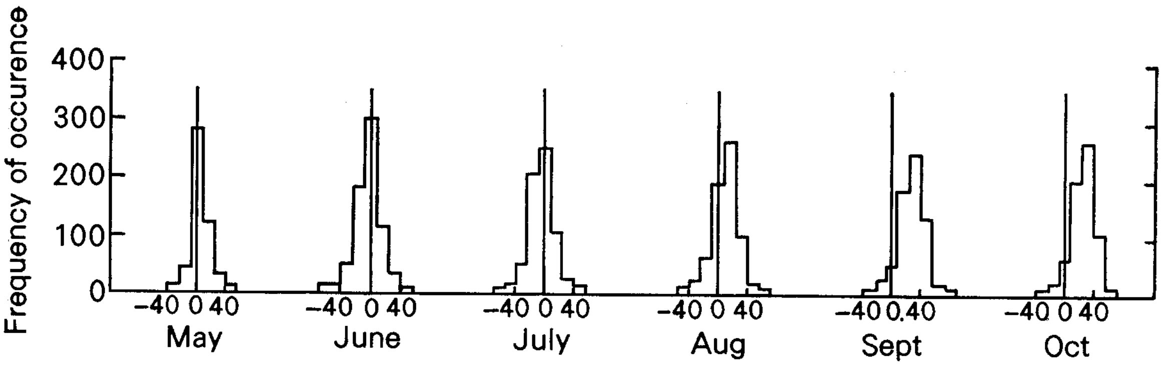

Figure 4. Histograms produced by the quality control program showing the effect of zero shift of about 30° in one of two anemographs.

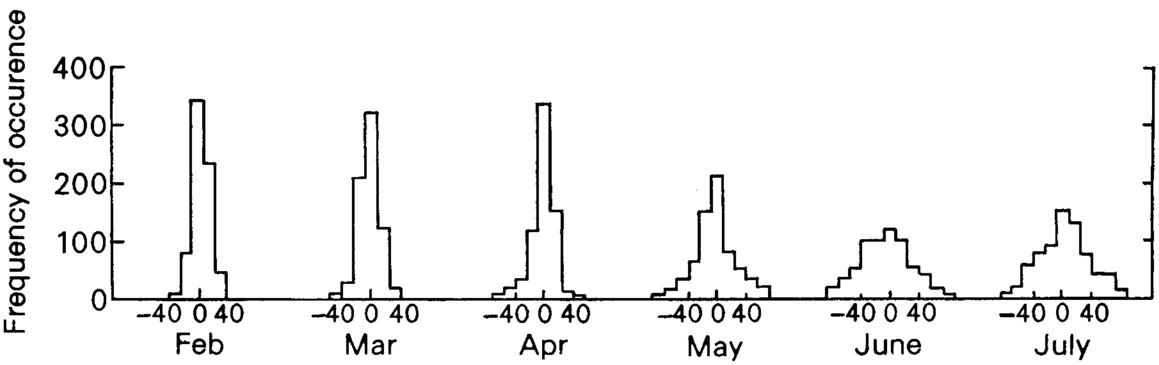

Figure 5. Histograms showing the effect of backlash produced by a loose mechanical coupling in one of the anemographs.

markers on the data set are adjusted, when a query is raised, to show which station was queried and the number of successive months for which the same query has appeared. The values of the two markers are printed out as part of the query message. To prevent the second marker from being incorrectly incremented if it should be decided to run the program for a second time on the same data, a marker is also set, for each station tested, in the anemograph data set.

Summary

Anemograph data received at the Meteorological Office are now subject to quite sophisticated quality control by computer. In particular, the most serious problem of detecting instrumental faults fairly rapidly appears to have been solved. The interstation comparison has now been in operational use for over two years with considerable success. Inevitably, a few stations, mainly in the Scottish Highlands, have not been included because of the magnitude of topographical influences and the lack of suitable reference stations but the majority of stations are tested.

In each case where a definite query has been raised, the fault has been traced to a zero shift or loose mechanical link at the anemograph and errors as low at 10° have been detected in this way. However, changes in exposure could produce similar results and, if no mechanical fault was found, this possibility would be considered.

In order to detect errors in wind speed, a similar technique is being developed in which the ratio of wind speeds replaces the difference in direction. However, such errors, which seem to be caused by incorrect adjustment of the instrument rather than by a mechanical fault, are too infrequent to have permitted any detailed testing so far.

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The lower boundary condition in the 10 level model

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Summary

A new way of applying the lower boundary condition in pressure co-ordinate numerical models of the atmosphere is described. An indication is given of the benefits of the new method for the operational 10 level forecast model.

1. Introduction

The use of pressure (p) as the vertical co-ordinate in numerical models of the atmosphere is attractive in view of the simple form which the governing equations then take. The Meteorological Office 10 level numerical model, first described by Bushby and Timpson (1967), is a pressure co-ordinate model and in it the heights (h) and the horizontal velocity vectors ($\boldsymbol{V}$) are arranged on the 10 isobaric surfaces 100, 200, 300 . . . . . 1000 mb as shown in Figure 1.

The major disadvantage of the pressure co-ordinate system is of course the fact that the earth's surface cannot coincide with a co-ordinate surface; indeed it does not even remain fixed in the co-ordinate space. For this reason the sigma (σ) co-ordinate system (Phillips 1957), which uses pressure divided by the pressure (p_*) at the earth's surface (i.e. $\sigma = p/p_*$) as the vertical co-ordinate, has been widely used in other numerical models. This paper describes a method of representing the true position of the earth's surface in hydrostatic pressure co-ordinate models. Some general relationships are derived in section 2, and the application of these to the 10 level model is described in sections 3 and 4. The method has been used operationally in the octagon version of the 10 level model since 14 March 1978 and in the rectangle version since 4 April 1978 (see Burridge and Gadd, 1977, for a definition of the octagon and rectangle grids). Section 5 of this paper indicates some benefits of the new method for the model.

The kinematic lower boundary condition required in dynamical models of the atmosphere expresses the fact that the air flow cannot cross the earth's surface below. The condition may be written

$$w = \boldsymbol{V}.\nabla H \text{ at } p = p_*, \quad \text{(1)}$$

where w is the vertical velocity, $\boldsymbol{V}$ is the horizontal velocity vector, and H is the topographic height ($H = 0$ over the sea). By definition, w is the rate of change of h following the motion.

$$w \equiv \mathrm{D}h/\mathrm{D}t. \quad \text{(2)}$$

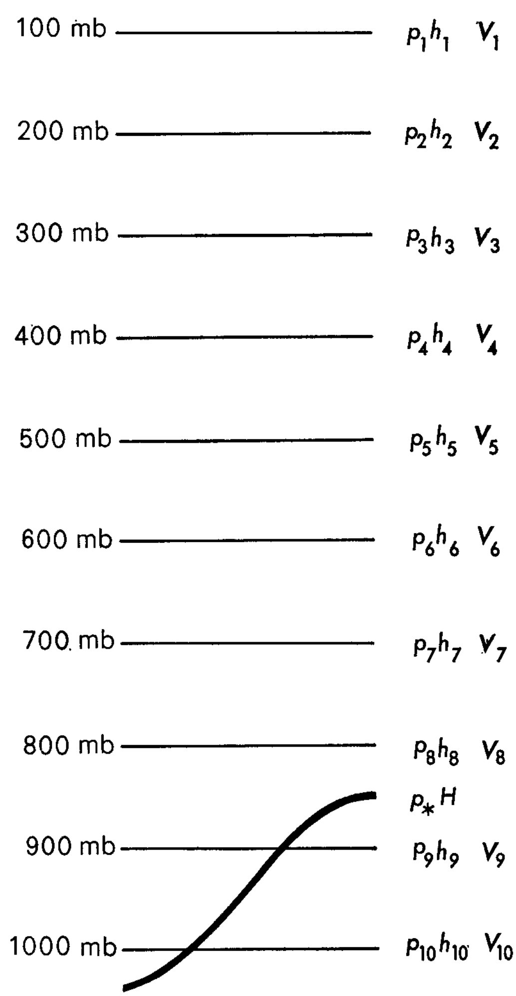

Figure 1. The vertical arrangement of heights (h) and wind vectors ($\boldsymbol{V}$) in the 10 level model, with an illustration of the earth's surface intersecting the co-ordinate surfaces. The earth's surface has pressure p_* and height H.

Earlier versions of the 10 level model, in common with most pressure co-ordinate models, used a lower boundary condition derived by setting $w = \boldsymbol{V}.\nabla H$ at the 1000 mb surface. Making use also of equation (2) this leads to

$$\mathrm{D}h_{10}/\mathrm{D}t = \boldsymbol{V}_{10}.\nabla H, \qquad (3)$$

where the subscript 10 indicates the 1000 mb surface as in Figure 1. Equation (3) is a predictive equation for h_{10}, i.e. the 1000 mb height tendency equation.

The application of the lower boundary condition at 1000 mb rather than at p_* seems a very crude approximation, especially over high mountains. However, equation (3) proved to be surprisingly effective in the 10 level model, for example in steering depressions to one or the other side of Greenland.

It was only when the effects of radiative exchange were included in the model that the unsatisfactory character of equation (3) finally became clear, as illustrated in section 5.

Previous attempts to overcome the deficiencies of equation (3) have been reported by Hayes (1975) and by Gadd and Lunnon (1977). Hayes applied surface frictional effects at model levels close to p_* and set $\boldsymbol{V}$ zero in any entirely subterranean layers. Gadd and Lunnon adopted Hayes's scheme, and in addition replaced equation (3) by

$$\mathrm{D}h_{10}/\mathrm{D}t = \boldsymbol{V}_{10} . \nabla H - (h_{10} - H) \operatorname{div} \boldsymbol{V}_{10}. \qquad (4)$$

The Gadd and Lunnon scheme achieved the benefits illustrated in section 5 below, but unfortunately led to numerical instability on some occasions. Thus the method described in this paper, which may be seen as a natural extension of Hayes's work, was developed as a more fundamental remedy to the inadequacies of equation (3). The idea of setting $\boldsymbol{V}$ zero in subterranean layers is due to Egger (1972).

2. Basic relationships

(a) *The surface pressure tendency equation*

The continuity equation in pressure co-ordinates for a hydrostatic atmosphere

$$\partial \omega / \partial p = - \operatorname{div} \boldsymbol{V}$$

may be integrated with respect to pressure to obtain

$$\omega_* = - \int_0^{p_*} \operatorname{div} \boldsymbol{V} \, \mathrm{d}p, \qquad (5)$$

where the subscript $*$ indicates a value at the earth's surface and $\omega \equiv \mathrm{D}p/\mathrm{D}t$. (The upper boundary condition $\omega = 0$ at $p = 0$ has been assumed.) By definition

$$\omega_* = \partial p_* / \partial t + \boldsymbol{V}_* . (\nabla_z p)_* + w_* (\partial p / \partial z)_* \qquad (6)$$

where ∇_z indicates the grad operator at constant z. If we substitute for w_* using the lower boundary condition, equation (1), we obtain

$$\omega_* = \partial p_* / \partial t + \boldsymbol{V}_* . [(\nabla_z p)_* + (\partial p / \partial z)_* \nabla H]. \qquad (7)$$

By a standard result in partial differentiation, the quantity in square brackets is precisely ∇p_* and therefore equation 7 gives

$$\partial p_* / \partial t = \omega_* - \boldsymbol{V}_* . \nabla p_* . \qquad (8)$$

Finally, recalling the general theorem that

$$\frac{\partial}{\partial x} \int_0^{L(x)} f(x,y) \, \mathrm{d}y = \int_0^{L(x)} (\partial f / \partial x) \mathrm{d}y + f(x, L) (\partial L / \partial x),$$

we may combine equations (5) and (8) to give

$$\partial p_* / \partial t = - \operatorname{div} \left[\int_0^{p_*} \boldsymbol{V} \, \mathrm{d}p \right]. \qquad (9)$$

Equation (9) is the basis of the method described in this paper. It represents the fact that, in a hydrostatic atmosphere, changes in ground-level pressure are the result of convergence or divergence of the vertically integrated mass flow above. The equation takes a similar form in the sigma co-ordinate system but the limit of integration is then a constant ($\sigma = 1$) so that the calculus is simpler.

(b) *Reduction to 1000 mb height tendency*

Several ways can be envisaged in which equation (9) might be used in practice in a pressure co-ordinate model. The method adopted here involves a conversion of the surface pressure tendency given by equation (9) to a 1000 mb height tendency. Like the reduction of surface pressure observations to mean sea level this conversion requires, in elevated land areas, an assumption about the temperature of imaginary subterranean air. If we assume that the (possibly fictitious) layer of air from the earth's surface (p_*) to the 1000 mb level (p_{10}) is characterized by a virtual temperature T_0, it follows from an integration of the hydrostatic equation that

$$\log_e(p_{10}/p_*) = g(H - h_{10})/RT_0 \quad \text{.. .. .. ..} \quad (10)$$

and, neglecting any time dependence of T_0, that

$$\partial h_{10}/\partial t = (RT_0/gp_*)\, \partial p_*/\partial t. \quad \text{.. .. ..} \quad (11)$$

The neglect of any time dependence of T_0 in deriving equation (11) is consistent with the method of reduction of surface pressure to mean sea level which is recommended in *WMO Technical Note* No. 61. There it is suggested that the temperature used should be based on the average of the current value of the surface air temperature and the value 12 hours previously, thereby eliminating the diurnal variation. In practice several different methods of reduction are in use by various nations (see *WMO Technical Note* No. 91).

Provided that T_0 can be specified, equation (11) can be used along with equation (9) to give the 1000 mb height tendency. However, the choice of T_0 is not without difficulty. In fact, a two-stage conversion process has been considered more satisfactory. In the first stage the surface pressure tendency is reduced to a mean sea level pressure tendency, and in the second stage the mean sea level pressure tendency is related to the 1000 mb height tendency. We assume that the fictitious layer of air from the surface (p_*) to mean sea level (p_{msl}) is characterized by a virtual temperature T_1 and the layer from mean sea level to the 1000 mb level (p_{10}) by a virtual temperature T_2. Then in place of equation (10) we have

$$\log_e(p_{msl}/p_*) = gH/RT_1 \text{ and } \log_e(p_{10}/p_{msl}) = -\, gh_{10}/RT_2. \quad \text{.. .. ..} \quad (12)$$

Neglecting any time dependence of T_1 or T_2 these equations lead to

$$\partial p_{msl}/\partial t = (p_{msl}/p_*)\, \partial p_*/\partial t \text{ and } \partial h_{10}/\partial t = (RT_2/gp_{msl})\, \partial p_{msl}/\partial t. \quad \text{..} \quad (13)$$

If T_2 is taken to be the temperature at mean sea level these equations may be combined in the form

$$\frac{\partial h_{10}}{\partial t} = -\left(\frac{\partial h}{\partial p}\right)_{msl} \frac{p_{msl}}{p_*} \frac{\partial p_*}{\partial t}. \quad \text{.. .. ..} \quad (14)$$

The advantage of the two-stage conversion, leading to equation (14), over the direct conversion, represented by equation (11), is that it can avoid any troublesome complications over high ground whilst retaining a realistic temperature dependence over the sea and over low ground. This is achieved by keeping T_1, and thus p_{msl}/p_*, fixed at each grid point throughout a forecast whilst allowing T_2, by way of $(\partial h/\partial p)_{msl}$, to vary in accord with the lowest available model information.

3. Application to the 10 level model

For the 10 level model equations (9) and (14) are used to give the required value of $\partial h_{10}/\partial t$ and this calculation replaces equation (4) of Gadd (1978). The other model equations and methods remain as described in that paper. The configuration of the variables used in this section is illustrated by Figure 2. The following numerical approximation is used for the integral in equation (9)

$$\int_0^{p_*} \boldsymbol{V}\,\mathrm{d}p = \sum_{i=1}^{m-1} \boldsymbol{V}_i\,\Delta p + \boldsymbol{V}_m\,(p_* - p_{m-\frac{1}{2}}), \quad \ldots \quad (15)$$

where m is defined such that $p_{m-\frac{1}{2}} \leqslant p_* < p_{m+\frac{1}{2}}$. Each velocity $\boldsymbol{V}_i$ represents a 100 mb layer from $p_{i-\frac{1}{2}}$ to $p_{i+\frac{1}{2}}$ where $p_{i+\frac{1}{2}} = (i + \frac{1}{2})\,\Delta p$ and $\Delta p = 100$ mb. Equation (15) contains no contribution from above the 50 mb level, consistent with the 10 level model upper boundary condition $\omega = 0$ at 50 mb. Note that when $i < m$ the velocity $\boldsymbol{V}_i$ is given the full weighting Δp. However, $\boldsymbol{V}_m$ is given the reduced weighting $p_* - p_{m-\frac{1}{2}}$, whilst if $i > m$, $\boldsymbol{V}_i$ does not enter the calculation at all. Note also that the level m may be below the ground (as in Figure 2(*b*)), but some part of the 100 mb layer represented by $\boldsymbol{V}_m$ is always above the ground.

The following method is used to calculate p_*:

$$p_* = \begin{cases} p_l + \Delta p\,(h_l - H)/(h_l - h_{l+1}) & \text{if } H \geqslant h_{10} \\ p_{10} + \Delta p\,(h_{10} - H)/(h_9 - h_{10}) & \text{if } H < h_{10} \end{cases}, \quad \ldots \quad (16)$$

where $h_{l+1} < H \leqslant h_l$. At present equation (16) is used directly each time step; an alternative would be to use it only to calculate p_* from the initial data, and then to update p_* each time step using the tendencies given by equation (9). Equations (9) and (14) are applied at the h gridpoints in the 10 level model, and since equation (15) clearly must be applied at $\boldsymbol{V}$ gridpoints it is the four point average $\overline{p}^{xy}$ that is used. (See Gadd (1978) for details of the staggered grid now used in the 10 level model and for an explanation of the notation $^{-xy}$.)

The ratio p_{msl}/p_* is calculated at each gridpoint from the initial data and is then held constant throughout the forecast for use in equation (14). For the initial calculation p_* is obtained using equation (16) and the following equation is used to calculate p_{msl}.

$$p_{\mathrm{msl}} = p_{10} + \Delta p\; h_{10}/(h_9 - h_{10}). \quad \ldots \quad (17)$$

Finally, the value of $\partial h/\partial p$ required in equation (14) is approximated by

$$(\partial h/\partial p)_{\mathrm{msl}} = (h_{10} - h_9)/\Delta p. \quad \ldots \quad (18)$$

4. Note on the friction layer

This part of the formulation is adapted directly from Hayes (1975), and is presented again here for completeness.

The velocity at level l, the lowest level above the earth's surface, is modified by friction according to the equation

$$\partial \boldsymbol{V}/\partial t = -\,g\;\partial\tau/\partial p. \quad \ldots \quad (19)$$

It is assumed that the friction layer, adjacent to the earth's surface, is 100 mb deep, and that within this layer the stress (τ) is given by

$$\tau(p) = \{(p - p_* + \Delta p)/\Delta p\}^2\tau_*. \quad \ldots \quad (20)$$

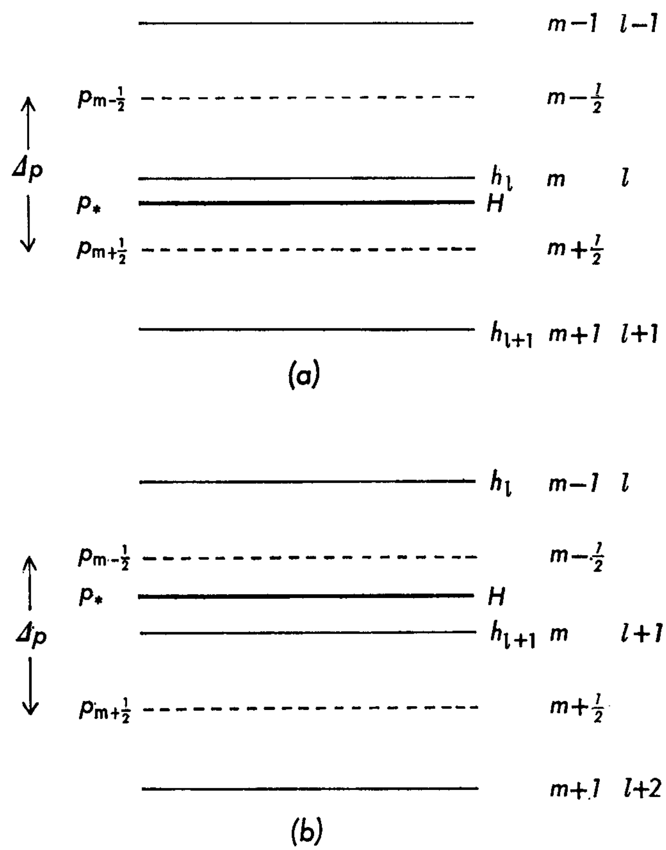

Figure 2. The 10 level model variables used in the calculations described in section 3. The solid lines correspond to levels shown in Figure 1. Two different configurations can arise, (*a*) $m = l$ and (*b*) $m = l + 1$, depending on the position of the earth's surface relative to the model's levels.

Thus $\partial\tau/\partial p$ at level l decreases linearly from $2\tau_*/\Delta p$ when $p_* = p_l$ to zero when $p_* = p_l + \Delta p = p_{l+1}$. The surface value of the stress as calculated from

$$\tau_* = \rho_l C_D |\boldsymbol{V}_l| \boldsymbol{V}_l, \quad \ldots \quad (21)$$

where ρ_l is a standard atmosphere density and the drag coefficient (C_D) is 10^{-3} over the sea and 4×10^{-3} over land. Although level $l+1$ is below the ground, $\boldsymbol{V}_{l+1}$ may be required for equation (15), as in the configuration shown in Figure 2(*b*). Frictional effects are applied at level $l + 1$ with $\partial\tau/\partial p$ always calculated as $2\,\rho_{l+1}C_D\,|\boldsymbol{V}_{l+1}|\,\boldsymbol{V}_{l+1}/\Delta p$. For any $i > l + 1$, $\boldsymbol{V}_i$ is set to zero. The frictional formulation is such that the numerical method given by equation (20) of Gadd (1978) may still be used.

5. Effect on 10 level model forecasts

Equation (3) was used as the lower boundary condition of the 10 level model for many years, and it was not until representations of the effects of radiative exchange were included in the model that the requirement for some improved lower boundary condition became unmistakably evident. For output purposes h_{10} is converted to p_{msl}, and the mean values of p_{msl} for the whole model area, denoted by $\overline{p_{msl}}$, are used in Figure 3 to illustrate model behaviour. Figure 3 shows the evolution of $\overline{p_{msl}}$ during three different six day octagon forecasts for each of two cases. The three forecasts are labelled A, B and C as follows:

A: The model used equation (3) but did not include the radiation scheme.
B: The model used equation (3) and included the radiation scheme.
C: The model used equations (9) and (14) and included the radiation scheme.

Considering first forecasts A and B we see that $\overline{p_{msl}}$ changes significantly during the integrations. In both cases the inclusion of the radiation scheme leads to higher values of $\overline{p_{msl}}$. In case (a) this increase offsets the loss of pressure seen in forecast A, but in case (b) the increase adds to an already existing gain of pressure. It was in cases of the latter type that the forecast charts produced were very obviously unrealistic.

The results of forecasts A and B may be explained as follows.

By expanding the total derivative in equation (3), rearranging terms, and meaning over the whole octagon area, we obtain

$$\overline{\partial h_{10}/\partial t} = -\overline{\omega_{10}(\partial h/\partial p)_{10}} - \overline{\text{div}\,(h_{10}-H)\boldsymbol{V}_{10}} + \overline{h_{10}\text{div}\boldsymbol{V}_{10}} - \overline{H\text{div}\boldsymbol{V}_{10}}. \quad \ldots \quad \ldots \quad (22)$$

The first term on the right of equation (22) is unlikely to be large whilst the second term, being in a divergence form, reduces to an effect of flow across the lateral boundaries. The third term, however, is likely to have a systematic positive bias as a result of the natural correlation of high surface pressure and low-level divergence. The effect of the final term may also be large but its sign and magnitude will depend on the configuration of high and low pressure systems with respect to topographic features.

Equation (22) shows that equation (3) places no constraint on the spatially averaged value of h_{10}. Even in a global model the third and fourth terms could lead to large changes in $\overline{h_{10}}$, and since h_{10} is representative of the surface pressure, one might say that a model using equation (3) does not conserve the mass of the atmosphere.

When the radiation scheme is included in the model, high and low pressure systems retain realistic intensities throughout six day forecasts. (Without radiation there is a gradual loss in the amplitude of features.) Thus the inclusion of radiation increases the value of $\overline{h_{10}\text{div}\,\boldsymbol{V}_{10}}$ and this accounts for the higher values of $\overline{p_{msl}}$ produced by forecast B.

By contrast with equation (3), the form of equation (9) ensures that the mean value of p_* in any region changes only as a result of fluxes across the boundary of the region. Mass conservation is directly represented and in a global model $\overline{\partial p_*/\partial t} = 0$. The constraint imposed by equation (9) is evidently quite effective for the octagon area average of $\overline{p_*}$, and this is reflected in the slowly changing values of $\overline{p_{msl}}$ produced by forecast C as shown in Figure 3.

The formulation described in this paper is of direct benefit to the 10 level model in that it gives a more accurate representation of the true lower boundary condition. It has also had the indirect benefit of making possible the inclusion of the radiation scheme. The annual average root mean square forecast errors for 1978 were the smallest since numerical forecasting began. It is likely that this may be explained by the combined benefits of the radiation scheme and the improved boundary condition.

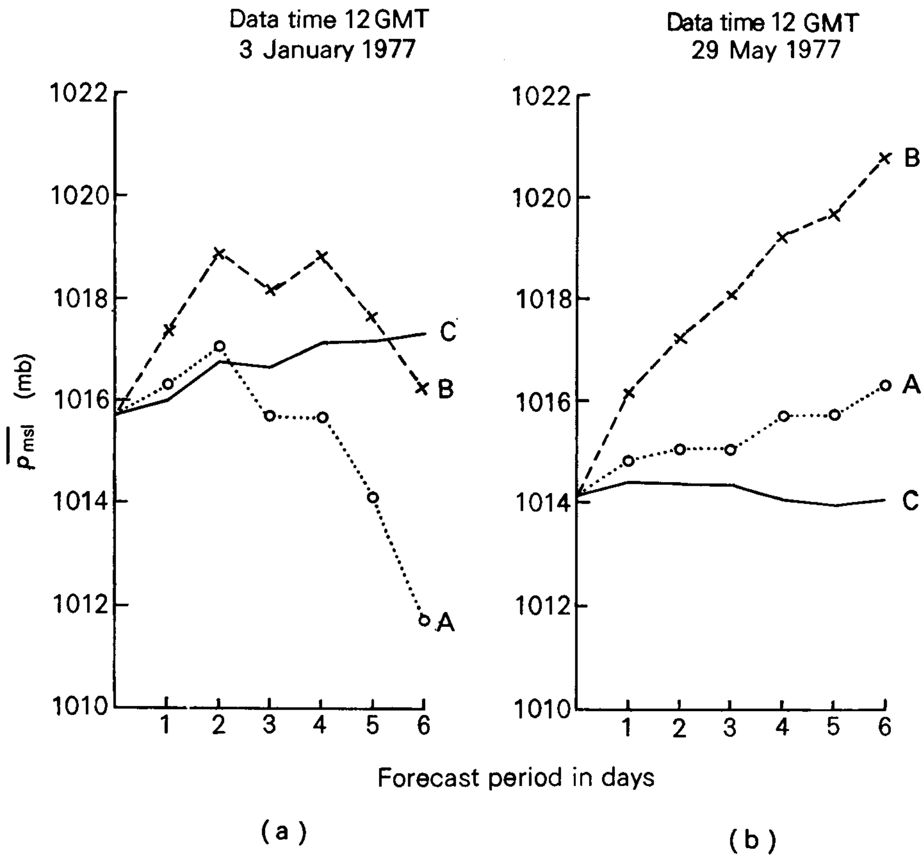

Figure 3. The forecast evolution of $\overline{p_{msl}}$ (see section 5) for the whole octagon grid for (a) a winter case and (b) a summer case. The three forecast model formulations A, B and C are identified in the text.

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Memoirs of an Army Meteorologist

By H. Cotton, M.B.E., D.Sc.

Part 2

My first duty assignment was to a double-observer station close to Sailly Labourse. This I found to be a drab, sizable village about four miles south of Béthune on the road to Arras. As there was no transport available I had to go by train to Béthune and then walk. The pitiful inadequacy of the French railway system was obvious. I actually found myself back at St Omer, then Hazebrouck, Lillers and finally Béthune, which I reached in the middle of the afternoon. If the Germans could have destroyed the railway system at and around Abbeville they would have gained a victory of enormous strategic importance —perhaps have brought the war to an end.

The two Meteor observers were attached to the 15th Division Headquarters in the imposing Château of Sailly Labourse. The 15th was an all Scottish Division which had been in action at the Battle of Loos, a few miles to the south, had fought with the courage characteristic of the Scots, and had suffered very heavy casualties, a waste of splendid men.

Our billet was a very large room at the top of the Château, obviously a bedroom for the staff in former days. It had two real beds and was indeed luxurious for wartime conditions. Close to the window was a large tree inhabited by little animals of a kind that I had never seen before. They were squirrel-like but smaller, their long tails bare except for a bush at the end, something like a miniature lion's tail. I made a little box for food which I suspended from the branch near the window and they used to queue up. The animal actually feeding would receive a nip from the next in the queue if it kept the others waiting too long.

My fellow observer was Corporal George, an artist who had served in the Artists' Rifles; although now officially an R.E., he retained the very distinctive Artists' Rifles cap badge, no doubt a kind of snobbishness. Actually the Artists' Rifles Regiment was kept so long at G.H.Q. that they came to be known as Haig's darlings. They had to be meticulously turned out. Not unnaturally there was a little resentment on the part of the troops who were doing all the dirty work and who were by no means so meticulously turned out.

Corporal George was given to introspection and was, in consequence, difficult to talk to at times. I was curious to learn how an artist had come to join the Meteorological Section and one day I asked him, receiving a characteristic reply:

'What was the first thing they asked you when you reported to the R.E. barracks in England?'

'Where the hell have you been all this time, or something like that.'

'Precisely, and if I were as stupid as the average warrant officer appears to be I should have said the same. The fact is that after the fiasco at Loos, it was obvious to everybody, even the brass hats at the War Office, that if we were to continue with the use of gas we must have up-to-date information about the local weather, particularly about the wind over the whole of the intended battle area. That meant a new organization including an ample number of observers, and as they couldn't wait for men like you to come out they had to make do first of all with what they could find on the spot.'

'Yes, I realize that, but, I hope you won't take offence at this, why did they choose an artist like you?'

'I haven't the least idea unless they thought that since an artist's job is to observe things he ought to be able to observe the weather. Now, will you tell me something?'

'Yes,' I said 'If I can.'

'Meteorology is a science, and science, so I have been told, is exact knowledge. But Meteorology is anything but exact—look at what happened at Loos, and think of all the weather forecasts which, all too frequently, are completely wrong.'

'That is a difficult question' I said 'and can only be answered at length.'

'All right, carry on.'

'It will be something like a lecture.' (This reply made in early 1916 is relevant even today.) 'The Laws of Science are founded on the results of experiments carried out under precisely specified conditions not once, but many times. They are substantiated by the fact that predicted results can be obtained over and over again, millions of times, at schools and universities all over the world. For example Faraday's Laws of Electrolysis predict the weight of a given metal that will be deposited on the cathode of an electrolytic tank by the passage of a stated quantity of electricity. I could give you many other examples. These and all other predictions which come within the realm of experimental science result from experiments made on manageable amounts of the substances concerned. Even Aristotle said that the principles of science are the result of experience. But you can't put a bit of the weather on a laboratory bench, dissect it, weigh it, boil it in a test tube or do any other of those manipulations appropriate to scientific research. With the weather it is impossible to vary at will one of the factors while maintaining the others constant. Just consider how many variables there are: barometric pressure, wind velocity and direction, temperature, humidity, all dependent on one another, but nobody knows just how and, in my opinion, never will. The best that can be done is to collect as much information as possible from as many widely spaced observations as possible, and—this is a most vital condition—all these observations must be made at exactly the same moment. There are four what are called fundamental hours, namely 1 and 7 a.m. and 1 and 6 p.m., all GMT. These are recognized the world over. From this mass of information the weather charts, synoptic charts as they are called, can be drawn and the probable weather for the next twenty-four hours or so predicted with more or less accuracy according to the nature of the chart. In very awkward cases it may be necessary to refer back to previous charts and the corresponding forecasts until one as nearly as possible to the current chart has been found. This is not very satisfactory as there are never two charts exactly alike, and quite small differences can result in astonishing differences in the weather pattern. This is another way of saying that local weather is only a microscopic part of the global distribution and furthermore that this global distribution is three-dimensional, not two-dimensional. I have not seen the chart for the day of the Loos battle, but I am quite sure that there would be no indication whatever of the change in wind which brought such tragic results.'

I was to experience this in the early spring of 1917 when, out of a serene blue sky, there suddenly erupted a storm of tropical violence accompanied by hailstones as large as goose eggs, but jagged. The storm was over in minutes and covered only a small area. It was probably due to temperature changes and could not possibly have been predicted.

'Quite a lecture, as you said. Obviously I criticized too soon. And now' Corporal George said 'I will tell you something you will be advised always to remember. They should have informed you at G.H.Q. so stop me if they have. We are not ordinary troops belonging to a regiment and never separated from it. We are, in a way, freaks, lone rangers. We are G.H.Q. troops, our Headquarters and our O.C. being at G.H.Q. Consequently, we are not subject to discipline by anybody outside G.H.Q. no matter who they are. So if you get into trouble with anybody, although I don't think it likely with you—'

'Thanks' I said.

'just tell them that you are a G.H.Q. troop and that if they wish to bring a charge against you it will be necessary for them to refer it to G.H.Q. since there must not, under any circumstances, be any interference with the observations you have to make and the time you make them. In many cases they won't like it but, if the need arises, and you never know in the army, just keep your nerve.' On more than one occasion I was to be grateful for that advice.

The observation post was about two hundred yards east of the Château close to an abandoned trench system. The ground was fairly level although rough, and after about one hundred yards further east it descended gently to the Béthune–Lens road. There were no obstacles to interfere with the true flow of the wind and the site was therefore about as good as could be found in the neighbourhood. Sailly Labourse was at the northerly edge of the Lens coalfield and I experienced again the impression of the sadness of the countryside adjacent to a mining district. The site was dominated by a very large colliery spoil heap, the Annequin Fosse, occupied by the enemy, of course, and giving perfect observation for miles around. When making observations I always had a feeling that I was being watched, even at 1 a.m., because I had to use a torch in order to manipulate the anemometer and read the thermometers.

I found it very strange and, in a way, very exciting, the realization that, at the fundamental hours, thousands of observers all over the world were performing manipulations identical to those I also was making.

Close by, but not enemy-occupied, were the small towns of Vermelles and Noeux-les-Mines. These were frequently shelled and occasionally salvos would fall close to the Château. It was said that there was a gentleman's agreement about shelling one another's Headquarters, although a six-inch high-explosive shell once wrecked the cookhouse. Perhaps this was a mistake. After the commencement of the Somme battles, when the Germans realized that the British really meant business, even although the balance sheet was a disaster, this agreement was dropped and the shelling of Headquarters became the norm.

One morning about half an hour before setting out to make the 7 a.m. observations I heard a salvo of shells coming over and they seemed to be close to. I only paid attention to them because the sound of their flight was different from anything I had heard before, and they did not seem to explode with the usual violence. On the way to the observation post I noticed about fifty yards away a patch of fog. Apart from the fact that the current weather type was not one associated with fogs, the area covered seemed to be very small. As it was unusual I decided to mention it in the weather diary and then thought no more about it. While I was making my observations the cloud had drifted across the path and it was not a meteorological cloud as I had thought but lachrymatory gas and I had not brought my protective goggles. I think I cried all the day and I was careful not to be caught again. Fortunately I always made out my telegram forms before returning to the Château so it was not necessary to grope my way upstairs and ask Corporal George to do them for me.

In all wars and to all arms, except perhaps the P.B.I., there are moments of sheer farce. I experienced a few. When it was my week to make the daytime observations my afternoons were free because the 3 p.m. results were not sent off straight away but were added to the end of the vitally important 6 p.m. telegrams.

On the far side of the Lens road there was a stream, according to the map designated by the description Courant de Bully. I decided to explore it. From an early age I had been fascinated by the creatures that lived in fresh water, not merely redpinks, and I cannot even now resist the temptation to examine any likely looking ponds. A pond is a little world of its own, ecologically self-sufficient and therefore fascinating to anyone who will take the trouble to study it.

On the Lens road there was an isolated estaminet, and after pond gazing I sometimes went in for a drink. It is probable that this was within prohibited hours, for the killjoy hand of Mrs Grundy reached out even to troops, many of whom would never go home again. If this was the case the young woman who served me was unconcerned; after all the French had no equivalent of Mrs Grundy so, as far as she was concerned, she was not breaking any law. I called mainly because it was a good chance to converse in French thereby improving my facility with the language. I was not aware that I was regarded as a suspicious person until, one afternoon, I found not the young woman, but an M.P.

'Good afternoon' I said.

'Good afternoon, I want to talk to you.'

'Well, I want a drink, where is m'selle? Are you serving the drinks today?'

'Don't try to be funny. What are you doing here anyway?'

'It's obvious isn't it: as I have just said I have come for a drink.'

'You won't see m'selle as you call her again. She is a spy and will most probably be shot.'

'Good God!' I exclaimed horrified 'I used to have quite long conversations with her, but I certainly never dreamed of anything like that. You are not pulling my leg are you? Are you quite sure?'

'Of course I'm sure. So you speak the lingo. That accounts for it.'

'Accounts for what?' I demanded, suddenly realizing what he was driving at.

'Well, who the hell are you. I have watched you for some time and for a mere corporal you seem to have a lot of time on your hands. You are an R.E., I see. Who is your commanding officer and where is your unit? I don't know of any R.E. Company being stationed anywhere near here.'

So that was it. How many more times would I have to explain the peculiarities of my role to some unbelieving person?

'My headquarters is at G.H.Q. I am a G.H.Q. troop.'

'Never heard of 'em.'

'Well, you are looking at one now.'

'All right, tell me what you do.'

'Now *you* are asking about secret information, perhaps you ought to be shot.'

'Well I'm buggered.'

'That is your own personal affair' I said nastily. I was becoming annoyed and also apprehensive. It was decidedly uncomfortable to be mixed up with spying even although one was innocent.

'Look' I said 'I am attached to 15th Division Headquarters, although I am not on the Divisional Staff. I think the best thing will be for you to come with me to the Château and I will take you to Signals. My work involves sending frequent telegrams, priority telegrams, to G.H.Q. and various Headquarters. The signallers know me and will vouch for me. If that does not satisfy you then I will take you to the General.'

'You can't do that. Who ever heard of a mere corporal going to a General?'

'Stop calling me a mere corporal. Perhaps it will interest you to know that I spoke to the General only this morning.' That was true as he had stopped and asked me what the 'glass' was doing while I was reading the barometer. 'As you must know there is always the possibility of reaching someone of high rank by starting at the bottom of the ladder and working upwards.'

'All right, I'll take your word for it although I have never seen any of your kind before. Anyway don't come here again.'

'There's not much point is there' I said 'if I can't have a drink. Still I can come for a pleasant walk unless the area is out of bounds, which it isn't as far as I know.'

Thinking about the incident later on I wondered if it had been a ruse on the part of the M.P. to find out what I was doing without asking directly and receiving a dusty answer. Certainly a soldier, not commissioned, wandering about apparently at will must have been a strange phenomenon, and his suspicions must have been increased by the fact that there was a battery of field guns only a little further along from the pond. I did not know about it because I had never heard it in action, but the M.P. might reasonably have believed that I had seen it. Certainly I should have found him out—if I had not been transferred the next day to another area—but by his ruse. If it was a ruse, he would have found out that I was harmless. On the other hand he might have been telling the truth as there was a considerable amount of the collecting of information by unwary troops and passing it on to the enemy. Such people were particularly keen on obtaining information about troop movements and attractive girls in estaminets were obviously the most successful enemy agents.

Le Touret is a village a few miles north-east of Béthune. I will describe it as I knew it. It straggles along the downward-sloping road to Laventie where there was bitter fighting during the first year of the war. Like nearly all the French villages I knew it had no pretence to beauty whatever but the surrounding countryside is pleasant. To the north-east, across the Canal d'Aire and a branch which links up with the River Lys is a large wood which was to provide recreational facilities in a few weeks' time. At the top of the road to Laventie, that is to say at the western extremity of the village, there is a large farm of typical Artois construction: an open rectangle having the farmhouse itself as the joining member to two wings, one comprising store-rooms and the other sheds for the animals. In the middle is the inevitable large midden, a paradise for flies and rats. The neighbouring village of Loisne is about half a mile to the south but by road it is a very long way away. The direct route is along a water-filled dyke with many willow trees, some of them appearing to be very old. The delightful demoiselle dragon-flies, some blue, some pale green, flit ceaselessly to and fro over the water and frequently they fly joined together in tandem for the purpose of their aerial lovemaking. There is no sign of the ugly complex of mining towns, Noeux-les-Mines, Vermelles, Mozingarbe and Loos of tragic memory, although these are only a few miles away.

Opposite the farm lands bordered by the south side of the Laventie road are two fields, one on either side of the dyke. In a corner of the field to the west is my observation post, consisting simply of a pole having fixed at the top, five feet from the ground, a square brass plate marked with the compass points and correctly oriented. At the centre of the plate is a pin to take the delicate anemometer. There is also a Stevenson screen, a small louvered cupboard, also about five feet from the ground, and containing dry and wet bulb thermometers. Wind and temperatures are the only measurements made at a single-observer station, but cloud kinds and amounts and estimates of heights have to be recorded in the weather diary. In particular it is necessary to be vigilant when the wind is in a quarter which is dangerous from the point of view of enemy gas attacks. The field to the east of the dyke is very extensive, falling away gently to the very confines of the village. At the top corner, adjacent to the road, there is a strong-point dug into the ground. It has a ten yard protective belt of barbed wire, the lowest strands being not more than a foot from the ground, and all arranged, not haphazardly as is usually the case, but to an intricate geometrical design which ensures that there are no gaps. No creature other than an animal small enough to crawl underneath can get through. Owing to the slope of the land there is an ideal field of fire except along the road where the perspective effect of trees growing close together along the roadside gives an unbroken barrier unless an attack delivered up the road reaches almost to the strong-point. The wire entanglements are so perfectly constructed as to give the impression of an exercise in fortification. If so, it was no doubt assumed that flank support would be provided by fortifying the farm buildings, and eventually this proved to be the case.

I was brought to Le Touret to take the place of a man who was going on leave. The farm was a Headquarters of an R.E. Company, the officers billeted in the farmhouse while the men occupied wooden hutments ranged round three sides of a field. A corner room in the yard was used as the orderly room. I had a hut to myself just off the road to the village. I was attached to the Company for rations, shelter and pay, but not for discipline, this being the concern of Meteor G.H.Q., since I was a G.H.Q. troop. I am afraid I was apt to flog this somewhat since it is human nature to make the most of circumstances which act to one's advantage. Apart from the necessity of carrying out the observations and sending the telegrams in code to a prescribed set of addresses, I was on my own and could occupy my spare time as I liked. I made many sketches of the least unlovely parts of the village, having abandoned further attempts at the human form divine, and gave them to the troops. [In an intervening section of his Memoirs Dr Cotton recalls that he became adept at producing sketches of nubile maidens by drawing on his imagination.] As there were no picture-postcards of Le Touret these were very popular and could have occupied most of my spare time.

Because I was, to all intents and purposes, on my own in a world where the life of everyone was strictly regulated, the position of the Meteor observers had been explained previously to the commanders of all units to which observers were attached and as a result I experienced no trouble. What was overlooked at Le Touret was the necessity to explain my presence to an incoming company if and when a change-over took place. When it did take place I expected that everything would be the same as before. When one such change-over took place the departing Company left at mid-morning but the relieving Company did not arrive until late afternoon. I made good use of this freedom of the camp to 'win' a number of very useful articles: a small 'coffin and flower-pot' stove which fitted very nicely into one corner of my hut, wood and wire netting with which I constructed a very comfortable bunk much superior to sleeping on the floor, a supply of coal which I stored under the bunk, and various odds and ends.

The new Company had arrived somewhat before the time of my 6 p.m. observations and when I went to the post at about ten minutes to the hour the place was full of people all milling around. The method of determining the wind direction was as follows: the anemometer was turned to such a position that the vane was stationary, the wind direction thus being along the plane of the vane. This direction was noted and entered on a special form CM 003; the anemometer was then turned through 180 degrees and the reading again taken. This observation was made three times so that altogether there were six observations, the mean being taken as the wind direction. The object of this procedure was to eliminate the effect of slight variation in direction. On this occasion the wind was in the most dangerous position, whereas it had not been even in the alert position when I made the 3 p.m. observation. Consequently, as no alert warning had been sent it was imperative to send the danger warnings immediately. I therefore abandoned for the time being the rest of the observations and hurried to the orderly room where the telephone was. The room was bare except for a long trestle table with a pile of papers. The O.C. of the new Company was seated at the middle and the R.S.M. at his side. Usually it would have been the orderly officer but as the Company had only just arrived he and the other commissioned officer were organizing the billeting, the officers in the farmhouse and the men in the hutments. There were two sappers standing at ease by the end wall and I was surprised to see that one of them was a student, Denton, from the St Helens days. He was equally surprised to see me.

I expected that everything would proceed exactly as before so I marched up to the O.C., saluted, and made the usual request:

'May I use the phone sir?'

'Who the bloody hell are you?'

'Meteor sir, I have a number of extremely urgent telegrams to send.'

'Well you can clear out and take your telegrams somewhere else. Who the hell are you anyway barging into my orderly room like this?'

Here we go again, I thought, I shall have to go through that rigmarole all over again. It is becoming monotonous. I tried to explain my position, realizing that this new man knew nothing about it.

'Sir' I said, 'it appears that my position has not been explained to you by the outgoing Company, this, of course, being impossible since they had departed before you arrived.'

'No it wasn't, and now will you get out or must I have you thrown out?'

'Keep your nerve' Corporal George had said and now was the time for it. Also for *l'audace.*

'I wouldn't advise that, sir, as you clearly do not know what authority I have' —'Blimey!' from the R.S.M.—'Surely you must realize by my interrupting your orderly business in this way that I possess the necessary authority. My telegrams are becoming more urgent with every second's delay. Will you please allow me to send my telegrams immediately and explain my position afterwards?'

He again threatened to have me thrown out so that I had no alternative but *l'audace.*

'Very well sir' I said 'somebody may get shot at dawn for this and I assure you it won't be me. There are witnesses.'

'Bloody hell' said the R.S.M.

The O.C., speechless by this time, waved his hand towards the phone, which was wall-mounted. I picked up the receiver and turned the handle.

'Is that Signals? I have a number of first priority telegrams . . . Who am I? Oh my God are you new as well? Is there an officer available? . . . Good, will you ask him to speak to me please, it is very urgent . . . Is that the Signals Officer? I am Meteor, I have a number of first priority telegrams to . . . What is my rank? What the hell has that to do with it? I am a corporal, but I belong to G.H.Q. . . . Look here, the wind has suddenly changed to the most dangerous direction, and if the Germans release gas now the men in the trenches won't stand a chance. The change of wind has been so sudden that it has not been possible to send a gas alert. As I said, I belong to G.H.Q., and I am acting with the authority of G.H.Q.'

Once again the R.S.M. muttered 'Blimey!' and I continued:

'You will take the message yourself. Thank you sir. First priority to Headquarters 40th, 50th, 51st and 55th Divisions. The message—Gas warning, wind at seventeen fifty five hours south esses by south ack ack ack. Signed Cotton, CO toc toc ON Le Touret LE Toc OURE toc.'

The two sappers grinned but straightened their faces on seeing the scowl on the O.C.'s face.

'Will you repeat that please? Thank you sir. I must now complete my observations after which I shall have more telegrams to send and this time in code. Priority but not first priority. Just one thing more sir. The gas warnings are to be sent to Meteor Second Army and to the Headquarters of the eleventh and fifteenth Corps, but these are for information only and are not priority. Thank you sir.' I replaced the receiver and turned to the O.C.

'You will have heard the conversation sir, at any rate my end of it and I am sure it will have made my position perfectly clear. I must now go and complete my observations. I had to interrupt them when I found that the wind had changed with unexpected suddenness to the most dangerous direction.'

'Yes, that is perfectly clear, but you will understand that I knew nothing about you. What I want to know is how you fit into my Company, what is your relationship to me?'

'I am attached to your Company for shelter, rations and pay.'

'What about discipline?'

'No sir. I belong to G.H.Q. as I had to explain to the Signals Officer and therefore in this respect I am not subject to you . . .'

'Blimey!' once more from the R.S.M.

'but if you have reason to believe that discipline is necessary, although I can hardly imagine it, I suggest that you contact Meteor Second Army. Alternatively since a D.R. (dispatch rider) from G.H.Q. calls on me once a week for my reports, you could give me a sealed letter addressed to my O.C., Colonel Gold, D.S.O. and I will include it with my material.'

'How many times during the day will you require to use my telephone?'

'Four times sir, 0-one hours, 0-seven hours, thirteen hours and eighteen hours, all GMT.'

'0-one hours, one o'clock in the morning. That means that the orderly room door will have to be unlocked.'

'That was the arrangement with the previous Company. There is one thing more. It was the rule for the sentry to waken me at 23.45 hours and I should be grateful if you will also arrange for this. And now I really must complete my observations. They should be made exactly at 18 hours, the exact time at which simultaneous observations are made all over the world.

'You have found yourself a nice cushy job' (sarcastic).

'There are many ways of doing one's duty sir.'

I then saluted and left. The remainder of the O.C.'s reaction I learned from Denton a few days later. The O.C. banged his fist on the table and shouted:

'Of all the bloody ridiculous nonsense, a mere corporal wished on me for rations and pay and actually having the bloody nerve to give me orders.'

Turning to the R.S.M. he asked 'What do you make of it?'

'I don't know what to make of it sir. I had no idea there were people like him in the Army. He certainly ticked you off, if you don't mind my saying so, and he certainly gave orders to the Signals Officer. And did you realize that he seemed to know the names and probably the locations of all the army units, information that even you do not possess. Authority of G.H.Q. is certainly a new one on me and I'm quite sure he wasn't bluffing. We shall have to put up with him I'm afraid. Still, I can't see that he will be any trouble.

'Yes, you are probably right'. The O.C. turned to the two men who both jumped to attention. 'Sapper Denton'.

'Sir.'

'You and this Meteor fellow seemed to recognize one another. Do you know him?'

'Yes sir.'

'Well, go on.'

'Before I joined up, sir, I was an engineering apprentice and I was sent to the technical school to take a part-time day course. Mr, er Corporal Cotton was one of my lecturers.'

'I see, it was a strange coincidence, what was his subject?'

'Electrical engineering and advanced Mathematics sir, although I was given to understand that he was a Physicist as well.'

'I suppose that accounts for it. All right, stand easy.' He turned to the R.S.M. 'We might as well transact *some* business before he comes and disturbs us again.'

'Yes sir.'

A day or so after this incident I was walking along the road in the direction of Béthune. The strong sun in a cloudless sky threw black shadows across the road, uniform like the rungs of a ladder. Sapper Denton was sitting by the roadside stripped to the waist, his tunic and shirt lying on the ground beside him. His vest was turned inside-out and he was diligently searching the seams, muttering angrily as he did so. Every now and then he pressed his thumb nails together and a sickening crack would indicate the end of one of those loathsome creatures which could make life a misery.

'Hello Denton, delousing? I think I will join you as I have a private menagerie of my own to attend to.'

'These bloody chats' Denton said 'wherever do they come from? We didn't have them in the training camps at home. They are enough to drive a fellow daft. Some of the chaps believe they come out of the ground because, they say, the Froggies are dirtier than we are.'

'If you go to the slums of any of our big cities you will soon find out that the French are no worse than we are. There are filthy people everywhere. No, it's the lack of civilized amenities. Very little water and the impossibility of getting a hot bath. Like you, I never saw a louse until I came here.'

'What about my O.C.?'

'Shh . . . if somebody hears you say that you'll most probably get a stint of pack drill.'

'Stint. Fancy hearing that word out here.'

'Yes, it appears to be associated largely with the mining industry. I never heard it until I went to teach in a mining community. How far away it all seems; the Technical School, the visits to industry like the glass works and the cable works at Prescot. Somehow I have a feeling that life is going to be very different when we get back.' 'There won't be any chats and that's something. Do you mind if I ask you something personal?'

'I will answer if I can. What is it?'

'The men have been very interested in you since the way you stood up to the Captain, especially as he is a holy terror and has a hell of a temper. They all wished they could have seen it. Another thing they want to know is how you got into your lot.'

'The only answer I can give to that is, unbelievably good fortune and the fact that I am a scientist doing a scientific job. But I cannot regard myself as a soldier. I am only a civilan in uniform.'

'Aren't we all?'

'It is not the same. I came out here with no military training whatever, no square bashing, no weapons training, and in spite of my corporal's stripes, if I was put in charge of a party of men I should have no idea what to do with them.' I little realized how prophetic that remark was to be. 'A few weeks ago somebody realized that I had been sent out without any weapons so I was issued with an enormous revolver which nearly knocked me down when I fired it. Perhaps it is because I regard myself as a civilian that I am not afraid of officers.'

We had no sooner finished dressing than there was the sound of gunfire.

'Damn!' I said.

'Why, what is it?'

'There must be a German plane about. Yes, there it is coming this way. The plane is nothing to worry about, not to us, it's the gunfire. The anti-aircraft guns are old R.H.A. twelve-pounders on make-shift mountings. They never hit anything because they can't follow quickly enough, but everything they send up has to come down, in the form of a vertical rain of shrapnel and shell fragments.'

'Ought we to lie down or something?'

'No, that is the worst thing to do. The explosions are high up in the sky, not at ground level like ordinary shelling. One way is to stand upright and make yourself as thin as possible so as to present the least possible target area, but that takes some nerve as it is contrary to all instinct. A tree affords as good a protection as anything. Come on' I said.

We ran across the road and stood with our backs to one of the trees, which were along one side only. The plane sailed on, apparently indifferent to its wake of little white puffs which, continually reaching out, never succeeded in catching up with it. Shrapnel began to fall, bringing leaves and twigs falling from the tree. With a crescendo of sound like the approach of a heavy goods train, an unfragmented shell body crashed on the place where we had been delousing.

'Blimey, no matter where you put your tin hat it wouldn't be much use against that.'

I returned to my hut and sat on my home-made deck-chair, another result of my successful scrounging expedition. 'How can one get into your lot?' Suddenly I realized that I must be one of the most fortunate men in the army and that, as the O.C. had said so nastily, I had found myself a cushy job. I knew by now something of what the P.B.I. had to put up with, and the worst was yet to come. Somehow it didn't seem right, but I consoled myself with the knowledge that in contrast to my Army pay, there were many thousands at home, safe from danger and hardship and making fortunes out of the war.

(*To be continued.*)

551.509. 313

Review

Boundary layer climates, by T. R. Oke. 230 mm × 150 mm, pp. xiv + 372, *illus.* Methuen & Co. Ltd, Andover, Hampshire, 1978. Price £10.50 (University Paperback edition £7.50).

This book is intended as an introduction to the nature of the atmosphere near the ground for those who wish or need to know but are 'daunted by the technical nature of most micro- or biometeorological texts which assume a reasonably advanced ability in physics and mathematics'. The author reinforces this statement in the Preface by steering those with the appropriate scientific background towards more rigorous and complete expositions of the subject, in particular Geiger's now classic study 'The climate near the ground' (1965). To achieve his aims the author's discourse is of an explanatory rather than of a descriptive nature and is illustrative rather than comprehensive. The book is structured in three main parts and its scope is displayed clearly and in detail in the Contents.

Part I. Atmospheric systems comprises two chapters intended as a simple scientific introduction to atmospheric boundary-layer processes and to surface and soil properties and exchanges. Here the physical foundations are laid for the subsequent discussions of a wide range of surface environments. In accordance with the stated intention, mathematical equations have been kept to a minimum and the text is much more of a qualitative rather than quantitative nature. The reader is guided carefully and steadily through the essential basic concepts of the surface energy and water balances and is given insight into the character of subsurface climates and the role of the turbulent processes in the boundary layer. The uninitiated student who dwells on these two chapters long enough to master the apparent plethora of cumbersome symbols which are a guaranteed feature of any discussion of the fate of solar radiation entering the earth–atmosphere system and to absorb the physical principles discussed, will be amply rewarded in the following sections. Fortunately, the considerate author has made decipherment easy by providing a comprehensive list of symbols. Part I gives a generally good, clear and informative introduction to the book.

Part II. Natural atmospheric environments comprises four chapters on an extensive variety of natural surfaces and systems. There is a planned, gradual progression from relatively simple surfaces to more complex systems as one advances through Chapters 3–6 which concern the climates of simple non-vegetated surfaces (including sandy desert, snow, ice and water surfaces), vegetated surfaces, non-uniform terrain and animals, respectively. The spirit of the book is embodied in an interesting section on snow and ice in Chapter 3 where, for example, the wavelength dependence of the albedo of snow is invoked to help explain the ease with which skin becomes sunburnt and why earlobes, throat and nostrils, areas which are sensitive and normally in the shade, become particularly vulnerable on sunny days on snow-covered mountains.

After two further sound and informative Chapters, 4 and 5, the section culminates in *Chapter* 6, *Climates of animals*. Bearing very much in mind the author's intention to be illustrative rather than comprehensive, this is the chapter which the reviewer found most intriguing, absorbing and simply enjoyable to read. Natural historians and avid followers of David Attenborough's 'Life on Earth' start here! Because animals are able to move and carry their own internal energy supply (metabolic heat) they and their immediate environment represent some of the most complex climatic systems. The special characteristics of the animal–atmosphere system are identified, one of which is animal metabolism, defined as the process in living organisms whereby substances are transformed into tissue with an attendant release of energy and waste. The reviewer was interested particularly in the table of adult human metabolic heat production at different levels of activity which vindicated his continuing efforts at squash which merited 710 W, surpassed only by wrestling (860 W). Unfortunately, sleeping (70 W) is the lowest level of activity evaluated and so no estimate is available for cricket!

There follows an engrossing section on climates of poikilotherms, which include 'cold-blooded' animals such as fish, amphibians, reptiles and insects. Who could deny that 'the incubating queen bumble bee represents a fascinating heat balance model'? The section also contains, for example, a discussion of the circulatory systems of certain large, fast-swimming fish such as swordfish and mackerel shark which use the principle of counter-current heat exchange to allow a certain de-coupling of the flow of heat from the flow of blood. This apparently efficient method of heat conservation is also employed by some homeotherms ('warm-blooded' animals, including humans, most mammals and birds) and by industrial design engineers. A section on the climate of homeotherms includes discussion about hypo- and hyper-thermia, the different problems of thermoregulation faced by large and small animals and the methods of solution they employ.

Chapter 6 closes with an excellent section on humans with comments on windchill effects, frostbite, dehydration, and a discussion of the effects of immersion in cold water. The advice is given that the ideal posture to prolong survival is a huddle, with the arms close to the sides of the thorax and the legs drawn up to decrease heat loss from the groin. This chapter can be recommended as general reading to all walkers, climbers, yachtsmen, and others who run the risk of exposure to extreme climates.

Part III. Man-modified atmospheric environments concludes the main text with three chapters on the consequences of human interference in otherwise natural climatic systems. Intentional modification is dealt with in Chapter 7, inadvertent modification in Chapter 8 and a full, final chapter is devoted to air pollution in the boundary layer.

The book is clearly well written and stylishly and carefully produced, with only a few minor typographical and grammatical errors. There are sufficient references and a supplementary reading list for those whose appetites have been whetted but not satisfied. If a personal quibble is allowed then it concerns the absence of scales from many of the figures. The reviewer appreciates and applauds the author's aim to be qualitative and general wherever possible and would be forced to agree that, where omitted, the scales are not absolutely essential; however, this absence of measure is occasionally irksome and frustrating. It should also be noted that a langley is 1 cal cm^{-2} and not 1 cal $cm^{-2} min^{-1}$ as defined in Table A4.2. These very minor criticisms apart, the author has achieved his goal of producing a well-structured, illustrative and informative text which can be recommended to all who desire an introduction to the complexities and subtleties of a wide range of boundary-layer climates.

D. J. Carson

Obituary

We regret to record the death on 25 April 1979 of Mr M. C. Oughton, Scientific Officer. Mr Oughton joined the Office in 1947 and served at a number of stations at home and overseas. At the time of his death he was working at Crawley.

We regret to record the death on 14 May 1979 of Mr M. Baynes, Scientific Officer. Mr Baynes joined the Office in 1950 and served at a number of stations at home and overseas before being posted to the Central Forecasting Office (Met O 2) at Bracknell in 1971.

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NOTICES

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Mesoclimatic studies in the Upper Don Basin, Aberdeenshire

By R. J. A. Jones*, J. Tinsley and M. N. Court

(Soil Science Department, University of Aberdeen)

Summary

Measurements of solar radiation, air and soil temperature, rainfall and exposure to wind from 14 stations, 270–700 m O.D., in the Upper Don Basin, Aberdeenshire, were recorded for 1966–70. From mid-July to late September solar radiation totals were slightly greater in this upland area than near the coast at Aberdeen and greater at 670 m O.D. than at 351 m O.D. A sucrose inversion method, giving exponential mean temperatures, θ_e values, was used for measurements in air and soil at all sites and comparisons were made with data collected from a limited number of calibrated thermographs and mercury thermometers. Monthly mean θ_e values averaged 2 °C higher than arithmetic means (θ values). The overall annual mean air temperature recorded by standard instruments was 6 °C. Lapse rates per 100 m rise of 0·64 °C for air temperatures and 0·61 °C for soil temperatures were established from θ_e values. Variations in the periods of the growing season when mean air temperatures remained above 6 °C (GL) and above 10 °C (HGL) were estimated from the temperature curves constructed from 5 day means measured by thermograph, and from θ_e values. Whereas GL decreased by 10 days for every 200 m rise, HGL fell by 10 days for each 50 m rise in altitude. The normal annual rainfall total of about 1000 mm for 1964–70 is compared with totals for other stations in north-east Scotland. A small potential soil moisture deficit of about 50 mm developed in 2 years out of 6 at one station below 400 m O.D. in the Upper Don Basin. The relative exposures of sites were assessed using the tatter flag method and data compared with anemometer readings. Strong correlations were found confirming that tatter flags are useful substitutes for or complements to anemometers for studies in exposed areas. The implications of changes in mesoclimate in this upland area of north-east Scotland are assessed and the value of the non-standard techniques tested is established.

1. Introduction

Detailed observations on the climate of inland areas in north-east Scotland are available from the long-term meteorological stations of Braemar (National Grid Reference NO 152914) and Balmoral (NO 260947) and for other meteorological stations including Dinnet (NJ 446025) and Glenlivet (NJ 188303). Records from Craibstone (NJ 872107) provide a comparison with coastal areas. These characterize the Grampian regional climate as one of rather cold winters and fairly cool summers with moderate rainfall evenly distributed throughout the year. On their climatic maps of Scotland,

* Present address: Soil Survey of England and Wales, c/o Ministry of Agriculture, Fisheries and Food, Woodthorne, Wolverhampton, West Midlands WV6 8TQ.

Birse and Dry (1970) and Birse and Robertson (1970) delineate the lower parts of the Upper Don Basin as fairly warm, moist, moderately exposed lowland and foothill, and the higher parts as cool wet foothill and upland which is exposed to very exposed with moderate to severe winters.

The data from established meteorological stations give little insight into variations of mesoclimate. To some extent these can be inferred from established relationships between climatic and physiographic variables (Gloyne 1968; Manley 1945; Smith 1950) but where the density of recording stations is low such interpolation can often be misleading.

As part of an experimental program to determine the factors affecting the productivity of mixed grass swards containing clover in the Upper Don Basin, Aberdeenshire, a net of 14 meteorological stations (Figure 1) was operated for 1966–70 by the Soil Science Department, University of Aberdeen. Solar radiation, air and soil temperature, rainfall and exposure to wind were recorded using standard and non-standard instruments (Table I). This paper describes the methods employed and examines the variations of climate with changing altitude and aspect. Although the emphasis is on the effects of changing topography, the results are also placed into a regional context.

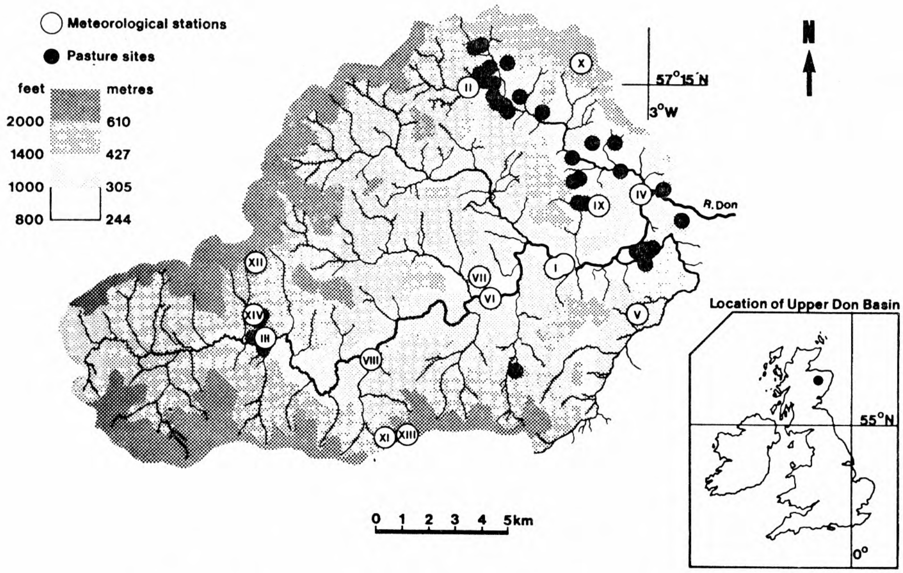

Figure 1. Meteorological stations in the Upper Don Basin.

2. Experimental

(a) *Solar radiation*

Differential interception of solar radiation in hill areas by differently oriented slopes greatly influences air and soil temperatures in northern Britain (Gloyne 1968). Despite its fundamental significance, few attempts have been made to measure solar radiation in the hill lands of the United Kingdom (Hughes and Munro 1968).

Measurements were therefore made at Stations VIII (351 m O.D.) and XII (670 m O.D.) from June to December 1969. At the lower site a Lintronic solarimeter (manufactured by Lintronic Ltd, London, in co-operation with Rothamsted Experimental Station) was connected to an integrating millivolt counter with a six digit recorder and mounted in a wooden box, the top of which provided a base

Table I. *Details of meteorological stations in Upper Don Basin*

No.	Station	Alt. (m O.D.)	NGR (NJ)	Period of operation	Sucrose tube*	Tatter flag	Max./ Min.†	Thermo-graph	Rain-gauge†	Anemo-meter	Solari-meter
I	Waterside	275	366119	30/04/66–30/04/70	×	×		×		×	
II	Glenbuchat Lodge	381	332189	30/04/66–30/04/70	×		×		×		
III	Allargue Hotel	411	256092	30/11/68–30/04/70	×			×			
IV	Mains of Glenbuchat	275	397147	30/04/67–30/04/70	×		×		×		
V	South Ardgeith	381	397102	31/05/66–30/04/70	×	×	×		×		
VI	South Candacraig	305	340107	31/05/66–31/10/68	×	×	×				
VII	North Candacraig	404	337116	31/05/66–30/04/70	×	×	×		×	×	
VIII	Tornahaish	351	296084	30/04/66–30/04/70	×		×		×		×
IX	Ben Newe	565	381142	31/05/66–30/04/70	×	×	×		×	×	
X	Creag an Sgor	600	375197	31/05/66–30/04/67	×	×	×		×		
XI	Glas Choille	549	301054	31/05/66–30/11/68	×	×	×		×		
XII	Lecht	670	252121	30/11/68–30/04/70	×	×	×		×	×	×
XIII	Scraulac	686	309055	31/05/66–30/04/70	×	×	×	×	×		
XIV	Allargue Hill	550	253100	30/09/68–30/04/70	×	×			×		

* for mean air and soil temperature measurements.
† daily readings at Station II, all other thermometers and rain-gauges read monthly.

for the solarimeter dome 1·6 m above ground level. A Kipp and Zonen solarimeter (as part of a Plessey automatic climatological recording station) with its dome mounted approximately 5 m above the ground was used at the higher site. A standard Kipp solarimeter mounted on the roof of the Natural Philosophy Building (30 m O.D.), University of Aberdeen, was used to calibrate these instruments and provide data from near sea level for comparison.

(b) *Temperature*

To relate air and soil temperatures to sward growth, the sucrose inversion method for measuring exponential mean air and soil temperatures was developed (Jones 1972; Jones and Court 1980). It was used at 46 sites throughout the Upper Don Basin between May 1966 and April 1970.

Two sealed polythene tubes containing a sucrose buffer solution were positioned at each experimental site and changed at monthly intervals as described by Jones and Court (1980). One tube was clipped in a north-facing recess $7{\cdot}5 \times 4 \times 4$ cm deep in a post also carrying a tatter flag (Plate I) such that the centre of the solution was 1 m above the ground. The second tube was placed in a stoppered copper tube 10 cm $\times$ 2 cm internal diameter inserted vertically into a hole in the ground beside the post such that the centre of the solution was at a depth of 10 cm below the surface.

At those sites where herbage yields were measured the sucrose tubes provided estimates of monthly mean temperatures throughout the growing seasons 1966–69. At the meteorological stations the tubes were mounted alongside standard thermograph and mercury thermometers for calibration purposes (Table I).

A Cambridge mercury-in-steel thermograph measured air and soil temperatures continuously at Station I (275 m O.D.) for the period April 1966 to April 1970. All the readings were reduced by planimeter to monthly means to permit comparison with data from other instruments. A Casella thermograph of the bimetallic type was installed in a Stevenson screen at Station III (411 m O.D.) and the period of recording was November 1968 to April 1970. Daily readings were obtained from a mercury thermometer at Station II (381 m O.D.) from April 1966 to April 1970. The temperature sensor in all these instruments was positioned 1 m above the ground and field calibrations against NPL mercury thermometers reading to $\pm 0{\cdot}1$ °C were undertaken.

(c) *Precipitation*

Rainfall is difficult to measure in rugged country where rain-gauging may suffer local bias depending on the relative directions of slope and the direction and speed of wind.

Rainfall and snowfall were measured daily at Station II (381 m O.D.) for 1964–70 using a standard meteorological copper rain-gauge with a 12·5 cm diameter funnel, the brass lip of which was 0·3 m above the ground, as part of the Meteorological Office program to collect precipitation data in the United Kingdom. Rainfall was also measured, at ten other stations in the Upper Don Basin, totals being recorded only at monthly intervals. Monthly totals were obtained from meteorological stations in areas adjacent to Donside for comparison.

(d) *Wind exposure*

To assess exposure at ten of the meteorological stations and at the sward sites, measurements of flag tatter and geomorphic shelter were made. Conventional 3-cup-type anemometers were also employed at four of the meteorological stations to provide data for comparison with the non-standard techniques.

(1) *Tatter-flag technique.* This cheap and convenient index of exposure involved the tattering of standard cotton flags. Their use is described elsewhere by Thomas (1959), Rutter (1968) and Gloyne, MacSween and Allen (1975). In the present study the method of Lines and Howell (1963) was used. The flags were made of Madapollam cloth (DTD 343A), 30 × 41 cm, each being dried at 60 °C, cooled in a desiccator and weighed to ±0·005 g before being sewn on to galvanized steel rods 61 cm long and 6 mm diameter. One flag post and holder was placed at each experimental site such that the top of the flag when mounted was 1·5 m above the ground (Plate I).

After exposure for 2 months or at very exposed stations (IX, XII and XIII) after 1 month, during which the corners and free edges tattered away, each flag was replaced by a new one, the tattered flag being carefully washed, dried at 60 °C, cooled and reweighed. The loss in weight was then converted to $cm^2 d^{-1}$ for the period of exposure.

Duplicate flags placed either side of the river Don (30 m apart) at Station I showed a mean coefficient of variation of 12 per cent over a period of two years (Jones 1971).

(2) *Geomorphic shelter.* The method used was that first suggested by Blust and de Cooke (1960), in which the geomorphic shelter at a particular site is found by measuring the angle between the horizontal and the skyline for each of the 16 principal compass bearings. The angles recorded in this way are then summed to give the exposure index of the site. If the index is high the site is sheltered and if low it is exposed. Three indices were determined for sites in the Upper Don Basin; the first described above, the second by summing only the 8 principal compass bearings of N, NE, E, SE, S, SW, W and NW, and the third by using the 16-point data and doubling the values for the SSW, SW, WSW, W, WNW and NW directions before summation, to weight the index with respect to the predominant wind direction.

(3) *Anemometers.* Three instruments were installed on level sites 1·5 m above the ground surface at Stations I (275 m O.D.), VII (404 m O.D.) and IX (565 m O.D.) alongside tatter flags (Table I). A fourth anemometer was located at Station XII as part of the Plessey automatic weather station.

3. Results

Full details of the data were recorded by Jones (1971).

(a) *Solar radiation*

Figure 2 presents the monthly means at Aberdeen for the years 1967–69, with data for the summer months in 1969 at Station XII (670 m O.D.). Daily mean totals at Stations VIII (351 m O.D.) and XII compared with those for Aberdeen for the period June to September 1969 are displayed in Figure 3. The values for Aberdeen are monthly means of consecutive daily totals whilst observations from Stations VIII and XII, especially in August and September, were interrupted by instrument failures. The monthly means from continuous observations in Aberdeen, however, compare favourably with means computed from the totals on only those days during which measurements were made in Upper Donside (Figure 2).

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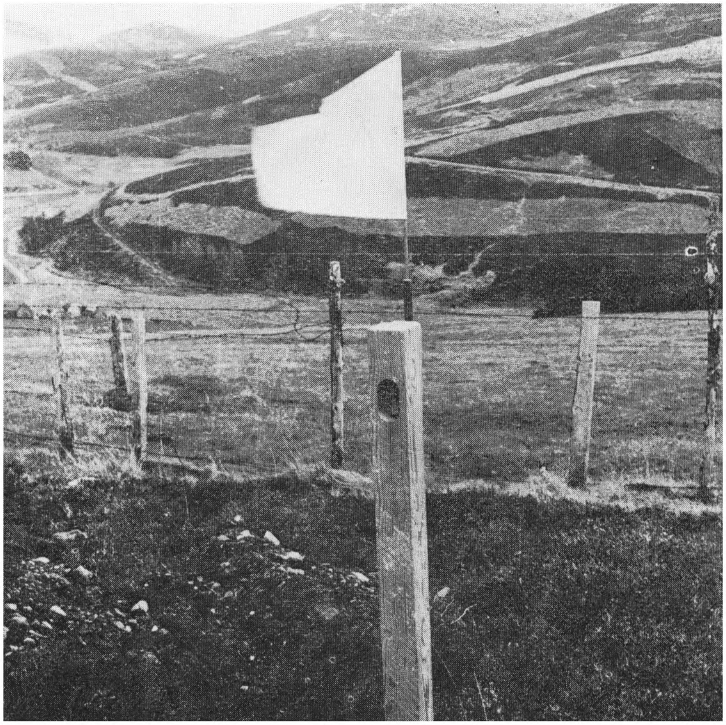
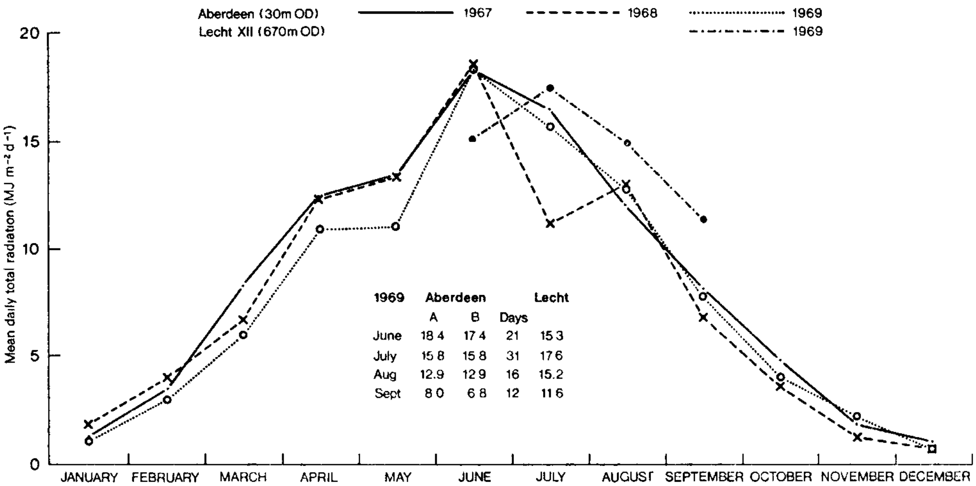


Plate I. A tatter flag for measuring wind exposure and a tube containing sucrose solution for mean air temperature measurement at Upper Badenyon, Glenbuchat, Upper Don Basin, Aberdeenshire.

The monthly peak at Aberdeen occurred in June each year of 1967–69 at slightly above 18 MJ m^{-2} d^{-1}. The Upper Donside figures show a contrast with a peak at Station XII in July 1969 at slightly below 18 MJ m^{-2} d^{-1} (Figure 2). Daily totals show that, although lower in June, solar radiation continued to be higher in the Upper Don Basin than at Aberdeen throughout August and September, a trend which is clear in Figure 3.



1969	Aberdeen A	Aberdeen B	Days	Lecht
June	18.4	17.4	21	15.3
July	15.8	15.8	31	17.6
Aug	12.9	12.9	16	15.2
Sept	8.0	6.8	12	11.6

The values for Aberdeen are derived (A) from continuous recordings and (B) from those days in each month when solar radiation was recorded at Station XII

Figure 2. Solar radiation, as monthly means of daily totals (MJ m^{-2} d^{-1}), at Aberdeen and the Lecht.

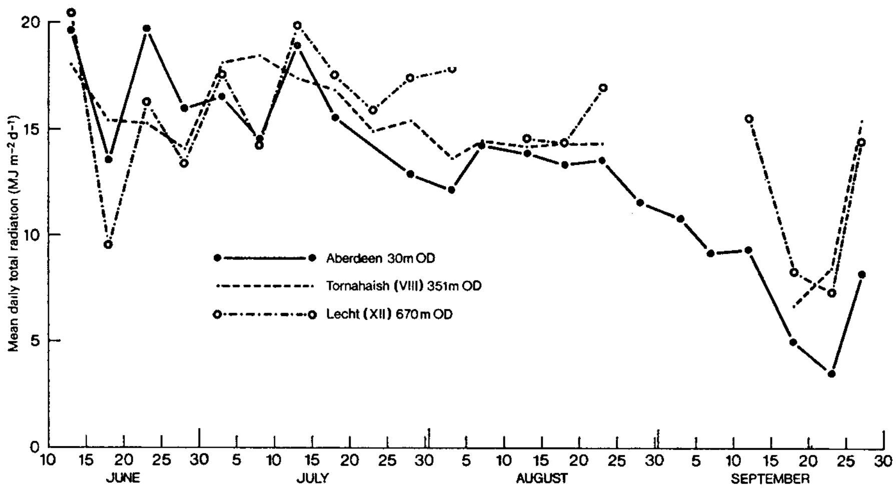


Figure 3. Solar radiation at two stations in the Upper Don Basin compared with Aberdeen in 1969.

(b) *Temperature*

The following *monthly* mean temperatures were measured by the sucrose inversion method, thermograph and maximum and minimum thermometers:

$\theta_{e(a)}$ exponential mean air temperature by sucrose inversion
$\theta_{e(s)}$ exponential mean soil temperature by sucrose inversion
θ_a mean air temperature from thermograph charts by planimeter
θ_s mean soil temperature from thermograph charts by planimeter
θ_d mean air temperature from daily maximum and minimum recordings
θ_m mean air temperature from monthly maximum and minimum recordings.

(1) *Air temperature.* The monthly mean air temperatures calculated from daily maximum and minimum peaks (θ_d) proved to be almost identical with those determined by planimeter from thermograph charts (θ_a). The close relationship was shown by Jones (1971) for Stations I (275 m O.D.) and III (411 m O.D.). Regression equations are:

Station I (Cambridge thermograph) $\theta_d = 1{\cdot}01\,\theta_a + 0{\cdot}366,$
$r = 0{\cdot}997;$

Station III (Casella thermograph) $\theta_d = 1{\cdot}03\,\theta_a - 0{\cdot}545,$
$r = 0{\cdot}992.$

Because it is inconvenient to take daily readings from simple mercury maximum/minimum thermometers at remote sites, the value of taking readings at monthly intervals was tested at Stations I and II (381 m O.D.). The regression equations for plots of θ_m (monthly) against θ_d were:

Station I $\theta_m = 1{\cdot}14\,\theta_d - 0{\cdot}745,$ $r = 0{\cdot}972;$

Station II $\theta_m = 1{\cdot}09\,\theta_d - 0{\cdot}737,$ $r = 0{\cdot}976.$

Clearly the mean of the monthly maximum/minimum values is of use for general comparisons but less precise for scientific purposes.

These data were also used to examine the relationships of arithmetic mean to exponential mean (θ_e) temperatures (Figure 4) and regression equations are given in Table II. It is clear that exponential

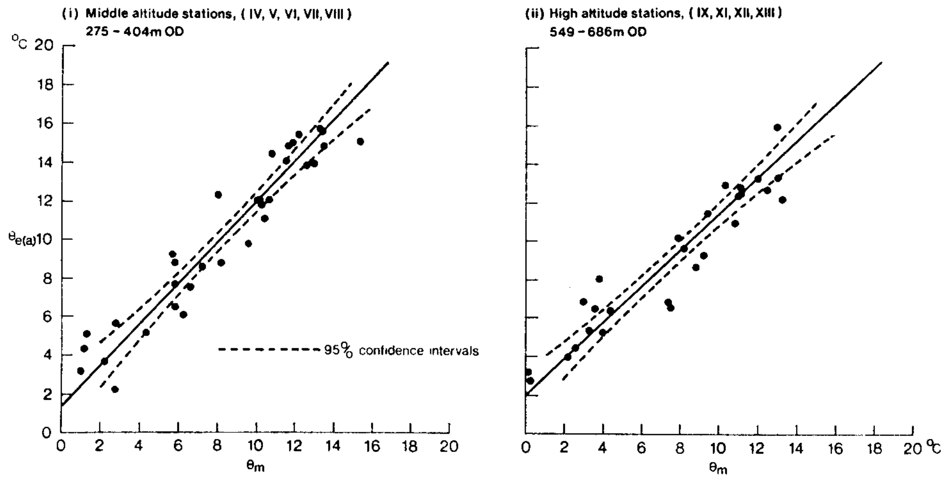


Figure 4. Relationship between $\theta_{e(a)}$ and θ_m values for several sites in the Upper Don Basin. (i) $\theta_{e(a)} = 0.956\,\theta_m + 2.183$, $r = 0.952$; (ii) $\theta_{e(a)} = 0.830\theta_m + 2.731$, $r = 0.942$.

Table II. *Relationship between air and soil temperatures at Station I, 275 metres O.D.*

	Percentage variance	Thermograph θ_s	Thermograph θ_a	Sucrose inversion $\theta_{e(s)}$	Sucrose inversion $\theta_{e(a)}$
		degrees Celsius			
(i) $\theta_s = -0{\cdot}25 + 0{\cdot}816\theta_a$	91	4·6 7·9	6·0 10·0		
(ii) $\theta_{e(s)} = -0{\cdot}90 + 0{\cdot}960\theta_{e(a)}$	94			7·2 11·0	8·4 12·4
(iii) $\theta_{e(s)} = 0{\cdot}96 + 1{\cdot}285\theta_s$	90	4·6 7·9		6·9 11·1	
(iv) $\theta_{e(a)} = 2{\cdot}49 + 0{\cdot}989\theta_a$	93		6·0 10·0		8·4 12·4
by equation (iii)		4·5 8·0		6·7 11·2	
by equation (ii)				6·8 10·6	8·0 12·0
Rounded mean temperatures		4·5 8·0	6·0 10·0	7·0 11·0	8·0 12·0

mean monthly air temperatures, $\theta_{e(a)}$, are on average 2 °C higher than means measured by standard instruments.

It is not strictly appropriate to compare the two different temperature means in this way, because of the inherent properties of the sucrose inversion method which biases the average obtained in favour of higher relative to lower temperatures. It is expedient to do so here, however, because only the sucrose method was used at some meteorological stations and all the pasture sites.

A profile of air temperatures θ_a, θ_d in the Upper Don Basin for 1966–70 (Figure 5) shows that they are low in winter and moderate in summer. Table III gives monthly mean air temperatures for a number of stations in north-east Scotland for comparison. Temperatures in the Upper Don Basin are similar to those at Balmoral and Braemar, with altitudes similar to Waterside (I) and Glenbuchat Lodge (II) respectively. By contrast, temperatures are higher throughout the year at Craibstone near Aberdeen and at Dinnet.

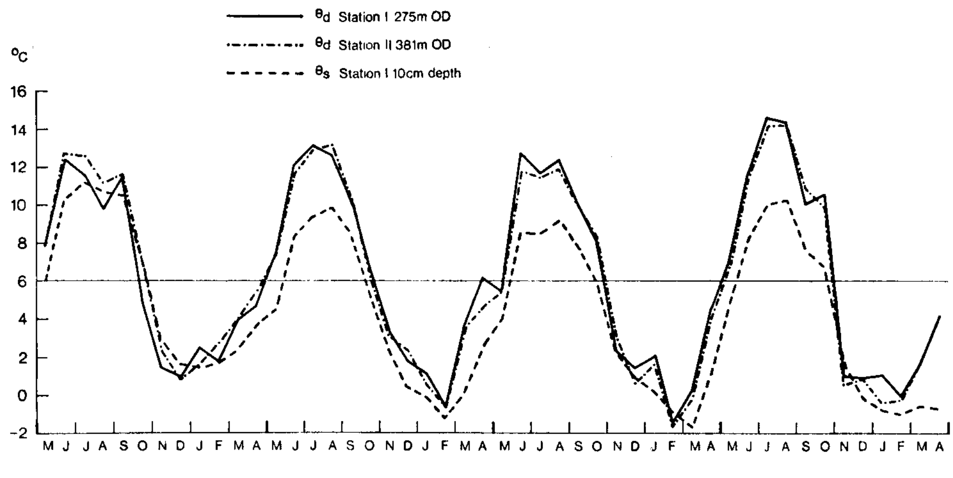


Figure 5. Monthly mean air and soil temperatures by thermograph and mercury thermometer in the Upper Don Basin, 1966–70.

Table III. *Standard monthly mean air temperatures for stations in the Upper Don Basin in relation to data from other meteorological stations in Aberdeenshire*, May 1966 to April 1970*

Station	Waterside	Glenbuchat Lodge	Braemar	Craibstone	Dinnet	Glenlivet	Balmoral
NGR	NJ 366119	NJ 332189	NO 152914	NJ 872107	NJ 446025	NJ 188303	NO 260947
Altitude (m O.D.)	275	381	339	91	177	215	283
				degrees Celsius			
May	6·6	6·8	7·0	7·8	7·9	7·7	6·6
June	11·8	11·9	12·1	12·2	13·0	12·5	11·5
July	12·2	12·8	12·8	13·4	13·6	(13·7)	12·5
Aug.	11·8	12·6	12·4	13·0	13·3	(13·0)	12·0
Sept.	9·9	10·8	10·9	12·0	11·9	11·4	10·4
Oct.	7·3	7·8	7·7	9·4	8·9	8·8	7·7
May–Oct.	9·9	10·4	10·5	11·3	11·5	11·2	10·2
Nov.	1·7	2·3	2·1	4·2	3·4	3·1	1·9
Dec.	1·2	1·2	1·6	3·3	2·5	2·3	1·3
Jan.	1·4	0·9	1·5	3·2	2·4	2·4	1·3
Feb.	−0·4	0·1	−0·7	1·8	0·5	0·6	−0·7
Mar.	1·8	2·2	1·9	4·0	3·3	3·1	2·0
Apr.	4·2	4·5	4·3	5·8	5·7	5·3	4·3
May–Apr	5·8	6·2	6·1	7·5	7·2	7·0	5·9

* Glenlivet is in Banffshire.
Figures in brackets are estimates because of incomplete data.

(2) *Soil temperature.* Few long-term records of soil temperature exist for stations in north-east Scotland and those for Craibstone (91 m O.D.), near Aberdeen, measured at 10 cm depth, are reproduced in Table IV for comparison with measurements from Waterside (I, 275 m O.D.). Soil temperatures, θ_s, in the Upper Don Basin during May 1966–April 1970 are lower than those near the coast though the difference is larger than might have been expected. The only explanation is that moderating maritime influences are strong at Craibstone and the frost pocket at Waterside (I) keeps soil temperatures low, particularly during winter.

The corresponding data measured by sucrose inversion, $\theta_{e(s)}$, are also given. As Jones and Court (1979) point out, θ_s values are 2·0–2·5 °C lower than $\theta_{e(s)}$ values, on a monthly mean basis. From the profiles of air and soil temperatures during the 1969 growing season it is clear that, in the altitude range 330–550 m O.D., mean soil temperatures lag below air temperatures until July/August (Figure 6).

Table IV. *Standard monthly mean soil temperatures at 10 centimetre depth* (θ_s) *for Craibstone and Waterside* (I) *in relation to* $\theta_{e(s)}$ *for Waterside, May 1966 to April 1970*

	θ_s		$\theta_{e(s)}$
Station	Craibstone	Waterside	Waterside
NGR	NJ 872107	NJ 366119	NJ 366119
Altitude (m O.D.)	91	275	275
		degrees Celsius	
May	8·4	4·8	7·4
June	12·9	8·8	12·4
July	14·2	9·8	14·7
Aug.	13·8	10·0	12·8
Sept.	12·2	8·6	12·3
Oct.	8·7	6·5	9·4
May–Oct.	11·7	8·1	11·5
Nov.	4·4	2·3	3·6
Dec.	2·9	0·7	3·4
Jan.	2·8	0·4	2·6
Feb.	1·9	−0·4	2·6
Mar.	3·0	0·1	2·8
Apr.	5·4	1·6	4·2
May–Apr.	7·5	4·4	7·4

(3) *The effect of altitude on temperature.* The use of the sucrose inversion method for mean temperature measurement permitted the collection of data from a large number of sites at different altitudes. Such data are lacking, particularly for soil temperature in upland areas (Harrison 1975). From the measurements, graphs have been constructed showing the rates of fall of exponential mean air and soil temperatures with rising altitude in the range 275–686 m O.D. (Jones and Court 1980). Lapse rates of 0·64 °C per 100 m for air and 0·61 °C per 100 m for soil temperatures are reported and these are similar to those measured or estimated over wider altitude ranges by Gloyne (1971), Manley (1945, 1952) and Oliver (1964).

(4) *The effect of aspect on temperature.* It has not been possible to assess the effect of aspect on mean temperatures measured at the 14 meteorological stations (Figure 1). However, using sucrose inversion measurements from the herbage sites, Jones and Tinsley (1980) found that southern aspects between 330–550 m O.D. were warmer during early summer when growth rates increase rapidly.

From the bi-monthly exponential mean temperatures shown in Figure 6 it is clear that the effect of aspect on $\theta_{e(a)}$ and $\theta_{e(s)}$ values is confined to April, May and June. During July, August and September the effect was not significant, presumably because most of the sites were on gentle or moderate slopes (3–7 degrees) which reduced the advantage of southern aspects. For grass growth, it is important to note that the average $\theta_{e(a)}$ value during May and June was below 12 °C ($\theta_a \approx 10$ °C, a threshold for vigorous growth) on north aspect sites but above that figure on south-facing ones.

These findings accord with the observations of Garnett (1939) that, in high latitudes, south facing slopes are not always the most favoured in every respect. She concluded from her experiments at Kinlochleven that the law of 'adret and ubac',* which applies so widely in Alpine regions of lower latitude, does not determine agricultural activity in deep Highland glens. In the Upper Don Basin

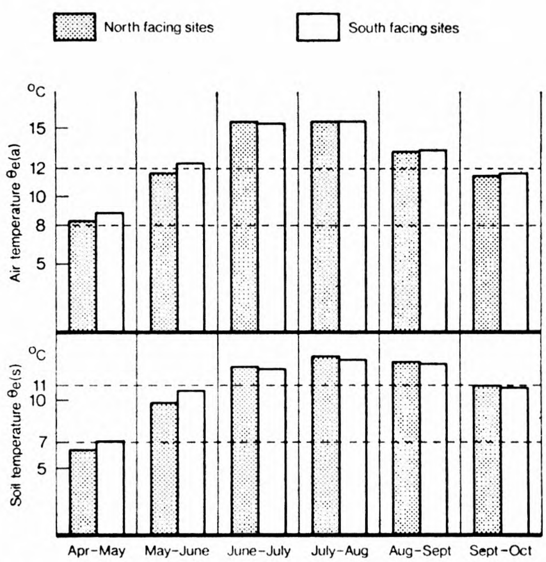


Figure 6. Effect of aspect on bimonthly mean exponential air ($\theta_{e(a)}$) and soil ($\theta_{e(s)}$) temperatures for pasture sites 330–550 m O.D. in 1969.

* These words come from the dialect of south-east France: *adret* means the sunny side of an Alpine valley or mountain and *ubac* the shady side.

and other areas of northern Britain where the slopes do not exceed 15 degrees and the ranges of altitude are small, the differential effect of aspect on light intensity and day length is minimal.

(5) *Growing season.* Peacock (1975, 1976a) studied the effects of air and soil temperatures on the growth of *Lolium perenne* at the Grassland Research Institute, Hurley (51° 31′N, 0° 48′W, altitude 50 m O.D.). Leaf extension was very slight when the air temperature around the shoot apex was 2–6 °C: such mean temperatures in the crop were closely correlated with air temperatures at standard screen height of 1·25 m. This species responded exponentially to temperature rises over the range 2–10 °C. In further studies involving subsurface increases of soil temperature, Peacock (1976b) followed the growth of four grass species into the flowering stage at temperatures up to 20 °C and reported an overall linear response to temperature for timothy and perennial and Italian ryegrasses but an exponential trend for tall fescue. However, if the data for the raised soil temperature treatments are excluded the leaf extension responses for all four species were broadly curvilinear in the range 2–16 °C.

Hence these studies lend support to the view of Gloyne (1958) that the conventional practice of defining the length of growing season as the period of the year when the mean air temperature at the standard height exceeds 42 °F (5·6 °C) is useful for evaluating the impact of climate on agricultural production, especially in the hill areas of Britain.

The notion of two threshold steps is introduced here, namely (i) the standard growing season above 6 °C (GL) and (ii) a 'high' growing season above 10 °C (HGL) in the light of the observations by Grant (1968) and Alberda (1966) that growth of sward species becomes vigorous only as the mean temperature rises to 10 °C and above: growth declines at temperatures above 28–30 °C.

From the graphs of 5 day mean θ_a and θ_d values for Stations I and II, (i) the standard growing season above 6 °C (GL) and (ii) a high growing season above 10 °C (HGL) have been estimated. In both cases the season was considered to have begun and ended when the temperature for two consecutive 5 day periods was above or below the base temperature.

Growing season data are listed in Table V and give an average length, GL, of 171 days at Waterside (I, 275 m O.D.) and 188 days at Glenbuchat Lodge (II, 381 m O.D.). Waterside is a valley bottom site close to the river Don in a distinct frost hollow, whilst Glenbuchat Lodge is at the head of a glen and though higher in altitude does not collect large descending masses of cold air. The high growing

Table V. *Length of growing season (days) in Upper Don Basin, estimated from plots of 5 day mean values of* θ_a *and* θ_d

		I Waterside 275 m O.D.		II Glenbuchat Lodge 381 m O.D.	
		Above 6 °C	Above 10 °C	Above 6 °C	Above 10 °C
1966	S	24 April	28 May	21 April	26 May
	L	162	98[1]	166	128
1967	S	6 May	29 May	5 May	26 May
	L	172	113	162	128
1968	S	20 May[2]	26 May	21 May[4]	27 May
	L	163	101[3]	161	105[5]
1969	S	7 May	4 June	9 May	2 June
	L	179	101	177	103
1966–69	S	9 May	29 May	23 April	27 May
	L	171	118	188	118

S is start, L is length

Notes:
1. The temperature was below 10 °C for almost 3 weeks in August.
2. The temperature rose above 6 °C between 15 April and 2 May.
3. The temperature was below 10 °C for 10 days in July.
4. The temperature rose above 6 °C between 12 April and 2 May.
5. The temperature was below 10 °C for 7 days in July.

season, HGL, when from the farmer's point of view herbage can be expected to grow vigorously, was estimated as 118 days at both sites.

The effect of altitude on growing season has been discussed by Manley (1945, 1952). Of considerable importance is a shortening of the period and reduction in the amplitude of the annual curve of average temperature with increasing height above sea level. In similar investigations, Gloyne (1958) showed that the length of the growing season (GL) at any place will change relatively uniformly with height above mean sea level, provided $\theta = 6$ °C does not cut the curve near its highest or lowest point. Further the amplitude of the curve will affect the reduction of GL with increasing altitude and, the more continental the climate, the less the effect will be.

In the absence of sufficient temperature data from standard instruments, mean monthly $\theta_{e(a)}$ values for five stations (350–700 m O.D.) for 1966–69 have been used to construct the temperature curves in Figure 7 for deducing the effect of altitude on growing season. Mean $\theta_{e(a)}$ values of 8 °C and 12 C° were chosen to correspond with 6 °C and 10 °C measured by standard methods (θ_a) for calculating GL and HGL.

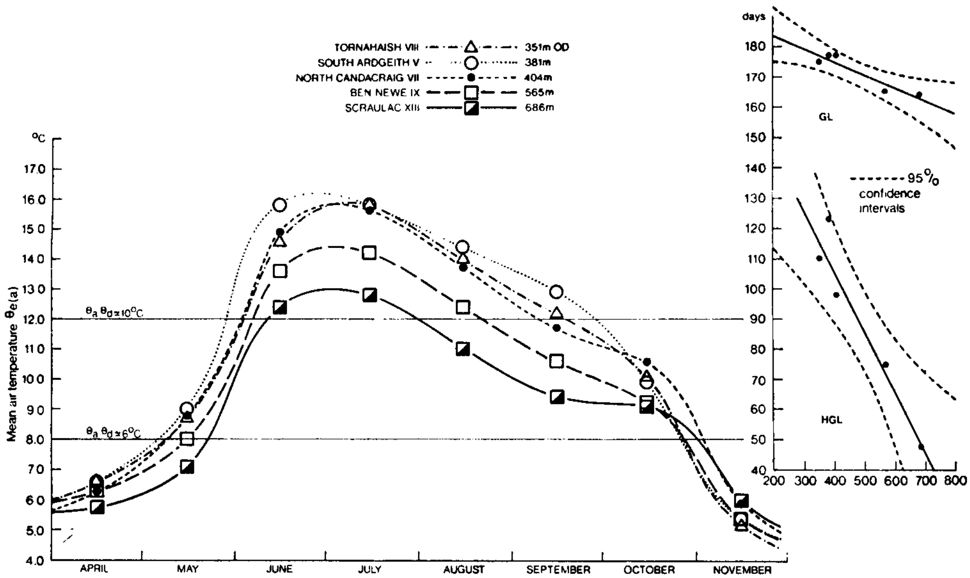


Figure 7. Effects of altitude on length of growing season in the Upper Don Basin, 1966–69.

The relationship with altitude is clearly demonstrated; GL reduces by about 10 days for every 200 m rise in altitude, though the relationship is imprecise owing to poor distribution of points; HGL reduced by 10 days for every 50 m rise in altitude, the regression being highly significant. Between 350 and 700 m O.D., in Upper Donside, the change in HGL with altitude is much more significant than the corresponding change in GL.

Tornahaish (VIII) had virtually the same GL but a significantly shorter HGL value than South Ardgeith (V) despite the fact that the former is 30 m lower in altitude than the latter. These results demonstrate the local influence of topography since Tornahaish is situated in a frost hollow whereas South Ardgeith is on a gentle slope with a southern aspect. By contrast North Candacraig (VII), Ben Newe (IX) and Scraulac (XIII) are hilltop (summit) stations.

The period above 10 °C is probably more important than that above 6 °C for the growth of cool temperate crops, suggesting that these results have added significance in assessing the potential productivity of grassland in the uplands of the Grampian Region.

(c) *Precipitation*

Rainfall data from stations in north-east Scotland are given in Table VI, for the period 1964–70. Totals for Glenbuchat Lodge (II) at 381 m O.D. are the highest, Derry Lodge and Corndavon Lodge both at 427 m O.D. recording smaller mean annual totals. The normal total of about 1000 mm for the region is evenly distributed through the year with roughly half falling between the beginning of May and the end of October.

Table VI. *Mean monthly rainfall in Glenbuchat in relation to other stations in north-east Scotland, 1964–70*

Station	Glenbuchat	Braemar	Glenlivet	Dinnet	Craibstone	Balmoral	Derry Lodge	Corndavon Lodge
NGR	NJ 333188	NO 152914	NJ 188303	NJ 446025	NJ 872107	NO 260947	NO 036932	NJ 228021
Altitude (m O.D.)	381	339	215	177	91	283	427	427
				millimetres				
Jan.	40	71	56	72	86	77	77	74
Feb.	58	62	55	51	63	70	81	66
Mar.	85	56	60	49	47	63	67	62
Apr.	78	58	62	59	53	67	63	74
May	111	83	79	81	92	85	88	95
June	66	63	63	52	59	57	79	60
July	92	55	63	68	66	63	67	75
Aug.	114	71	99	76	79	78	87	98
Sept.	87	80	80	65	63	66	85	80
Oct.	99	84	79	62	74	74	109	94
Nov.	121	80	96	66	68	85	113	92
Dec.	87	70	81	60	66	77	85	89
Totals	1038	833	873	761	816	862	1001	959

Mean monthly totals for stations in the Upper Don Basin for the period 1966–70 are shown in Table VII. The gauges at South Ardgeith (V), Tornahaish (VIII) and Scraulac (XIII) were read at monthly intervals and by comparison with readings from Glenbuchat, which were made daily, could have suffered small evaporation losses. Furthermore, Glenbuchat totals include snowmelt, also measured daily, whilst totals for the other stations include only meltwater from snow retained in the funnel.

Table VII. *Mean monthly rainfall totals for stations in the Upper Don Basin, May 1966–April 1970*

Station	Glenbuchat	South Ardgeith	Tornahaish	Scraulac	Edinglassie*
NGR	NJ 333188	NJ 397102	NJ 296084	NJ 309055	NJ 328123
Altitude (m O.D.)	381	381	351	686	358
			millimetres		
May	147	113	112	106	117
June	70	65	66	77	40
July	69	59	52	43	82
Aug.	78	73	76	74	95
Sept.	63	56	53	76	63
Oct.	118	96	100	84	93
May–Oct.	545	462	459	460	490
Nov.	117	72	90	132	76
Dec.	87	75	84	69	91
Jan.	43	118	119	92	116
Feb.	(58)	55	76	112	74
Mar.	(85)	44	79	70	73
Apr.	82	63	85	80	102
May–Apr.	1017	889	992	1015	1022

Figures in brackets are estimates for the period 1964–70.
* 1967–70.

On mountain tops, such as Scraulac, snow accumulations on the gauge could periodically have been blown away. Nevertheless, the records show that the Upper Don Basin is moderately dry for its height above sea level and the rainfall pattern is not markedly affected by altitude.

Snowfall begins as early as October or November and on high ground snow cover persists into May or early June, particularly on north-facing slopes above 800 m O.D., where thick drifts often build up during the winter. Records kept at Candacraig House (305 m O.D.) for 1961–67 show that on average snow falls on 45 days in any one year, the range being from 26 to 61 (Jones 1971). A similar pattern was found at Achnagoichan (305 m O.D.) in the western Cairngorms by Pears (1965).

(1) *Soil moisture deficit*. Average potential transpiration estimates for west Aberdeenshire were interpolated from Smith (1967) and compared with monthly rainfall totals for 1964–70, as described by Jones and Evans (1975) and Jones (1979). These permit the calculation of the potential soil moisture deficit (PSMD), the cumulative total excess transpiration over rainfall, and it was found that Station II suffered a significant (>40 mm) accumulated PSMD in only two years (Table VIII). In 1967 and 1969 the accumulated PSMD reached 65 mm and 42 mm respectively at the end of July. Birse and Dry (1970) calculate an average maximum PSMD of 0 mm in western parts of the Upper Don Basin above 400 m O.D., 0–25 mm below 400 m O.D., and 25–50 mm in eastern parts of the basin below this altitude. For most purposes therefore, rainfall is adequate but not excessive, though occasionally a small deficit will occur in soils at elevations below 400 m O.D.

(d) *Wind exposure*

(1) *Flag tatter*. Average tatter values in $cm^2 d^{-1}$ are given in Table IX for five sites in the Upper Don Basin; the yearly average was 2–4 $cm^2 d^{-1}$ for sites 270–400 m O.D., whilst above 500 m this increased to over 20 $cm^2 d^{-1}$. For the period November–December, the corresponding figures were 2·5–6 and 25–30 $cm^2 d^{-1}$, and 1–2 $cm^2 d^{-1}$ and 12–18 $cm^2 d^{-1}$ for July–August.

Ignoring tatter values for damaged flags, relationships between flag tatter and wind run by cup-type anemometer were examined. Dealing first with 'within site' dependency, strong linear correlations were found between untransformed tatter data and wind run (Figure 8) which agrees with Rutter's (1966) findings from studies of the tattering of dry flags in wind-tunnels.

The 'between site' dependency of tatter on wind run was established using data for the three sites in the range 270–570 m O.D. Jones (1971) showed that the square-root transformation of flag-tatter data against wind run gave the best fit regression line (Figure 8). This also accords with the findings of Rutter (1968) who experimented with tatter flags under field conditions at Aberystwyth.

Different expressions were calculated for the 'within site' and 'between site' dependencies of tatter on run of wind or mean wind speed. Tatter at individual sites is linearly related ($F = a + bW$) to run of wind, except when ribbon tearing causes excessive losses, whilst tatter between sites, ranging from very sheltered to very exposed, is curvilinearly related to run of wind (Rutter 1968; Jones 1971): $\sqrt{F} = a + bW$ where F is area loss (in $cm^2 d^{-1}$), W is wind run or mean speed ($km\ d^{-1}$), and a, b are constants.

Although tatter flags have not previously been used as a direct substitute for anemometers, the correlation is sufficiently close to suggest that they may be so employed. However, if flags are to be used for direct intersite comparisons, it must be recognized that exposure to wind can be exaggerated by rain, even within a small range of exposure (Rutter 1966) and a limited number of anemometers will still be desirable.

Correlations of geomorphic shelter with flag tatter were studied; those of shelter index against average annual and May–October area loss by flag tatter were strongest, though a maximum of only 28 per cent of the variation was accounted for. Geomorphic shelter can therefore be regarded as a

Table VIII. *Accumulated potential soil moisture deficit for Station II (381 metres O.D.)*

millimetres

Month	PT	1964 R	1964 PSMS	1964 PSMD	1964 APSMD	1965 R	1965 PSMS	1965 PSMD	1965 APSMD	1966 R	1966 PSMS	1966 PSMD	1966 APSMD	1967 R	1967 PSMS	1967 PSMD	1967 APSMD
Jan.	−3					27	30			45	48			35	38		
Feb.	4					79	75			89	85			84	80		
Mar.	17					50	33			125	108			105	88		
Apr.	41					129	88			27		13	13	95	54		
May	64	34		30	30	100	36			123	59			129	65		
June	71	72	1		29	63		8	8	162	91			35		36	36
July	67	77	10		19	113	46			84	17			36		31	65
Aug.	48	196	148			88	40			107	59			80	32		33
Sept.	29	107	78			188	159			54	25			92	63		
Oct.	11	52	41			59	48			154	143			137	126		
Nov.	0	59	59			154	54			256	256			92	92		
Dec.	−4	50	54			138	142			169	173			138	142		

Month	1968 R	1968 PSMS	1968 PSMD	1968 APSMD	1969 R	1969 PSMS	1969 PSMD	1969 APSMD	1970 R	1970 PSMS	1970 PSMD	1970 APSMD
Jan.	84	87			10	13			42	45		
Feb.	54	50			—	—			6	2		
Mar.	59	42			—	—			—			
Apr.	160	119			58	17			17		24	24
May	184	120			151	87						
June	37		34	34	48		23	23				
July	108	41			48		19	42				
Aug.	43		5	5	81	33		9				
Sept.	73	44			34	5		4				
Oct.	109	98			74	63						
Nov.	71	71			50	50						
Dec.	11	15			30	34						

All data in millimetres.

PT Average potential transpiration figures from Smith (1967) for Aberdeenshire (high level areas—365 m O.D.)

R Actual rainfall totals

PSMS Potential soil moisture surplus or the excess of rainfall over average PT

PSMD Potential soil moisture deficit or the excess of average PT over rainfall

APSMD Accumulated (month by month) PSMD

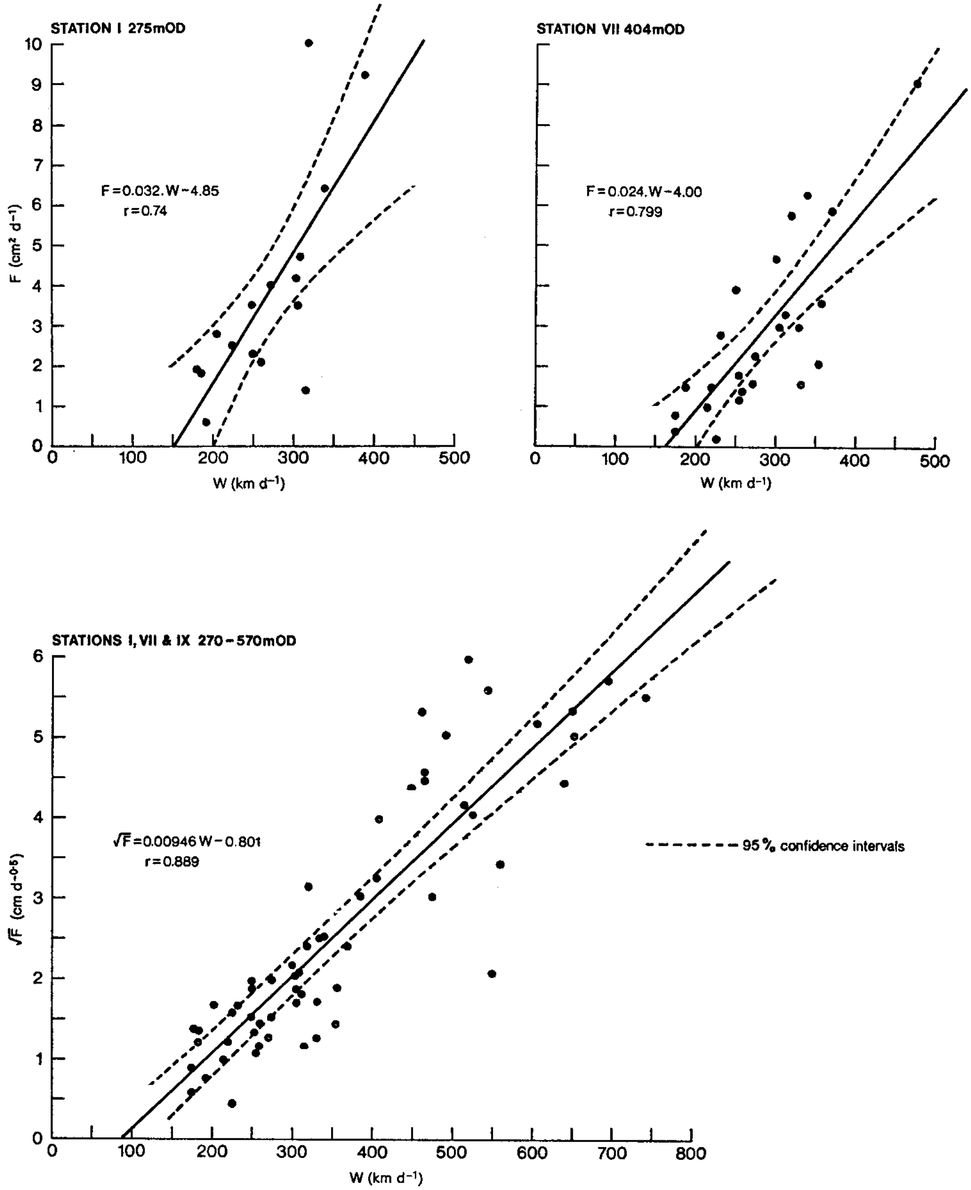


Figure 8. Relationship between flag tatter (F) and wind run (W).

diagnostic index which allows only crude ranking of sites according to relative exposures and it is understandably not closely related to average wind speed.

(2) *The effect of altitude on exposure.* Average annual flag tatter, calculated from bi-monthly values, correlated strongly with altitude (Figure 9). The best fit was obtained with square-root transformation of the tatter data. The tatter-flag method therefore clearly reveals a marked increase in exposure with

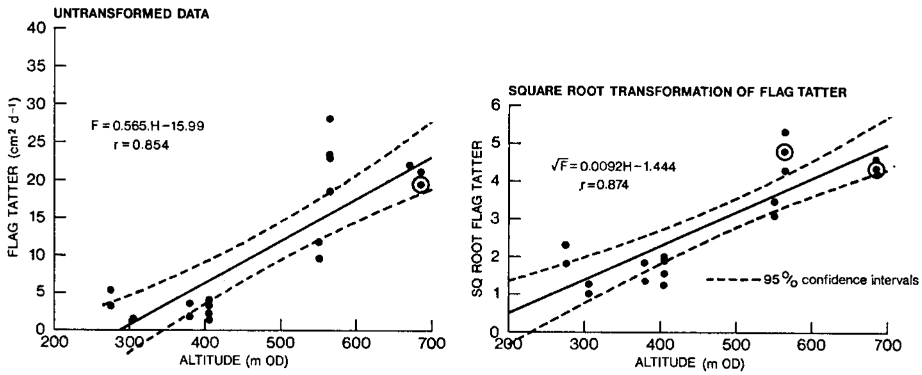


Figure 9. Correlation of flag tatter (F) and altitude (H) bimonthly means for period May–April (Year) 1966–70.

Table IX. *Flag tatter in the Upper Don Basin, May 1966–April 1970*

	Station Altitude (m O.D.)	May–June	July–Aug.	Sept.–Oct.	Nov.–Dec.	Jan.–Feb.	Mar.–Apr.	Year May–Apr.
				square centimetres per day				
I	Waterside 275	(3·2)	1·2	2·3	5·6	4·7	4·7	3·6
V	South Ardgeith 381	1·5	1·2	1·8	2·5	2·4	2·9	2·0
VII	North Candacraig 404	1·3	1·1	2·7	3·6	4·5	4·0	2·9
IX	Ben Newe 565	24·2	17·6	27·3	30·8	22·1	22·4	24·1
XIII	Scraulac 686	17·2	12·2	20·0	25·6	27·8	19·8	20·4

( ) some data missing.

altitude in the Upper Don Basin. Pears (1967) reported similar findings after exposing tatter flags for two years (1961–63) at sites (381–884 m O.D.) in the western Cairngorms.

Figure 10 presents wind run by anemometer for the three sites in Upper Donside in relation to Dyce Airport, near Aberdeen, for the period May 1966–April 1970. It shows the significant increase in mean wind speed, measured directly, which occurs with increasing altitude. The windiest periods were September–October and January–April during the four year period.

4. Discussion and conclusion

Although the climate of the Upper Don Basin was monitored for only 4 years the results add to our knowledge of hill climates. The paucity of data on upland climates has been noted by other workers (Crompton 1958; Gloyne 1968; Harding 1978; Hughes and Munro 1968; Jones 1967; and Oliver 1964) and, although attempts have been made to rectify the problem, it is still necessary to draw on the long-standing observations of Buchan (1905) and Manley (1936, 1942) for insight into extreme conditions. Particularly relevant here, however, are the results published by Munro (1973) describing the climate of hill centres (30–335 m O.D.) in Wales for the same period (1966–69) as the Donside records, and the review of upland temperature data by Harding (1978).

(a) *Solar radiation*

Although lower in June, solar radiation continued to be higher in the Upper Don Basin (350–670 m O.D.) than at Aberdeen (30 m O.D.) on the coast throughout August and September 1969. These

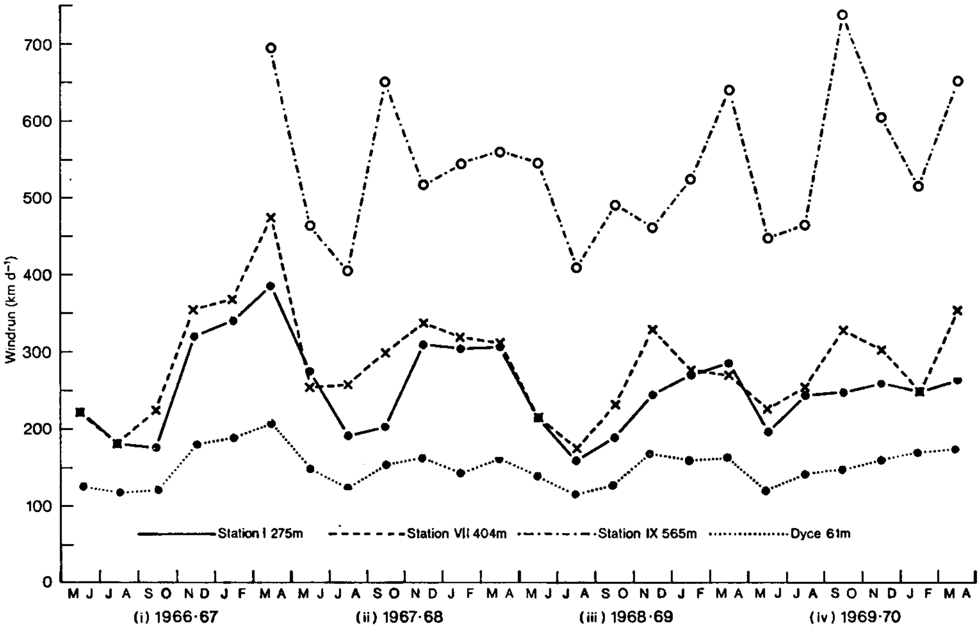


Figure 10. Anemometer wind run (km d^{-1}) in the Upper Don Basin compared with Dyce.

results concur with the findings of workers from the Welsh Plant Breeding Station in North Wales (Hughes and Munro 1968; Munro 1973) who showed that solar radiation during late summer was higher at 305 m O.D. in the drier eastern uplands than at 30 m O.D. in the western lowlands. Furthermore, the fact that from late July until the end of August 1969 solar radiation was greater at the Lecht site (XII, 670 m O.D.) than at Tornahaish (VIII, 351 m O.D.) casts some doubt on the generally held view that insolation declines with increasing altitude. The data presented here, however, are far from exhaustive and more work is needed to establish whether they represent a consistent pattern.

(b) *Air and soil temperatures*

The successful use of a cheap and effective method of mean temperature measurement (by sucrose inversion) at numerous diverse sites is a significant advance in agricultural research. The method has permitted the study of the variation of mean air and soil temperatures with altitude and aspect on a relatively large scale. Whilst the lapse rates with altitude compare with traditionally accepted values, there is evidence to suggest that measurements from standard instruments did not adequately reflect the significance of declining temperatures on plant growth over the relatively small altitude range of 270–670 m O.D. As Jones and Court (1980) point out, the exponential mean is probably more useful for demonstrating temperature differences between sites of different topography than the mean from standard instruments.

(c) *Growing season*

Standard measures of mean daily air temperature have been used to estimate the growing season above 6 °C and a 'high growing season' above 10 °C. These data permit comparisons with other parts of Britain. However, by using the relationship with arithmetic mean air temperature, exponential means for 1966–69 measured at several sites have revealed the effect of altitude on growing season with greater sensitivity. The period above 6 °C declines significantly with altitude in the range 350–700 m O.D. but more significantly there is a 50 per cent reduction in the period above 10 °C within this range. This effect is probably the most important constraint on herbage production at sites above 350 m O.D. in the Upper Don Basin and other similar upland areas.

(d) *Exposure to wind*

Tatter flags have been used successfully in the Donside experiments to measure the relative exposure of sites, in concurrence with the findings in other regions of the United Kingdom. They provided a cheap and suitable alternative to anemometers in these experiments.

The foregoing array of meteorological data characterizes the mesoclimate in considerable detail and should prove valuable in evaluating the cropping potential for agriculture and forestry in land capability studies. From this pilot exercise it seems very desirable that similar data on summer rainfall, air and soil temperatures and exposures to wind in relation to altitude be collected for other upland catchments, not only in the Grampian but in other hill regions of the United Kingdom.

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Archiving and quality control of climatological data

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Summary

A very large amount of climatological data is now handled every month by the Climatological Services Branch. As a result, a routine procedure has been developed which uses computer methods to control the quality of and to archive the data. An account of this procedure is presented together with a brief description of some of the quality control techniques which are used.

1. Introduction

Meteorological observations for climatological purposes have been made at stations throughout the United Kingdom for many years. The data are transcribed at the stations on to manuscript forms which are returned monthly to the Meteorological Office where they are held as permanent archive records; since 1884, the data have been published in the *Monthly Weather Report*. Some 30 years ago, the need for more powerful methods of climatological data processing led to the use of punched cards, which had already been used successfully with marine data. More recently, climatological archives have been compiled on magnetic tape, and the availability of information in this form has made possible much greater and more sophisticated exploitation of the data for research and enquiry purposes. Moreover, computer processing methods have a further major advantage in that a much more consistent and rigorous inspection of the data can now be undertaken.

During the transfer from visual and instrumental observations to archive records the information is first recorded in the observation register and is then transcribed to manuscript tabulations at the station; on receipt at the Meteorological Office, data are keyed to disc and are subsequently transferred to magnetic tape. With about 650 stations in the United Kingdom now making returns, over 3 million pieces of information go through this process every month, and errors can occur at every stage. Detailed quality control of this volume of data by visual inspection is quite impracticable, but by the use of computer methods all the data are subjected to a large number of quality control checks; corrections are made at several stages in the course of data entry, and archived data are now of very high quality.

The introduction of computerized methods of quality control required the solution of many problems. Although the solutions must depend both on the type of data and on the computing power available, the problems themselves must be common to all national meteorological services faced with the need to archive climatological data. However, apart from the general survey of Filippov (1968) and descriptions of the methods used in Canada (Potter 1969) and Israel (Walther and Elbashon 1974), there appears to be little published information on the subject. The following report describes the techniques which have been developed during the past few years by the Meteorological Office, and which are currently used for land surface data by the Climatological Services Branch.

2. Types of data

The stations recording climatological data within the United Kingdom vary greatly in the facilities that they have available and the hours during which they can operate and this is reflected in the type and volume of data submitted to the Meteorological Office.

The largest volume of data is collected by official Meteorological Office stations which are staffed by trained observers who make a full range of observations, usually every hour. Data recorded include not only such fairly standard items as wet- and dry-bulb temperatures, pressure, visibility and present weather but also more detailed observations such as hourly rainfall amounts and duration, hourly mean wind speeds and directions (usually), and the type, height and amount of low, medium and high cloud. There is some variation but each station observes about 30 weather elements each hour of the day, and is referred to as an 'hourly station'. There are about 50 such stations in the United Kingdom; their main purpose is to offer forecasting services to the public, to commercial interests and to military and civil aviation. Most of them are in fact based at airfields and weather centres.

Many Meteorological Office stations which would otherwise be included in the list of hourly stations are not staffed to make hourly observations throughout the day. Auxiliary stations, whose prime duties do not involve forecasting, are in a similar situation and these all form a class of 'fixed hourly stations' which, wherever possible, make observations at each of the eight synoptic hours (00 GMT, 03 GMT, 06 GMT and so on). However, some stations do not operate at night, others close at week-ends, and at some (coastguard stations, for example) the observer may be called away on more pressing duties. The result is a considerable variation of frequency of observation among these stations.

Both the hourly and fixed hourly stations also complete a monthly summary of daily values. This summary includes day and night maximum and minimum temperatures, grass and concrete minimum temperatures, rainfall totals, sunshine duration, 09 GMT soil and earth temperatures and brief weather descriptions which indicate the occurrence during each day of events such as fog, hail and snow.

The official stations are, however, in the minority; the majority of stations are operated by voluntary observers. These are known as 'co-operating stations', and are maintained by such diverse groups as health resorts, schools, water authorities and many private individuals as a voluntary service. Most of these stations supply their own instruments which are inspected regularly by Meteorological Office staff. Observations are made only once per day at 09 GMT and the range of data reported is restricted in some cases by the availability of suitable instruments. The items reported by co-operating stations are generally similar to those in the summary of daily data mentioned above with the addition of such items as spot wind speed and direction, visibility and pressure which relate only to conditions at the observing hour, usually 09 GMT. Although the standard of data tends to be rather more variable than at the hourly and fixed hourly stations, the co-operating stations form an extremely valuable part of the climatological network in the United Kingdom.

Finally, there is an anemograph network of about 160 stations; these are each equipped with an anemometer usually exposed at a height of about 10 m above the ground. They tabulate, from the anemograph traces, the speed and direction of both the hourly mean wind and maximum gust in each hour. Some of these stations are also part of the climatological network and a few are equipped with a second anemometer at a higher level.

3. Data archiving and quality control

At the end of each month, the observations are transferred to the appropriate forms which are then sent to the Meteorological Office. The forms arrive at a fairly steady rate for the first three weeks of the following month, by the end of which time about 80 per cent of them have been received. Thereafter, the forms arrive at a slower rate and it is usually another three weeks before the last of them are available. Because of these late arrivals, there is always some overlap from month to month but the aim is to complete the processing of each month's data before work begins on the next. For this reason, the archiving and quality control system has been formed into a standard sequence which, although it is a continuous process, may be regarded as consisting of four distinct stages which will now be described in detail.

(a) *Data entry*

The process begins during the second week of each month when the forms are examined by scrutineers to ensure that the items known as indicatives (month, year and station number) have been correctly entered. This is vital because, throughout the rest of the process, these items are the only means by which the computer can identify the data and assign them to the correct data-sets. When the indicatives have been checked and, if necessary, corrected, the forms are passed to the keying section.

The keying section at the Meteorological Office is equipped with a Seecheck data entry system. This consists of a minicomputer controlling 19 keying stations each with a keyboard, similar to that used in a typewriter, and a screen which displays the line of data being keyed. Each keying station, acting independently of the others, is used to key data directly to magnetic disc storage.

The data are keyed at a rate of 12 000 key depressions per hour and even with the simplification that the data are mostly numerical, keying errors are inevitable. These only occur at a rate of about 2 errors per 1000 key depressions but since a single error can corrupt a complete observation, they can present serious problems. Quality control at this stage has, therefore, become very important. Some elementary checks are carried out during keying. For example, the hour or day is keyed at the beginning of each line and a count reveals any missing or duplicated observations. The main check, however, consists of complete re-keying of the data in verification mode by a different operator. If there is a discrepancy between the results of the first and second keyings, the keyboard being used for verification will lock until the query is resolved.

The minicomputer is capable of limited quality control operations and possible applications are being investigated. However, at present, verification keying offers the most reliable method of ensuring that the data are accurately transcribed from the manuscript to the computer data-sets.

After verification, the data are sorted from the keyed order to files based on the type of data (hourly or daily, for example). Once this has been completed, the data are transferred to the main computer for archiving and quality control.

(b) *Data archiving*

At this stage, the files contain only the data which happen to have been keyed during that particular day and these data are now added to more permanent (archive) data-sets. With the exception of hourly data (which includes fixed hourly data), archive data-sets are prepared at yearly intervals for each type of data (daily, anemograph, soil and earth temperatures, and observations made at 09 GMT). Each of these sets has space for data for all stations for an entire year and they are retained on line until complete. Because of their much greater volume, hourly data are stored in monthly data sets.

The archive data-sets have been carefully designed to achieve compact storage and easy access and to facilitate the subsequent copying of data to single-station archive sets. A series of accessing subroutines has been written in the Meteorological Office specifically for use with this type of data-set but the design also offers considerable advantages with standard access methods.

The data are stored as half-word binary integers which, for the IBM system, have a range of −32 768 to +32 767, sufficient for all surface climatological values. Each data-set has the same basic design of a main header block followed by a series of data blocks each beginning with a short, descriptive, header record. For yearly data-sets, each block contains data for one station-month and the blocks are stored by month so that all the data for a given month follow those of the previous month. Within the monthly groups, the data for each station always occupy the same relative position. The main header block contains an index which gives the first block number for each month and the relative block number of each station within each monthly group. The data for each station-month are thus easily located.

The format of the hourly data is very similar except that each block contains data for one to eight days, depending on the number of observations made each day. In this case, all the data for each station are stored together.

Each completed set is transferred to magnetic tape soon after the new one is created, with some overlap to allow for the late arrival of data.

(c) *Internal quality control*

The transfer of data to the main data-sets is completed before quality control begins. There is, however, a preliminary format check carried out during the transfer which examines each line of data for errors such as illegal characters, invalid overpunches, embedded blanks or characters in the wrong field. The data should be mostly numerical, so this type of error suggests serious corruption of that line of data and the entire line is printed out for inspection and re-keying.

Errors in format are relatively rare and so the main quality control process is part of the same program and begins after transfer of the data but before any corrections are made. The first step in the main process, carried out only for 09 GMT and daily data, consists of a check for missing data and the computation of totals and means and statistics such as the number of days with rainfall or air frost. Subsequently these statistics can be compared with the values entered on the original form.

The next step, which varies with the type of data, involves a large series of tests. The first and simplest of these requires that the values of the various elements should fall within a valid range. For most elements, the ranges are constant but for temperature and sunshine they are made to vary with the month; the possibility of making them a function of latitude is being investigated. The second type of check involves an examination of internal consistency of observations, and this is rather more complex in that it ensures that the parameters observed at a particular hour are consistent with each other. For example, dry-bulb temperature should not be less than wet-bulb temperature and the amount, type and height of low, medium and high cloud should all be mutually consistent. A wide range of checks can be applied to the data using the past and present weather codes in the hourly and fixed hourly observations.

This step concludes with time sequence checks which are mainly used with hourly and fixed hourly data and ensure that each value of temperature, pressure, wind speed and wind direction is consistent with the preceding and subsequent values. This test is of limited use because it assumes that the element concerned should change by only a relatively small amount between successive measurements. Consequently, its use with daily data is confined to soil and earth temperatures.

This program generates queries at a rate of about 10 000 per month and these are passed back to the quality control scrutineers, each of whom has responsibility for checking the data for a particular area containing up to 100 stations. Checking begins with a comparison between the queried values and those entered by the observer on the manuscript form; this eliminates keying errors missed by verification. If the keyed value agrees with that on the form then the data must be examined more closely. The interrelationship between various elements often makes it fairly easy to judge the validity of a query and to calculate the correct values. (A typical example would be cloud type reported as cirrus but cloud height coded as 020 (2000 ft) instead of 200 (20 000 ft)). Each of the scrutineers specializes in a particular group of stations and this allows them to become acquainted with local effects. In doubtful cases, the observer is contacted to compare the queried value with that in the observing station's register; in such a situation, the observer's decision is usually accepted.

The computer print-out lists with each query an immediately keyable error message consisting of the indicatives including date and (if applicable) hour, a mnemonic for the type of element being queried and a code giving the reason for the query. With the addition of the correct value, this message then contains all the information necessary for the corrections to be made, and the further addition of a standard marker causes an entry to a quality control data-set. A batch of such messages can then pass through the keying section to the computer in much the same way as the original climatological data.

About 50 per cent of the queries raised by the computer quality control are rejected at this stage as spurious, and require no further action. Of the remainder, about 40 per cent of the queries are accepted and are due to keying or transcription errors. The remaining 10 per cent fall into a different category where, although there is a firm belief in the validity of the new value, there remains a slight possibility that the original value may have been correct. It is a World Meteorological Organization requirement, in this situation, that both the old value and the reason for the change should be preserved. The quality control data-set, referred to earlier, was therefore created to hold this information.

When the corrections have been made, the only step remaining in this intermediate stage is to re-run the quality control checks to ensure that the corrected values and the rest of the data are mutually consistent. Throughout the month, therefore, all incoming data are processed in this way to build up data-sets which are relatively error-free.

(d) *Quality control by spatial comparisons*

The data may be regarded as substantially correct as soon as the queries raised by internal quality control have been dealt with. However, there are a number of elements whose values are not easily checked by any of the preceding programs and so a series of spatial checks has been introduced. These are based on the principle that climatological parameters measured at neighbouring stations are likely to be correlated to some extent. Such parameters can therefore be checked by comparison after allowance is made for differences in station altitude or topography.

Ideally, such comparisons should be made within groups of about ten stations but the dense network which this requires is only available for daily data. Areal quality control, as opposed to interstation comparison, is therefore only used to quality control maximum and minimum temperatures and sunshine duration. For this purpose the UK, excluding Scotland, is divided into areas containing between seven and fourteen stations which are regarded as having a similar climatology. Quality control then begins by 'normalizing' the daily values for each station. For temperature, this is done by subtracting the station value from the monthly mean temperatures while sunshine values are normalized by dividing the station value by the monthly mean sunshine duration. Each normalized value is then compared with the mean of the values from all the other stations in that area for that day. The value is queried if it differs from this mean by more than two standard deviations and either 2·5 °C for temperature or 20 per cent for sunshine duration. When a value is queried, it is excluded from further analysis.

Areal comparison was found to be unsatisfactory for Scotland where the complex topography greatly reduced the number of stations in each area, and so the second program in this series was developed. For the Scottish stations, the values of the temperature extremes for each station are compared with those at two neighbouring stations and queried if they differ from both by more than 2 °C. However, quality control of sunshine duration proved impracticable except by inspection. This technique requires much more time from the scrutineers than those previously described and, to make the job easier, the print-out lists, for each Scottish station, the maximum, minimum, grass minimum and 09 GMT temperatures and the sunshine duration if reported. The print-out itself has been simplified by arranging the stations in a chain, with some breaks and duplications, in which each station is compared with the previous and subsequent stations.

The errors detected by these methods must obviously be fairly large to exceed the limits which have been set but half the queries are still rejected. The problem probably lies in the methods used to select the stations which make up each area. More scientific methods involving factor analysis are being investigated and it appears that these will give more representative areas which will vary with element and weather type.

The two remaining programs both rely on interstation comparisons. The first of these checks pressure measurements at stations which do not report at all synoptic hours by comparing every such station with the nearest hourly station. The theoretical pressure difference between the two sites is first computed at all relevant hours by using the measured values of wind speed and direction to estimate the geostrophic wind field and, hence, the pressure gradient. From this value and the value of pressure at the hourly station, the pressure at the subject station is calculated. If it differs from the reported value by more than 1–2 mb (depending on the separation of the two stations) then a query is raised. Since the pressures reported at the hourly station will have been quality controlled by time sequence checks, the error is assumed to be in the data from the subject station.

The final program to be run is quite different from the others in that it checks for errors in the instrument rather than in transcription or keying. Every year, about 5 per cent of the anemographs in use in the United Kingdom network develop faults which are often only detected at the next site inspection. A quality control program has therefore been developed which can detect some of these faults by comparing the wind direction at each station with that at the nearest two stations.

There are usually differences between the hourly wind directions at any two sites in the short term owing to synoptic effects, and in the longer term owing to differences in topography and exposure. The program solves this problem by first estimating long term effects by examining past data and computing the average difference in wind direction at the two sites for each of the eighteen 20° sectors, using the wind direction at one of the sites as a reference. These eighteen values, which represent the steering effect of topography, are subsequently used to adjust the hourly wind direction at the second site to remove that effect. The differences in direction after adjustment are then averaged over the entire month to remove the short-term effects. If both anemographs are correctly adjusted and the exposure has not changed then the average difference should be close to zero and the standard deviation will be a measure of the short-term effects. When either value exceeds limits chosen for the two stations, a query is raised. If the scrutineer decides that the query is justified then the instrument is inspected and, if necessary, readjusted and any consequent corrections made to the data.

Conclusion

The large amount of climatological data reaching the Meteorological Office every month has led to the development of techniques which enable the data to be quality controlled and archived in machinable form on a routine basis. The quality control routines, which have involved considerable development work, ensure that very few significant errors in the data escape detection, while the archive methods are designed to achieve compact storage and easy access to the data.

The quality control and archiving of the data is not, of course, an end in itself. While the last corrections are being made, the data are already being processed for the preliminary run of the *Monthly Weather Report* which presents a published summary of the climatological data in the United Kingdom for the month. This publication, which was first produced in 1884, is still the most readily available source of climatological data and since 1974 has been largely produced by computer methods. However, the growing realization of the value of climatological data has led to a considerable increase in requests for more detailed information from industry, farming and research organizations. This has been enhanced by the ability to produce complex analyses with the aid of the computer. There is also a large demand for data by such bodies as the Ministry of Agriculture, Fisheries and Food, the Department of Energy, British Gas and the Central Electricity Generating Board, either for internal use or for dissemination to the public in processed form.

The effort which has been expanded has therefore helped to meet a commercial need for reliable land-surface climatological data in machinable format. Although there will continue to be gradual refinements of the procedures, this work is now virtually completed and similar attention is now being paid to upper-air and sea surface data where different problems occur.

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Major K. G. Groves, O.B.E., J.P., M.A., LL.M.

It is with great regret that we record the death on 7 March 1979 of Major K. G. Groves, co-founder with his wife of the L. G. Groves Memorial Prizes and Awards.*

Keith Grimble Groves was born on 31 December 1887, fifth of the nine children of James Grimble Groves, M.P., of Oldfield Hall, Cheshire, and educated at Uppingham and Trinity College, Cambridge, where he stroked the College boat to gain his oar and took the Law Tripos which saw him into the Middle Temple in 1912.

He joined the Territorial Army when it was first formed in 1908, and enlisted in the Inns of Court Regiment on 4 August 1914. He served in France, Salonika and Palestine and was mentioned in Haig's Despatches after Vimy Ridge.

He married Dorothy Atwater Moore, daughter of the American foreign editor of the *Daily Express* (and descendant of Ensign John Moore of the Civil War). Their only son, Louis Grimble Groves, was killed on 10 September 1945 when the Halifax in which he was Meteorological Air Observer hit a Cornish hilltop when returning from a sortie over the Bay of Biscay. The four Memorial Prizes were founded in his memory by his parents, and they had personally attended every presentation ceremony from 1946 at the Air Ministry (which after 1963 was incorporated in the Ministry of Defence) until prevented by illness last year.

Major Groves was awarded the O.B.E. in 1968 for 'services to the Royal Air Force'.

Although Keith Groves had enjoyed a varied and full life, both during the war years—and subsequently as Barrister, Chairman of Groves and Whitnall Ltd, and a most active Justice of the Peace in the Isle of Man—the Louis Grimble Groves Memorial Awards remained the mainspring in the lives of both his wife Dorothy and himself.

We offer to her our sympathy and respect.

* A description of the awards is given in the *Meteorological Magazine* for February 1975 (Volume 104, p. 57).

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NOTICES

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

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The use of probabilities in forecasts of maximum and minimum temperatures*

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Summary

The inclusion of probabilities in weather forecasts provides a means of quantifying the uncertainty inherent in such forecasts as well as potentially useful information not available in traditional categorical forecasts. Subjective probabilistic temperature forecasting is studied in this paper. Alternative summary measures of a forecaster's probability distribution of temperature are considered, and 'credible intervals' are suggested as a suitable choice for operational forecasts of this continuous variable. A credible interval temperature forecast is an interval of temperature values accompanied by a probability that expresses the forecaster's degree of belief that the temperature will actually fall in the interval. An experiment involving the formulation of variable-width and fixed-width credible interval forecasts of maximum and minimum temperatures by U.S. National Weather Service forecasters is discussed. The experimental results indicate that experienced forecasters can formulate reliable and skilful credible interval temperature forecasts. Reliability is measured in terms of the correspondence between the probabilities associated with the forecasters' intervals and the observed relative frequencies of temperatures, whereas skill is determined by comparing the precision (or accuracy) of the credible interval forecasts with that of forecasts based on standards of comparison such as climatology and persistence. It is important to note that these successful probabilistic temperature forecasts were prepared without the aid of objective probabilistic guidance information. Some implications of these results for operational procedures and practices in temperature forecasting are considered.

1. Introduction

Weather forecasts are traditionally expressed in categorical (i.e. deterministic) terms. However, it is widely recognized and generally acknowledged that an element of uncertainty exists in almost all such forecasts. At present, when uncertainty is mentioned in a forecast, it is most often described by means of one or more verbal qualifiers (e.g. possible, likely, occasional, frequent). However, studies of the

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understanding of such terms on the part of recipients of the forecasts indicate that these terms are subject to very wide ranges of interpretations (and misinterpretations). Such misinterpretations substantially degrade the quality and value of the information contained in many forecasts.

The language of probability provides an economical and unambiguous means of describing the uncertainty inherent in weather forecasts. In an effort to provide more precise and useful information concerning the occurrence of precipitation, U.S. National Weather Service (NWS) forecasters have expressed their forecasts of precipitation occurrence in probabilistic terms on an operational basis since 1965. Specifically, these probability of precipitation (PoP) forecasts represent the likelihood of occurrence of measurable ($\geqslant$0·01 inch) precipitation at a particular point during a specific period (generally 6 or 12 hours). For example, a typical PoP forecast for Denver, Colorado during the summer might state, 'the precipitation probability today is 20 per cent'. These probability forecasts initially encountered some resistance on the part of both forecasters and the general public, but they are now considered to be an important and integral part of public weather forecasts in the U.S.A. Moreover, extensive evaluations of these forecasts demonstrate convincingly that weather forecasters can quantify the uncertainty in forecasts of precipitation occurrence in a reliable and skilful manner.

In contrast to their forecasts of precipitation occurrence, NWS forecasters still express forecasts of maximum and minimum temperatures in categorical terms. More specifically, these forecasts generally are expressed in terms of an interval of temperature values. For example, 'the maximum temperature in Denver today will be between 85 and 90 °F' (all temperatures in this paper will be expressed in °F). However, the forecasters do not attempt to assign a probability to such an interval. Thus, the recipient of the forecast does not know whether the probability is 90 per cent that the temperature will fall in the interval or whether the chances are even. Recently, the inclusion of probabilities in temperature forecasts has been investigated in a few experiments (Peterson, Snapper, and Murphy, 1972; Sanders, 1973; Murphy and Winkler, 1974; Bosart, 1975; Gregg, 1977). The results of these experiments indicate that probabilistic temperature forecasting is quite promising in the sense that such probabilities provide information that should be valuable to many users of temperature forecasts (for example see Murphy and Winkler, 1979). Thus, further study of this potentially important area appeared to be warranted, and an experiment was designed and conducted in the NWS Forecast Office (WSFO) in Milwaukee, Wisconsin in order to obtain additional information from which to make inferences concerning probabilistic temperature forecasting.

The purposes of this paper are to discuss probabilistic temperature forecasting, to present some experimental results involving probabilistic forecasts of maximum and minimum temperatures, and to examine the implications of these results for operational weather forecasting. In section 2, some lternative formats for the expression of uncertainty in temperature forecasts are compared, and 'credible intervals' are suggested as a suitable choice for operational forecasts. Section 3 contains a description of the Milwaukee experiment, together with a presentation of some results from this experiment. Section 4 consists of a brief summary and a discussion of implications of the results of the Milwaukee and other similar experiments for operational temperature forecasting.

2. Probabilistic temperature forecasts

In order to consider probabilistic temperature forecasts, we first need to define the events of interest. It will be assumed that a maximum or minimum temperature forecast pertains to the high or low temperature recorded during a specific period of time (the forecast period) at a particular point (generally the local NWS office). Thus, the uncertainty in question relates strictly to the uncertainty about the temperature at the given point during the forecast period. It does not, for example, relate to spatial variability in temperature (e.g. the interpretation of an interval forecast as a range of temperatures for different points in the forecast area). This variability is an interesting and important but separate issue.

In contrast to precipitation occurrence, which is a dichotomous event, maximum and minimum temperatures are continuous variables. Thus, whereas a single probability is sufficient to represent formally a forecaster's uncertainty concerning precipitation occurrence, a complete description of uncertainty in forecasting temperature requires an entire probability distribution. Ideally, then, a probabilistic temperature forecast would consist of a probability distribution for a continuous variable, i.e. maximum or minimum temperature, and various techniques are available for assessing such a distribution (for example see Winkler, 1967; Hampton, Moore, and Thomas, 1973). Fractiles, cumulative probabilities, probabilities for intervals, probability densities, and summary measures are among the types of assessment that could be considered.

For important decisions in which uncertainty about temperature plays a key role, the time and effort required to assess an entire distribution may be worth while. On an operational basis, however, the consideration of an entire probability distribution is not practicable as regards either the time required of the forecaster or reporting to the general public. It is desirable to keep a temperature forecast (and forecasts of other weather elements as well) relatively simple to make the forecast understandable to its recipients and minimize the amount of time required to communicate the forecast. Instead of an entire distribution, then, a temperature forecast consisting of some summary measures from that distribution might be preferable.

'Summary measures' such as moments of a probability distribution provide useful information, but they are difficult to assess directly (thereby returning us to the assessment of an entire distribution) and would not, for the most part, be meaningful to the public. Intervals, on the other hand, seem feasible both in terms of assessment and interpretation. As noted previously, temperature forecasts in the U.S. are now expressed frequently in the form of intervals, but probabilities are not included in these forecasts. A credible interval temperature forecast, which consists of an interval of temperature values accompanied by a probability (e.g. 'the probability is 0·80 that the high temperature today will be between 66 and 70 °F'), represents a straightforward extension of the interval forecasts often used in current temperature forecasting practice. Credible intervals provide some probabilistic information without necessitating the assessment of an entire distribution, and a credible interval temperature forecast should be no more difficult to communicate effectively than a precipitation probability forecast.

The choice of credible intervals as the mode of expression for probabilistic temperature forecasts still allows some flexibility in the selection of a particular interval to be included in a forecast. In fact, the forecaster could be given complete freedom in the choice of an appropriate credible interval for a particular situation. A more systematic approach, however, might aid the forecaster by simplifying the assessment task. Moreover, if the same types of credible interval forecasts are issued on each occasion, then recipients of the forecasts should find them easier to interpret. Thus, certain restrictions on these interval forecasts seem desirable.

A restriction that is consistent with common practice in interval estimation in statistics is to predetermine the probability associated with the interval. For example, the forecast might always consist of a 50 per cent credible interval or a 75 per cent credible interval (or both). Sometimes a 50 (or 75) per cent credible interval for high or low temperature will be only 4° wide, whereas at other times such an interval may be 8° wide. Since the probability of the interval is fixed but the width of the interval will vary from occasion to occasion, such a forecast will be called a variable-width credible interval. Furthermore, the use of credible intervals that are central in terms of probability (i.e. the probability that the observed value falls below the interval equals the probability that the value falls above the interval) seems reasonable, so that all variable-width intervals considered in this paper will be central credible intervals.

An alternative to variable-width forecasts involves a restriction that predetermines the width of the interval but allows the forecaster to vary the probability associated with the interval. For example, the forecast might always consist of a credible interval that is exactly 5° or 9° wide (or both). In some cases the probability of such an interval might be 0·50, whereas in other cases it might be 0·90. Such a forecast will be called a fixed-width interval. Additional restrictions can be placed on fixed-width credible intervals, and in this paper all such intervals will be centred at the median of the distribution.

In summary, then, various types of probabilistic temperature forecasts could be considered. Credible interval forecasts seem to represent a reasonable compromise between current temperature forecasts, which ignore uncertainty (or probability) completely, and the reporting of an entire probability distribution, which is impracticable in terms of communicating to the public. Since intervals without probabilities are frequently included in current temperature forecasts, credible interval temperature forecasts do not represent a major change for the forecaster or the recipient of the forecasts. With regard to the time and effort required on the part of the forecaster, a variable-width credible interval that is central in terms of probability requires the assessment of two fractiles, whereas a fixed-width interval that is centred at the median requires the assessment of the median and the probability associated with the interval. Of course, forecasters applying these procedures may find it helpful to make additional assessments. In terms of interpretation by the public, the interval limits *and* the probability change from occasion to occasion with fixed-width forecasts, whereas only the limits change with variable-width forecasts.

3. An experiment in probabilistic temperature forecasting

(a) *Design of the experiment*

The experiment in probabilistic temperature forecasting of concern here was conducted in the Milwaukee WSFO. The five forecasters who participated in the experiment were experienced weather forecasters, averaging 10·5 years of forecasting experience and 5·1 years of experience of making precipitation probability forecasts. During the period of the experiment the forecasters made credible interval forecasts of high and low temperatures for 12-hour periods centred approximately 12, 24, and 36 hours in the future. On the morning shift, the forecasts were for 'today's high', 'tonight's low', and 'tomorrow's high', whereas on the evening shift they were for 'tonight's low', 'tomorrow's high', and 'tomorrow night's low'. The experiment was conducted from October 1974 to July 1975, thereby including all seasons and hence a wide variety of meteorological situations. The forecasters formulated 42, 44, 45, 45, and 57 sets of forecasts, for a total of 233 sets or 699 forecasts.

Three of the forecasters worked with variable-width, fixed-probability forecasts, using 50 per cent and 75 per cent central credible intervals. To obtain these intervals, the method of 'successive subdivisions' (for example see Raiffa, 1968, pp. 161–168) was used, requiring the forecaster to assess a median, a 0·25 fractile, a 0·125 fractile, a 0·75 fractile, and a 0·875 fractile, in that order. Each fractile necessitated an equal-odds indifference judgement to divide an interval into two equally likely subintervals (e.g. the median temperature is the temperature that the forecaster feels is equally likely to be exceeded or not exceeded). The 50 per cent and 75 per cent central credible intervals are the intervals from the 0·25 fractile to the 0·75 fractile and from the 0·125 fractile to the 0·875 fractile, respectively. All fractiles were assessed (and actual temperatures were measured) to the nearest degree, and all interval forecasts included their end points. After the fractiles were assessed, the forecasters were asked (as a check) if the resulting intervals seemed reasonable (e.g. if the temperature falling inside the 75 per cent interval was three times as likely as the temperature falling outside the interval) and were told to reconsider the assessments if they did not satisfy such consistency checks.

The remaining two forecasters worked with fixed-width, variable-probability forecasts, using intervals of width 5° and 9° centred at the median. First, the median was determined as for the variable-width forecasts, thus establishing the interval limits for the two fixed-width intervals. Then the forecasters assessed probabilities for the intervals, just as they might assess precipitation probabilities.

Before the start of the experiment, lengthy sets of written instructions were given to the forecasters, who were encouraged to read the instructions, to make several 'practice' forecasts, and to notify the experimenters if any difficulties or questions arose. The instructions included discussions of how credible intervals can be used to describe a forecaster's uncertainty about temperature, careful definitions of relevant terminology, hypothetical dialogues between an 'experimenter' and a 'forecaster' to illustrate the procedures, and brief summaries of the procedures. During the experiment proper, the forecasters formulated their credible interval forecasts without any assistance from (or contact with) the authors, and no difficulties were encountered.

(b) *Results of the experiment*

(1) *Medians.* The first task on each forecasting occasion was the determination of a median, and a comparison of these 699 medians (denoted by M) with the corresponding observed temperatures (denoted by T) is presented in Figure 1. The correlation between M and T is 0·966, and most of the points in Figure 1 are close to the $M = T$ line. In this regard, $M = T$ for 9·4 per cent of the forecasts, and the corresponding figures for $M < T$ and $M > T$ are 53·4 per cent and 37·2 per cent respectively. This result indicates a slight tendency for M to underestimate T.

Further evidence concerning the performance of the median temperatures is presented in Table I. For the entire sample, the average difference between M and T is —0·78°. If we assume that $M - T$ is normally distributed, an assumption that appears from the frequency distribution to be reasonable, standard normal theory can be used to make inferences about the population mean difference μ_{M-T}. These inferences (see Appendix, A.1) reveal a tendency for M to underestimate T, although this tendency is very slight in magnitude, particularly in view of the fact that all forecasts are recorded to the nearest degree.

Table I. *Averages (standard deviations) of forecast errors for medians (M), climatology (C_1), persistence (C_2), and autoregression (C_3)*

		Errors				Absolute Errors			
Forecasts	n	$M—T$	$C_1—T$	$C_2—T$	$C_3—T$	$\|M—T\|$	$\|C_1—T\|$	$\|C_2—T\|$	$\|C_3—T\|$
All	699	—0·78 (4·8)	—1·33 (8·9)	—0·46 (7·5)	0·52 (9·6)	3·66	7·10	5·89	6·71
Variable-width	432	—0·63 (4·4)	—0·68 (8·7)	—0·63 (7·1)	—0·57 (8·5)	3·39	6·75	5·54	6·11
Fixed-width	267	—1·03 (5·3)	—2·40 (9·2)	—0·19 (8·1)	2·28 (11·1)	4·10	7·67	6·46	7·70
Maximum	361	0·37 (4·8)	0·65 (8·9)	0·69 (7·8)	0·65 (9·2)	3·52	7·00	6·13	6·58
Minimum	338	—2·02 (4·5)	—3·45 (8·4)	—1·69 (7·0)	0·38 (10·1)	3·82	7·21	5·64	6·86
12-hour	233	—0·71 (4·6)	—1·01 (9·3)	—0·25 (7·2)	0·58 (8·7)	3·45	7·35	5·58	6·24
24-hour	233	—1·18 (4·2)	—1·75 (8·5)	—0·54 (6·7)	0·20 (8·0)	3·31	6·88	5·22	5·70
36-hour	233	—0·47 (5·5)	—1·24 (8·9)	—0·59 (8·5)	0·78 (11·7)	4·22	7·07	6·88	8·20
Forecaster 1	135	—1·30 (5·2)	—1·31 (9·9)	1·17 (9·0)	4·67 (13·0)	4·07	8·21	7·26	9·18
Forecaster 2	132	—0·76 (5·4)	—3·52 (8·3)	—1·59 (7·0)	—0·17 (7·9)	4·14	7·12	5·65	6·18
Forecaster 3	126	—0·16 (4·1)	—1·09 (6·3)	—0·66 (5·6)	—1·50 (6·7)	3·02	5·28	4·45	5·23
Forecaster 4	171	—1·39 (4·4)	—0·47 (9·2)	—0·20 (7·8)	0·52 (9·8)	3·44	7·04	6·04	6·94
Forecaster 5	135	—0·12 (4·6)	—0·55 (9·9)	—1·13 (7·4)	—1·08 (7·9)	3·67	7·75	5·92	5·87
Denver experiment	254	—0·50 (4·9)	0·60 (12·0)			3·80	8·90		

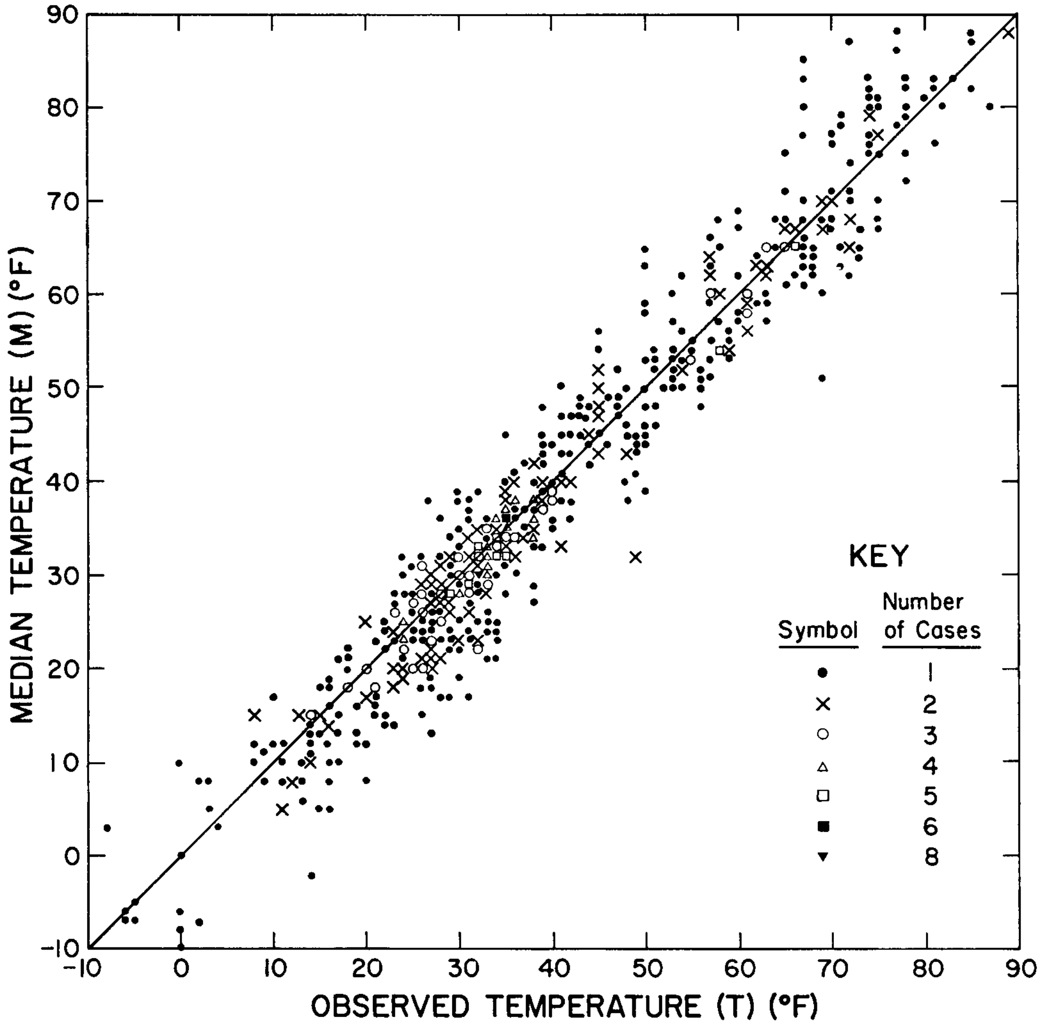

Figure 1. Median temperature (M) versus observed temperature (T) ($n = 699$).

The average $M - T$ is negative for all five forecasters, with underestimation greatest for Forecasters 1 and 4 and virtually nonexistent for Forecasters 3 and 5. No pattern in average $M - T$ appears to exist for the three lead times (12, 24, and 36 hours), but forecasts of maximum and minimum temperatures differ considerably. Forecasts of minimum temperature exhibit the most extreme average $M - T$ in Table I, $-2{\cdot}02°$, whereas forecasts of maximum temperature are slight overestimates on the average. One possible explanation for such differences involves asymmetries in the forecasters' distributions of temperature that could cause differences between median and mean temperatures. However, differences between maximum and minimum also occur in the frequencies with which $M < T$ and $M > T$, and these frequencies should not be affected by such asymmetries. Moreover, similar results pertaining to forecasts of maximum and minimum temperatures were obtained in a previous experiment conducted in the Denver WSFO (Murphy and Winkler, 1974).

To investigate the precision of the medians, the standard deviation of $M - T$ can be used, and we also consider the absolute error, $|M - T|$. From Table I, the average $|M - T|$ is 3·66°. We would expect $|M - T|$ to increase with increasing lead time, but a reversal occurs for the 12-hour and 24-hour forecasts, with the latter being slightly more precise. This result might be due in part to the fact that, with respect to the point in time that the forecasts are formulated, 24-hour forecasts are made for approximately the same point on the diurnal temperature curve, whereas the 12-hour forecasts are made for the 'opposite' point on this curve. In any case, the 36-hour forecasts are less precise than the forecasts for the two shorter lead times.

Note that Forecasters 1 and 2, who worked with fixed-width forecasts, have larger values of $|M - T|$ than the remaining forecasters, who worked with variable-width forecasts. In the variable-width scheme, the forecasters made several assessments that were similar to the assessment of a median (i.e. equal-odds indifference judgements), whereas the fixed-width scheme involved only probabilities for fixed intervals once the median was chosen. Perhaps the additional experience with similar assessments enabled the variable-width forecasters to improve in terms of precision of median forecasts.

In order to evaluate the medians further, three standards of comparison are considered: (i) climatological forecasts, (ii) persistence forecasts, and (iii) autoregression forecasts. The climatological forecasts (C_1) are median maximum and minimum temperatures for Milwaukee for the five-year period immediately preceding the experiment, computed on a 30-day basis twice a month (i.e. for each half-month C_1 is based on the climatological data for that period as well as for the preceding and following quarter-months). The persistence forecasts (C_2) simply represent the most recent observations of maximum and minimum temperatures (e.g., yesterday's high temperature is the forecast for today's high temperature). The autoregression forecasts (C_3) are derived from a first-order autoregression computed from the five years of data used to generate C_1.

The results for C_1, C_2, and C_3 are presented in Table I along with the results for M. First, note that for almost all sets of forecasts considered, the average $C_1 - T$ is further from zero than the corresponding average $M - T$. In addition, the percentage of occasions on which $C_1 < (=, >) T$ is 54·8 (4·6, 40·6), which indicates that the temperatures during the period of the experiment are above the five-year average. A comparison of such percentages and values of $C_1 - T$ for maximum and minimum temperature forecasts shows that the minimum temperatures are considerably above average, whereas the maximum temperatures are slightly below average. These results might explain the tendency of M to underestimate T slightly as well as the previously noted difference between forecasts of maximum and minimum temperatures. The results for C_2 are similar to but not as extreme as those for C_1, whereas the results for C_3 actually indicate overestimation instead of underestimation on the average. The fact that $C_2 - T$ and $C_3 - T$ tend to be less extreme than $C_1 - T$ undoubtedly is due to the consideration of yesterday's temperature in the determination of C_2 and C_3, which therefore are adjusted in part for the above-average temperatures during the experimental period.

The most striking difference between M and the other forecasts relates to precision. The most precise of the three standards of comparison is C_2, with an average absolute error of 5·89°, yet this error is still 1·61 times as large as the average absolute error for M. The median forecasts, therefore, represent considerable improvements over the climatological, persistence, and autoregression forecasts. In general the medians seem to be very good point forecasts.

(2) *Variable-width forecasts*. The three forecasters who formulated 50 per cent and 75 per cent variable-width credible intervals made a total of 432 forecasts, and some results from these forecasts are presented in Table II. The variable-width forecasts are very reliable in the sense that the degree of correspondence between the probabilities and the observed relative frequencies associated with the intervals is quite high. If the occurrences of observed temperatures within the 50 per cent and 75 per cent intervals are

Table II. *Relative frequency of temperature in variable-width intervals, average (standard deviation of) interval width, and average loss.*

Forecasts	n	Relative Frequency 50% Intervals	Relative Frequency 75% Intervals	Width 50% Intervals	Width 75% Intervals	Loss 50% Intervals	Loss 75% Intervals
All	432	0·539	0·794	5·90 (1·98)	10·06 (3·08)	11·53	14·63
Maximum	216	0·579	0·829	5·87 (2·02)	10·06 (3·15)	11·24	14·50
Minimum	216	0·500	0·759	5·94 (1·94)	10·06 (3·01)	11·83	14·77
12-hour	144	0·500	0·819	5·48 (1·83)	9·31 (2·79)	10·90	13·76
24-hour	144	0·569	0·778	5·99 (2·08)	10·27 (3·29)	11·32	14·44
36-hour	144	0·549	0·785	6·24 (1·97)	10·60 (3·02)	12·38	15·71
Forecaster 3	126	0·532	0·722	4·76 (0·89)	8·10 (1·30)	10·95	14·89
Forecaster 4	171	0·591	0·825	6·50 (2·46)	10·53 (3·44)	11·39	14·46
Forecaster 5	135	0·481	0·822	6·21 (1·55)	11·30 (2·90)	12·25	14·62
Climatology (C_1)	432	0·569	0·817	14·52 (3·91)	23·68 (4·91)	23·02	29·51
Persistence (C_2)	432	0·576	0·813	11·22 (2·94)	18·53 (4·98)	18·83	23·94
Autoregression (C_3)	432	0·590	0·780	11·55 (1·75)	18·97 (3·32)	21·58	29·35
Denver experiment	132	0·455	0·735	6·23 (1·28)	11·67 (2·23)		

treated as Bernoulli processes with a parameter for each interval, then we can make inferences about the parameters. These inferences (see Appendix, A.2) indicate that 95 per cent credible intervals for the parameters contain, or very nearly contain, the 0·500 and 0·750 values.

In experiments involving probability assessment in other contexts (e.g. in psychological laboratory experiments), assessors often appear to be too confident in the sense that a surprisingly high proportion of observations fall in the tails of the assessed distributions, indicating that the distributions are too tight (for example see Hogarth, 1975). In contrast, the variable-width temperature forecasts from Milwaukee (as well as those from Denver) are extremely reliable, particularly in view of the fact that the forecasts and observations are given only to the nearest degree. With respect to specific subsets of forecasts, the forecasts of minimum temperature are almost perfect in terms of reliability, whereas the relative frequencies for forecasts of maximum temperature are slightly high in relation to the probabilities. The relative frequencies are also too high for Forecaster 4, but no systematic deviations from the overall results seem to exist for the other two forecasters or for the three lead times, as can be seen from Table II.

The variable-width intervals considered here are supposed to be central credible intervals, and the overall relative frequencies are 0·280 (0·125) above the intervals and 0·181 (0·081) below the intervals for the 50 (75) per cent intervals. The disparity between these relative frequencies is consistent with the slight tendency to underestimate noted in the analysis of the medians, and variations in this disparity for particular subsets of forecasts are consistent with the results involving medians. For example, only for forecasts of maximum temperature is the relative frequency below the interval higher than that above the interval.

Of course, central credible intervals need not be symmetric about the medians in terms of width, and asymmetries in width indicate that the forecasters' distributions of high and low temperatures are not symmetric. Only 54·2 (47·9) per cent of the 50 (75) per cent intervals in the Milwaukee experiment are symmetric in terms of width. Furthermore, the average absolute differences in width between the two equally likely subintervals (created by dividing the interval forecasts at the median) are 0·64° and 1·13° for the 50 per cent and 75 per cent intervals, respectively. These figures are consistent over most of the subsets of forecasts, although Forecaster 4's intervals are quite symmetric (average absolute differences 0·29° and 0·26°) and Forecaster 5's intervals are especially asymmetric (1·25° and 2·45°). It should be noted that intervals based on climatology are also asymmetric, which suggests that an underlying meteorological basis may exist for such asymmetries.

The precision of the variable-width forecasts, as measured by the average widths of the intervals, is also of considerable interest. From Table II, the average widths are 5·90° and 10·06° for the 50 per cent and 75 per cent intervals respectively. As expected, the average widths are increasing functions of lead time. Among the forecasters, Forecaster 3's intervals are considerably narrower (and have much smaller standard deviations of width) than the other forecasters' intervals, and this increased precision is not attained at the expense of a reduction in reliability.

A positive relationship between interval width and the error associated with the median forecasts would be expected. In this regard, the correlations between interval width and $|M - T|$ are 0·348 and 0·383 for the 50 per cent and 75 per cent intervals, respectively. Moreover, the correlation between the widths of the 50 per cent and 75 per cent intervals is 0·898.

Variable-width forecasts can also be evaluated in terms of average losses, where these losses can be considered to represent the average 'expenses' incurred by an individual who makes decisions on the basis of the forecasts. A loss function of this type is defined in the Appendix, A.3, and the average losses according to this function are presented in Table II. These average losses reflect both the reliability and precision of the relevant forecasts.

As with the medians, forecasts based on climatology, persistence, and autoregression are considered to provide standards of comparison for the variable-width intervals. These forecasts are simply C_1, C_2, and C_3, as defined earlier, with the appropriate limits (0·125, 0·25, 0·75, and 0·875 fractiles) based on the temperature data for Milwaukee for the five years immediately preceding the experiment. The results for these standards of comparison, which are included in Table II, indicate that the forecasts produced by the different procedures are comparable in terms of reliability but that C_1 is less precise than C_2 and C_3. In terms of average loss, persistence performs best, followed by autoregression and climatology.

When C_1, C_2, and C_3 (collectively referred to as C) are compared with F, the forecasts formulated by the forecasters, the superiority of F clearly emerges. The reliability, as measured by the divergence of the probability associated with an interval from the corresponding relative frequency, is slightly better for F than for C, although the difference is not great. In terms of observations above versus observations below the intervals, C and F are very similar. With regard to average interval width and average loss, however, F is vastly superior to C. The smallest average widths and losses among C_1, C_2, and C_3 are almost twice as large as the corresponding average widths and losses for F. In general, then, the variable-width forecasts seem to be very good interval forecasts.

(3) *Fixed-width forecasts.* The two forecasters who formulated 5° and 9° fixed-width credible intervals made a total of 267 forecasts, and some results involving these forecasts are presented in Table III. In this case the interval probabilities are not fixed, but reliability can be defined in terms of the correspondence between the average probabilities and the relative frequencies associated with the intervals. In this sense, the fixed-width intervals do not appear to be quite as reliable as the variable-width intervals. Unlike the variable-width case, in which the relative frequencies were slightly higher than the probabilities, the average fixed-width probability is higher than the corresponding relative frequency by 0·07 and 0·06 for the 5° and 9° intervals respectively. Moreover, the average probability exceeds the relative frequency for all specific subsets of forecasts included in Table III with only one exception, the 5° intervals for a 24-hour lead time. We can offer no explanation for this exception, and no systematic results involving maximum versus minimum temperature forecasts, different lead times, or individual forecasters can be discerned from the data. Note from Table III, however, that the reliability of the fixed-width intervals is much better in the Milwaukee experiment than in the Denver experiment.

The precision of the fixed-width forecasts can be investigated by examining the average probabilities

Table III. *Average (standard deviation of) interval probability and relative frequency of temperature in fixed-width intervals.*

Forecasts	n	Probability 5° Intervals	Probability 9° Intervals	Relative Frequency 5° Intervals	Relative Frequency 9° Intervals
All	267	0·47 (0·11)	0·72 (0·11)	0·40	0·66
Maximum	145	0·48 (0·11)	0·73 (0·12)	0·43	0·69
Minimum	122	0·45 (0·11)	0·70 (0·11)	0·37	0·62
12-hour	89	0·54 (0·12)	0·80 (0·10)	0·45	0·75
24-hour	89	0·48 (0·09)	0·73 (0·08)	0·49	0·71
36-hour	89	0·39 (0·07)	0·63 (0·09)	0·27	0·52
Forecaster 1	135	0·50 (0·12)	0·73 (0·11)	0·40	0·67
Forecaster 2	132	0·44 (0·09)	0·71 (0·11)	0·41	0·64
Climatology (C_1)	267	0·22 (0·06)	0·37 (0·11)	0·19	0·36
Persistence (C_2)	267	0·27 (0·07)	0·46 (0·11)	0·24	0·42
Autoregression (C_3)	267	0·26 (0·06)	0·44 (0·09)	0·26	0·45
Denver experiment	122	0·60 (0·16)	0·80 (0·11)	0·46	0·66

assigned to the intervals. These average probabilities are 0·47 and 0·72 for the 5° and 9° intervals respectively. If the distributions of probabilities for the 5° and 9° intervals are approximated by normal distributions, then standard normal theory can be used to determine distributions for the mean probabilities. The results of such an analysis (see Appendix, A.4) indicate that these distributions are very tight (i.e. virtually all the probability is concentrated close to the sample means). The relationship between the probability assigned to an interval and the error associated with the median forecasts would be expected to be negative, and the correlations between probability and $|M - T|$ are $-0{\cdot}222$ and $-0{\cdot}285$ for the 5° and 9° intervals respectively.

Forecasts based on climatology, persistence, and autoregression also can be determined in the form of fixed-width intervals. The intervals are simply 5° and 9° intervals centred at the point forecasts C_1, C_2, and C_3 discussed in connection with the median temperature forecasts. The probabilities assigned to the intervals are based on the relative frequencies obtained for such intervals from the Milwaukee data for the five-year period immediately preceding the experiment. The results for C (C_1, C_2, and C_3 collectively), which are included in Table III, indicate that the average probabilities are closer to the corresponding relative frequencies than is the case with F (the forecasters' probabilities). The autoregression procedure yields almost perfectly reliable forecasts on the average. In percentage terms, however, the differences between the average probabilities and relative frequencies for C_1 and C_2 are similar in magnitude and direction to those for F.

As with the variable-width intervals, F is much more precise than C. The average probabilities for the forecasters' 5° and 9° intervals are almost twice as high (more than twice as high in one case) as the corresponding average probabilities for C. Of course, some of the precision in F was attained at a cost in reliability, and slightly lower probabilities would have improved reliability while still maintaining a high precision. In general, the basic difference in performance between the fixed-width and variable-width forecasts consists of the slightly lower reliability of the former compared to the latter.

4. Discussion and conclusion

Unlike forecasts of precipitation occurrence in the U.S.A., forecasts of maximum and minimum temperatures there and elsewhere generally do not include probabilities. Nevertheless, many different decisions are made each day that depend at least in part on temperature forecasts, and the absence of information concerning the uncertainty in these forecasts frequently may lead to decisions that are less than optimal. Uncertainty regarding maximum or minimum temperature can be expressed in terms of a probability distribution, and summary measures of this distribution can be used to communicate the uncertainty in a temperature forecast to specific users or to the general public. Of the alternative summary measures that might be considered, credible intervals seem to provide the best compromise between (a) current practice in temperature forecasting, in which probabilities are not assessed but forecasts are frequently expressed in terms of intervals, and (b) the reporting of the entire distribution or of other summary measures that would be difficult for users of forecasts to interpret.

The results of the experiment reported in this paper demonstrate that weather forecasters can successfully use credible intervals to quantify the uncertainty inherent in their temperature forecasts. The credible interval forecasts were very reliable—the variable-width forecasts outperformed the fixed-width forecasts in this respect—and very precise. Moreover, the credible intervals assessed by the forecasters were considerably more reliable and precise than corresponding intervals based on climatology, persistence, and autoregression (except for the reliability of the fixed-width forecasts). More sophisticated standards of comparison that would also be expected to outperform climatology, persistence, and autoregression could be developed, but as yet no such procedures exist that provide probabilistic forecasts.

In terms of point (i.e. categorical) forecasts of temperature, the model output statistics (MOS) system (Klein and Glahn, 1974) is used in the U.S.A. to generate objective statistical forecasts of maximum and minimum temperatures, based on the output of numerical models. Some recent results of the MOS program (Klein, 1978) indicate that the average absolute errors for these forecasts tend to be slightly larger than the average $|M - T|$ obtained in the Milwaukee experiment but much smaller than the average absolute errors for climatology, persistence, and autoregression at Milwaukee. Unfortunately, the MOS system does not as yet provide *probabilistic* forecasts of maximum and minimum temperatures.

The performance of the forecasters in the Milwaukee experiment is particularly noteworthy in view of the fact that they never had made probabilistic temperature forecasts before the experiment, although they did have a considerable amount of experience in formulating precipitation probability forecasts. For precipitation occurrence, however, NWS forecasters have access to MOS guidance forecasts expressed in probabilistic terms (Klein and Glahn, 1974). As indicated above, such guidance forecasts are not available in probabilistic form for maximum and minimum temperatures. In addition, the forecasters did not receive any feedback concerning their performance during the course of the experiment. Some feedback might make forecasters aware of any systematic deviations from perfect reliability or any differences between, say, forecasts of maximum and minimum temperatures and thus might enable the forecasters to improve by a process of self-calibration. Of course, the excellent results obtained in the Milwaukee experiment suggest that the prospects for further improvement are limited.

The temperature scale used in the Milwaukee experiment was the Fahrenheit scale. However, since almost all the countries in the world except the U.S.A. now report temperatures on the Celsius scale, perhaps it should be mentioned that the concept of probabilistic temperature forecasting in general, and the use of credible intervals as summary measures of probability distributions in particular, are equally applicable in the Celsius system. Of course, since a degree Celsius is nearly twice as wide as a degree Fahrenheit, credible interval forecasts in the Celsius system will be narrower than corresponding intervals in the Fahrenheit system. Moreover, the Celsius system generally will allow forecasters less flexibility in formulating credible interval forecasts than the Fahrenheit system. However, if temperatures in degrees Celsius were reported to the nearest 0·5°, then both the width and amount of flexibility would be almost the same in the two systems. In any case, uncertainty exists in temperature forecasts regardless of the scale that is used to report the temperatures, and this uncertainty should be quantified and included in the forecasts provided to potential users.

In conclusion, credible interval forecasts could be very useful in temperature forecasting, and consideration should be given to formulating such forecasts on a routine operational basis to supplement (not replace) point forecasts of maximum and minimum temperatures. The choice of types of credible intervals (e.g. variable-width versus fixed-width; selection of particular probabilities or widths) need not be limited to the types considered in the Milwaukee experiment, although the latter seem especially promising. In some cases, it may be desirable to formulate probabilistic forecasts of critical temperature events (e.g. the probability of below-freezing temperatures). These issues, as well as issues related to the implementation of an operational program of probabilistic temperature forecasting—including the dissemination of such forecasts to specific users and the general public—are discussed in some detail in a recent paper by Murphy and Winkler (1979).

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APPENDIX

A.1. Under the assumption that $M - T$ is normally distributed, standard normal theory can be used to make inferences about μ_{M-T} (Lindley, 1965; De Groot, 1970). Assuming an improper diffuse joint prior distribution for μ_{M-T} and σ_{M-T}, the posterior distribution for μ_{M-T} is Student with mean $-0{\cdot}78°$, standard deviation $0{\cdot}18°$, and 698 degrees of freedom. A 95 per cent credible interval for μ_{M-T} is then $(-1{\cdot}13°, -0{\cdot}43°)$. If instead of using a diffuse joint prior distribution, some results ($n = 254$, $\overline{M - T} = -0{\cdot}50°$, $S_{M-T} = 4{\cdot}9°$) from the Denver experiment (Murphy and Winkler, 1974) are considered as prior information, then the posterior distribution for μ_{M-T} is Student with mean $-0{\cdot}71°$, standard deviation $0{\cdot}16°$, and 952 degrees of freedom. In this case, a 95 per cent credible interval for μ_{M-T} is $(-1{\cdot}02°, -0{\cdot}40°)$.

A.2. Treating the occurrence of observed temperatures within the 50 per cent and 75 per cent intervals as Bernoulli processes with parameters p_1 and p_2, respectively, inferences can be made about these parameters (Lindley and Phillips, 1976). Assuming a uniform prior distribution in each case, 95 per cent credible intervals for p_1 and p_2 based on their posterior distributions are (0·490, 0·584) and (0·755, 0·831) respectively. On the other hand, assuming Beta prior distributions that reflect the results from the Denver experiment, 95 per cent posterior credible intervals for p_1 and p_2 are (0·477, 0·559) and (0·745, 0·813) respectively.

A.3. The loss function used to evaluate the variable-width forecasts in this paper can be defined as follows:

$$L(a,b,T) = \begin{cases} k(a - T) + (b - a + 1) & \text{if } T < a, \\ b - a + 1 & \text{if } a \leqslant T \leqslant b, \\ k(T - b) + (b - a + 1) & \text{if } T > b, \end{cases}$$

where a and b are the lower and upper limits (or end points) of the interval forecast. The interval that minimizes expected loss must satisfy the relationship $G(a) = 1 - G(b) = k^{-1}$, where G is the forecaster's cumulative distribution function for T (Winkler, 1972). For 50 per cent and 75 per cent central credible intervals, $k = 4$ and $k = 8$, respectively.

A.4. If the distributions of probabilities for the 5° and 9° intervals are approximated by normal distributions, then inferences can be made concerning the distributions for the mean probabilities (Lindley, 1965; De Groot, 1970). If a diffuse prior distribution is used, then the posterior distributions indicate that virtually all the probability is concentrated within 0·015 of the sample means.

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On relationships between tropospheric circulation patterns and both the date of spring reversal of stratospheric winds and the strength of winter stratospheric flow

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(Polish Meteorological Service)

Summary

Two independent but similar investigations into possible connections between stratosphere and troposphere are reported with regard firstly to the date of the spring reversal of winds in the stratosphere and secondly to the strength of flow at 30 mb in winter. On a half-monthly scale there is little evidence to suggest that it is possible to predict both stratospheric parameters on the basis of preceding tropospheric developments, but there is some evidence that the date of the spring reversal may have a predictive value as far as tropospheric circulation patterns are concerned. However, more data are needed to confirm this suggestion.

Introduction

For the purposes of forecasting over time-scales of one to six months, it is essential to be aware of any relationships between variations in the seasonal evolution of the stratosphere and subsequent development in the circulation patterns of the troposphere. Conversely, it is of interest to know whether the stratosphere is influenced by previous developments in the troposphere.

Observational and theoretical studies have been carried out using dynamical models into connections between planetary wave motions in the troposphere and stratosphere (O'Neill and Taylor 1979, Holton 1975, Hines 1974, Murgatroyd and O'Neill forthcoming publication). Additionally, investigations have been made into two particular features of the stratosphere and their possible connections with tropospheric weather patterns: the first, and perhaps most important, phenomenon, is the fairly regular change in direction and strength of stratospheric winds in equatorial regions, known as the 'quasi-biennial oscillation' (QBO); the second is the change from winter westerly to summer easterly stratospheric winds at middle and high latitudes, which is termed either the 'final warming' (to distinguish it from temporary winter stratospheric warmings) or the 'spring reversal'. It has been found that there are some significant relations between the QBO and both local weather conditions (Perry 1977, Ugrjumov 1971a) and the tropospheric circulation over the northern hemisphere (Ebdon 1975). The existence of such connections may be useful, especially since it appears to be possible to predict future phases of the QBO (Parker 1976).

Investigations into whether the date of the spring reversal is related in any way to subsequent developments in the troposphere and is therefore of value for weather forecasting have been made in the United Kingdom (Ebdon 1966, 1972), Germany (Labitzke 1962), the Soviet Union (Ugrjumov 1971b, Ped' 1973a, 1973b), Japan (Wada and Asakura 1967) and Poland (Suryjak 1974, Pawłowska 1976). Some results have been found to be statistically significant and these are used in conjunction with other methods in preparing long-range forecasts.

The purpose of this paper is to report the results of two independent but similar investigations into possible stratosphere/troposphere relationships: the first is concerned with the date of the spring reversal, and the second with the strength of stratospheric flow during the period January to March, henceforth

* This work was carried out whilst the Author was with the Meteorological Office on a World Meteorological Organization Fellowship.

referred to as the 'reference period'. The possibility of predicting these two features of the stratosphere on the basis of preceding tropospheric circulation patterns is discussed, and also whether they themselves are of value as predictors of subsequent tropospheric developments. A half-month was considered to be a reasonable time-scale having regard to the possible practical application of any relationships found, and both half-monthly mean surface pressure and 500 mb geopotential data for the northern hemisphere from the period 1958–78 were used.

Spring reversal

The date of spring reversal was classified by reference to 5-day (pentad) mean zonal wind components at 30 mb at Shanwell, Scotland, for which almost complete data were available from 1958. Although it would have been desirable to use zonal components averaged round the hemisphere, the problems created by missing data could not be overcome in the time available. Following Ebdon (1972) the date of the spring reversal was taken as the commencement of that pentad over which the mean zonal wind component was easterly exceeding 5 kn and after which it remained either easterly or less than 5 kn westerly.

Eight years from a total set of 21 cases were selected as having an early change-over; these were 1959, 1964, 1969, 1972, 1974, 1975, 1977, and 1978. It was then necessary to test whether tropospheric circulation patterns associated with this set of years differed significantly from those associated with the other set (the remainder), considering separately periods preceding and succeeding the spring reversals. For each of the 12 half-months preceding (September–February) and 14 half-months following (June–December) spring reversals, composite surface pressure and 500 mb geopotential charts were produced for both groups of years independently. The composite charts were differenced to give an areal representation of mean differences in any half-month which might be related to the time of the spring stratospheric reversal but which would inevitably include a considerable random component.

The difference charts were examined for significance using a computer program to carry out Welch's test (Mack 1966), i.e. *t*-test when population variances may differ. Ratcliffe (1974) used this program in his study of 500 mb anomalies in long-range forecasts and also estimated the significance of the results obtained. He considered 198 grid points from 50°N to the north pole and found, using a random number generator, that an average of 32 points passed Welch's test at the 5 per cent level by chance. He was also able to compute the 95 per cent confidence interval about this chance value.

In this case, the area considered was extended southwards to 30°N and Ratcliffe's results cannot be strictly applied. However, by taking into account only those difference charts which have 50 or more significant values at grid points, or in excess of 35 significant values in consecutive half-months, it is unlikely that any real circulation differences have been excluded. These criteria were applied and the results provide little evidence to support the suggestion that the mean tropospheric circulation patterns of preceding half-months may provide an indication of the date of forthcoming spring reversal. However, one case is of interest, namely that of the mean surface pressure pattern in the second half of November, for which 53 grid-point values passed the 'W' test. The difference chart with significant areas is shown in Figure 1. It is probable that even in this instance the differences were random. If they were not then it would be seen from this figure that the second half of those Novembers preceding an early spring reversal would tend to have enhanced cyclonic activity over northern Russia and south of Greenland, with an increase of pressure in polar regions.

There is more evidence to suggest some relationship between the date of final warming and subsequent tropospheric circulation patterns beginning from the second half of the following October. The significance of the differences shown in Figures 2–6 is such that they are unlikely to have occurred by

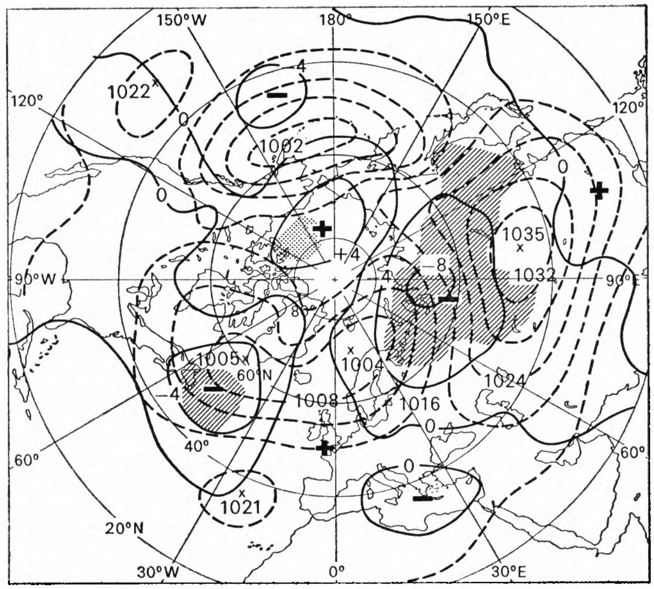

Figure 1. Differences in half-monthly mean surface pressure in millibars for the second half of November in years preceding early and late spring reversal of winds in the stratosphere. Dashed lines indicate half-monthly mean surface pressure from 1958 to 1978, solid lines show differences between means of two subsets of years. Stippling denotes significant areas of positive differences and hatching significant areas of negative differences.

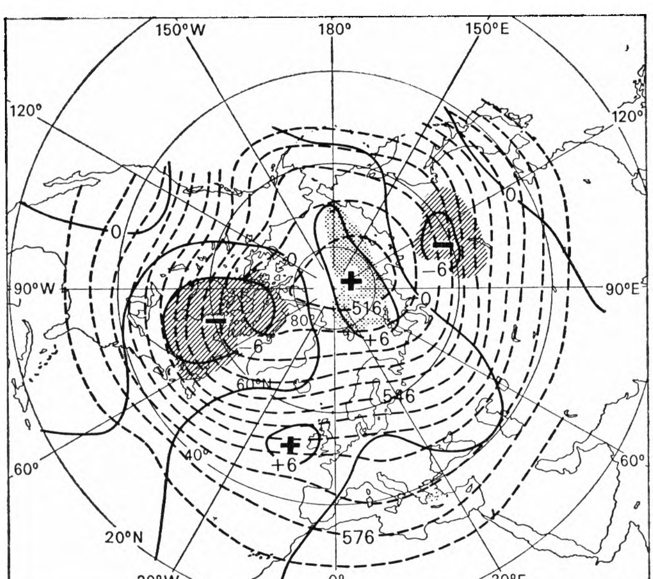

Figure 2. As Figure 1 but for 500 mb geopotential in the second half of October following spring reversal. Values are in decageopotential metres.

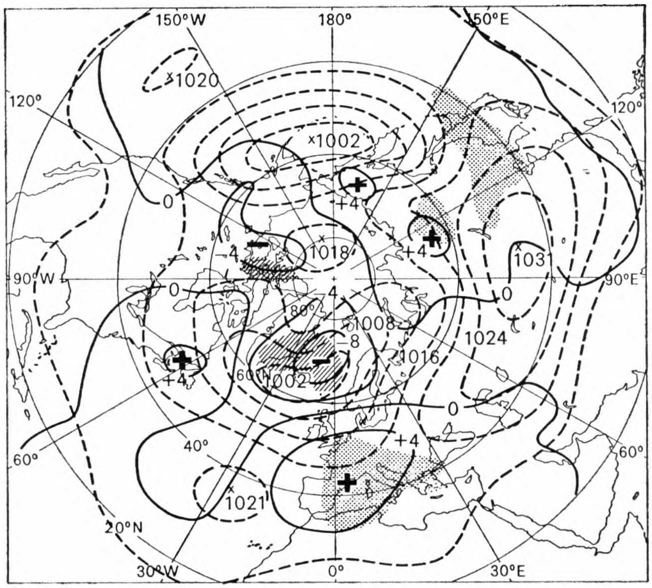

Figure 3. As Figure 1 but for surface pressure in millibars in the first half of November following spring reversal.

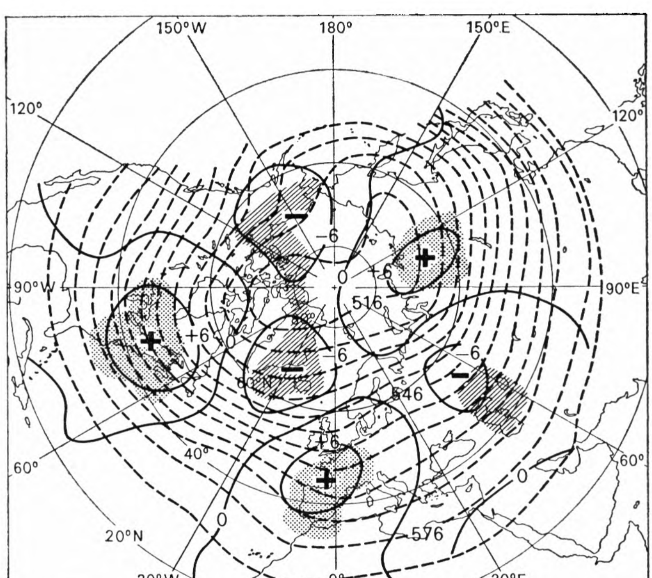

Figure 4. As Figure 1 but for 500 mb geopotential in the first half of November following spring reversal. Values are in decageopotential metres.

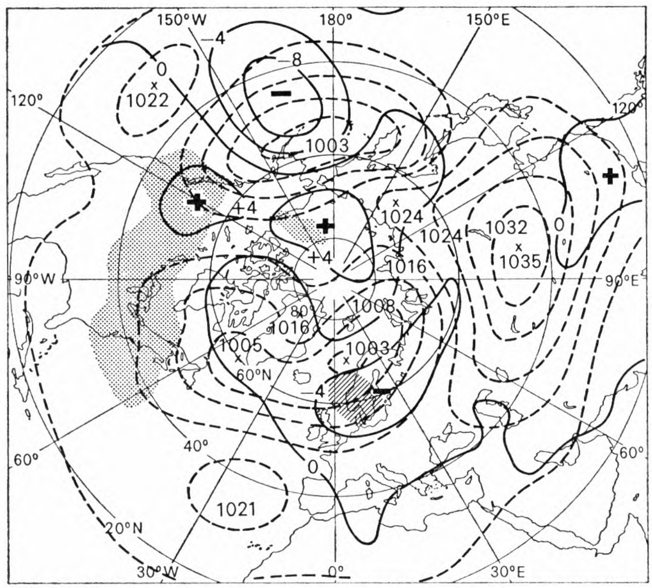

Figure 5. As Figure 1 but surface pressure in millibars in the second half of November following spring reversal.

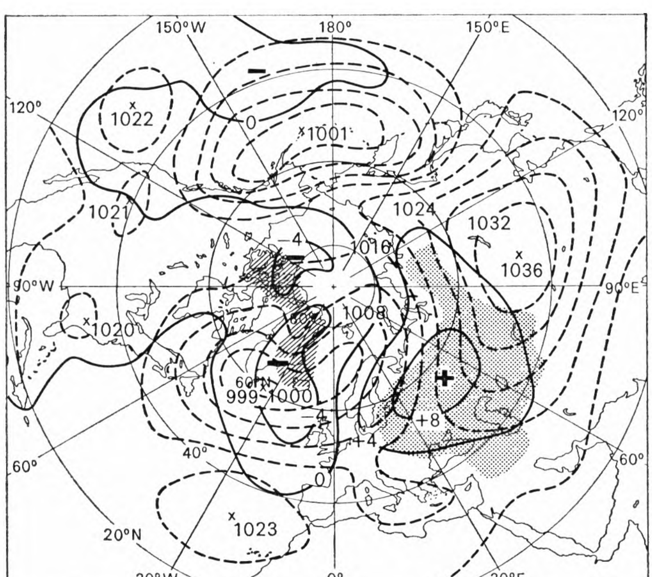

Figure 6. As Figure 1 but for surface pressure in millibars in the first half of December following spring reversal.

chance, since these charts include consecutive half-months; however, more data are needed to confirm this suggestion. If the behaviour of the past 21 years is repeated, then it is reasonable to expect in the second half of October (Figure 2) that 500 mb troughs over eastern Canada and over Siberia will be much deeper after early spring reversals than after late reversals, and the polar low less intense.

For the first half of November charts of differences between sets of years with early and late reversals are shown in Figure 3 for surface pressure and in Figure 4 for 500 mb geopotential. Two significant areas of particular interest in Figure 3 are those over Iceland and south-west Europe, which together indicate a substantial increase in surface westerly flow over north-west Europe during the first half of November following early spring reversals. Another interesting feature is the eastward shift of the centre of the Russian 'high', with more pronounced ridging to the north-east. The main effect at 500 mb (Figure 4) is seen to be increased zonality around much of the hemisphere after early spring reversals, with weaker troughs over Canada and western Europe, compensated to some extent by a more marked trough from central northern Russia to the Caspian Sea.

In the second half of November (Figure 5) the distribution of areas with positive and negative differences in surface pressure is the reverse of that in the first half of the month over much of the hemisphere, with the exception of the north-east Atlantic and northern Europe. There is a large area with positive differences extending southwards and then eastwards across most of North America and the western North Atlantic. The area of negative differences over northern Europe may represent a south-eastward movement of the centre near Iceland in the first half of November, which was noted earlier.

The difference chart for the first half of December (Figure 6) shows two significant areas, the first suggesting increased anticyclonicity over central and eastern Europe after early spring reversal, and the second suggesting lower pressure over the Canadian Arctic and Greenland, one result of this being a much strengthened cyclonic south-westerly airstream over the British Isles and Scandinavia.

Winter stratospheric flow

The second investigation into possible stratosphere/troposphere relationships was concerned with the strength of winter stratospheric flow. The pentad means of the zonal 30 mb flow at Shanwell, Scotland, were used to select years when the average zonal wind component over the 18 pentads from January to March exceeded 38 kn. This threshold was chosen to obtain adequate sample sizes for the application of the available statistical computer program.

Nine out of a possible 20 years (1962 was omitted because of missing data) were found to have strong westerly flow; they were 1959, 1964, 1965, 1966, 1967, 1969, 1974, 1976, and 1977.

In exactly the same way as described earlier for the spring reversal investigation, composite surface pressure and 500 mb geopotential charts were produced both for the group of years with strong stratospheric flow and for the remainder, and they were then differenced. The period considered extended from the September preceding the January–March period, when stratospheric winds were determined (reference period), to the following December. Grid-point differences were tested for significance using the same criteria as for the spring reversal investigation.

The numbers of grid-point values which passed Welch's test at the 5 per cent level are given in Figure 7 for each of 32 half-months considered. There is little evidence for any relationship between the strength of winter stratospheric flow and the tropospheric circulation. However, the significance of the four difference charts shown in Figures 8–11 might be real, because the number of points passing the W test exceed both the criteria for significance adopted in this note (see previous section) and that used by Ratcliffe. If this is the case then it can be seen from Figure 8 that there tends to be enhanced meridional

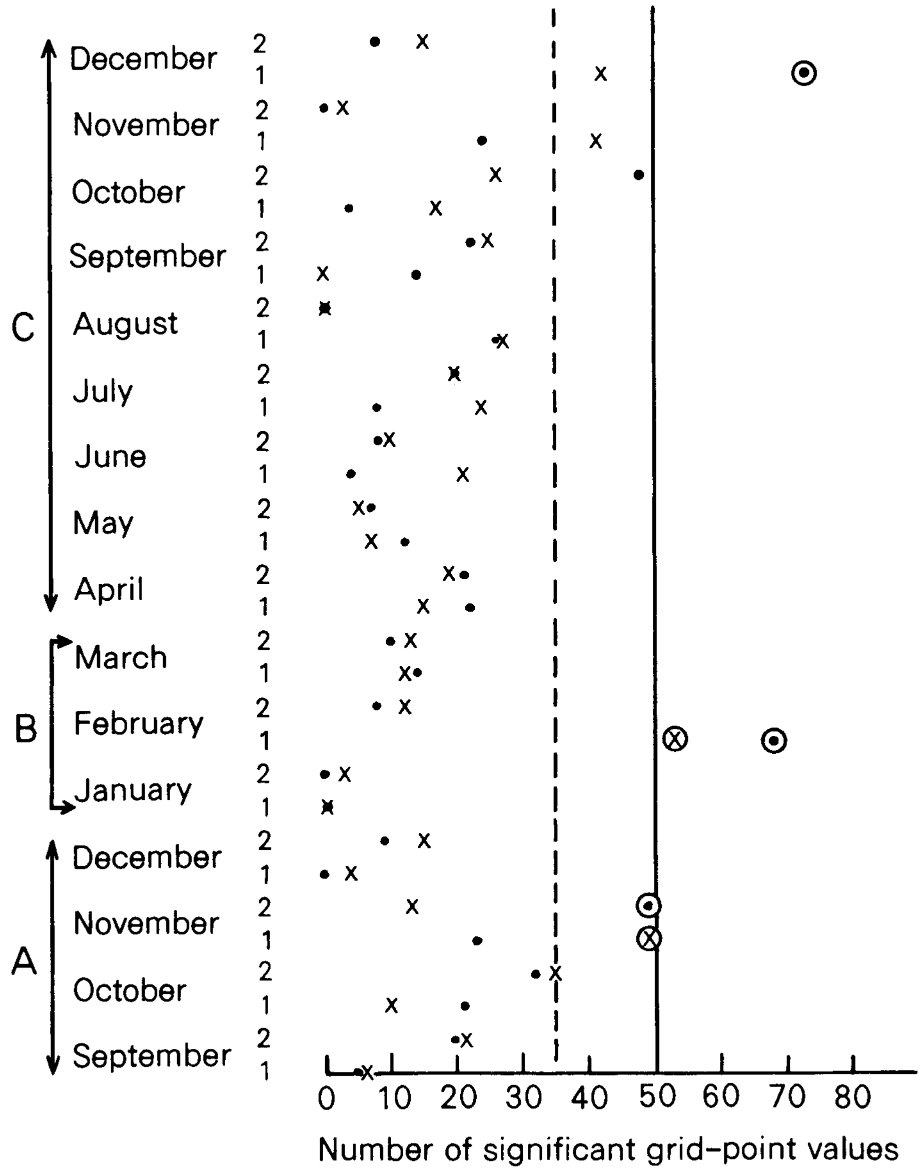

Figure 7. Numbers of grid points where differences were significant between the subset of years with strong winte westerly flow at 30 mb over Scotland and those with weak flow for half-monthly mean surface pressure and 500 mb geopotential.

A, B and C indicate half-months before, during and after the period of measurement of the strength of the stratospheric flow; 1, 2 indicate the first and second halves of a month. Dots indicate the number of grid points for surface pressure, crosses the number for 500 mb geopotential, and dots or crosses within circles the number which satisfied the criteria used by Ratcliffe.

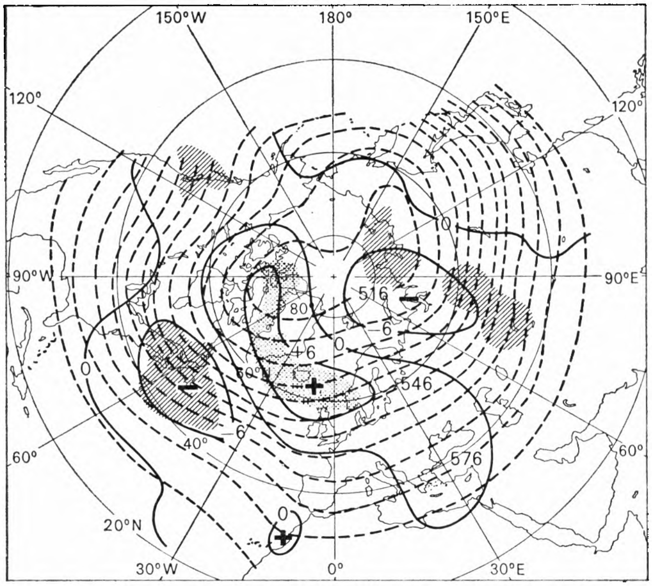

Figure 8. As Figure 1 but differences in half-monthly mean 500 mb geopotential for the first half of November in years preceding strong and weak winter stratospheric flow. Values are in decageopotential metres.

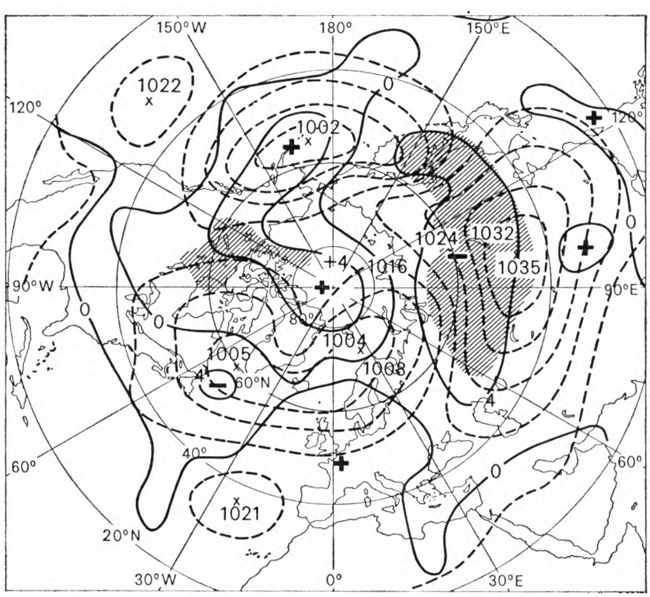

Figure 9. As Figure 1 but differences in half-monthly mean surface pressure in millibars for the second half of November in years preceding strong and weak winter stratospheric flow.

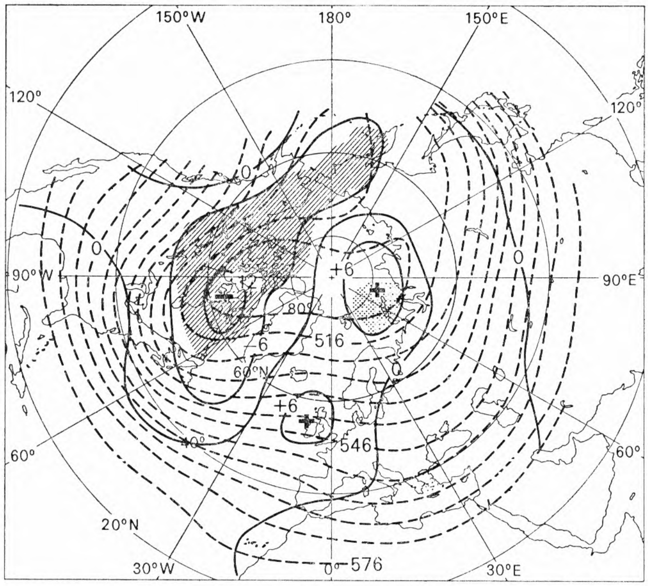

Figure 10. As Figure 1 but differences in half-monthly mean 500 mb geopotential for the first half of February in years during strong and weak winter stratospheric flow. Values are in decageopotential metres.

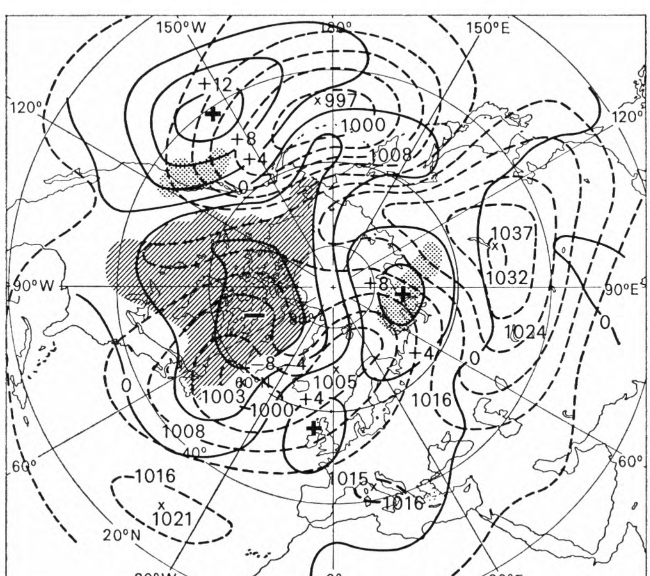

Figure 11. As Figure 1 but differences in half-monthly mean surface pressure in millibars for the first half of February in years during strong and weak winter stratospheric flow.

flow at 500 mb over much of the northern hemisphere in the first half of November preceding strong winter stratospheric flow. The surface pressure in the second half of November (Figure 9) shows the centre of gravity of the Russian anticyclone to be weaker and displaced slightly southwards.

In the first half of February (Figure 10), which is part of the 'reference period', the strong westerly flow at 30 mb is accompanied by a deeper 500 mb trough over North America and a ridge over the British Isles. The areas of significant positive and negative differences on the surface pressure chart (Figure 11) correspond to those at 500 mb.

It is also evident from Figure 7 that no coherent relationship between the strength of stratospheric flow and subsequent tropospheric circulation appears to exist.

Conclusion

It has been shown that, using data averaged over a half-month period, there is little evidence to suggest that it is possible to predict the date of spring reversal in the stratosphere or the strength of winter stratospheric flow from preceding tropospheric circulation patterns. Similarly, both stratospheric parameters appear to have little predictive value as far as subsequent developments in the troposphere are concerned. If there are such connections, then it seems from this analysis that they are most likely between the troposphere in autumn and the date of preceding spring reversal. However, more data are needed to confirm these suggestions.

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Memoirs of an Army Meteorologist

By H. Cotton, M.B.E., D.Sc.

Part 3

(Continued from the September 1979 issue.)

[From Le Touret Dr Cotton was posted to Querrieu]

Querrieu is a small town situated at a right-angle bend in the road from Amiens to Albert. In the corner, well back from the road, are the great iron gates of the Château, a building like the Château at Sailly Labourse but with much more extensive grounds. When I was there it was the Headquarters of the Fourth Army. Opposite the gates is a white-washed estaminet almost big enough to be called a small hotel. Practically the whole of the town is on the west side of the bend. About one hundred yards or so towards Albert the road crosses a little stream and a single-track railway line. A rough side road at the right-hand side doubles back sharply, ascends for about a hundred yards and then falls more steeply to the stream which by now has widened into a series of lagoons called *les étangs*. Strung along this side road is the village of Pont Noyelle.

To the south of the Albert road the land rises to a height of perhaps two hundred feet and then falls away southwards to the valley of the Somme River. I recalled a beautiful painting of 'The sleepy river Somme' in the Manchester Art Gallery. A pleasant land very different from the Artois I had known up to now; undulating, with wide fields and many scattered woods, but with none of the hedgerows which add so much beauty to the English landscape. At the highest point there is a monument to the 1870 war, but why they should want to commemorate the defeat of gross stupidity—being repeated even now in this far greater war—by machine-like efficiency I couldn't imagine.

The meteorological station was in a house at the top of the street of Pont Noyelle. It had a very complete equipment: inside the house a meteorological pattern barometer, a modification of the more familiar Fortin type, and a barograph which recorded on a clockwork-driven chart the changes with time of the barometric pressure. The rate of change, and whether up or down, was a valuable aid to forecasting. On the opposite side of the road, at the highest point, was a high platform with a cup anemometer mounted at one corner. This recorded not wind speed, but the number of feet travelled by the wind. The difference of the two readings, one at the beginning and the other at the end of a time interval as measured by stop-watch, divided by that time interval, gave the average wind speed over that interval. There was also the graduated plate mounted at a height of five feet from the ground and used with the portable anemometer as at Le Touret and Sailly Labourse. The cup anemometer was valuable because it could withstand high winds which would damage the delicate portable type. In such a case the wind direction had to be estimated and with experience this could be done with good accuracy. There were also a louvered Stevenson screen containing dry-bulb and wet-bulb thermometers, a rain-gauge, and a sunshine recorder.

Last, and of very great importance, was the theodolite specially designed for the observation of pilot balloons, like toy balloons which, when filled with hydrogen so as just to lift from the ground a specified weight, rose, when released, with a vertical speed of 500 feet per minute. Strictly speaking this could only be the rate of vertical climb if there was no vertical component of the wind's total velocity, a condition which was reasonably fulfilled with all but very light winds and with thundery conditions. The balloon's trajectory through the air was therefore the resultant of this free lift and the horizontal motion imposed by wind force and direction. This varied with altitude, sometimes considerably, and it was then difficult to get the balloon into the field of view again after the eye had been taken from the eye-piece in order to read the two verniers giving orientation and elevation. The theodolite, an expensive instrument, was taken indoors after each ascent and it was therefore necessary to orient it each time on some object whose exact bearing was known. We used the 1870 memorial for this purpose.

The Meteor Office, where I received telegrams and drew the synoptic charts, was one in a little town of Armstrong huts in the grounds of the Château. I was delighted to find that Corporal George was the other observer, two being required for pilot balloon ascents, one to use the theodolite, the other to record the readings. There was also the officer's batman, a young Irish boy, Banaghan, who should not have been in the army because of his youth, although he was safe enough at an Army Headquarters. He also acted as messenger; he was very simple. Our billet was the top storey of a barn at the top of the street at Pont Noyelle. It did not have the luxury of my hut at Le Touret, but it was comfortable enough except during the bitter winter of 1916/17 when the nights were exceedingly cold. I then missed my little stove.

The purpose of the balloon ascents was the computation of wind corrections for the artillery, this being necessary for three reasons: the use of many calibres of gun with ranges of a few thousand yards to several miles, each range having its own time of flight and its own height to climb into the upper air; map firing at targets which could not be seen but whose position was known on the map, this being particularly important at night and at all times when the weather was too unfavourable for artillery spotting; the use of howitzers with their high-angle fire and a trajectory quite different in shape from the flat trajectory of ordinary artillery—with times of flight as long as sixty seconds the absence of wind corrections could render a costly bombardment almost useless, or even result in the shelling of our own trenches. Four ascents were made during the twenty-four hours, at the fundamental hours. For the 1 a.m. observations the balloon carried a little home-made Chinese lantern and its weight had to be taken into account when filling the balloon. During the day-time observations the one who was recording was able, after some practice, to compute the upper winds in the time intervals between successive readings, a twenty-inch slide rule being useful for this purpose. The artillery corrections were computed indoors and the telegrams to Meteor and to the various artillery Headquarters were prepared in a remarkably short time.

Early in the September of the apparently never-ending Somme battles the adjutant came by H.Q. car and told me that I was to be taken to G.H.Q. He brought with him a replacement. As he sat at the front with the driver and I sat at the back, I had no chance to ask him where I was to go. I did get the information that I should only be staying at G.H.Q. for a few days and I had visions of miserable nights at the infantry barracks. Fortunately I was given a very comfortable room over the sweet-shop of M'sieu Brely Fatou in the Grand' Place. Each night before going to bed, I was given a cup of coffee with a generous lacing of cognac, and the only snag was the mattress, one of those things about two feet thick and, of course, no bedclothes. Still I didn't grumble when I thought about the infantry barracks.

As I was only staying at Meteor for a few days, no attempt was made to fit me into the organization. Because of my draughtsmanship I drew the weather charts based on the 7 a.m. observations and on the local observations. Copies were made on a jellygraph, the best copy going to the Commander in Chief, Sir Douglas Haig, and others to various headquarters.

My most important task, and the real reason for my staying several days, was the analysis of wind observations taken over a long period in the neighbourhood of Armentières. If a straight line is drawn in a south-easterly direction from Cap Gris Nez, the land to the east is, on the whole, very flat, the Flanders plain, while to the west it is much more elevated, there thus being an irregular escarpment running in a south-easterly direction. My job was to find out if some peculiarities in the early morning winds were due to this escarpment. Later events were to show that this was not a mere theoretical exercise but that, on one occasion at least, it was to be of very great importance. The investigation consisted of determining the north-east flowing and south-east flowing components of all the winds in this locality for which data were available. A comparison of the two components showed that, no matter what the total wind direction, there was a marked component in the north-east flowing direction but not in the other in the early hours of the morning. This component was particularly marked during anticyclonic conditions when, with very small or even zero barometric gradient, the gradient wind, that is, the wind appropriate to the concentration of isobars—the ordinary wind—was also either very light or zero. This component was a katabatic wind produced by the draining of cold, and therefore heavy, air from high to lower ground.

When I had completed the investigation the C.O. sent for me. He asked,

'Are you afraid of heights?'

'I don't think so, Sir', I replied 'although I have had no experience of great heights. I can look over the edge of a high steep cliff or from a top floor window of a tall building without feeling in any way dizzy.'

He then abruptly changed the subject.

'Pilot balloons give only the wind velocity and direction, and therefore the results can be used only to determine the correction necessary to neutralize the wind pressure on a projectile. They give no indication of the resistance to motion. For this it is necessary to know the density of the air at various heights, and as it is impossible under war conditions to attach instruments to pilot balloons it follows that an observer must be employed for this purpose.'

'But we have someone doing this', I pointed out.

'Yes', he said 'but he doesn't like heights, that is why I asked you if you are afraid of heights.'

'You want me to undertake this work, Sir?'

'That is the idea. Lieut. Young is going to England tomorrow and will be away for a fortnight. I want you to take his place for that time to see if you can do the work successfully. If you can it may be that it will be your contribution until the end of the war.'

So the following day I went by H.Q. car to a kite balloon almost due east of the ruined city of Ypres. The accommodation was in a large farm so that there was plenty of room for officers' and men's messes and, very important, for the packing of the parachutes, this necessitating a long room and a long wide table. When I arrived it was almost time for the 1 p.m. ascent, the fundamental hours of 7 a.m., 1 p.m. and 6 p.m. being kept whatever the purely military requirements of artillery spotting. Actually this combination of two entirely different duties did not work well and soon afterwards the balloon was withdrawn from the fighting zone and used solely for meteorological purposes.

It was an ideal day for one's first essay in upper-air observations, and I asked if I might make the ascent. There was very little wind, the sky was blue and there were many small detached cumulus clouds, all having the horizontal base indicating the level at which condensation took place. I estimated that height to be 3700 feet—I had become expert by this time; actually it was just under 4000 feet. I wore the leather Sidcote suit, a leather flying helmet, leather gauntlets with a flap which could be fastened back so as to leave the fingers free; also parachute harness. If one has to jump, the velocity of free descent before the parachute opens can be quite high and there is a violent jerk at the moment of opening. Knowing this, I decided against a harness which had a strap passing from front to back between the legs. If it was not quite in the right place one might suddenly lose interest even in the problem of landing. There was also a razor-sharp knife for cutting myself free of the parachute on landing, if this should be necessary.

I climbed into the glorified clothes basket along with the balloon officer who was making the ascent with me. A rigger tied by special knot the parachute rope to a ring in the harness and I then checked my instruments; a beautiful portable aneroid barometer, graduated in hundreds of feet and so sensitive that the needle would deflect for the small change in height if one placed it on the ground; a prismatic compass; Pitot tube for indicating the wind velocity; psychrometer. This was an elaborate form of wet and dry thermometer. Each thermometer was housed in a metal tube which projected from a chamber containing a clockwork-driven fan. When the fan rotated air was drawn up the tubes and therefore past the thermometer bulbs, this being much superior to the static thermometers used in the usual Stevenson screens. The compass was used to determine the wind direction. The balloon, being attached at one end of the cable, set itself along the wind direction and thus all that was necessary was to take a bearing on the attachment to the cable, this being in the form of a steel V. When I had checked the instruments and also the telephone connection with a signaller on the ground, the balloon officer gave the thumbs-up sign to the flight sergeant. He in turn gave the order:

'Let go the guys',

and I began to laugh. It was a joke I enjoyed every time I made an ascent but, strangely enough, nobody else seemed to see it. As the balloon's height increased everything appeared progressively smaller so that eventually it was, I suppose, something like looking at the surrounding country from the top of a mountain except that there was no terra firma under one's feet. The balloon was stopped at five hundred foot intervals, the heights being given by the barograph. At the height of the cloud base there was a sudden and beautiful change. There was a very slight haze on the ground although hardly enough to affect visibility. At this particular height it had the appearance of the surface of a dead-smooth, milky coloured sea and the clouds looked like little icebergs floating on it. At the level of the cloud base condensation commences and the latent heat of evaporation is given up, thereby producing a rise in temperature instead of the progressive fall in temperature as the height increases. I therefore stopped the balloon at this level so that I could take this temperature. I knew about inversion, as the phenomenon is called, but it was very exciting actually to be in the middle of one. As far as I remember we reached four thousand feet, the inclination of the cable due to the slight wind causing the winch to pay out more than would have been the case with a dead calm. At this height I could just make out the white cliffs of Dover.

It was during an ascent at sunrise that I had the most beautiful experience. It was perfectly calm with a cloudless sky apart from a few pink wisps of cirrus. To the east the sun had just cleared the horizon, an orange-coloured disc. For some reason I turned round and looked to the west and there, diametrically opposite the sun and about to set behind the ruins of Ypres, was the full moon, looking very pale as though shocked by what she had seen. The sun and full moon both in the sky together; God-made beauty in the heavens, man-made hell on earth.

While there was still happiness in the world, and love instead of hatred and slaughter, Graham Peel composed a lovely little song called 'The Early Morning' to Hilaire Belloc's words:

'My brother, good morning:
My sister, good night'.

Another beautiful phenomenon was the rainbow round the shadow of the balloon when we ascended into sunshine above a uniform cloud sheet. The bow was a complete circle with the balloon's shadow at the centre and occasionally, but not always, there was a faint secondary bow of greater diameter and with the order of the spectral colours reversed. I was to see this several times but I never again saw the rising sun and the setting full moon in the sky together. Cecil Lewis in *Sagittarius Rising* also saw the circular rainbow but apparently only once. It was early evening with the sun's rays almost horizontal and his shadow and the surrounding rainbow were on the almost vertical face of a vast cumulonimbus cloud. He entered the cloud through his own shadow.

Since I was engaged in war duties it was inevitable that there should be a certain amount of unpleasantness. For example there was a German six-inch high-velocity gun a few miles away. It was spotted by the flashes and located by intersections from my own balloon and those on either side. It fired at us from time to time but I think it was merely devilment on the part of the gunners since a visibly small object several miles away and several thousand feet up in the air is an exceedingly difficult target.

More disturbing were the antics of young pilots flying Sopwith Camels. They had great fun, to them, zooming on to the balloon and almost running their wheels along the top. A very small error and they would have ripped the balloon from end to end. We could see their grinning faces and on such occasions one of the balloon officers used the most awe-inspiring language I have ever heard. Of course they were only having fun, and as the average life of a pilot was only about three weeks they had some justification in getting their fun when they could. All the same I wished that they would go somewhere else for it.

In spite of the gun and in spite of the crazy pilots I was sorry when my fortnight with the balloon came to an end and I was taken back to Fourth Army Headquarters and the Somme Battles.

The long drawn-out struggle called the Battle of the Somme has been written about many times. At the time of the Battle of the Marne in 1914, a battle which decided the ultimate outcome of the war, that Germany should not win and thereby achieve mastery over the whole of Europe, Joffre, at the most critical moment, turned to Sir John French and said 'Monsieur le Maréchal c'est la France qui vous supplie'. And now Britain was answering Joffre's prayer and tens of thousands of young men to whom France meant nothing whatever were watering the land of France with their blood. It looked as though the mass sacrifice would go on for ever and with nothing gained, for with each obstacle overcome they were confronted with another one almost similar. Our High Command, not having been brought up to control vast armies of hundreds of thousands, was learning the hard way, and the troops paid the bill.

For me and for all of us at Meteor life continued unchanged. Occasionally I would go to Amiens on the Section motor bike, a Douglas horizontally opposed twin cylinder machine, and very good too. This was to make purchases for the officers' mess, and it gave me a chance to look at the shops, especially a big bookshop in the Rue des Trois Cailloux. I also visited the Cathedral, the front heavily sandbagged. Also Corporal George thought it was time he gave me a few drawing lessons as he thought my efforts were all too niggling. In return I gave him lessons in Physics although without Mathematics one cannot get very far. There was a shortage of the little tin holders for the candles of the home-made lanterns and the Headquarters workshops received an indent for a fresh supply, surely the most strange assignment ever given in wartime.

The winter of 1916/17 was bitterly cold and the 1 a.m. balloon ascents on nights of clear sky and bitter east wind were something to be dreaded. On one such night but with hardly any wind I was at the theodolite, and as my sight in those days was very keen I kept the lantern in sight up to 20 000 feet, which meant that the observations took forty minutes. As I could not move about and stamp my feet and as I was only wearing mittens so as to keep the fingers free, I was frozen by the time I lost the balloon. I hurried to the office and was foolish enough to warm my hands by the fire. The resulting aching was excruciating and I never did that again. We had a jar of ration rum, thick like treacle and red like wine, and I took a good dose of that and went to bed, but it was a long time before the intolerable ache went from my fingers.

The office was next door to a cottage occupied by an old lady who also remembered the German occupation of 1870 (although she, apparently, did not experience any ill treatment), her daughter and little granddaughter, aged about five. We used to visit them just for a talk, and instead of the thin rather sour white wine they favoured I brought a packet of tea which they had not tasted before. On one occasion while talking to the little girl, pointing to various things so that she could say what they were, I put salt in my tea thinking it was sugar. After that I was always M'sieu Sel.

In the early spring of 1917, the German Army of the Somme disappeared. One day they were there, the next day they were gone. They withdrew, a strategic withdrawal in the real sense, a victory not a defeat. They withdrew a distance of thirty miles to a position so strong as to be thought impregnable. And it would have been impregnable to the bull-at-a-gate tactics currently employed. They turned the beautiful countryside they evacuated into a desert, destroying towns, roads, crops, orchards, everything which could contribute to human habitation. The wrecked towns and villages became the back areas and not a single civilian was left in them. They shortened their communications by thirty miles, they increased the British lines of communication by the same distance. The land they gave up and destroyed was French, not German, and was therefore of no emotional significance to them.

There was nothing for it but for the British Army to move after them, and that meant Meteor as well. We loaded all our equipment and our belongings on to a large lorry and said goodbye to the little family next door. The little girl's goodbye to her M'sieu Sel was very tearful. We climbed the hill leading to Corbie and I looked at the Calvary for the last time. At Corbie we joined the road from Amiens to St Quentin which runs due east, straight as an arrow, except for a small conformity with the gradient at Foucancourt. There was no mistaking the battle areas, there were so many shell-holes that there was hardly one which did not overlap its neighbours. The trees were mere stumps giving a disquieting air of desolation and some were blown completely out of the ground. The sides of the road were littered with the debris of motor vehicles of all kinds.

At Estrées, or what was once Estrées but now almost in the real Biblical sense had not one stone on another, a branch road runs south to Villers Carbonnel and then to a group of once pleasant towns, Marchelepot, Briost, Misery, all deserted. At Villers Carbonnel a narrow road runs eastwards, parallel to the main St Quentin road. There must have been a bridge over the river, but this had been mined and the river was now widened into a very extensive swamp. By the river bank were the ruins of a small village and in the churchyard, leaning at a crazy angle, a large iron cross decorated with elaborate strap-iron curlicues. The Somme River takes a roughly northerly course as far as St Quentin, where it turns west and then takes a very meandering route to Amiens and finally Abbeville and the sea. It formed the junction between the Third Army to the north and the Fifth Army to the south.

I went fishing occasionally but there was not much pleasure in it as I only caught eels. These are dreadful creatures for, apart from refusing to die, they swallow bait, hook, and as much of the line as they can get down. To recover the tackle it is often necessary to slit them to almost half-way down. I would not have eaten anything from that river no matter what I caught.

The road east from Villers Carbonnel is at first flat, then rises gently to about half a mile from the river to which it then descends, rather sharply. Fourth Army Headquarters was in an enormous Nissen hut erected on the flat area. This was the operations room. The Headquarters staff were housed in small Nissen huts, lining both sides of the road, almost like a street. Small gardens had been constructed in front of these and they looked very gay when the flowering plants were in bloom. If it had not been for the war, and if the life of the neighbouring towns had been that of peace time, the situation would have been almost idyllic.

The Meteor office was a large hut sited at the highest point and opposite, on the other side of the road, was a high platform with a cup anemometer exactly as at Pont Noyelle. The underneath of the platform was closed in so as to make a room in which the theodolite could be stored when not in use. There were also the Stevenson screen, the pole-mounted graduated brass plate for surface wind measurements, and the rain-gauge. The sunshine recorder was on the platform placed so no shadow would fall across it. It consisted of a glass sphere which brought the sun's rays to a focus on a strip of special paper which was blackened by the heat, the intensity of the blackening being a rough measure of the intensity of the light. This paper strip was graduated in hours, the times of sunshine and of no sunshine being indicated.

The cross-section of a Nissen hut is roughly semicircular, the walls leaning inwards. Also they are not very rigid and are therefore quite unsuitable for the mounting of important scientific instruments. For this reason a solid brick pillar had been built in one corner, the barometer fixed on one side and the barograph resting on the top. The furnishing of the hut was a large centre table, stools, and at the end remote from the door three bunks. There was a shelf for books, a cupboard for odds and ends and hooks for greatcoats, hats and revolvers. Banaghan had no arms of any kind; if he had been issued with a rifle he must have been allowed to hand it in when he became a batman.

The fighting front was very quiet for the whole of the time Fourth Army Headquarters was at Villers Carbonnel and it would have been crazy to have attacked the new German defences at that time and without vast preparation also for the Germans to leave these defences so soon after their withdrawal and to cross the desert which they themselves had made. They could afford to wait. I had a feeling that our stay here was meant to be a quiet interlude before the fireworks started again. I had no complaints and neither had the others, particularly as the food was now very much better than that we had been getting at what the troops called 'Bacon fat corner' at Querrieu. There was precious little bacon.

An idyllic situation can only be enjoyed if one is in an idyllic state of mind and that was far from the case. The whole of the terrifying casualties suffered during the course of the Somme battles were not disclosed, although we now know that on the very first day alone there were losses of about 60 000 men. One of the regiments to be decimated on that tragic first day was the 5th North Staffs., the regiment I most probably would have joined. If it had not been for that letter from the War Office I realized that most probably I should have been one of the 60 000.

(To be continued.)

Notes and News

Retirement of Mr G. A. Howkins, M.B.E.

Mr G. A. Howkins, M.B.E., Assistant Director (Data Processing), retired from the Meteorological Office on 3 October 1979 after a meteorological career of 39 years, the first six years of which were spent in uniform.

Having won a County Major Scholarship to King's College, London in 1938, Gordon Howkins obtained his degree two years later and immediately entered the RNVR where he received his introduction to meteorology. Early in his period of service, he spent 18 months in the Falkland Islands. After receiving a commission in 1943, he returned to the south as a member of Operation Tabarin which laid the foundation for the subsequent establishment of the Falkland Islands Dependencies Survey.

On demobilization in 1946, he joined the Office as a Scientific Officer and immediately took charge of the meteorological office in the Falkland Islands. He was promoted to Senior Scientific Officer in 1950 and was subsequently seconded to oversee the creation of the Dependencies' own meteorological service.

In 1956, Mr Howkins returned to the United Kingdom and, after attending the Training School, spent eight years at London (Heathrow) Airport, initially on upper-air forecasting, and from 1961 as a Senior Forecaster following promotion to Principal Scientific Officer. In 1964, he moved to Bracknell where he spent two years on the development of computer-based methods of forecasting upper winds for aviation. This was followed by a spell as Senior Forecaster in the Central Forecasting Office, and he later took charge of the team which developed the operational numerical forecast suite.

In 1968 he joined the Data Processing Branch as Secretary of the Working Group which was set up to select and acquire the new COSMOS system based on the IBM 360/195 computer. Two years later, he became its first Computer Manager in which post he played an active part in the progressive transfer of computing work from the KDF-9 system, and implementation of the present-day wide-ranging computing services to branches throughout the Office.

When, in 1973, Mr Howkins took charge of the Data Processing Branch, he was soon occupied in planning for the acquisition of the front-end 370/158 computer and its integration into the COSMOS system. As users of the system repeatedly found, he took endless pains to tailor services to meet their requirements and was apt to worry until the smallest details were settled. He was fascinated by complex systems and was often tempted to reorganize areas outside those under his own control.

Of late, his colleagues have been increasingly concerned that Gordon Howkins's tendency to work too hard might seriously affect his health. Fortunately, he has discovered that hard physical exertion helps his condition. For this reason, we wish him and Mrs Howkins a long and active retirement, with plenty of gardening at their new home in Ascot and vigorous interludes of hill walking to add variety.

M. J. Blackwell

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NOTICES

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

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Aircraft measurements in the GARP Atlantic Tropical Experiment

By J. M. Nicholls

(Meteorological Research Flight, Royal Aircraft Establishment, Farnborough*)

Summary

Measurements made by a research aircraft on three flights in the tropics are described. The measurements were made in a cloud cluster, in convective cloud associated with the intertropical convergence zone, and in suppressed boundary-layer conditions. The primary aim of the paper is not to investigate the overall dynamics of these systems, but rather to demonstrate how well the data from the aircraft can be combined with those from ship-borne weather radar and from tethered and radiosonde balloons, and with data from other aircraft, to provide an excellent quantitative description of the phenomena.

Introduction

The aim of this paper is to describe how measurements from a modern research aircraft can be used for the exposition of a wide range of meteorological phenomena which are much less clearly described by the application of measurements from only the more conventional sources of data, such as radiosondes, ground-based weather radar, and tethered balloons. This is done by co-ordinating data from one such aircraft with those from other aircraft and the sources mentioned above for three days of the GARP† Atlantic Tropical Experiment (GATE).

The field phase of GATE lasted from June to September 1974. The observational program completed during this period was of unprecedented size and complexity, involving the provision and effective deployment of an international fleet of 12 research aircraft over the eastern tropical Atlantic and of 39 specially equipped ships from the West African coast to the eastern coast of South America; additional observations were secured from a specially launched satellite and from land stations.

The massive volume of data collected by these 'platforms' is being used by scientists to answer questions on the structure and evolution of tropical weather systems and interactions between these systems and those of temperate latitudes. For example, how much water vapour, heat and momentum is transported upwards by tropical convective clouds and then polewards by these and other mechanisms; how are the synoptic-scale easterly waves in the trade winds modified by the motions within the associated, smaller-scale (100–1000 km) cloud clusters—and vice versa; how are the clusters themselves

* Now at Meteorological Office Headquarters, Bracknell.
† GARP = Global Atmospheric Research Program.

affected by cumulonimbus groups or lines (of scale 10–100 km) which they frequently contain, and how is the development of a line modified by an individual large cumulonimbus (of scale 1–10 km) and its downdraught; and in what way is the cloud development dependent on the subkilometre-scale properties of the atmospheric boundary layer over the ocean, and vice versa?

By 1977 most of the agencies from the 10 countries which operated the aircraft and other equipment had by extraction of instrumental drifts improved the quality of the data collected to a state in which they were capable of being distributed to the world-wide scientific community to use in its investigation of problems just mentioned. It is therefore an opportune time not only to display the kind of information collected by an aircraft (in this case the United Kingdom's C-130, one of three superbly instrumented 'gust-probe' aircraft which took part in GATE) but also to demonstrate how successful the aircraft program was in supplementing and complementing the data from other sources.

The aircraft role in GATE

The phenomena of larger scale, i.e. the easterly waves and the cloud clusters, were investigated mainly by meteorological instrument packages on, or launched from, the ships. The most concentrated arrangement of ships was deployed in the eastern Atlantic and consisted of outer and inner hexagonal arrays, and—for the last three week period of the Experiment only—an inner triangle, as shown in Figure 1.

Eight long-range aircraft (flying from Dakar) were the most important instrument platforms for the investigation of the wind, temperature and humidity fields above the surface and the transports of momentum, heat, and moisture associated with the mesoscale convective systems (of scale <100 km) mentioned earlier. Three of these aircraft were equipped with 'gust probes', each carrying wind vanes and rapid response thermometers, which allowed measurements at a very high frequency (up to about 50 samples per second) to be made of the two horizontal and the vertical components of the wind velocity and of temperature, and a microwave refractometer from which similar measurements of humidity could be derived. This capability of high-frequency measurement also made these aircraft as important a tool as the tethered-balloon systems operating from the ships for investigating the microscale structure of air motions in the boundary layer, on scales down to 10–20 m.

Most flights were made in the area of the inner hexagonal array of ships shown in Figure 1, so that aircraft data would be combined with the large amount of data from upper-air soundings, weather radars, and tethered balloons operated from, or on, the ships. The specific objectives of a mission on any given day, and the flight plan necessary to achieve those objectives depended primarily on the structure and development of the clouds within the array on the day. 'Basic GATE missions', to investigate the dynamics of mesoscale cloud systems, were normally carried out by a stack of three to seven aircraft flying at different altitudes (typically from 500 to 37 000 ft) along the same ground track on any one of the patterns shown in Figures 2(a)–(c); these patterns were normally repeated by each aircraft, either in the same area or being moved with the group of clouds being studied. Such missions, including six flown outside the ship array to investigate the intertropical convergence zone (ITCZ), were flown on 29 days. On most other days emphasis was placed on determining the transports of momentum, etc., in the atmospheric boundary layer with a better vertical resolution than could be achieved from a basic GATE mission. One way of doing this was to concentrate the stack (but using at most four aircraft) into a layer from about 50 ft to 5000 ft above sea level (a.s.l.); more frequently a supplementary flight plan was used, as shown in Figure 2(d), in which 'L'-shaped patterns were flown by one or more aircraft frequently near a ship with a tethered balloon which also carried boundary-layer instrumentation. On

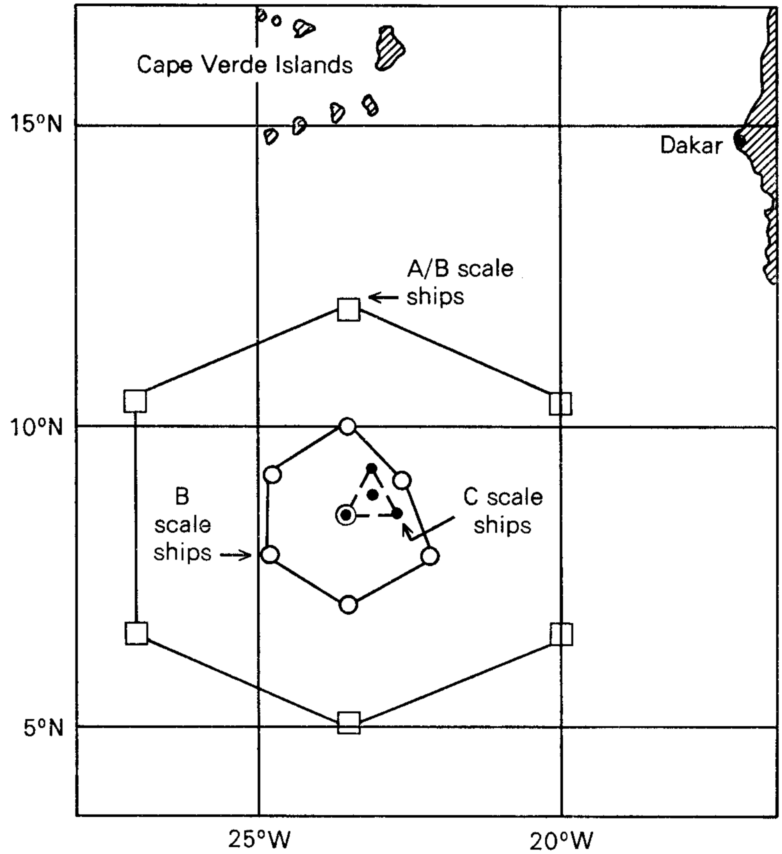

Figure 1. Location of ships in the eastern Atlantic for the third phase of GATE (30 August–19 September 1974). The A-scale is over 1000 km, B-scale 1000–100 km and C-scale 100–10 km.

these patterns the aircraft often made measurements at 4 to 11 levels between 50 and 5000 ft a.s.l. Boundary-layer missions were flown on 14 days.

The emphasis in this paper is on describing aircraft measurements made on basic GATE and boundary-layer missions and correlating aircraft data with data from ships' radars and balloon systems for each such mission. However, it should be mentioned that other missions were made by some of the eight long-range aircraft with other aims—for example measurement of the physical properties of clouds, of atmospheric (including cloud) radiation, and of sea-surface temperature fields (by a radiative method)—which were also essential to the main purposes of GATE. Additionally a further four aircraft were used in different roles—one examined wave profiles of the sea surface and performed detailed mapping of sea surface temperatures, two short-range aircraft performed a variety of special missions near Dakar, over both the ocean and the African Continent, and finally one aircraft was used to drop sondes over the east Atlantic thus supplementing ship data on large-scale phenomena. This last role exemplifies the wider usage to be made of research aircraft in future projects.

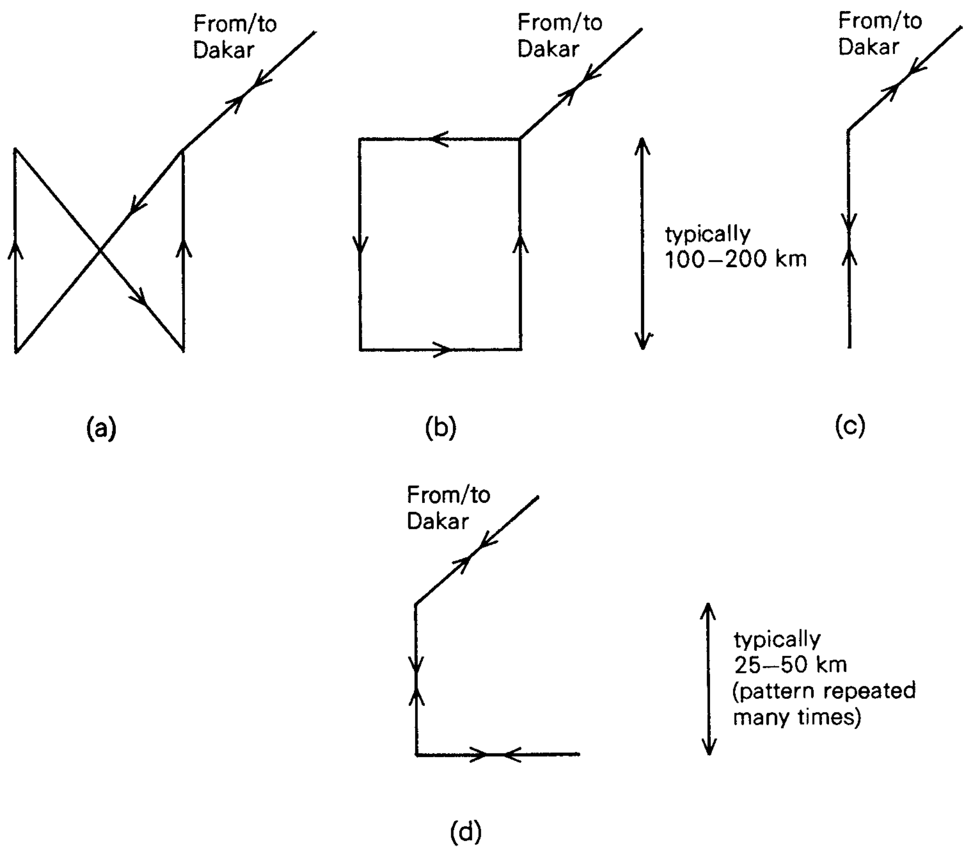

Figure 2. Basic GATE mission flight tracks: (a) butterfly pattern, (b) box pattern, and (c) line traverses; (d) shows the 'L'-pattern used for the boundary-layer missions only.

The United Kingdom's aircraft contribution

The United Kingdom's Hercules (or C-130) aircraft of the Meteorological Research Flight (MRF) was one of the three gust-probe aircraft used throughout GATE. This aircraft flew on 40 missions in all—27 basic GATE missions (including six crossings of the ITCZ), 8 boundary-layer missions, 1 sea-surface temperature mapping mission, and 4 flights solely to compare its measurements with those from other aircraft and an instrumented tower. Flying time totalled 386 hours, and about 10^9 samples of data were collected on the aircraft's magnetic-tape data-recording system.

Detailed information on the instrumentation of this aircraft may be found in the papers by James and Nicholls (1976) and Nicholls (1978). The importance of any errors in calculations derived from instrument measurements varies with the use which is to be made of the data. For example a calculation of convergence of air into a box will be most affected by the error of the mean wind component across one side of a box *relative* to that across the opposite side; the calculation of the vertical flux of heat on a leg of a boundary-layer flight will depend not on any absolute errors, but on any random noise and unreal drifts remaining in the computed vertical component of air velocity and on how the noise and drifts were correlated with those in the computed temperature. For this reason the accuracy of measurements made by the aircraft is a complicated issue and will not be discussed in great detail here. However, in general the absolute accuracy of any individual calculation of the horizontal wind vector, temperature and humidity are about 2 m s^{-1}, 0·3 °C and 0·3 g (of water) per kg (of moist air) respectively, the contributions to these values from noise and drifts over short periods (over about five minutes) being about one-fifth of the value quoted. Detailed visual examination of continuous time series for parameters from which the vertical component of air velocity is calculated reduces the total error of any one sample to about 0·2 m s^{-1}, this contribution coming almost entirely from noise and short-period drifts of instrumental origin. Similar errors will apply to data from other aircraft.

In common with other research groups, the MRF has taken about 2½ years to complete the processing (mainly by computer) of the large volume of data, the removal of known instrumental drifts and errors, the derivation of meteorological data from the basic instrumental outputs, the 'validation' of data (see below), and the presentation of three data sets in an internationally agreed format on magnetic tape. The primary data set contained the three components of wind, and temperature and specific humidity at 20 samples per second (i.e. 20 Hz) of flight time, and the other two included one-second and one-minute mean values of these and all other recorded parameters. 'Validation' consisted of the checking by eye of plotted output of all the data to assess if the numerical procedures for 'cleaning up' the data had worked; in all about 20 000 plots of the 20 Hz output, together with a similar number showing 2 Hz output (for non-gust-probe parameters) were checked. Any remaining periods of poor data were listed in a set of documents completed for each flight, and the magnetic tapes and documents were then dispatched to the two World Data Centres (WDCs) in Washington and Moscow, and to five other data centres, scattered world wide, whose responsibility is to check the data from one platform against that from all others which were operating at the same time. It is not necessary, however, to await the results of this final verification in order to make a reasonable assessment of how well the aircraft data correlated with those from other sources. In the following description of two basic GATE missions and one boundary-layer mission a very good agreement is demonstrated.

Basic GATE mission of 5 September—cloud cluster

On this day six aircraft flew box patterns at levels from 500 to 39 000 ft within the dumb-bell-shaped cluster shown at midday near 10°N on the visible satellite photograph (Plate I). The U.K. C-130 flew two box patterns at the lowest level. The cluster was associated with a wave of synoptic scale propagating from the east in the trade wind flow. The internal structure of the cluster at 1252 GMT as shown on the radar picture from the Canadian ship *Quadra* (positioned at 9°1′N, 22°32′W) can be seen in Plate II, with the aircraft's flight track superimposed on the picture. The flight started at the north-east corner of the box at 1215 GMT, the first run being southbound, and ended at the same point at the end of the fourth (eastbound) run at 1405 GMT. Since significant changes in the structure of some of the cumulonimbus groups took place over the period of the flight, it is not reasonable to correlate aircraft observations with the features on this particular photograph; in order to examine the correlation between aircraft and radar data it is necessary to look at sequential radar photographs, throughout the flight period, of convective structure near to the aircraft's location as it flew along the four legs of the box.

The basic features of the radar echo are shown again in Figure 3, but in this case the features are reconstructed in segments from shots taken at quarter-hour intervals from the ship *Oceanographer* (at 7°45′N, 22°12′W). The *Oceanographer* radar had an isoecho-contouring facility, and in the figure only the second and third levels of intensity, corresponding to rainfall rates of greater than 1·5 and 6·1 mm h^{-1}, are shown. It can be seen that a very complex mesoscale rainfall system existed within the cluster boundaries with the most active convection near the southern edge of the cluster.

Figure 3 also shows a few of the aircraft measurements. On run 1 (southbound) generally light easterly winds were found. Large directional changes at the start of run 2 (westbound) were followed

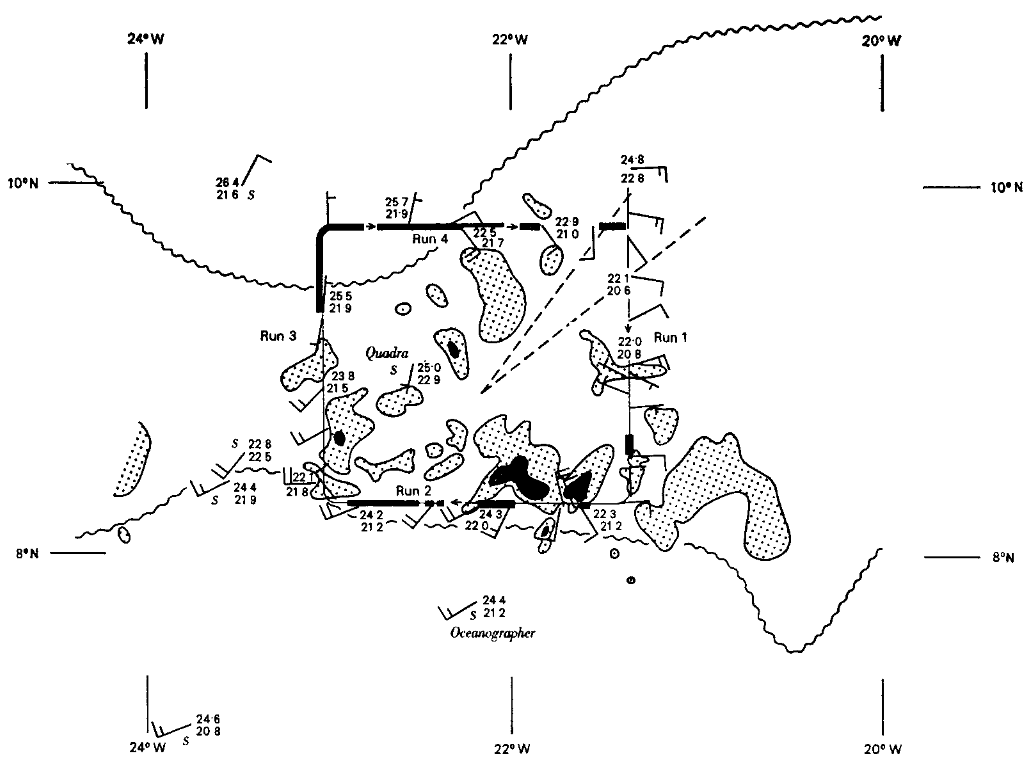

Figure 3. Montage of radar echoes from segments centred on aircraft positions at quarter-hour intervals, with apexes all at the centre of the box. Second and third levels of radar intensity are shown stippled and solid respectively. Aircraft flight track is shown by a thin solid line (in rain) or a thick solid line (in dry conditions). Winds, temperature (upper figure, degrees Celsius) and dew-points (lower figure, degrees Celsius) measured at points along the flight track are also shown. Ship measurements are annotated *S*. Cluster boundary as shown by satellite photograph denoted by a wavy line.

by a moderate south-westerly flow which persisted until a very abrupt change occurred to a light northerly flow near the end of run 3. At the same point a change also occurred from the cool humid disturbed air to warmer (by some 2 °C), calmer conditions (temperatures and dew-points are shown near some of the wind arrows). The region of northerly winds was found along the north-west quadrant of the box, with a further abrupt change in wind and temperature conditions (to humid south-easterlies) occurring halfway along run 4. If the track of the aircraft has been correctly derived relative to the radar and satellite features, we can see that the light easterlies, on run 1, with localized zones of slight convergence are associated with the limited convective activity on the eastern (trailing) edge of the cluster, and that the much larger convergence zones at the start of run 2, where rapid changes of wind from 10 kn southerlies to 20 kn northerlies were found, appear at the southern boundary of the most active convective elements. Also the south-westerlies at the southern edge of the box appear to be associated with air to the south of the active part of the cluster, with the change to the northerly regime occurring on and persisting after transition to the north of the cluster. As already stated, the structure of features of scale about 10–20 km—the cumulonimbus groups—changed significantly during the

2-hour period of flight around the box, but the general cloud distribution within the box did not. It thus seems reasonable that the wind field around the box changed only slowly during this period, and the aircraft measurements show an overall convergence of $4 \cdot 0 \times 10^{-8}$ s^{-1} into the 30 000 km^2 box. The correlation of aircraft wind and rainfall, and radar rainfall data, critically dependent on the accuracies of the derived aircraft and ship positions, is discussed in more detail later.

Observations of wind, temperature and dew-point measured at (or interpolated at) the 500 ft level by six ships in the B- and C-scale arrays close to the flight track are plotted on Figure 3. Splendid agreement can be seen between the aircraft and ship data within, to the south and to the north of the cluster (although the ship data presented here were not taken from a set of finally validated data).

Figure 4 shows wind, vertical air velocity and rainfall data from the aircraft as a function of time for each run individually, together with levels of radar intensity from *Oceanographer* photographs taken at 5-minute intervals. The scale of time is reversed for run 2 to preserve the west end of the run on the left of the figure, and similarly the north end of run 3 is so preserved; one minute of flight time corresponds to about 6 km flown. Wind vectors at 2-minute intervals are supplemented in active convergence zones by further vectors. The vertical component of air velocity shown is the maximum updraught in any 10-second period where the mean exceeded 0·5 m s^{-1}. The rainfall observations from the aircraft are derived from direct observations by the on-board scientist and from refractometer indications of the presence of rain; rainfall intensities are given when qualitative estimates were made by the observer. It can be seen that there is a good correlation of these rainfall observations to the radar intensity levels, with zones of no observed rainfall corresponding well with zero radar return and heavy precipitation falling where the most intense radar echo was found, even though the radar was 'seeing' the convective elements at levels above the flight level (some 10 000 ft above for the northern part of the box). Even the transition from continuous rain to showers noted by the observer on run 2 (at 1300 GMT) corresponded to a transition from continuous echo to an area of individual convective elements on the ship's radar photographs. Minor differences in the location of rain observed from the aircraft and radar echo could be due to the discrepancy in levels of observation, or to an error of aircraft location relative to the ship radar of about 2 km which for a mid-oceanic rendezvous indicates a good performance of aircraft navigational equipment and of procedures for correcting the output of that equipment. The correlation, using radar photographs taken at intervals of a few minutes, indicates that even in a complex mesoscale convective system embedded in a cluster the aircraft positions were known with sufficient accuracy to relate on-board dynamic and physical measurements to radar echoes and their development.

The vertical velocity fields measured by the aircraft's gust probe are shown by the vertical bars. The largest updraughts and downdraughts were measured at the edge of the major convective system at the start of run 2 in the transition zone from easterlies to south-westerlies, with an updraught of nearly 4 m s^{-1} at the position of most enhanced convergence and a mean updraught of 2 m s^{-1} over about 1·5 km centred at this point. Several sustained updraughts of 0·5 m s^{-1} (persisting 0·5 to 3·0 km) were found in the south-westerly regime in the south-west of the area, indicating that the development of localized convergence followed by showers within that airstream (rather than any large-scale convergence) was the main cause of any precipitation encountered there, and possibly that at the 500 ft level (on run 3 only) the aircraft was flying parallel to but marginally away from the major convergence zone whilst experiencing the rain produced by it.

The answer to suppositions such as these would probably follow from an analysis of data (including photographic data) from *all* the aircraft. It has, however, been demonstrated here that aircraft and radar data can be very effectively correlated even in a very complex situation. The next case illustrates how well data from several aircraft, as well as from radar, fit together when the mesoscale dynamics of a cloud line in the intertropical convergence zone are examined.

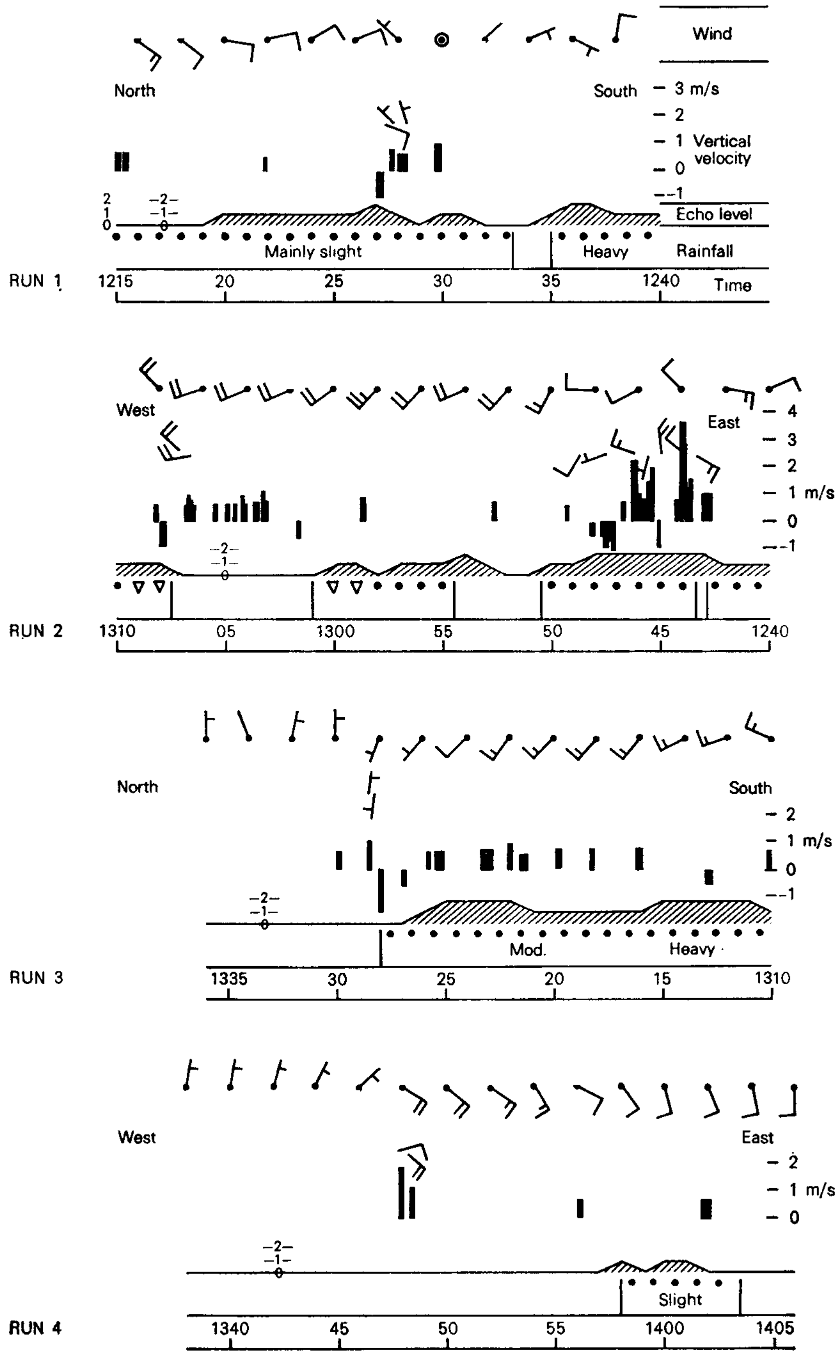

Figure 4. Aircraft wind, vertical air velocity and rainfall measurements as a function of time. Winds (usual notation) are shown at 2 min intervals, supplemented by further measurements in active convergence zones. Vertical bars show maximum updraught velocities in any 10 s period when the mean exceeded $\pm 0{\cdot}5$ m s^{-1}. Rainfall is shown as a dot (continuous) or a triangle (showers) and intensities are indicated when known. Radar-echo intensities from the *Oceanographer* are derived from photographs, taken at 5 min intervals, of cloud structure near the aircraft.

Basic GATE mission of 3 August—cloud line

A brief discussion of data obtained from two American aircraft on this day has already been presented by LeMone (1975) and some of these are used here. On this day the three gust-probe aircraft (the Electra at 600 ft, the U.K. C-130 at 1300 ft and the DC 6 at 5000 ft) each flew several traverses along straight lines through a group of cumulonimbus clouds on the northern edge of a marked intertropical convergence zone; the zone is shown in the satellite photograph (Plate III). An aircraft without a gust probe flew at 10 000 ft but data were not available from this aircraft at the time of writing. The structure of that part of the zone investigated by the aircraft is shown by the 1324 GMT radar picture (Plate IV) taken from the ship *Oceanographer* (at 8°31′N, 23°28′W). The group consisted of an almost east–west line of clouds some 130 km south of the ship and successive radar photographs show that the line maintained its identity and intensity through most of the flight period, although other lines (probably of 'feeder' cumulus clouds) were sometimes present to the south of the primary line. Figure 5 shows details of the 1324 GMT photograph with the aircraft track (which remained fixed with time), winds and temperatures (for the run from 1322 GMT to 1338 GMT) superimposed. It can be seen from the wind field that it is the variation in northerly component which is the chief cause of convergence within the cloud.

Figures 6 and 7 respectively show the vertical and southerly wind components averaged over about 5 seconds, measured by the U.K. C-130 gust probe for 5 traverses of the line over a 2-hour period. At the flight level the convection is associated with a convergence (marked S on Figure 7) of up to 6 m s^{-1} over about 7 km, the zone of convergence moving steadily south at 3 m s^{-1} throughout the period. As seen from Figure 6 the convergence zone produced up- and down-draughts of up to 4 m s^{-1} at 500 ft; the associated cloud (as noted by the on-board observer and from the aircraft radar) was also found to be moving south at 3 m s^{-1}. Figure 8 shows fluctuations of water vapour content (or specific humidity), temperature and the vertical component of air motion on the penultimate run (run 4). There was very little difference between conditions on different sides of the convergence zone, the air to the north being very slightly warmer and drier than that to the south. The intensity of the radar echo is also shown and correlates perfectly with the zones of principal updraught both near 6·9°N and between 7° and 7·1°N. The correlation with the observed rainfall is not as good because the radar was 'seeing' the precipitation at 15 000 ft, well above the aircraft and 'feeder' cumulus clouds which were producing the rain experienced at the southern end of the run.

The southerly wind component measured by all three aircraft flying in a stack on run 4 is shown in Figure 9; the location of the convergence zone is almost identical at all levels and even a consistency in some of the mesoscale structure is identifiable from level to level; for example a minimum in the southerly component can be seen at point A in the centre of the shear zone. Since the cloud was moving southwards at 3 m s^{-1}, the aircraft measurements indicate that at the 500 ft level air was entering the cloud almost entirely from the south (at about 7 m s^{-1}), at the 1300 ft level it was entering primarily from the south at about 5 m s^{-1}, and at the 5000 ft level it was entering almost entirely from the north at about 2 m s^{-1}. The air motions relative to the cloud with a few spot-temperature measurements are shown in the schematic representation of a north–south cross-section of the cloud in Figure 10. Radar-intensity levels measured above the flight tracks from the *Oceanographer* are also shown, and there is perfect agreement between the location of the convergence zone and that of the maximum radar intensity.

This case illustrates primarily a marked consistency between mesoscale measurements from the three gust-probe aircraft as well as a good correlation again with ships' radar data.

We will next look at data from a boundary-layer mission to demonstrate a consistency between measurements of microscale features as measured by aircraft and some tethered-balloon data.

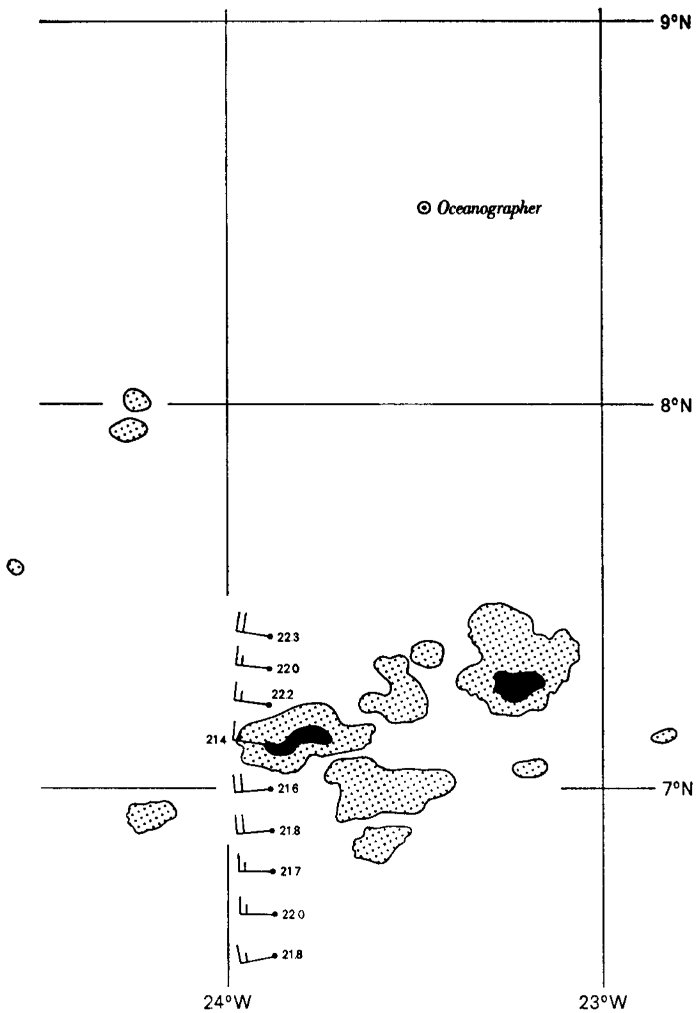

Figure 5. Details from the 1324 GMT radar photograph, annotation as for Figure 3. The flight track for the run from 1322 to 1338 GMT is shown, with wind and temperature measurements at 2 min intervals. The wind direction is shown in tens of degrees.

Boundary-layer mission of 7 September—suppressed convective conditions

The U.K. C-130 and American DC 6 flew 'L'-shaped patterns at several levels between 50 ft and 2500 ft a.s.l., close to the ship H.M.S. *Hecla*, which was operating a tethered balloon with attached turbulence sensors. The legs of the L patterns were about 45 km (25 n. mile) long. Convection was generally suppressed, with small randomly distributed cumulus clouds (base at 1400 ft) which at the start and the end of the flight were just producing rain.

Data presented here are from the six runs along-wind (over the same track) flown by the C-130 at 100, 300, 700, 1250, 1900 and 2500 ft a.s.l. The first and second runs passed through localized precipitation, and run 6 traversed a few small cumulus clouds. During runs 3, 4, and 5 little cloud was present at all, generally 1 okta of small cumulus. Figure 11 shows representative 2 Hz vertical velocity data from one-

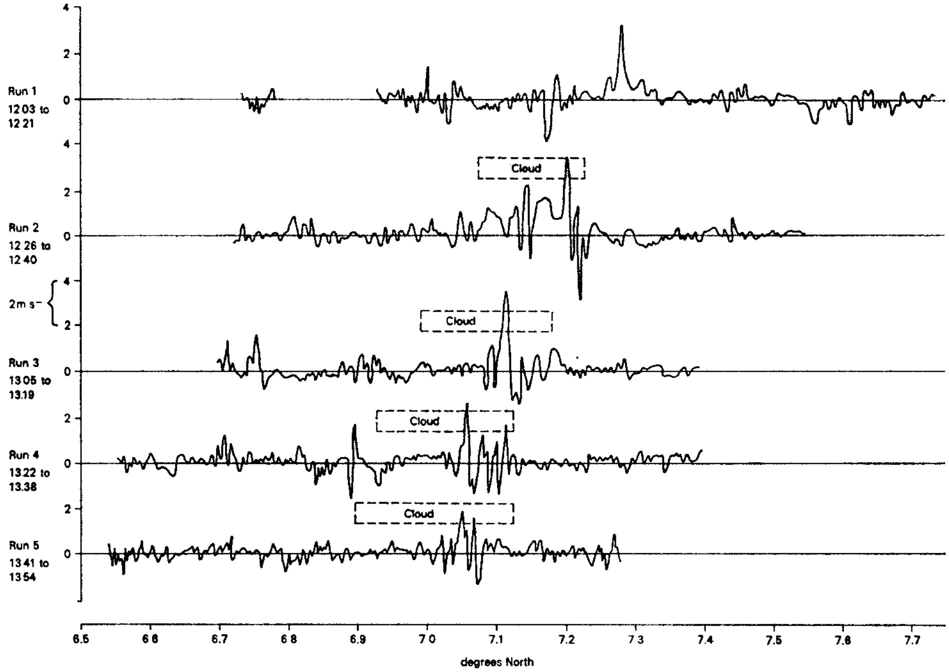

Figure 6. Vertical wind component measured on the aircraft on five sequential traverses of the cloud line on 3 August, as a function of latitude. The location of the principal cloud line on the last four runs is also shown.

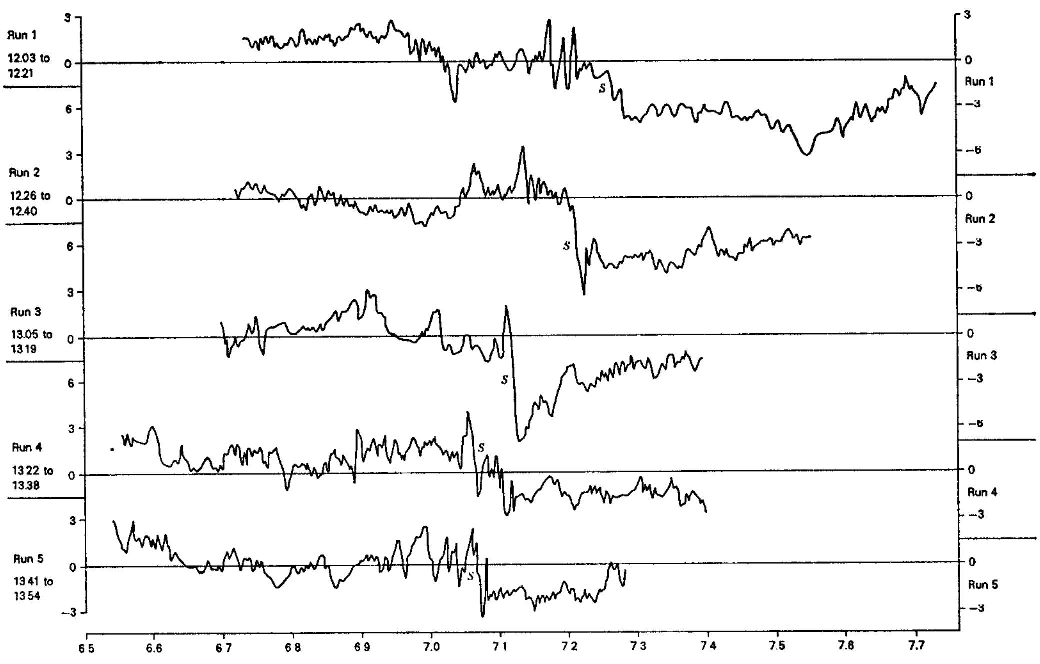

Figure 7. Southerly wind component measured on 3 August as a function of latitude. The major shear zone is annotated 'S'.

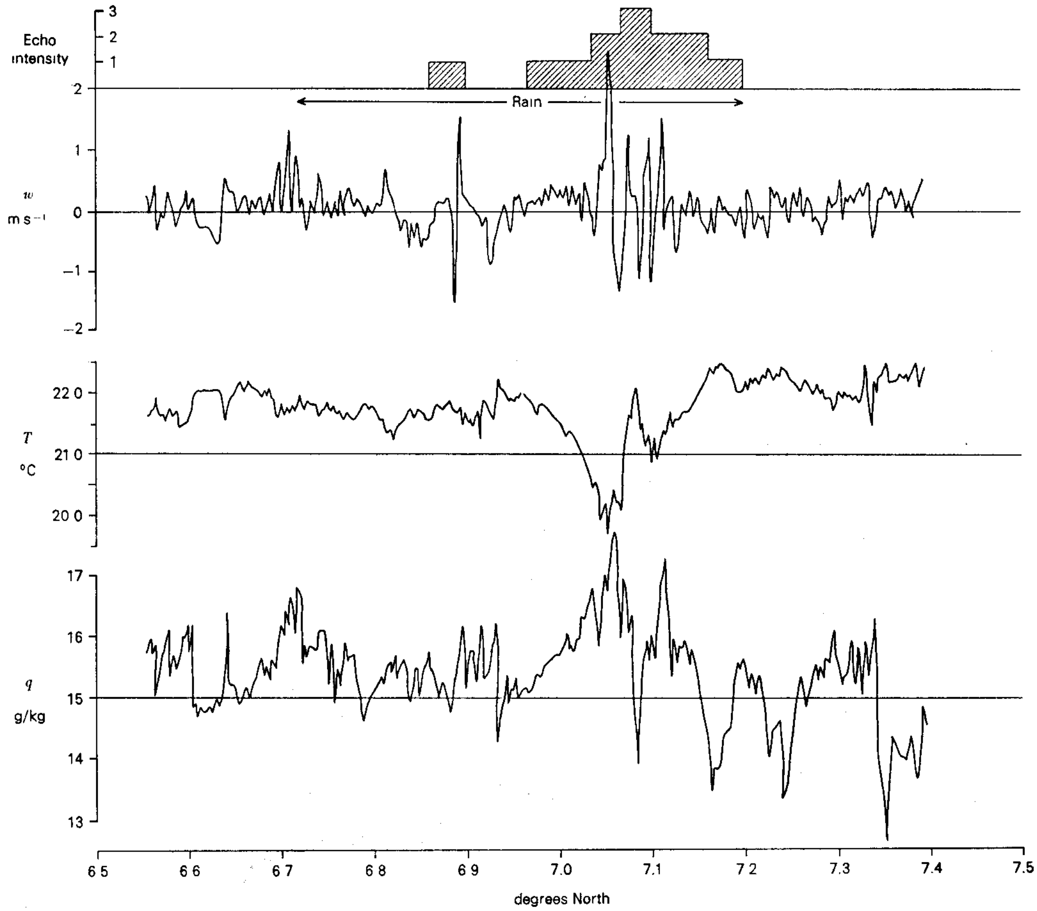

Figure 8. Profiles (as a function of latitude) of the vertical component of air motion, temperature and specific humidity measured on the penultimate run (1322–1338 GMT) by the aircraft. The radar intensity is also shown, as derived from the 1324 GMT data from the *Oceanographer*.

minute sections of each run. It can be seen that above the 300 ft level the amplitude of the high-frequency content decreases, and (except in cloud) by run 6 only longer-period oscillations (of about 1 km wavelength) were evident. Although convective conditions appeared to be highly suppressed during the middle of the flight, significant mesoscale perturbations in temperature and water vapour content were still in evidence as are shown by the data from run 3, (Figure 12), and are perhaps indicative that the properties of the air at sub-cloud levels had been modified by precipitation which had fallen earlier.

The vertical fluxes of momentum $\rho\overline{u'w'}$, heat $\rho C_p\overline{w'T'}$ and latent heat $\rho L\overline{w'q'}$ are shown in Figure 13 as a function of height; u', w', T' and q' are respectively the perturbations in horizontal wind, vertical wind component, temperature and specific humidity. The sensible-heat flux is rather randomly scattered but in any case is an order of magnitude less than the latent-heat flux, which reaches 140 W m^{-2} at the 300 ft level. The latent-heat flux then drops markedly but is still positive at the 2500 ft level, some 1000 ft above cloud base. The component of momentum flux along the wind also decreases rapidly with height, from 0·9 N m^{-2} at 300 ft to zero at 2500 ft. Unfortunately data from the DC6 are not available,

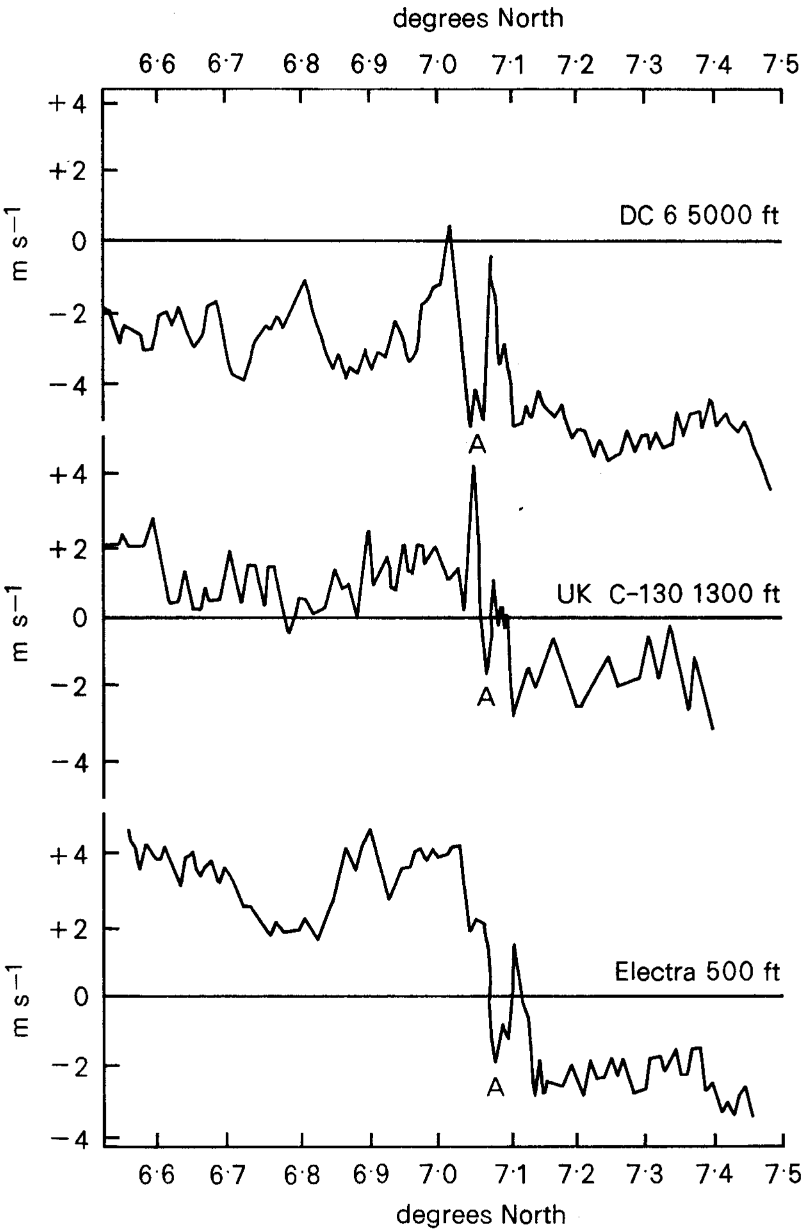

Figure 9. Southerly wind component measured by three aircraft flying in a 'stack' between about 1322 and 1338 GMT. For an explanation of point 'A' see text.

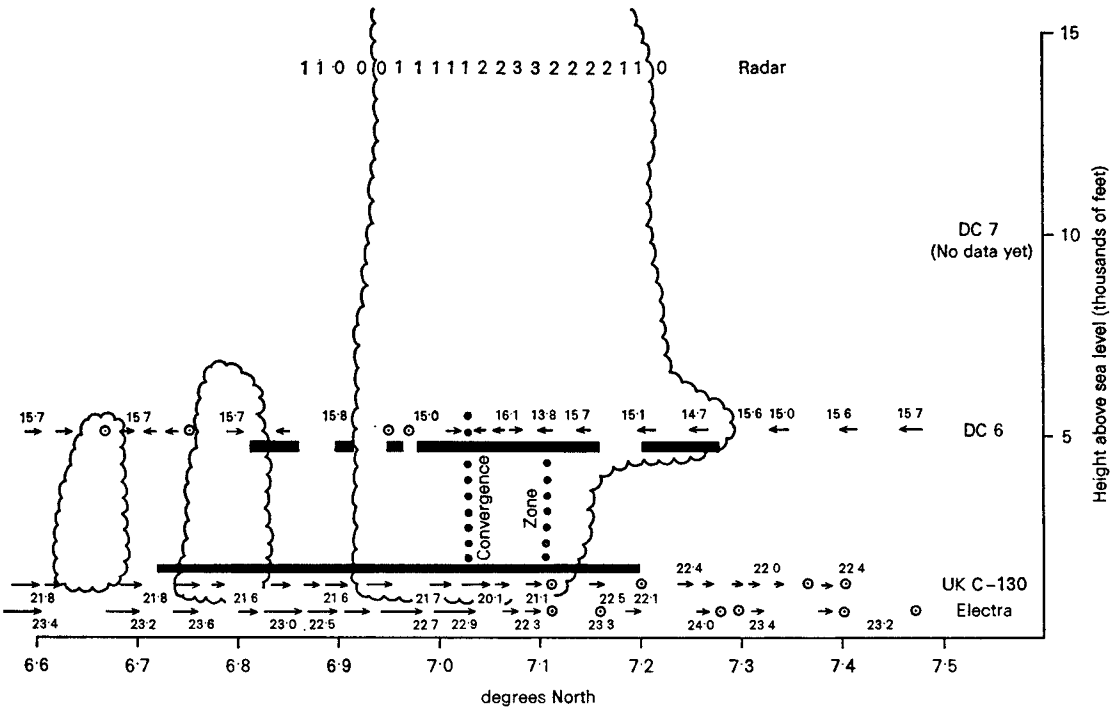

Figure 10. Schematic representation of a north–south cross-section through the cloud from the 1322–1338 GMT data on 3 August. Arrows represent the southerly component of the air motion relative to the cloud, with $1\frac{1}{2}$ mm representing 1 m s^{-1}, as measured by the three aircraft. A circle with a dot in it represents calm. Temperatures are also shown at a few locations. Solid bars represent observed rainfall (from DC 6 and C-130 only). The radar intensity is shown at the level of intersection of the radar beam with the rain.

but data gathered by the American Electra aircraft on GATE in similar conditions (with small cumulus based at 1500 ft and a surface wind of about 7 m s^{-1}) presented by Grossman (1975) give profiles which are almost exactly the same as those for the C-130, and these profiles are also shown in Figure 13. A detailed meteorological description of the microscale and mesoscale phenomena giving rise to similar profiles near and below cloud-base level can be found in a paper by Pennell and LeMone (1974). Latent-heat fluxes computed at three heights from the tethered-balloon measurements on H.M.S. *Hecla* on 7 September are indicated on the same figure by crosses for observations as near as possible in time to the aircraft measurements. Again there is good agreement between the two sets of data although the comparison is obviously limited.

Conclusions

In each of the case studies illustrated above much more data were available than has been described, and of course the analysis of the data could have been carried much further. However, it has not been the object of this paper to present in detail an analysis of convective and boundary-layer dynamics, but rather to illustrate the success of the aircraft role in GATE, the type of data gathered by the aircraft and in general how well this complements and supplements data from all other sources. It has also been shown how well data from different aircraft fit together, although this point is better established by

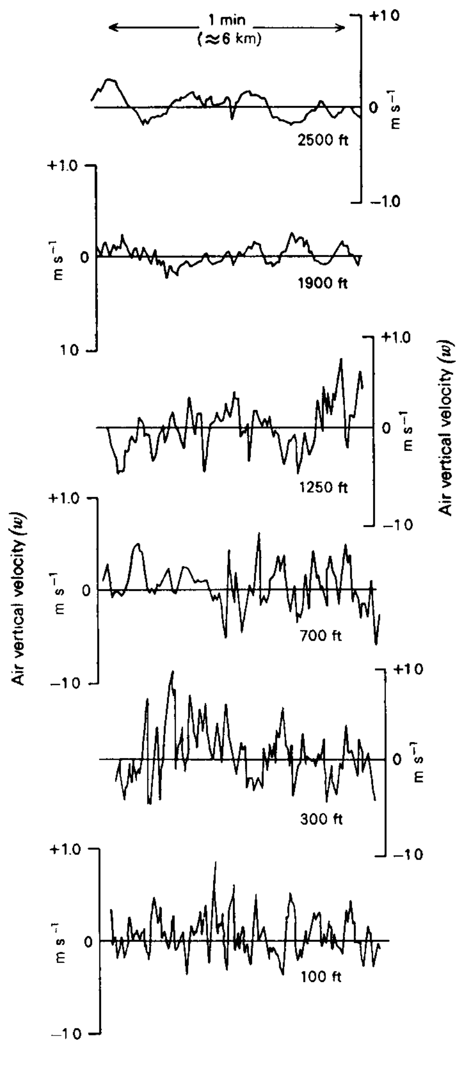

Figure 11. Representative 2 Hz vertical velocity data from along-wind runs of the U.K. C-130 on 7 September 1974. Flight levels (from the bottom of the diagram upwards) were 100, 300, 700, 1250, 1900 and 2500 ft.

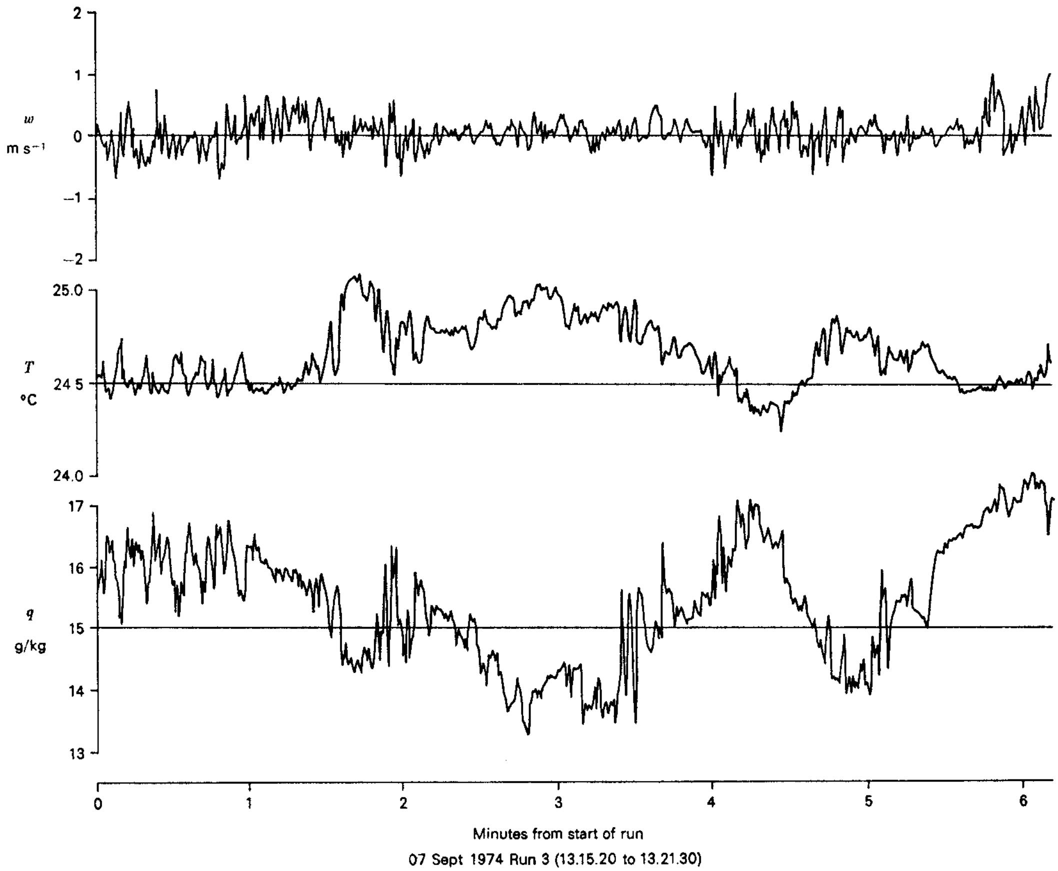

Figure 12. Profiles (as a function of time) of vertical air motion, temperature, and specific humidity from the along-wind run at 700 ft on 7 September.

examination of intercomparison data. Finally it should be emphasized that the data collected by aircraft and ships throughout GATE consist of samples collected in a variety of synoptic situations, ranging from very disturbed weather to samples in completely undisturbed boundary layers. It is the largest, cleanest volume of field data available to those working in many sub-disciplines of meteorology —boundary-layer fluxes, cloud dynamics, cloud physics, radiation, etc. The success of the project will finally rest on the use made of these data.

Acknowledgements

The author would like to acknowledge the work of and dedicate this paper to all those Meteorological Research Flight staff and Royal Air Force aircrew who participated in GATE, but especially to the data-processing team of R. Crawford, R. Ellis, D. Levy, P. Joy, S. Sherrington, R. Thackray and S. Wass who were responsible for two years of sustained effort to produce an outstanding data set available for international use. Thanks are also due to S. Nicholls for processing the boundary-layer data.

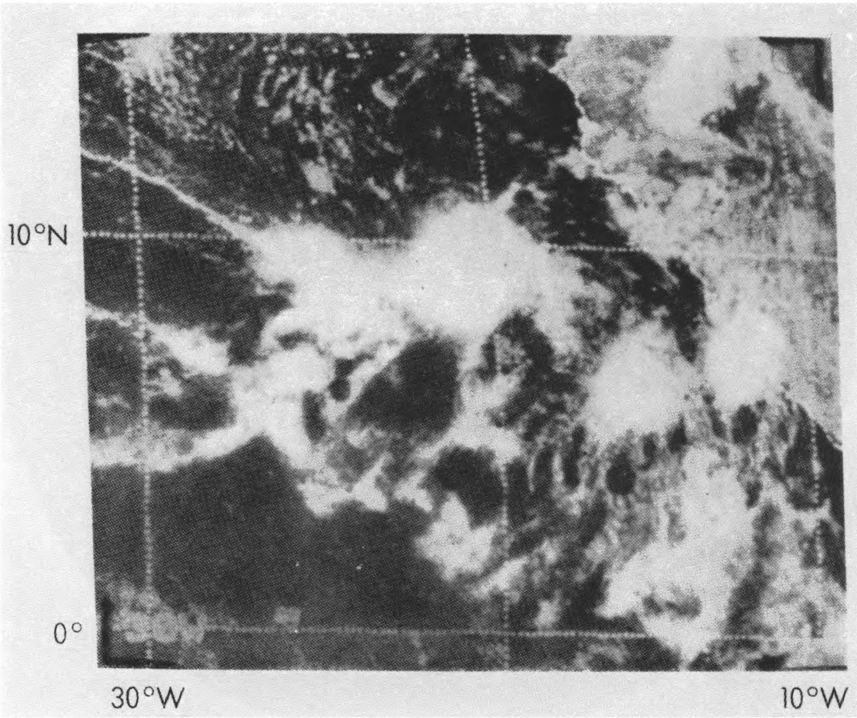

Plate I. Dumb-bell shaped cluster near 10°N at 1200 GMT on 5 September 1974 as seen from a geostationary satellite (radiation in the visible spectrum).

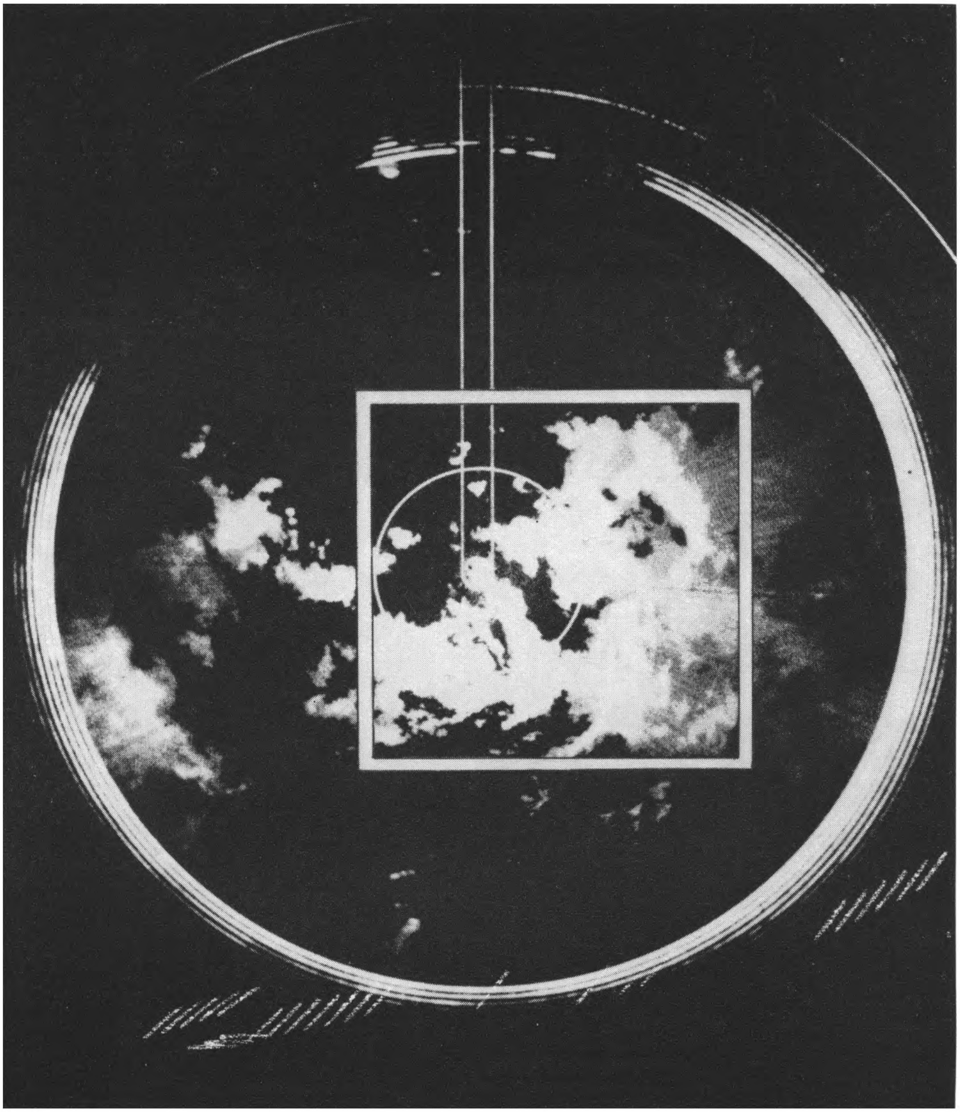

Plate II. Internal structure of cluster as seen on ship *Quadra's* radar at 1252 GMT on 5 September 1974. The ship is at the centre of the picture and true north is indicated by the two parallel vertical lines. The inner range marker (white circle) indicates a radius of 25 n. mile, and the radar range is just over 100 n. mile. In general the 'whitest' echo shows the heaviest precipitation. The aircraft flight track between 1215 and 1405 GMT is also shown by the box.

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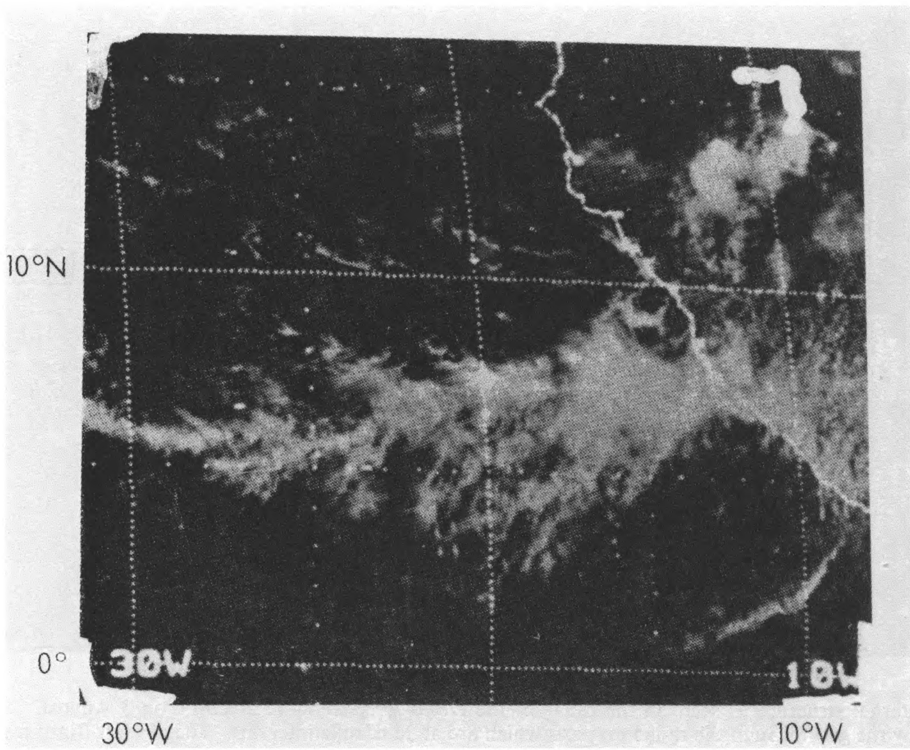

Plate III. Intertropical convergence zone cloud at 1200 GMT on 3 August 1974 as seen from geostationary satellite (visible spectrum).

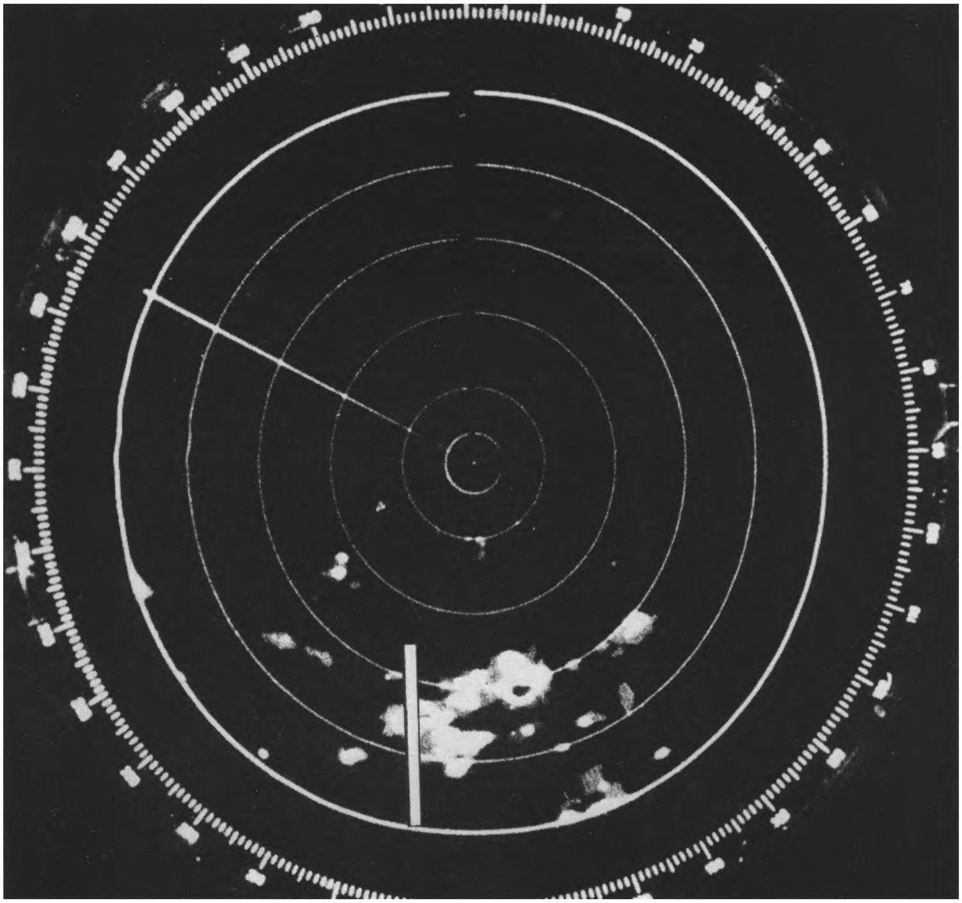

Plate IV. Internal structure as seen on the radar of the *Oceanographer* at 1324 GMT on 3 August. True north is indicated by the gap through the range markers which are at 25 n. mile intervals. The aircraft flight track, repeated between 1203 and 1354 GMT, is also shown.

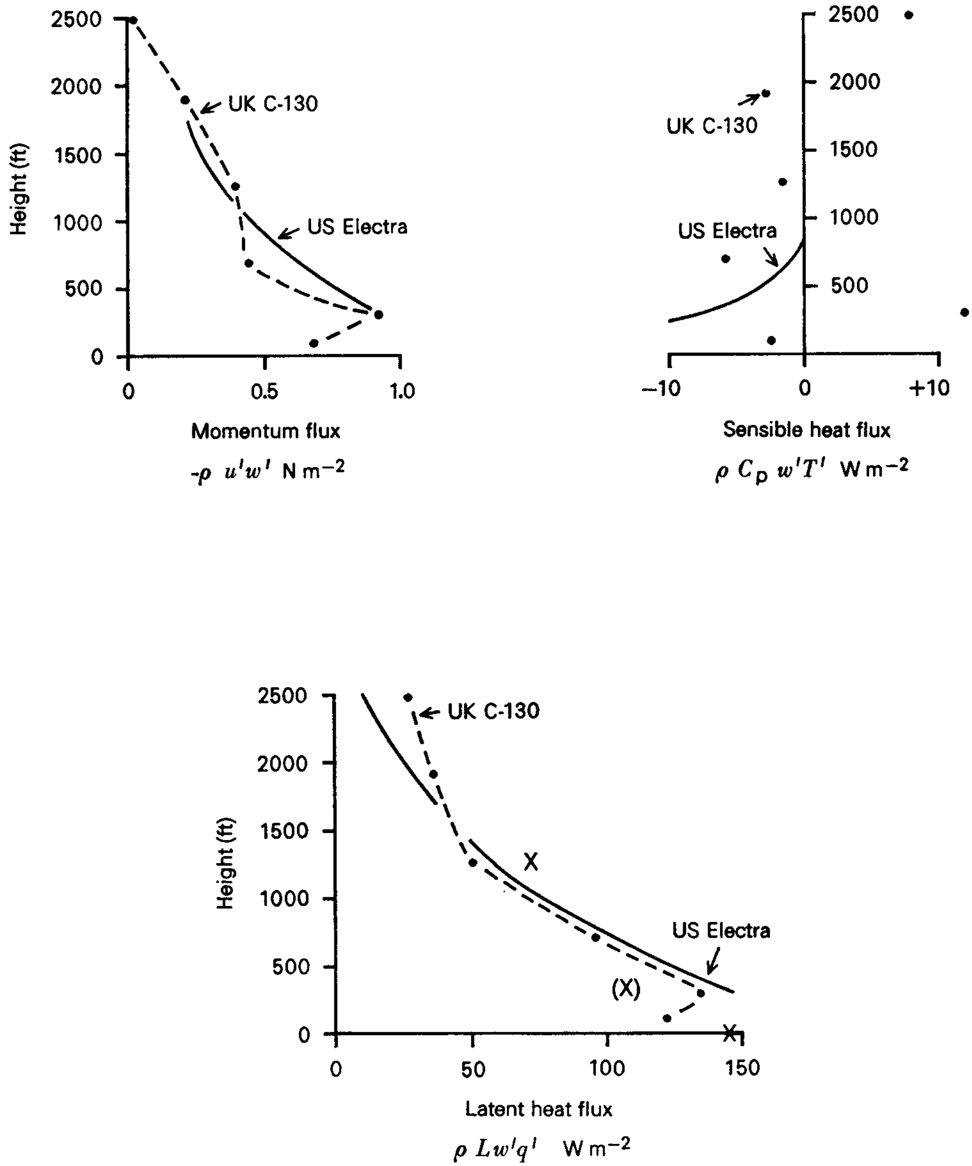

Figure 13. Profiles (as a function of height) of momentum, sensible-heat and latent-heat fluxes as measured by the U.K. C-130 on 7 September, and (from Grossman 1975) the U.S. Electra in identical conditions during GATE. Tethered-balloon measurements from H.M.S. *Hecla* on 7 September are shown by crosses. The bracketed value was obtained shortly after the flight.

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Diurnal variations of temperature and wind in the 25–65 kilometre region of the equatorial stratosphere

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Summary

A WMO sponsored comparison of meteorological sounding rocket sensors held in French Guiana in 1973 produced a set of stratospheric temperature and wind data up to a height of 60 km recorded near local midday and midnight. Measurement of the diurnal variation of these parameters was thus possible. Sinusoidal variation of temperature and zonal wind with height in the stratosphere was most noticeable from night to day, with an almost equal and opposite variation occurring from day to following night. Vertical wavelength of the main oscillation was around 11 km, with amplitudes of around 14 °C peak to peak for temperature and 16 m s^{-1} peak to peak for zonal wind. Diurnal variation of meridional wind component was more confused, with a combination of oscillations with smaller amplitude and vertical wavelength. The similarity to some rocket observations recorded from the island of Gan, in the Indian Ocean, was noted.

During the latter part of September and early October 1973 the Meteorological Office participated in the World Meteorological Organization sponsored Comparison of Meteorological Rocket Sensors, held at the Centre Spatiale Guyanais (CSG), Kourou, French Guiana in South America. The object of the comparison, organized by the Commission for Instruments and Methods of Observation (CIMO) was to resolve inconsistencies noted in meteorological observations to 60 km or higher being made by a number of countries. In essence it involved near-simultaneous firings of the different rocket systems employed by member countries, namely the American 'Super Loki Dart', the Russian M100, the British 'Skua' and the French 'Super Arcas' (of American origin), both in day-time and night-time conditions. This campaign was the second phase of a two-part comparison, the first held at Wallops Island, U.S.A. (Figure 1), during March 1972 in which France, Japan and the United States of America took part, and with Brazil and India observing.

In practice the total time required to fire all four types of rocket sequentially was approximately one hour, therefore it was assumed that changes occurring in the stratosphere over this length of time were considered negligible in order that a valid comparison of data could be made. As a check on the validity of this assumption, an extra Loki Dart was fired on five occasions, after the sequence of four, and its results compared with the first Loki Dart of the sequence. Since analysis of comparison data was performed by Leviton (1975) it is not the purpose of this paper to discuss the data in a comparative manner. However, the wealth of soundings made in a period close to local midnight and near local midday presented an excellent opportunity to investigate diurnal changes of both temperature and wind (in the form of zonal and meridional components) in the equatorial stratosphere (Table I). Data from the Russian M100 were not used in this analysis since large systematic errors were known to exist at that time.

The four types of rocket fired during the comparison were those most commonly used by the meteorological sounding-rocket agencies of the countries already mentioned. Each system carried its payload to apogee (with the exception of the M100, which liberated its payload and retardation device on the up-leg at around 50 km) between 70 and 80 km. At apogee the temperature sensor (either a fine wire filament, or a thermistor bead in the Loki Dart) and data transmitter were deployed, then descended,

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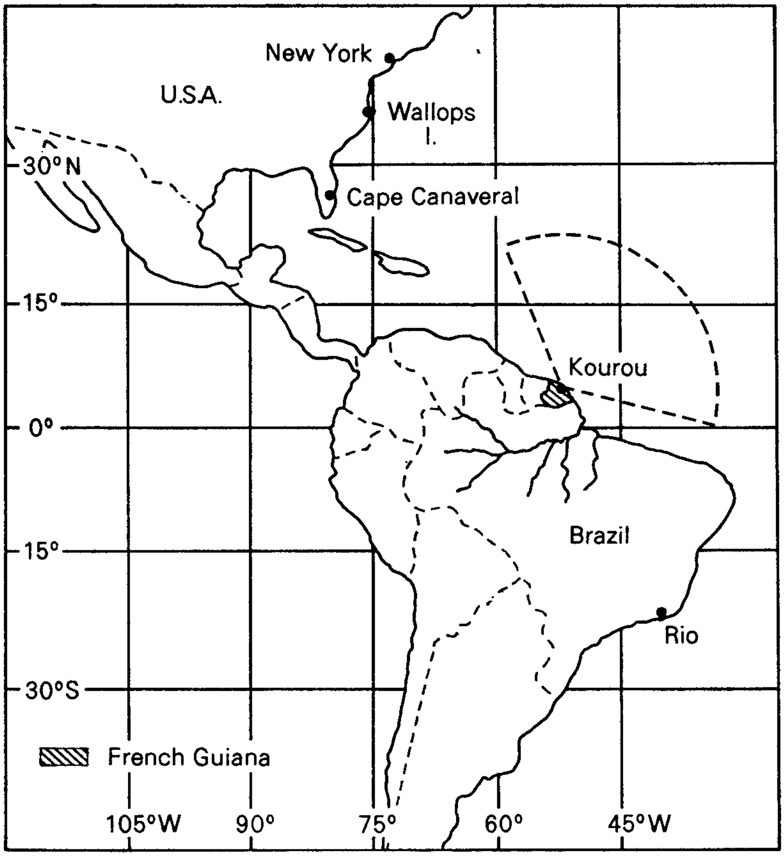


Figure 1. The position of the Centre Spatiale Guyanais, French Guiana, showing approximate range boundaries.

Table I. *Daily sequences of rocket firings.* (*All times local, i.e. GMT minus 3 hours.*)

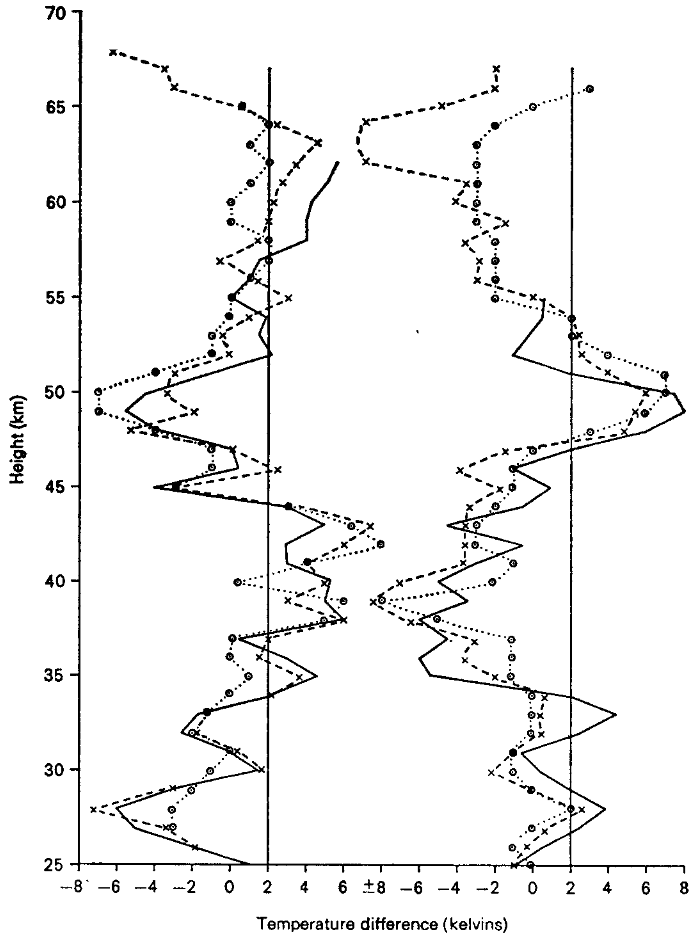
Date	Loki Dart		M100		Skua		Super Arcas		Loki Dart	
20 Sept.	1049		1142				1054			
21	0028	1213	0120	1223	0044	1239	0032			
22	0102		0112		0131		0137			
23										
24	1410	2119	1421	2129		2151	1415	2156		
25	1500	2110	1510	2122	1535	2201	1540	2206		2239
26	1104		1113		1135		1143		1214	
27	1037	2333	1106	2343	1120		1126		1158	
28		2352			0006		0011		0042	
29			0001		0024		0029			
30										
1 Oct.	0030		0040		0102		0108			

supported under some suitable retardation device, usually a silk parachute. The American system employed a Starute, a ram-inflated device rather similar in appearance to a high-level ballooon but with a collar or 'burble fence' around its horizonal diameter to increase drag. Coating these retardation devices with some radar-reflecting material enabled them to be tracked from the ground during descent, thus permitting the calculation of winds at various levels in the stratosphere. Temperature information was received at the ground via the various telemetry systems and suitably corrected. By far the most important corrections were those for dynamic heating (very large fall-speeds often well in excess of 150 m s^{-1} occur during the initial stages of descent) and for solar radiation (largest at apogee, falling off rapidly during the descent). Further corrections were applied to compensate for the imbalance of infra-red radiation between earth, space and the sensor, net albedo of the earth and cloud distribution below the sensor (daylight soundings), heat transfer between the sensor and its supporting structure and corrections for thermal lag in the sensor itself. For details of these corrections as applied to the Skua system, see Almond (1965) and Mason and Acres (1972). Wind information above 60 km was discarded for the comparison and also for this analysis since it was generally agreed that, above this level, momentum imparted to the descending payload by the rocket at separation was still present and would produce large errors in the computed wind components. Comparisons of night and day temperatures and wind profiles were always made with data from the same rocket system to eliminate errors arising from the different measuring characteristics of each payload. Values of temperature or wind component incorporating data from all systems are identified in the diagrams where appropriate.

An assessment of the mean temperature and wind variation from night to day (i.e. day observation minus previous night's observation) for each rocket system was made. There were three cases for Loki Dart, two for Skua and two for Super Arcas. A similar assessment was performed for the day-to-night variation (night observation minus previous day's observation) and the cases available for consideration this time were 5, 2 and 4 respectively. This is a small sample, but if similar variations were seen to occur using three independent measuring systems then confidence in the validity of the results would be greatly enhanced. The mean of all diurnal variations for each system is shown in Figure 2, together with average time difference between pairs of observations.

Immediately apparent from Figure 2 is the sinusoidal variation of temperature with height during the night–day comparison indicating warming near 62 and 40 km and cooling near 49 and 27 km. During the day-to-night change the exact opposite is seen to occur at almost identical levels although slightly larger amplitudes are apparent, a function of different time interval between observations. Time periods of the night-to-day sequences are about five hours longer than those for day to night, and the amplitudes of the main oscillation about 2 degrees smaller. Therefore an oscillation with a half period closer to 10 hours than to 15 hours can be inferred from these observations.

Due account must be taken of the effect of solar radiation on the sensors in biasing day-time temperature values during any night–day comparison. A typical correction with height, as employed on the Skua system, is shown in Figure 3. It can be seen that the largest correction occurs at apogee then decreases rapidly to small values below 40 km. The addition of a further 20 per cent (a typical correction for Kourou) was to take account of the reflection of solar radiation from the earth's surface. This albedo was computed giving due consideration to the type of surface in a circle of 500 km radius below and centred on the sensor, and the quantity and type, hence the reflectivity, of any clouds in this area. All four countries adopted various values for albedo, as used in their normal correction procedures. This accounts for systematic differences prominent above 60 km between pairs of observations. The oscillatory characteristic of the temperature profile is maintained however, despite these differences, with nodes at nearly equal height levels. This infers that variation in corrections for solar radiation below 60 km is not significant and the resulting diurnal oscillation is real. Small-scale differences



Key system	Night to day (day minus previous night) Ascents	Period (Hours)	Day to night (night minus previous day) Ascents	Period (Hours)
—— LOKI	3	14·1	5	10·7
×---× SKUA	2	15·7	2	9·6
•·····• ARCAS	2	15·7	4	10·1

Figure 2. Diurnal variations of temperature with height recorded by three different rocket systems during the CIMO comparison 1973.

between profiles demonstrate the rapid changes of temperature with time at certain levels. These are produced by a mixture of gravity waves of shorter unknown periods of oscillation and with varying vertical wavelengths. One oscillation with a vertical wavelength of 6–7 km is apparent in both day–night and night–day profiles with nearly equal and opposite amplitudes detectable up to at least 45 km. Above this level the profiles become confused, although small oscillations with similar vertical wavelengths are apparent in places. Roy *et al.* (1972) noted during an intensive night-time series of Skua firings from the island of Gan in the Indian Ocean in the autumn of 1972, that this short vertical wavelength fluctuation was a common feature on comparison of dusk/dawn soundings, with typical amplitudes of 4 K in the 30 to 40 km region.

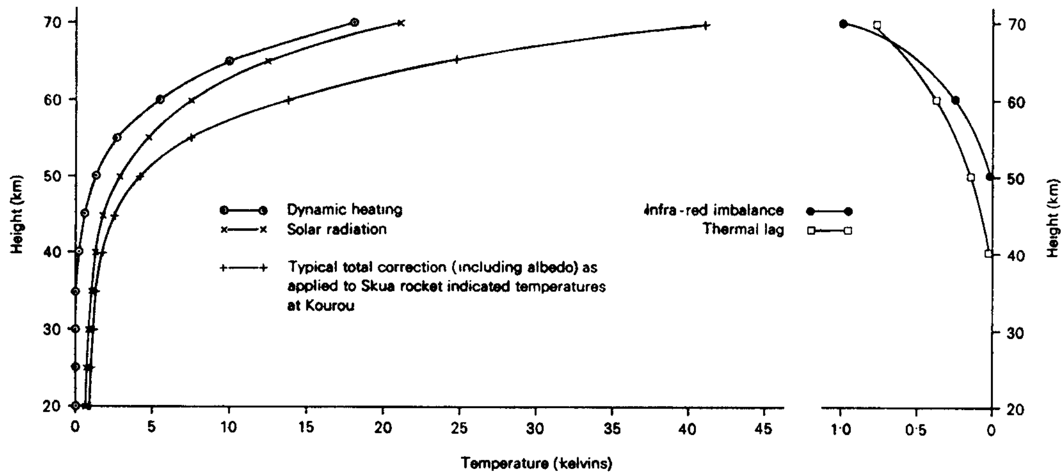


Figure 3. Principal corrections to temperature as applied to the Skua system. The curves on the left of the diagram (dynamic and solar radiation correction) are subtracted from the indicated temperature and those on the right (infra-red imbalance and thermal lag corrections) are added.

Individual daily mean temperature profiles are shown in Figure 4, together with the total period of day and night appropriate to each sounding. Some modification with time of the general profile shape is evident although the consistency of the major oscillation is reassuring. On each ascent the number of rockets making the mean profiles is indicated; the Loki Dart plot for night–day (21st) is included solely for the sake of continuity. Figure 5 shows the difference between mean profiles of day- and night-time zonal and meridional wind components. Reversal of westerly flow aloft to easterly flow below 41 km is well marked. Consistency between rocket systems seems good despite the use of two different retardation devices (two because the British Skua and the French Arcas employ parachutes with similar fall characteristics). Once again time difference between soundings may well account for much of the variation between profiles from the three rockets. Differences between day and night are clearly seen on both zonal and meridional component profiles, with positive and negative changes occurring at similar heights, displaying the marked oscillatory characteristic once again. Night profiles of meridional components exhibit very well-pronounced oscillations with vertical wavelengths between 5 and 7 km at 30 km, increasing to around 11 km above 42 km with a corresponding sudden increase in amplitude. Day-time profiles show similar fluctuations around 30 km but generally in antiphase with the night observations. Above 42 km large vertical wavelengths appear non-existent and the 5 to 7 km oscillation persists to at least 60 km. Discrepancy occurs between Skua results and the others above 60 km because momentum imparted by the rocket to the parachute is still present. The other rocket systems liberate their payloads at much higher altitude and therefore are affected by this bias to a lesser degree.

It was noted from the Gan observations of 1972 that short-time-period oscillations of meridional components over a period of 1 to 2 hours were a regular feature during the night and would presumably occur during the day, although no such observations were made in day-time during that experiment. Similar fluctuations appear to be also present in the Kourou observations and may well account for much of the difference between meridional component profiles. Again, however, the slightly different time of day or night involved for each pair of soundings is an equally important factor.

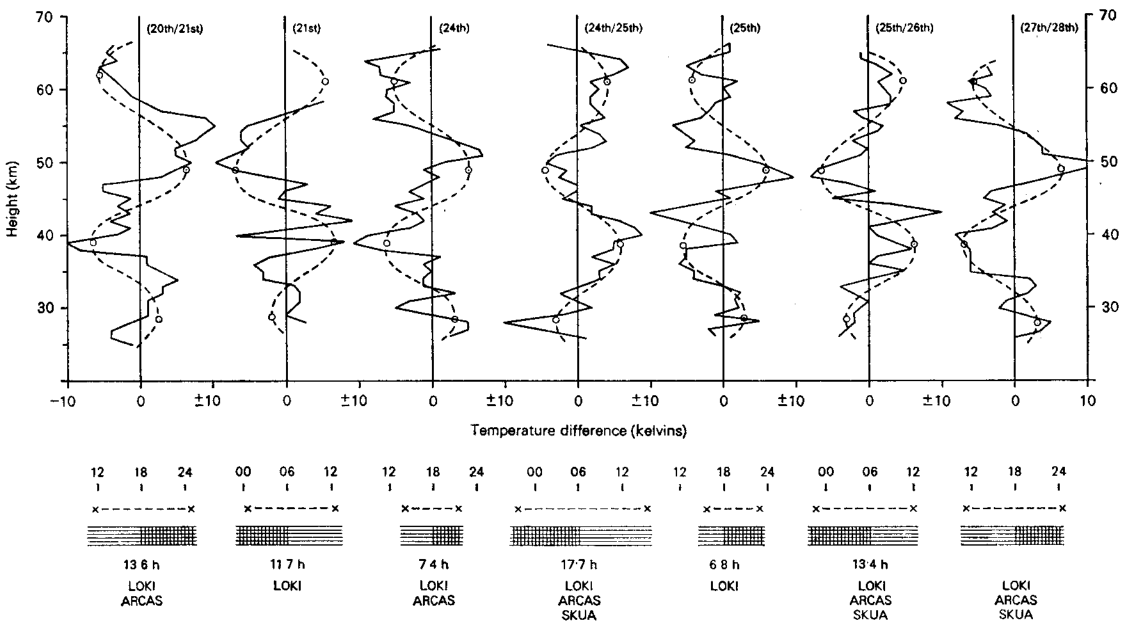
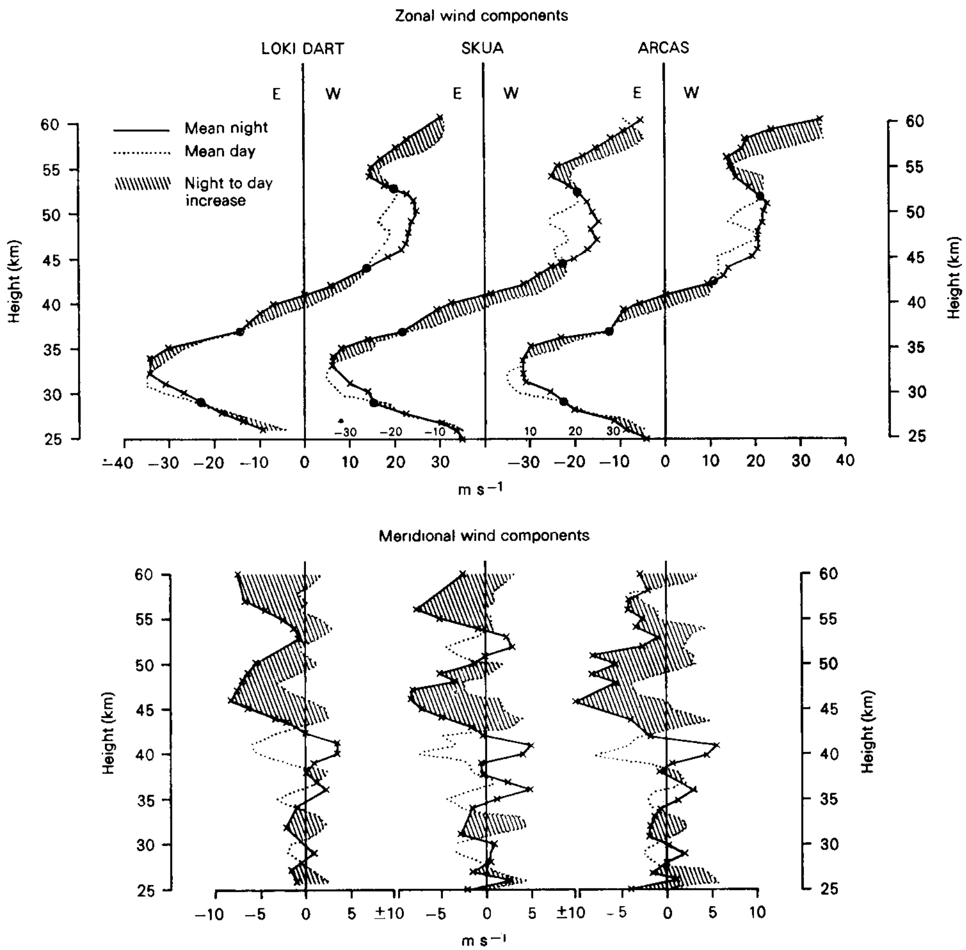


Figure 4. Individual daily mean diurnal variation of temperature. Dotted curves are simplified sine waves, constructed by eye with maximum amplitudes and constant height nodes taken from Figure 7 (a).

Figure 6 displays the actual diurnal variation with height of the data used in Figure 5, and, once more, a pronounced sinusoidal oscillation is apparent in the zonal component plots with vertical wavelength of around 18 km and an amplitude of 7 or 8 m s^{-1}. The similarity to temperature variation curves (Figure 2) is most striking, even to the superimposition of a 6–7 km vertical wavelength oscillation. Meridional component variations, on the other hand, do not show any large oscillatory characteristics; however, the 6–7 km wavelength appears to be present, at least up to 45 km. Above this level profiles become very confused, with many small wavelengths present, but a generally positive bias is present on the night-to-day periods and a negative between day and night.

Mean temperature and wind variations from the combination of the three systems appear in Figure 7 by way of a summary. From the foregoing results it would appear that the amplitudes and vertical wavelengths of the main oscillations in temperature and zonal wind component seem closely related, especially in the 25–55 km region of the stratosphere, with a change of 1 degree apparently corresponding to a variation of around 1 m s^{-1} in zonal wind component. The amplitude of zonal component oscillation is seen to increase with height, a result to be expected if energy dissipation with height is assumed to be negligible. This rate of increase is inversely proportional to the square root of the density of the environment although modification through absorption in critical layers (sudden changes in lapse rate) can occur.

Taking the 6–7 km oscillation up to a height of, say, 52 km there seems to be generally negative correlation between meridional and zonal components and with temperature variation. Above this level, meridional components appear quite independent of changes occurring in the other two parameters. The characteristic of the main oscillation generally agrees with that predicted by tidal theory developed by Lindzen (1967) which shows that for a dominant diurnal oscillation, vertical wavelengths



	h min	h min	h min	
Mean night time	(7) 23 36	(6) 23.49	(7) 00.00	LOCAL
Mean day time period	(6) 12.32	(4) 12 47	(5) 12 47	LOCAL

Numbers in brackets indicate total number of ascents

Figure 5. Differences between mean day and night profiles of zonal and meridional wind components (three rocket systems).

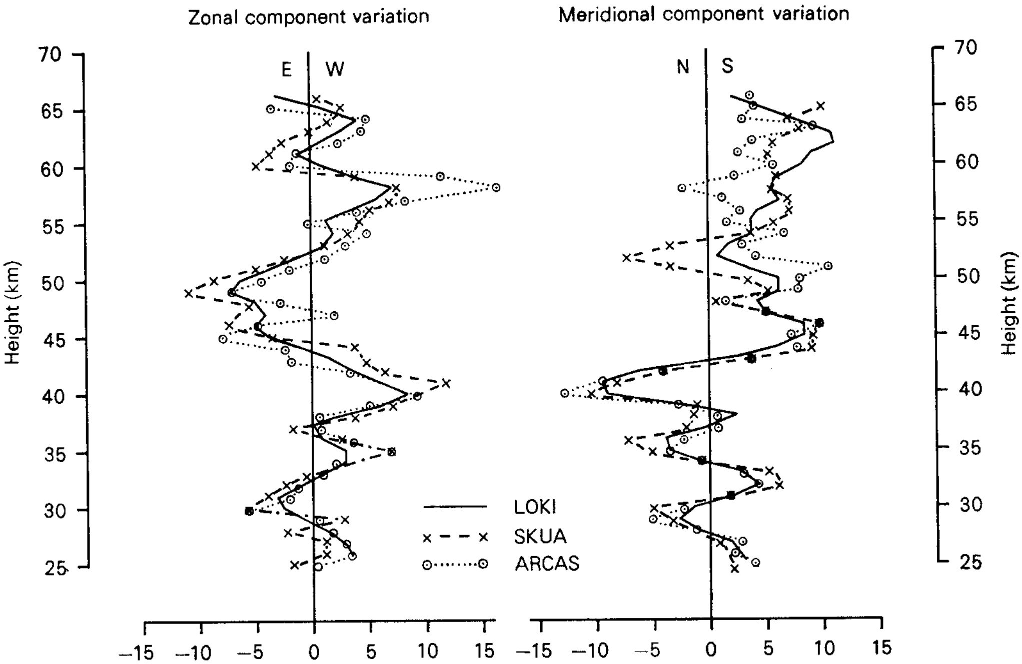


Figure 6. Variation with height of diurnal changes in zonal and meridional wind components (night-to-day increase). Components are in m s^{-1}.

very similar to those present here would be expected, with large variation in amplitude and phase occurring with height. Detection of a diurnal downward progression in the height of the oscillation, also predicted by this theory, is not possible because of the large time differences between night and day observations. The Gan observations in 1972 did, however, show this downward progression in the oscillation of both temperature and zonal wind component variation between 40 and 60 km during the 10 hour period from 1900 to 0500 local time. Any assessment of the length of the oscillation time period is obviously affected by the frequency of observations defining that oscillation. In this case the nearly equal magnitudes of the variation (amplitude) in temperature and zonal wind during night to day and day to following night imply that a diurnal mode is dominant. Let us consider a simplified sine wave oscillation (constructed by eye) in temperature variation with height with maximum amplitudes at the heights and times indicated in Figure 7 (dotted curve) with nodes at constant height level. If this oscillation is now superimposed on the daily curves of Figure 2 (dotted curves), suitably modified to take account of the time intervals between night and day observations, then the resulting oscillation has amplitudes similar to those of the actual profiles (ignoring small-scale fluctuations). If a semi-diurnal oscillation were present as the main mode then the magnitude of the amplitudes indicated in the profiles for the 24th and 25th in Figure 2 (7·4 and 6·8 hours observation periods repectively) would suggest a very small amplitude for the profiles of, say, the 20th/21st and 27th/28th (13·6 and 12·6 hours duration between observations). It follows further that since the 12–13 hour period amplitude is only slightly greater than that of the 6–7 hour period, temperature change with time is not uniform and the largest rates of change appear to occur near the start and end of the periods under observation. The change

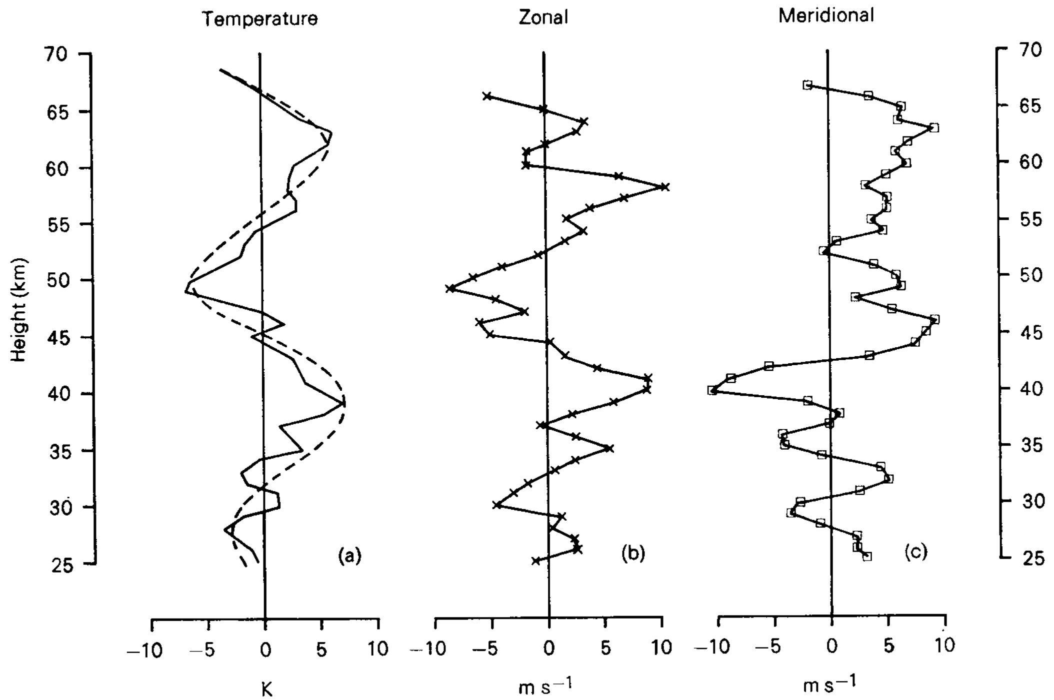


Figure 7. Mean temperature and wind variations from the three rocket systems (night-to-day increase). Dotted curve in (a) is a simplified sine wave constructed by eye.

indicated on the profiles for day to night (25th and 27th/28th) certainly suggests an irregular rate of change, with largest values near to local midnight. A similar rate of change occurred on all three night-firing sequences at Gan with largest temperature changes occurring in the layers above 35 km between 2200 and 2300 local time.

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International Conference on Climate and History, University of East Anglia, 8–14 July 1979

By D. E. Parker

(Meteorological Office, Bracknell)

About 250 participants from over 30 countries gathered for a week at Norwich for the International Conference on Climate and History. The subject matter, presented in over 50 half-hour lectures and 15 shorter contributions, aimed to cover the whole range of disciplines involved in the study of past and present climate and of the complex interactions between climate and human activity.

The conference began with review papers on scientific and historical methods of climate reconstruction, including a summary of past climates. The first paper, a concise presentation of the use of tree-ring evidence, set the tone of the conference: one of marked progress but of even more marked uncertainty because of the complex relationships involved; the reconstructions of weather in the U.S.A., from tree rings for years with meteorological data, are far removed from the observed meteorological conditions although positively correlated with them. The review of glaciological evidence of recent climatic change stressed the problems of timing—for instance, how long does it take for a glacial moraine to become able to support the growth of trees? The summary of pollen analysis laid strong emphasis on the complexity of climate–vegetable interactions, for even at the present time species are not in equilibrium with climate; in Finland certain trees are becoming established progressively farther north at a rate far in excess of what might be expected from current changes in climate. Isotopic data, too, can give ambiguous results; oxygen isotope ratios in ice-caps depend not only on the temperature but also on the atmospheric circulation when the snow falls.

Having been enlightened as to the problems of scientific analysis of past climate via proxy data, the conference was then presented with a summary of the problems of analysis of historical records. A warning was issued concerning the use of syntheses of ancient records by recent compilers, as these volumes may contain many errors and omissions; however, at the end of the conference it was admitted that without these compilations our knowledge would be much scantier than it is. There are also linguistic and cultural problems with old records. What do 'drought', 'haze', 'fog' mean? When exactly is summer? (Many writers probably mean May to July—August and September were 'autumn' (German *Herbst*, cf. English harvest)). Has an author used over-exaggerated language? A small group was formed to begin a study of these problems by means of a 'content analysis'.

Notwithstanding these difficulties, some speakers appeared well satisfied with the quality of their data, notably Dr C. Pfister of Switzerland, who has been carefully sifting Swiss documentary evidence for 1525 to 1825, using only primary sources (i.e. original reports) covering for example crops, vine yields and freezing of lakes. Later in the conference Professor G. Manley presented similar work for Britain for 1550 to 1658.

The review of archaeological evidence for climatic change further stressed the difficulties of interpretation and the complexities of cultural response to climatic variations, but it included an interesting presentation of the relics of past Eskimo settlements on islands in the Canadian Arctic, with tentative results which agreed with the generally accepted warmth 1000 and 4000 years ago.

Professor H. H. Lamb's lecture illustrated the spatial and temporal variability of climate, mainly for the benefit of participants from the historical disciplines. A temperature anomaly chart for summer

1976 made the many British delegates realize that our hot summer was very localized. It was estimated that the coldest year in England since 1700 would, other factors being equal, have generated twice the fuel demand for the warmest year, the corresponding factor for decades being 1·2.

All the review papers except that on isotopes were published beforehand by the Climatic Research Unit of the University of East Anglia, though some authors modified their views considerably for presentation.

Most of the remaining papers were on specific geographical and disciplinary areas. Early instrumental data have been used to produce maps for China and north-west Europe, and have been applied to studies of the Rocky Mountains, Hudson Bay, Australia, and New Zealand. Documentary evidence has been employed in studies of rainfall over Africa, India, China and parts of South America. The inadequacy of many of the records was made very clear.

Tax relief records were used to infer the 17th/18th century climatic conditions in Norway, and the authors of this work deduced that the 'Little Ice Age' period of cold climate began a century later in Norway than in the Alps. Some participants questioned the relationship of tax relief to climate, but the suggestion that the colder climates were not contemporaneous in different regions was supported by tree-ring studies indicating warmth in the 'Little Ice Age' in the western U.S.A. By the end of the conference Professor Lamb summarized the general feelings on the 'Little Ice Age' very well by saying that the term was a convenient one for a certain period of climatic behaviour and must not be taken literally to mean increased coolness everywhere.

Great difficulty was often found, and great ingenuity shown, in attempts to relate population statistics (births, marriages, deaths, migrations) to climate. Even the link between climate and agriculture was found to be complex, and to deduce climate from agricultural statistics, study of marginally viable locations was necessary. Reports of harvests were shown to be influenced dramatically by the political mood of the day: when Edward III came to the throne in 1327 there was a sudden improvement in the reported harvests!

A variety of papers illustrated the specific effects of floods, droughts and severe frosts on communities or on specific events in past centuries. The coverage was virtually world-wide. The influence of such catastrophes was, yet again, very dependent on the cultural and political environment and on agricultural practices. Some past societies may have been too inflexible to withstand the vagaries of climate. An important concept was that the impacts of climate are affected by the popular perception of climatic variation—thus the notion that 'rain follows the plough' westward in the U.S.A. helped to set the stage for the dust-bowl of the 1930s.

Several papers tackled the subject of variability of rainfall and temperature, the resulting effects on man in modern times and the need to take steps to reduce our vulnerability to such climatic variability. Included among these were two presentations by delegates from the Meteorological Office. Mr D. M. Houghton discussed the effects of the recent severe weather in Britain, which he estimated cost the nation in the region of £500 million, £300 million of this for extra fuel consumed, mostly for space heating. The cost to the National Bus Company was £12 million. A 'misery index' defined on the basis of combinations of cold and wet half-months showed that January up to mid-June 1979 was the most miserable such period for over 150 years. But a table of extreme cold, warm, wet and dry months and seasons in the last 20 years was used to illustrate that in recent years the extremes experienced have not exceeded expectations based on the past three centuries. Mr D. E. Parker used 5-year mean charts of 1000–500 mb thickness over most of the northern hemisphere to illustrate spatial and temporal variability since the early 1950s, and to show that regional temperature variations depended on circulation changes, and almost cancelled when averaged over the hemisphere. It was also shown that the reduced average strength since 1940 of the North Atlantic surface westerlies represented an increase in frequency of occurrence of the weak westerly mode at the expense of the strong westerly mode in a bimodal distribution.

The possible effect of advancing technology on our vulnerability to climate was well illustrated by Professor M. J. Bowden by a qualitative diagram showing how the geographical spread of the burden of drought occurring in the Great Plains of the U.S.A. was changing with time: in the 1890s effects were locally large and globally negligible, at present they were evenly spread, and in the future they might well be locally small but globally severe; that is to say local catastrophes may be ameliorated by technology at a cost to the global system. Also our demand for a higher standard of living may have made us more susceptible to long-term climatic changes even though we have gained some skill in relieving the effects of short-term disasters.

It was stressed that the climatic historian needs to verify the influence of climate on past events by using known causal relationships to 'retrodict' the events. Mere coincidence or correlation of climatic and human events is insufficient. A correlation does not constitute a cause or even prove that a common cause underlies both phenomena. The notion that a correlation does constitute a cause (based on Hume's philosophical concept of a cause as being merely man's interpretation of observed correlation) was found by the writer of this report to be the basis of one participant's approach to the problem of solar influences (sunspots etc.) on the climate. In fields of research where information is lacking or only qualitative, 'results' are often largely the product of researchers' scientific philosophy. Some of the papers presented concerning earlier historical times were largely speculation.

The conference served its purpose well in stimulating thought and promoting interdisciplinary and international co-operation in the field of climate and history. The scope was so broad that several participants proposed that conferences be arranged on particular aspects or on particular eras of history. This added weight to the conclusions of the conference that there is still a very long way to go.

Notes and news

Dr K. A. Browning, F.R.S.—Special merit promotion to Deputy Chief Scientific Officer

It is a pleasure to record that Dr Keith Browning has been granted promotion to Deputy Chief Scientific Officer under the scheme which permits the promotion of scientists of exceptional ability without consequential change in their administrative responsibilities. Dr Browning was appointed to the Meteorological Office in 1966 as a Principal Research Fellow and was given his first individual merit promotion to Senior Principal Scientific Officer in 1972. From the beginning of his career in the Office he was given the task of leading the joint Office/RSRE radar meteorology group at Malvern. This was a field of research in which Dr Browning had already made significant contributions, since studying under the late Professor Ludlam at Imperial College, and at the Air Force Cambridge Research Laboratories in the U.S.A.

Under Dr Browning's guidance the Malvern group have made impressive progress in the application of radar to the investigation of precipitation processes in both frontal and shower clouds and in the interpretation of radar echoes received from clear skies, and about 50 scientific papers have resulted from this work. Dr Browning is now applying his expertise to the practical problem of improving our capability of forecasting precipitation and wind over short periods ahead of up to 6 to 12 hours. The Malvern group is at present involved in setting up a mini-network of precipitation radars covering much of England, and in processing their output so that the rainfall can be presented in an easily assimilated form in real time on a TV screen in such a way that the colour of each 5 km sided square positioned on a map of England represents the rainfall at that location. Similar arrangements have been made to process infra-red satellite data from Meteosat. In this case the different colours represent different cloudtop -temperatures. With the establishment of this new experimental data base we look forward to the optimization of its use for short-period forecasting which will be the main thrust of Dr Browning's work over the next few years. P.G.

Dr F. B. Smith—Transfer to special merit Senior Principal Scientific Officer

Dr F. B. Smith, at present Assistant Director of the Boundary Layer Branch, has been awarded a transfer to the ranks of the individual merit Senior Principal Scientific Officers. At a time when worldwide concern is focused on environmental problems, many of them concerned with the diffusion of pollutants in the atmosphere, it is fitting that Dr Smith should be released from all administrative burdens so that he can concentrate on furthering the understanding of the meteorological factors controlling the spread and deposition of material emitted from the earth's surface.

Dr Smith joined the Office in 1956 after gaining his Ph.D. in Professor Lighthill's Mathematics Department at Manchester University and spent his early career, like so many world authorities on boundary-layer problems, with the Office's research group at CDEE Porton. In 1974 he was promoted to Senior Principal Scientific Officer and subsequent to that time has progressively taken on the role in the field of atmospheric diffusion once held with such distinction by Dr F. Pasquill.

The Meteorological Office is indeed fortunate to have a scientist with Dr Smith's flair, recently illustrated in his treatment of the long-range transport of sulphur compounds, for achieving down-to-earth practical results when tackling problems in an area which can be a minefield of mathematical complexity.

P.G.

European Association of Remote Sensing Laboratories (Council of Europe)

A postgraduate Summer School on Remote Sensing in Meteorology, Oceanography and Hydrology will be held at the University of Dundee from 1 to 20 September 1980.

The school is intended for postgraduates and other research workers in the fields of meteorology, oceanography, and hydrology and for teachers in these subjects in institutions of tertiary education who are contemplating introducing more material on remote sensing into the courses within their own institutions.

The course will be concerned with the processing and interpretation of remote sensing data. The topics covered will include:

Data Collection Systems
Digital Methods and Processing
Principles of Image Interpretation
Pattern Recognition
Geometric Registration of Images and Maps
Methods of Motion Display and Change Detection
Sea Surface Temperatures and Fronts
Winds and Currents
Atmospheric Motions
Meteorological Models
Hydrology
Pollution Monitoring.

Some bursaries may be available to assist students to attend.

Further particulars and registration/application forms can be obtained from:

Professor A. P. Cracknell,
Carnegie Laboratory of Physics,
University of Dundee,
DUNDEE DD1 4HN,
Scotland, U.K.

Climatic variations: facts and causes, Erice, Sicily, 9–21 March 1980

The title of the Erice School 'Climatic Variations: Facts, Causes' (see Vol. 108, page 252) has been changed into 'Nato Advanced Study Institute on: Climatic Variations and Variability: Facts and Theories'.

The Australian climatic environment. E. Linacre and J. Hobbs.

The above-named book, which was reviewed on p. 159 of the *Meteorological Magazine* for May 1979, has now been published in the United Kingdom by John Wiley & Sons Ltd, Chichester, Sussex, and is on sale at £11.35.

Meteorological Magazine—increase in price

As from January 1980 the price of an issue of the *Meteorological Magazine* will be £1.60 and the annual subscription will be £20.82 including postage.

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NOTICES

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

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