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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.

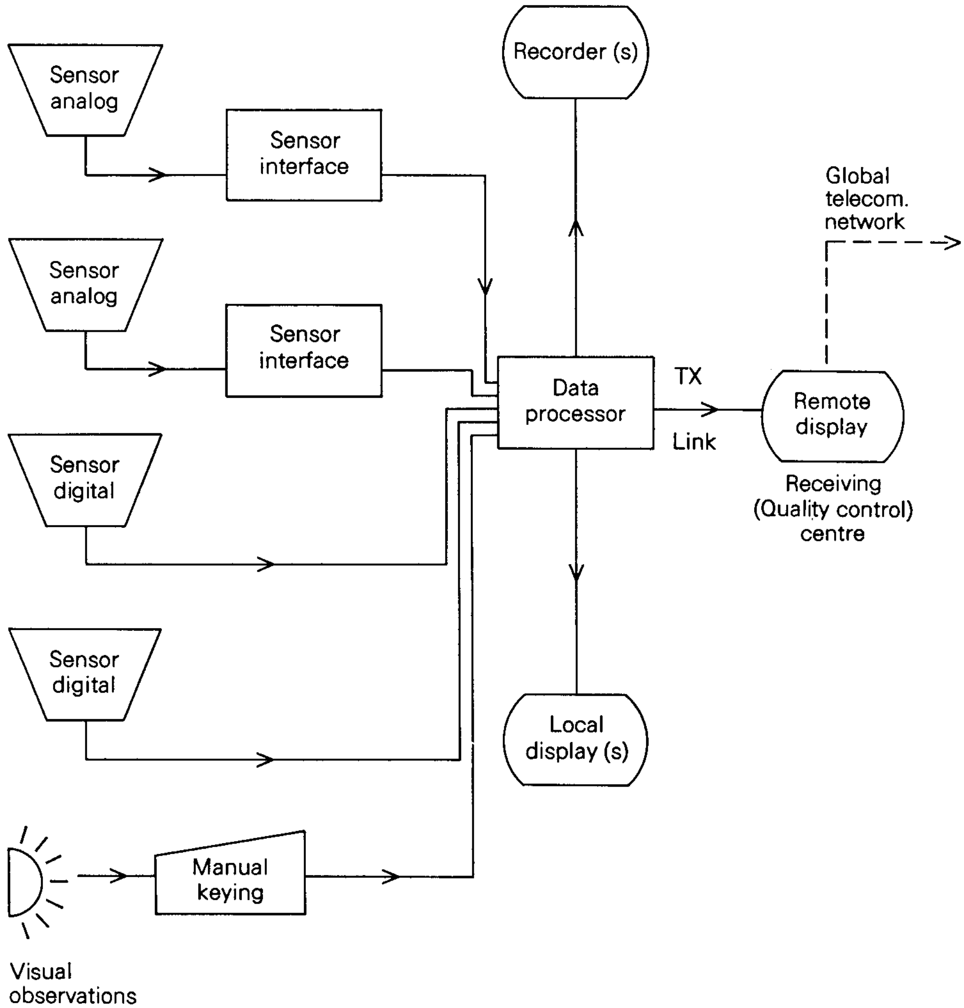

Figure 1. The essential ingredients of an automatic weather station.

(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.

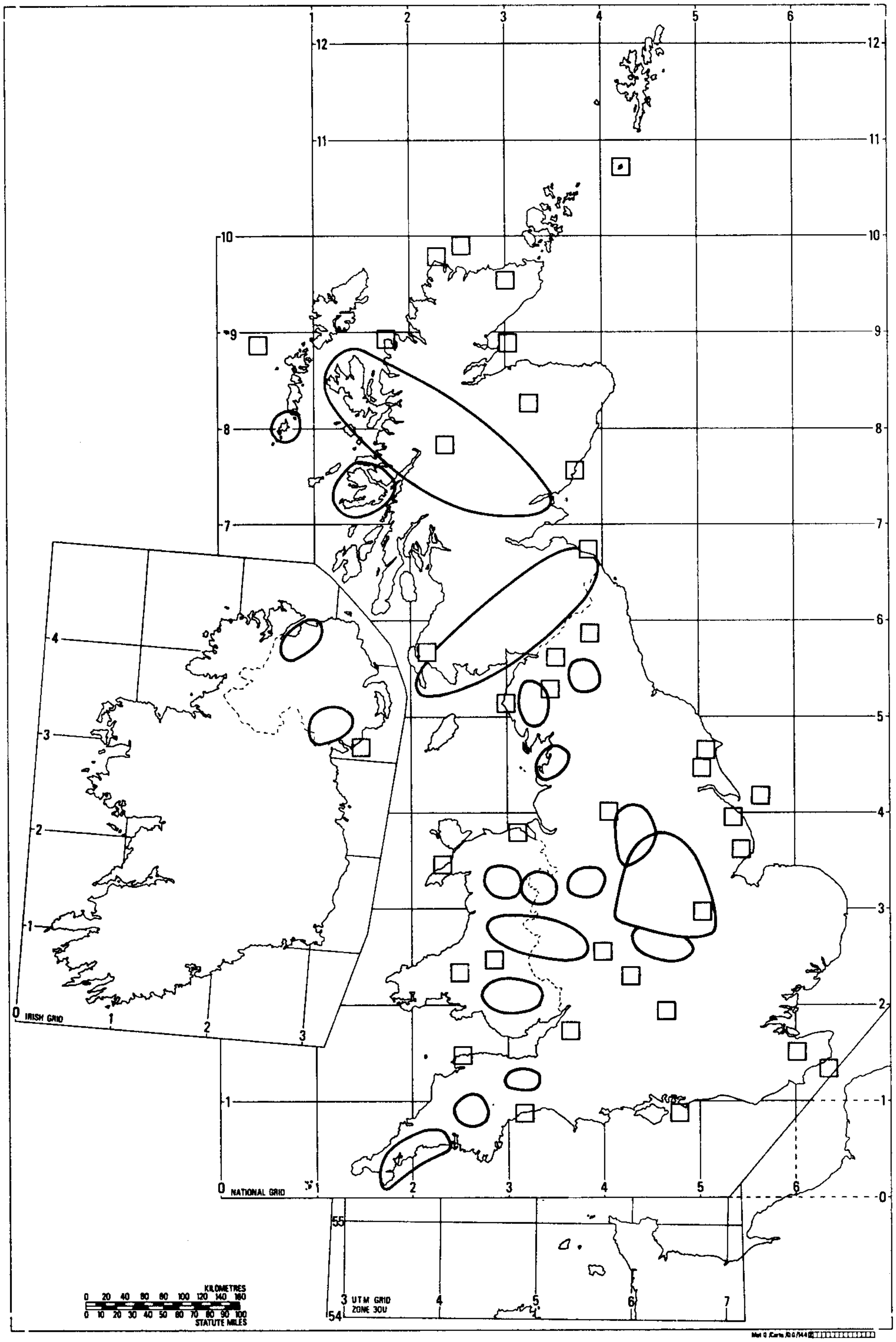

Figure 2. Stations and areas where synoptic automatic weather stations exist or are proposed.

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 ($2\frac{1}{2}$ 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

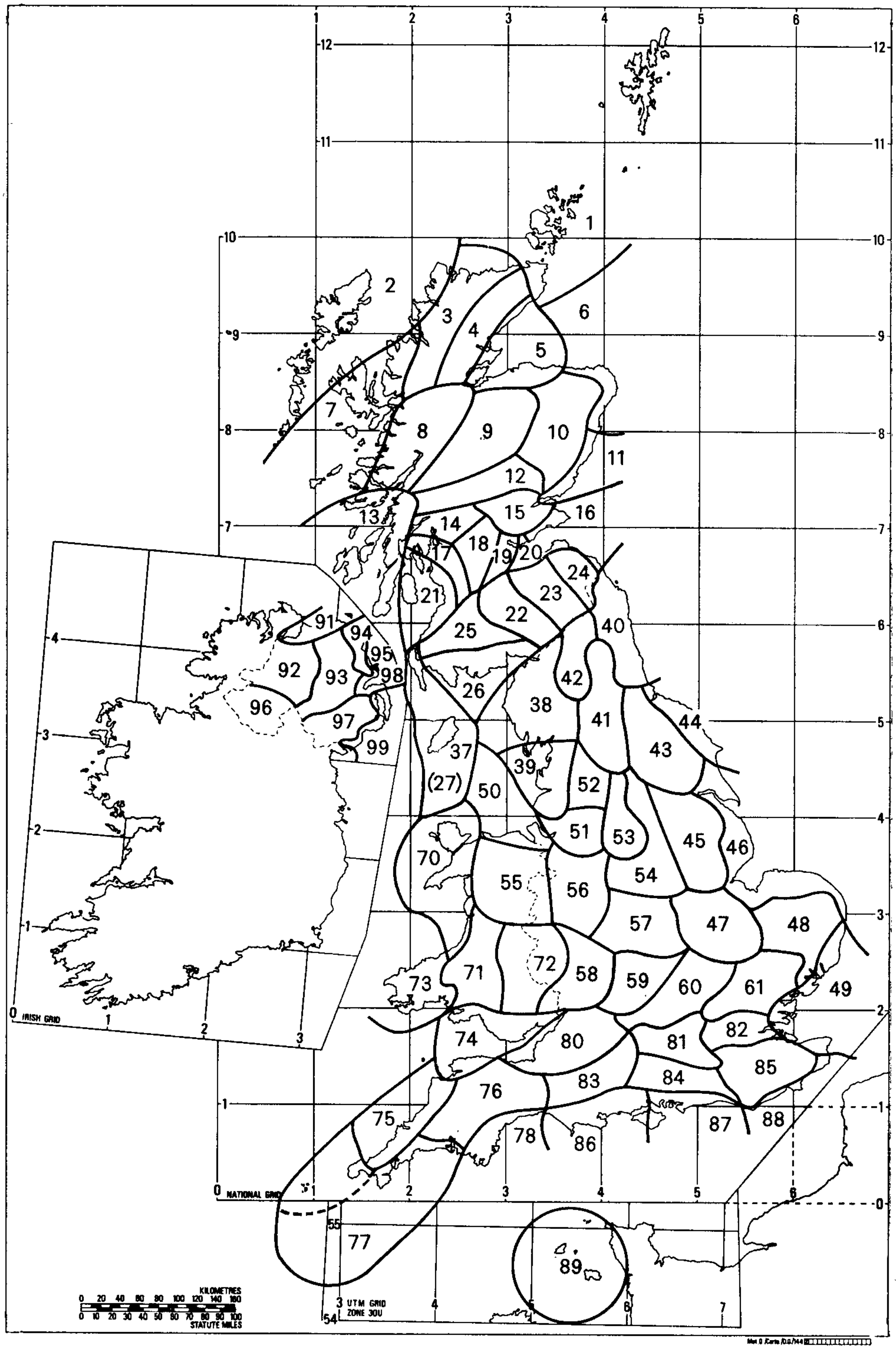

Figure 3. Climatologically distinct areas of the United Kingdom.

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:

$$R_N = H + G + E \quad \text{.. .. ..} \quad (1)$$

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

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

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.

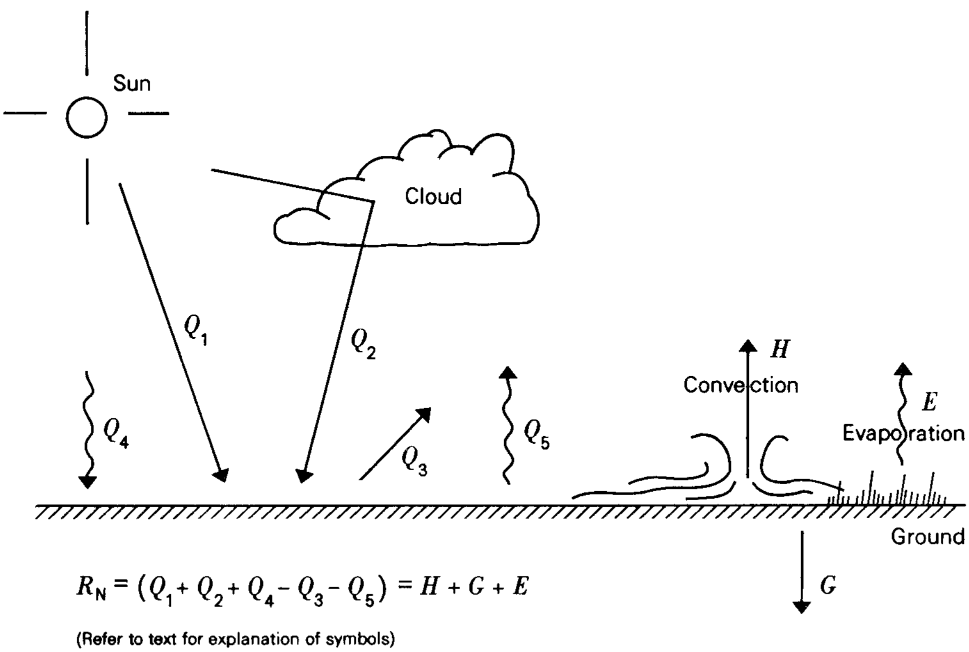

Figure 1. Principal components of the energy balance over a horizontal surface.

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

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

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

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

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

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

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.

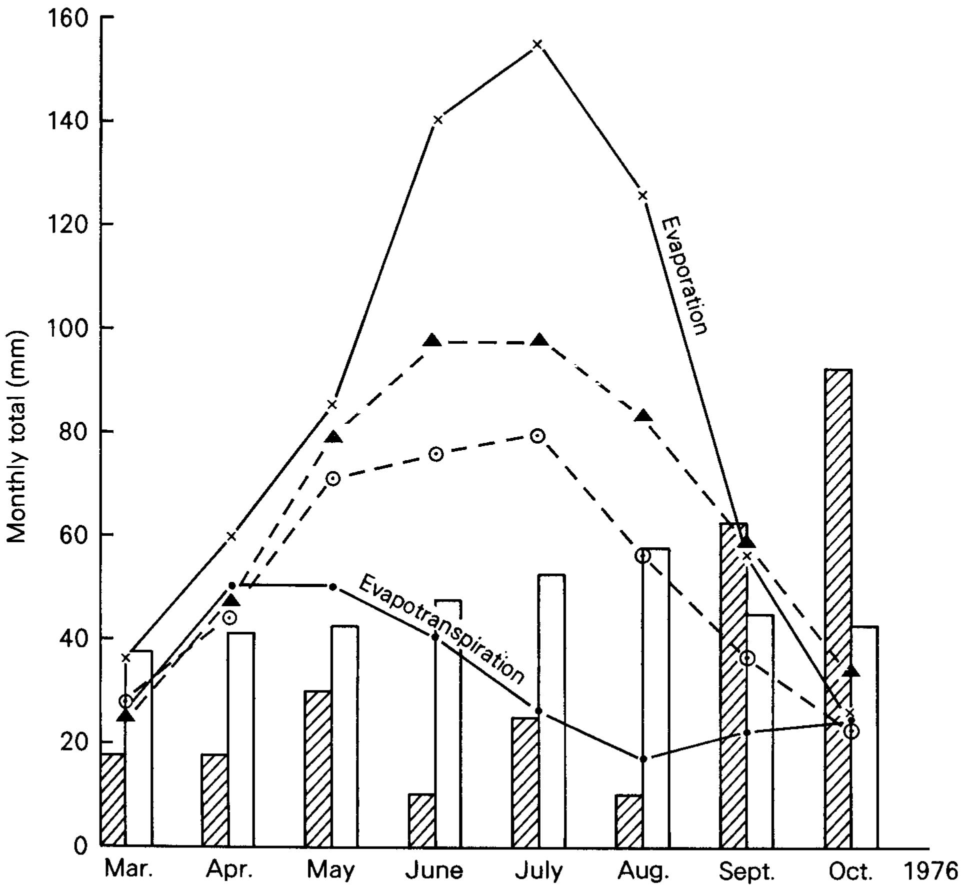

Figure 2. Monthly evaporation and rainfall at Cardington, March–October 1976. ▲– – –▲ Mean monthly evaporation, 1970–75, ⊙– – –⊙ Mean monthly evapotranspiration, 1970–75. Hatched verticals represent monthly rainfall for 1970, unhatched verticals represent mean monthly rainfall, 1951–70.

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

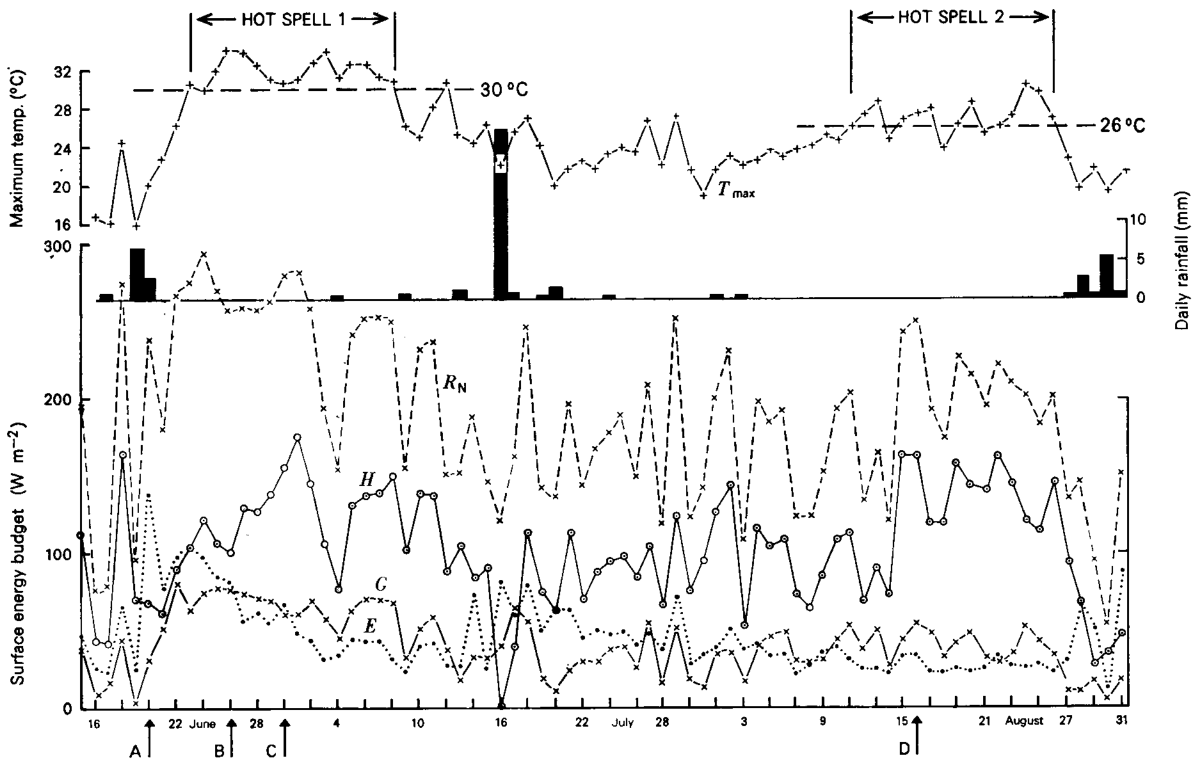

Figure 3. Mean daily (06–18 GMT) surface energy budget at Cardington, June–August 1976, with rainfall and maximum temperature.
R_N is net radiation, G is soil heat flux, E is latent heat flux, H is sensible heat flux and T_{max} is maximum temperature.

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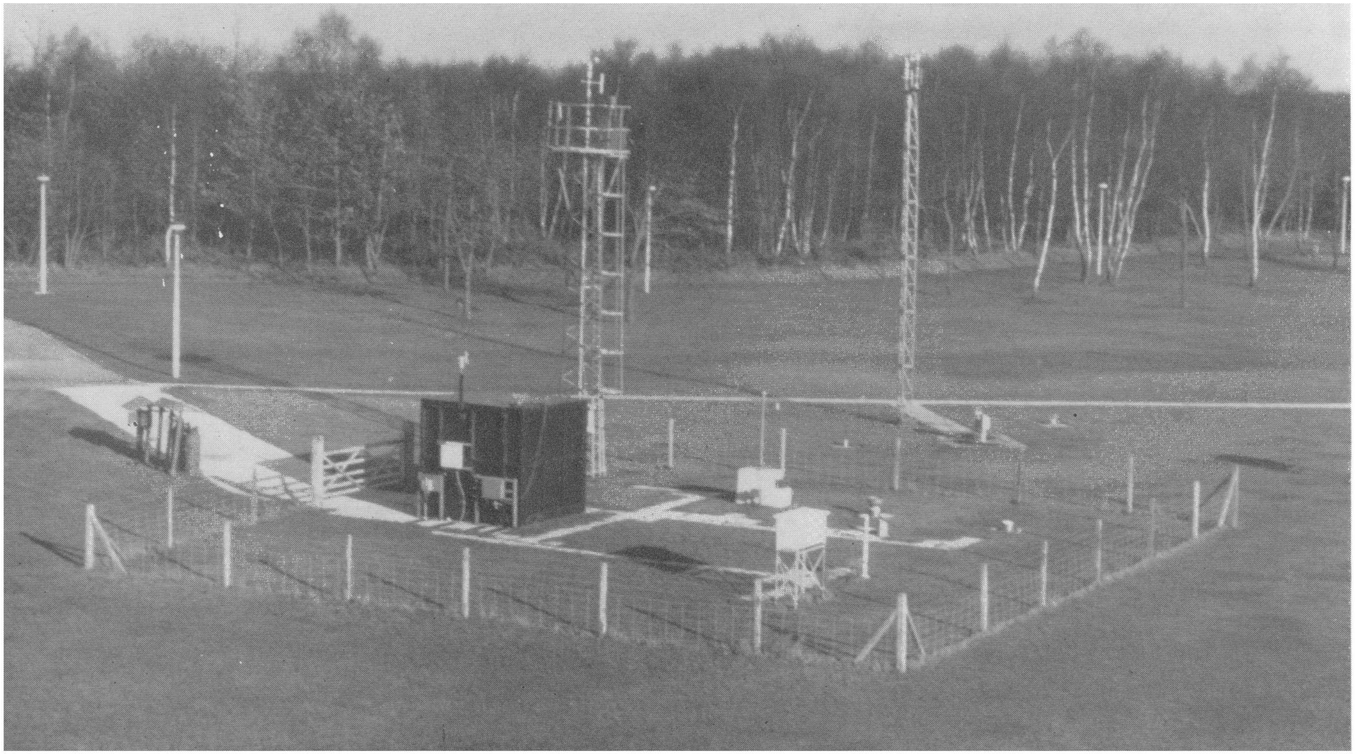


Plate I. The Meteorological Office Weather Observing System (MOWOS) Mk 2 at Beaufort Park.

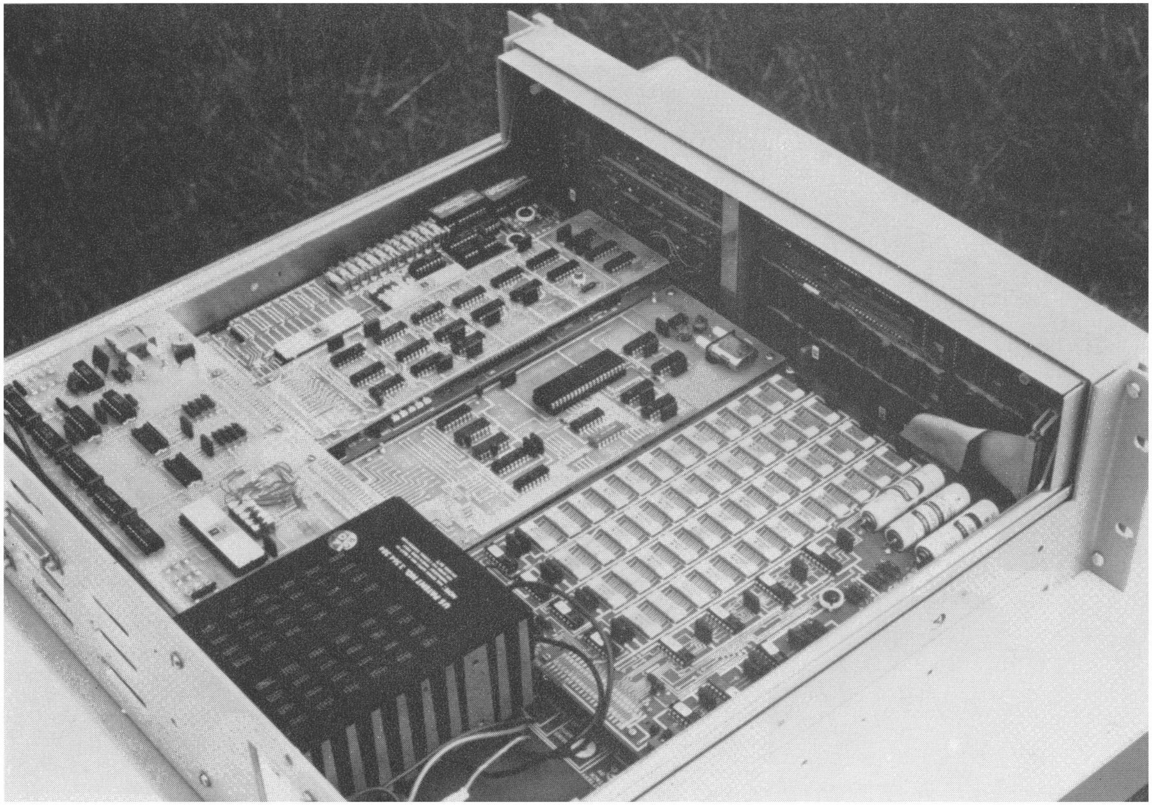
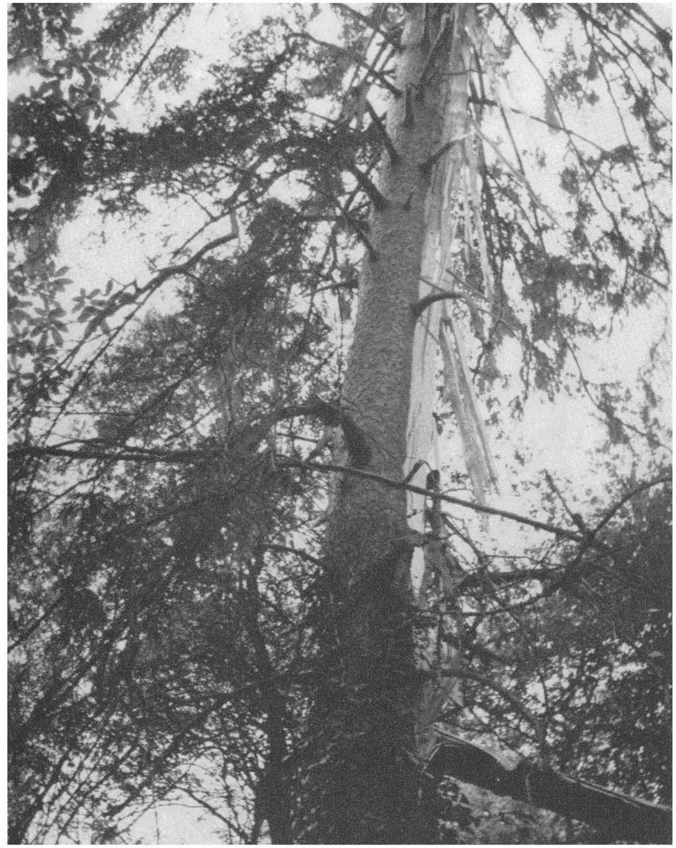


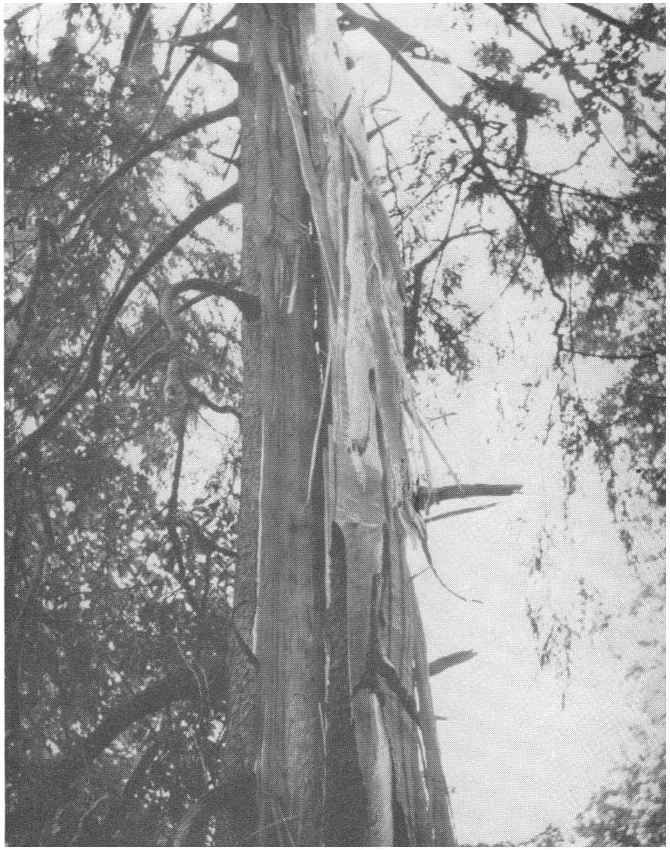
Plate II. The Meteorological Office designed 'Automet' Micro-Computer.



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.



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)

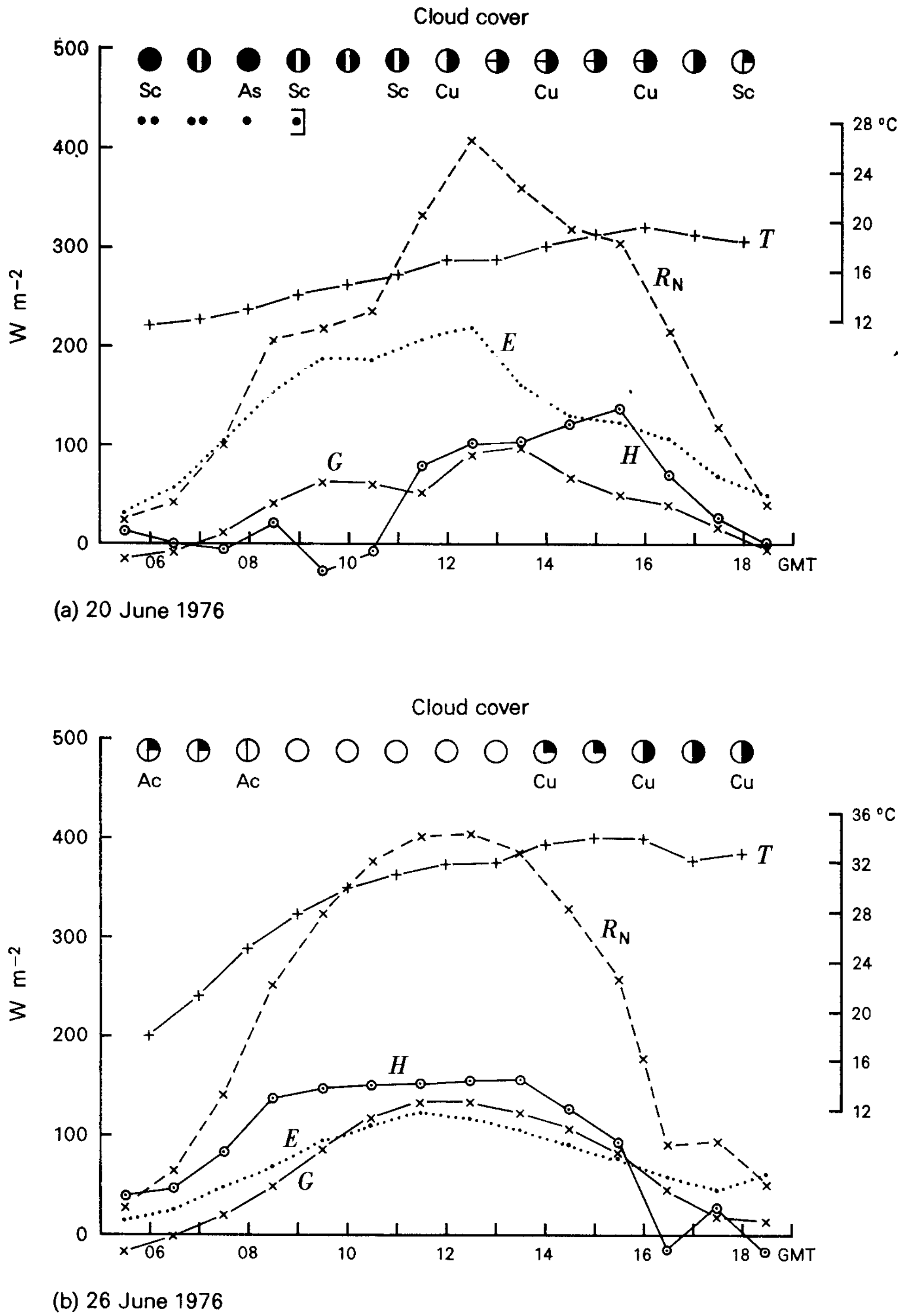
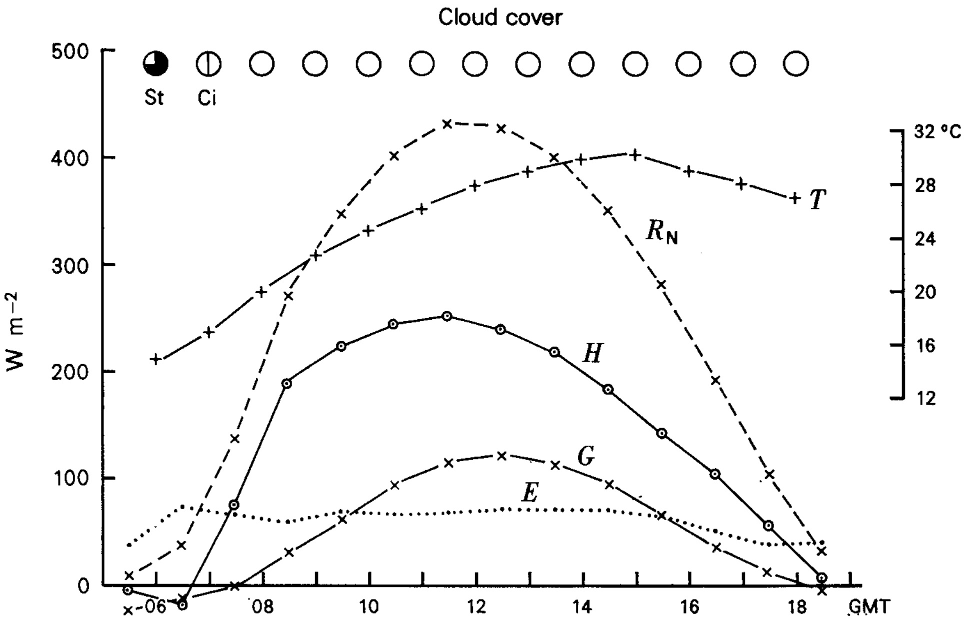
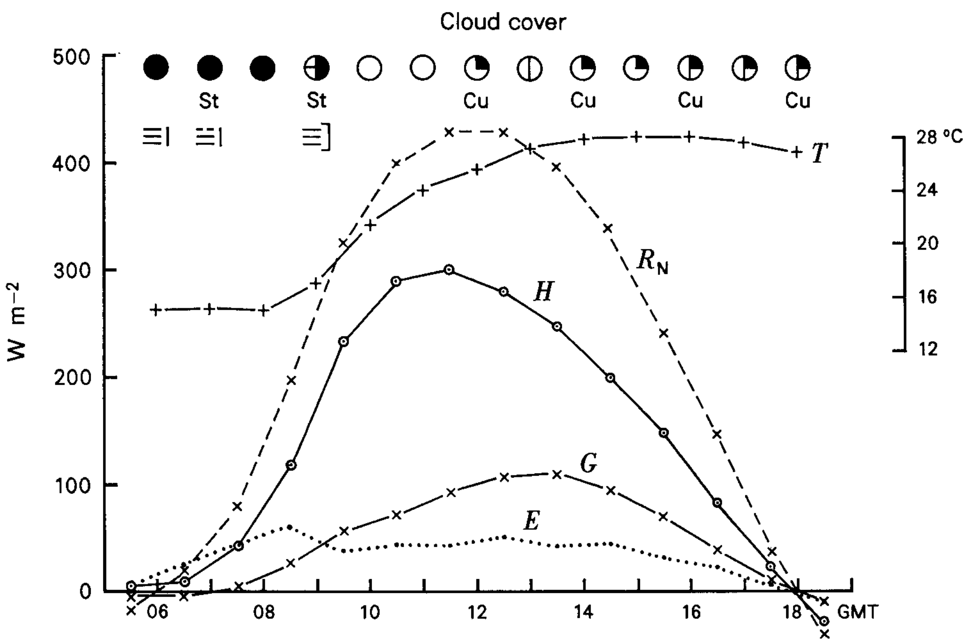


Figure 4. Hourly energy budget (06–18 GMT) with cloud cover and screen temperature
R_N is net radiation, *G* is soil heat flux, *T* is screen temperature, *E* is latent heat flux and *H* is sensible heat flux.



(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

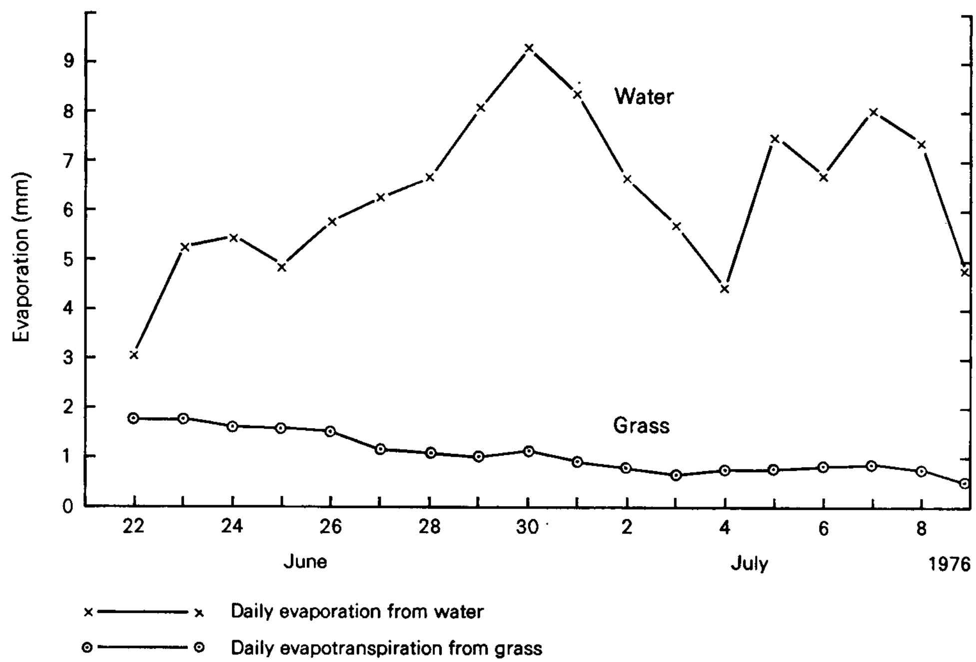


Figure 5. Daily evaporation from water and from grass at Cardington during Hot Spell 1.

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

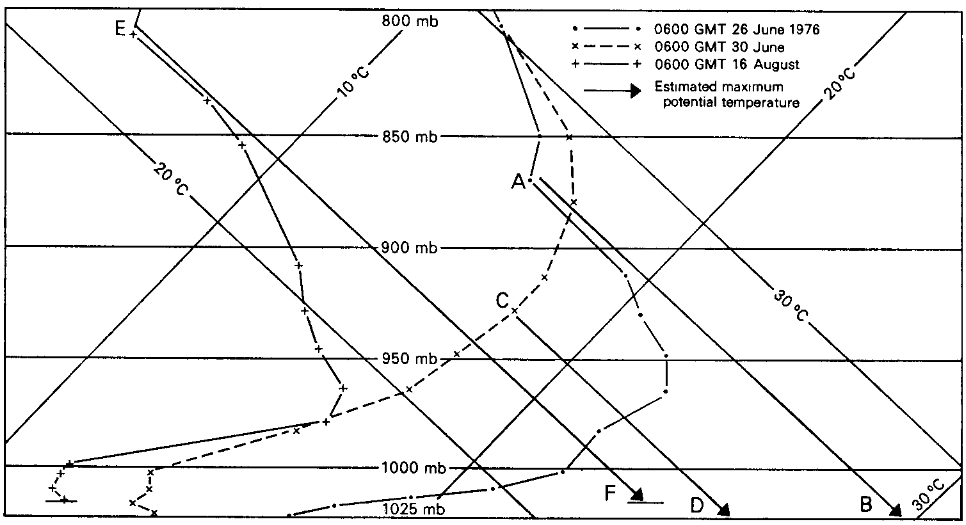


Figure 6. Calculation of boundary layer heating on 3 days using Cardington BALTHUM soundings.

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,

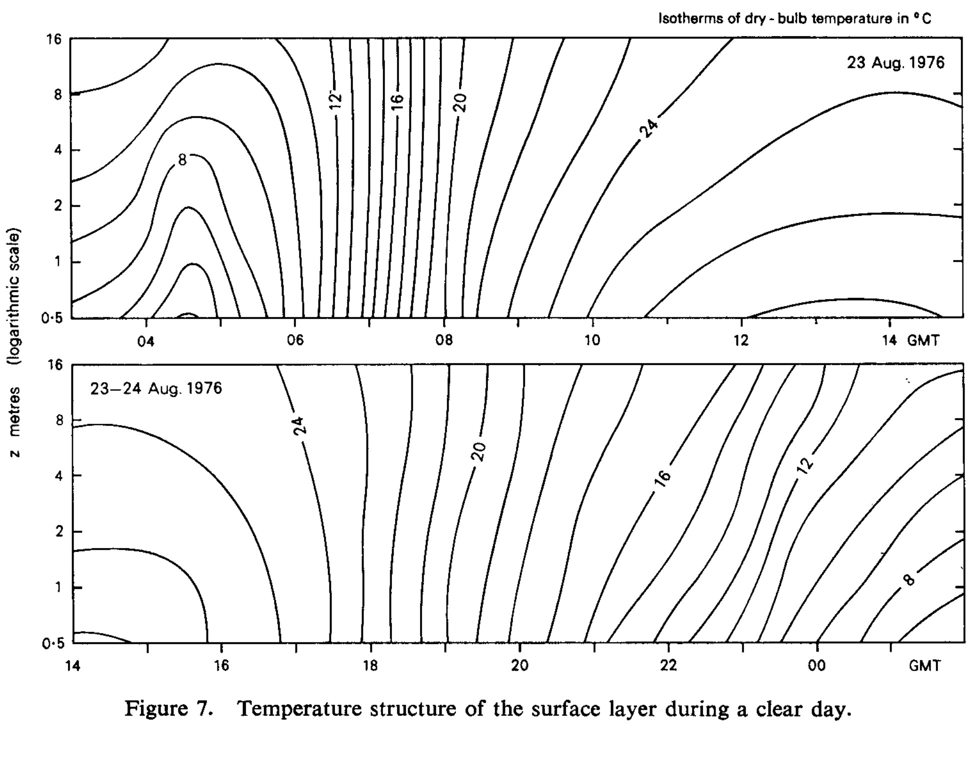


Figure 7. Temperature structure of the surface layer during a clear day.

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

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

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

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

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

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

where

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

is the thermal diffusivity of the soil (in units of $\mathrm{m}^2\,\mathrm{s}^{-1}$). 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

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

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

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

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

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

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.

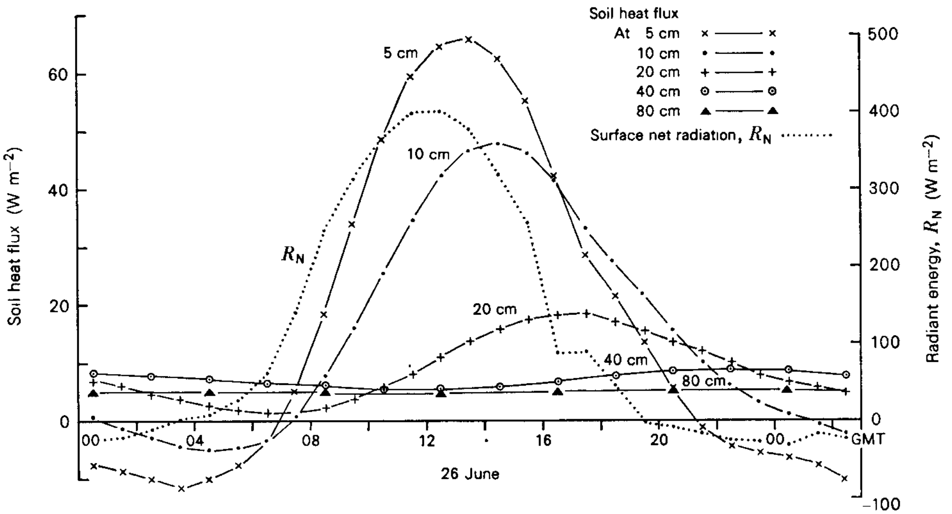


Figure 8. Variation of soil heat flux with depth at Cardington, 26 June 1976.

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

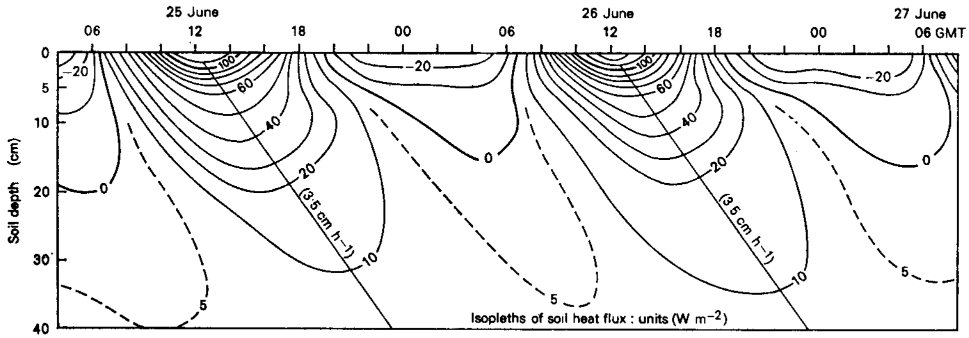


Figure 9. Diurnal variation of soil heat flux at Cardington, 25–27 June 1976.

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

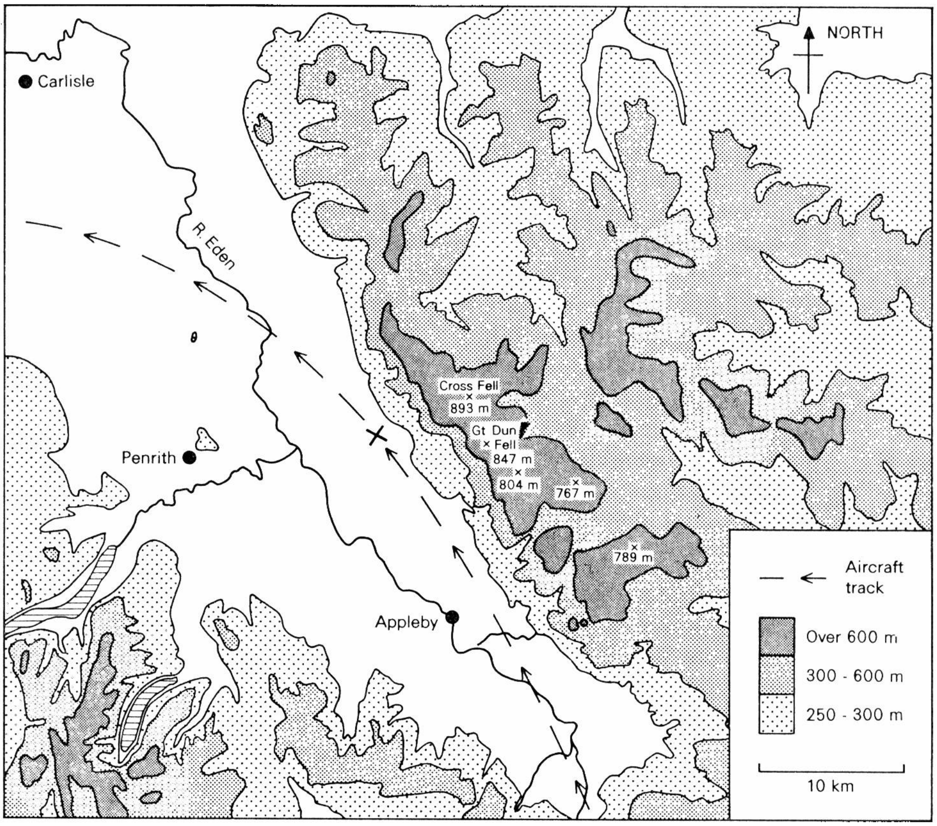

Figure 1. The Cross Fell Range and the Eden Valley. X marks the position where severe turbulence occurred.

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

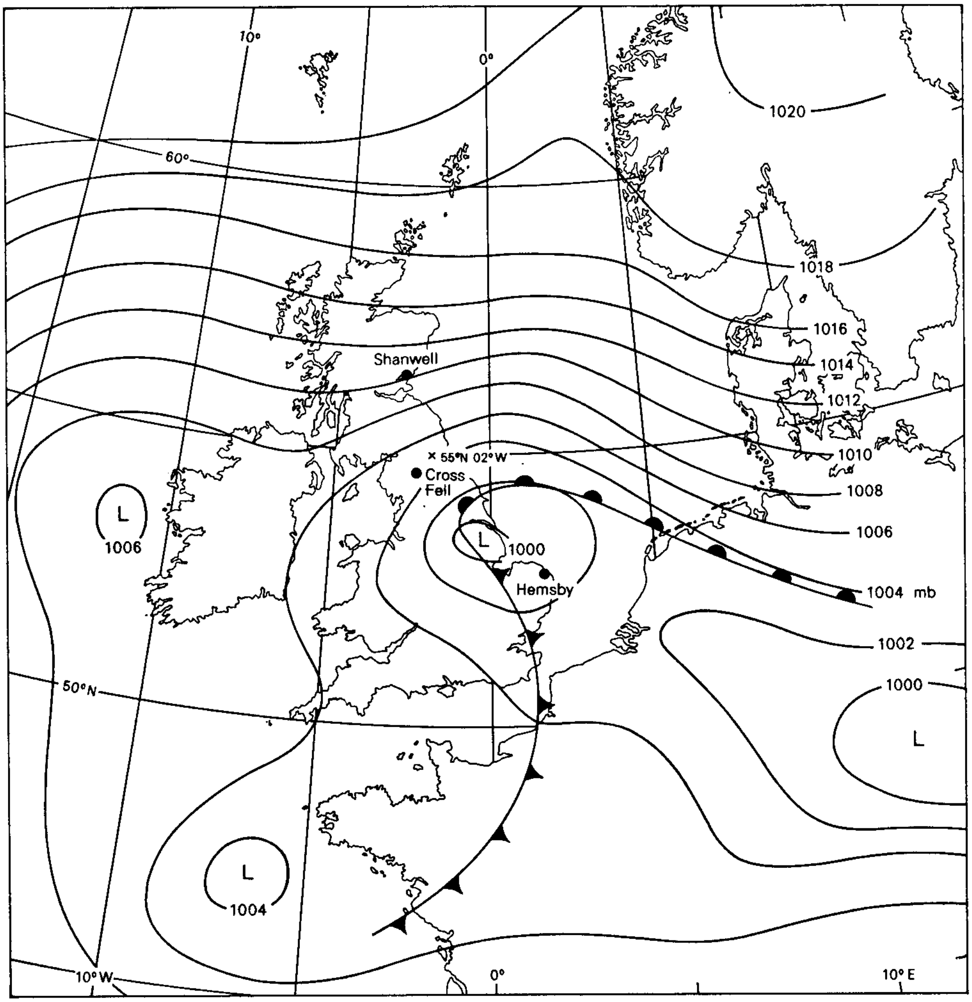

Figure 2. Surface synoptic chart for 12 GMT on 27 April 1978 with isobars drawn every 2 mb.

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

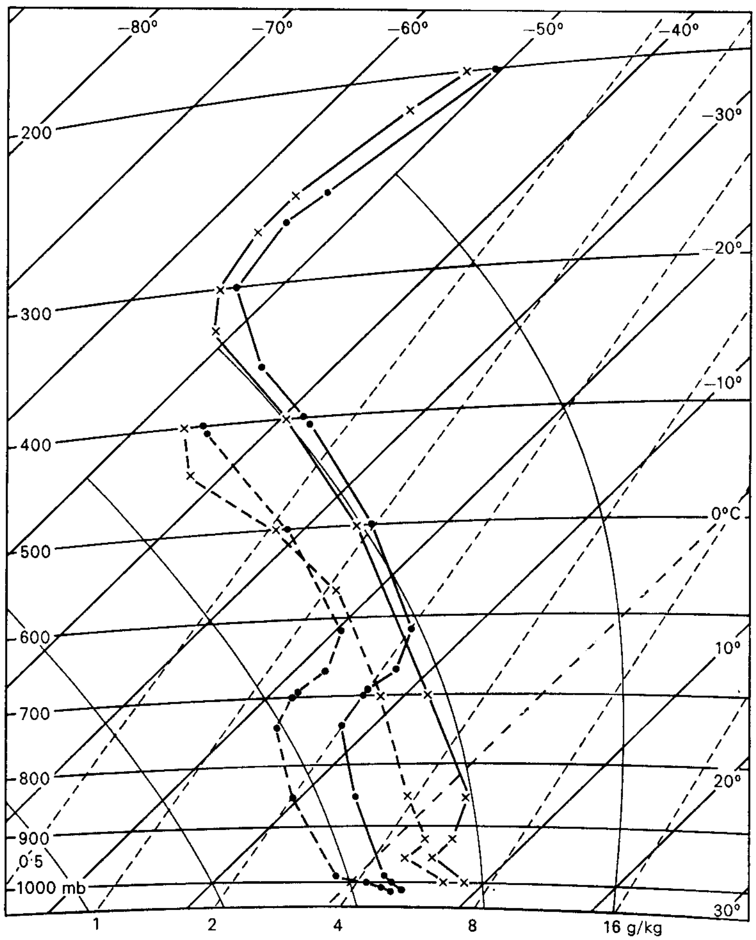

Figure 3. Tephigrams for 12 GMT on 27 April 1978.

·———· ·- - - -·	Shanwell	×——× ×- - - -×	Hemsby

may be that in this particular case the cold air beneath the frontal surface and the streaming layer wer**ə** 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.

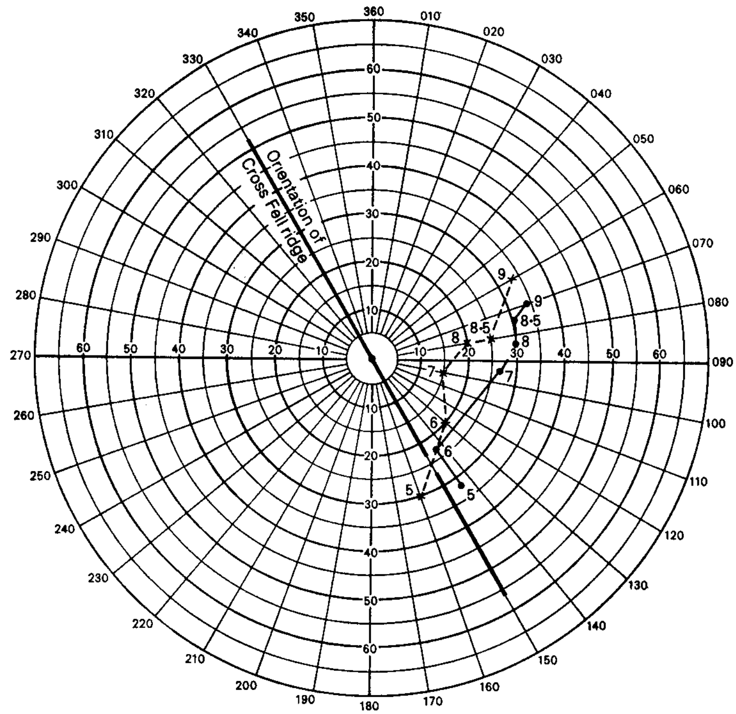

Figure 4. Hodograph showing change of winds with height over Cross Fell ridge at 12 GMT on 27 April 1978.

•——• 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

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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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