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## LONG-RANGE FORECASTS BY THE METEOROLOGICAL OFFICE

By the DIRECTOR-GENERAL

On 13 November 1963 the Secretary of State for Air announced, in a written answer to a Parliamentary Question, that a decision had been taken to publish monthly weather prospects prepared by the Meteorological Office.

The publication consists of a single sheet. The front is devoted to the climatology of Britain for the forecast month in the form of a short descriptive passage followed by tables and maps of climatological averages for 31 stations throughout the country. The back of the sheet has (*a*) an account of the actual weather in Britain during the month just past, (*b*) northern hemisphere maps of (i) mean pressure at sea level and (ii) temperature anomalies of the lower half of the atmosphere (1000–500 mb) for most of the month just past, (*c*) a general survey of the large-scale weather patterns of the month just past and inference therefrom, (*d*) weather prospects for the coming month and (*e*) a note on interpretation and use of the prospects.

On the 15th of the month a statement on weather prospects for the next 30 days will be published, so that every month there will be two forecasts, overlapping for a fortnight.

The decision follows research on minor climatic fluctuations and long-term trends that began, about eight years ago, with the statistical investigations of Mr. J. M. Craddock and his co-workers. During this period Mr. H. H. Lamb also studied climatic variations over much longer periods. Gradually, these investigations led to the formation of a systematic approach to the forecasting problem, and since 1960 there have been available written monthly forecasts which could be analysed for evidence of skill, i.e. of a degree of success above that which would result from chance. The analysis indicated that these forecasts do show skill and therefore could be of value to many interests.

The method currently in use depends principally on finding months in earlier years with such a degree of resemblance to the month just past that their sequels may be expected to give some guidance about the coming month.

This resemblance is sought in:

- (i) The synoptic sequence over the British Isles. Using a high-speed computer, numerical comparisons of the sequence of the past month are made with the same months in a type calendar going back to 1873.

- (ii) The temperature anomaly pattern over a large part of the northern hemisphere. Numerical comparisons are made using various indices of similarity, again with the aid of a computer.
- (iii) The monthly mean pressure chart over much of the northern hemisphere. This is at present being done visually.

This procedure usually results in ten or twelve possible analogous months and the daily synoptic maps for these months are then examined. Any months in which, say, the tracks of depressions across the Atlantic, the strength and position of the Azores anticyclone or the pressure distribution in high latitudes differ appreciably from the past month are rejected as unsuitable analogues. The sequels of the remainder (usually two, three or four) are then examined and in the absence of uniformity additional arguments are used to establish what weighting should be given to the various indications. These arguments may be based on the limits of the polar ice pack, sea temperatures, snow cover or some marked anomaly of the general circulation.

The forecasts will usually say:

- (i) whether the mean temperature of the month is expected to be average, above, much above, below or much below average;
- (ii) whether the total rainfall is expected to be above, near or below average; and
- (iii) something about the expected sequence, or the predominant character of the month, e.g. more than the usual amount of northerly weather types.

It will be noted that this system differs in many respects from those used elsewhere, e.g. by the United States Weather Bureau, which depends chiefly on extrapolations from trends in the large-scale atmospheric circulation as shown by the patterns of the hemispherical 700 mb surface. No reliance is placed on statistical relations, either with terrestrial anomalies or with extra-terrestrial events, such as an abundance or deficiency of sunspots. The Meteorological Office method is to argue by physical reasoning, using past situations as a guide.

It should hardly be necessary to emphasize, in a professional journal, that there will be no attempt to predict the day-by-day variations of weather in the coming month. The 'prospects' will do no more than state in broad terms, the expectation of mean temperature and rainfall for the period in relation to long-term or climatic averages, together with some indication of the sequence of weather types for the next 30 days. Nor will any attempt be made to foresee the character of a coming season.

Long-range forecasting is recognized by meteorologists as the most formidable problem in the science of the atmosphere. Attempts to find a solution go back for many years with a depressing chronicle of high hopes not realized. One has only to recall the immense but abortive efforts that have been made to discover significant periodicities, or correlations between extra-terrestrial phenomena (such as sunspots) and weather. The economic value of a reliable system of long-range forecasting is beyond question and it is for this reason, and for the intrinsic interest of the problem, that in the Office research has been intensified in recent years. At present, and probably for some time to come, the preparation of the forecasts will remain the responsibility of the Synoptic



Climatology Branch (M.O.13), with the newly formed Dynamic Climatology Branch (M.O.20) conducting basic mathematical investigations into the general circulation and large-scale features of the atmosphere. The decision to institute a regular service, which was made after the results of the trials had been examined by both the Meteorological Research Committee and the Meteorological Committee, does not imply a major break-through in the problem. Instead, it reflects the fact that the methods now in use are capable of producing forecasts that on a majority of occasions can be useful guides, but it is freely acknowledged that in the present state of the art, a single forecast might be so wide of the mark as to be misleading. This is a risk that must be accepted, as it is in short-range weather forecasting. The monthly weather prospects will be of the greatest value if they are used in conjunction with the daily forecasts and it is hoped that this will become the accepted practice.

## **EXPANSION OF METEOROLOGICAL OFFICE RESEARCH IN DYNAMICAL CLIMATOLOGY**

By R. C. SUTCLIFFE—Director of Research

It is commonly accepted that among the advances in meteorology during the last twenty years a leading place must be given to the development of the basic dynamical theory of depressions and anticyclones and of large-scale synoptic systems generally. Like many another success story it has been the result of the exploitation of a lucky break, we might say a lucky break-through, it having been discovered that in this particular part of the spectrum of meteorological disturbances the behaviour can be largely explained by ignoring all other processes, all other parts of the spectrum. Without considering the origin of the energy, in the non-adiabatic differential heating and cooling of the atmosphere, or the dissipation of the energy, ultimately through smaller-scale disturbances, developments on the large synoptic scale have been explained sufficiently completely to provide a firm basis for forecasting by fundamental calculation: numerical weather prediction in the accepted phrase.

The soft spot in the spectrum having been discovered, further progress could be almost guaranteed by assigning able people to the task of exploitation and in the Meteorological Office the branch for Dynamical Research, headed by Mr. E. Knighting, has made important and well known contributions. In the course of the work, improved understanding and greater success has come in part by invading the wings of the spectrum, taking account of 'friction' on the one hand and 'non-adiabatic processes' on the other, but it is not to be expected that the many distinct problems of dynamical meteorology will yield to attack developed from this one salient and, with encouragement given by success, aided by the mechanized weapon of electronic computing, theoreticians are looking for new points of entry: the Meteorological Office aims to adapt its organization to provide facilities. Within the existing branch of Dynamical Research, M.O.11, attention is being given to the dynamics of fronts, and arrangements have been made to use an Atlas computer, the most advanced high-speed computer yet available, as may be necessary in the course of the research. This may be looked upon as an extension into the smaller scale of meteorological events. At the same time it is hoped to make progress on the larger-scale problems, the general circulation of the atmosphere and the variations on the time-scale of weeks and longer which must be understood if

long-range forecasting is to be put on a sound scientific basis or the theories of climatic change or climatic control are to be raised above the level of speculation.

Progress will depend, as always, first upon the skill and insight of the people concerned but good organization has a modest part to play and in the Office the successful policy of establishing teams of about six research scientists headed by a Senior Principal Scientific Officer and supported by ancillary staff has once more been followed by dividing the old branch for Climatological Research into two, the one to carry the name Synoptic Climatological Research, the other Dynamical Climatological Research. There is nothing in a name—except that it is a handle—but in these cases the names are reasonably indicative of the objectives in mind. Synoptic climatology implies the analysis of the structure of climate with interest directed to geographical distributions and to practical prediction for different parts of the world. In this branch, taking the old number M.O.13, with Mr. M. H. Freeman as its first head and Assistant Director, practical long-range forecasting will be an important interest. Dynamical climatology (accepting the distinction drawn in the *American Glossary of Meteorology*\*) gives emphasis rather to the fundamental theoretical approach and to the behaviour of the atmosphere as a whole, the general circulation in other words, and this defines closely enough the task of the new branch M.O.20 which Mr. G. A. Corby will lead. That the two branches will have many points of contact goes without saying.

The problems are very difficult and it is far from clear how progress is to be accomplished, but the importance of the subject fully justifies this further investment in research. It may be an investment for capital growth over the next ten years with little in the way of short-term dividend. We must wait and see.

551.524.37:551.525.4

## SOIL TEMPERATURES DURING THE FROST OF EARLY 1963 IN SOUTH-EAST ENGLAND, PART—I

By E. N. LAWRENCE, B.Sc.

**Summary.**—Minimum soil temperatures and the rates of change of soil temperature at various depths during the very cold winter of early 1963 are given in tabulated form for three types of soil—sand, loam and clay. Further tables give a sequence of temperature changes in these soils at various depths at the end of January 1963, and tables are given also for long period absolute minimum values of soil temperature.

After a short account of soil physics with special reference to soil freezing and thawing, the following topics are discussed for various stations in south-east England: depth of freezing; effects of snow cover, and of soil type and condition on soil temperature.

**Introduction.**—It is estimated<sup>1</sup> that the three months of December 1962 and January and February 1963 were the coldest in the English lowlands since 1740, judged by the mean air temperature over the period, and that the Thames in the central London area might well have frozen over, had it not been for artificial warming. Soil temperatures during the recent winter are therefore of special interest. Change of soil temperature normally lags behind that of air temperature and thus the period of extremely low soil temperature was delayed until January 1963. A common yardstick by which to judge winter severity is depth of frozen soil, but this factor varies according to topography, as early 1963 reports confirm. In the present paper, air and soil data

\*HUSCHLE, R. E.; *Glossary of Meteorology*. Boston, Mass., American Meteorological Society. Boston, Mass., 1959, p. 184.

from Kew Observatory (mainly sandy loam over rubble) are compared\* with those from Woburn, Bedfordshire (sandy soil), Rothamsted, Hertfordshire (clay with flints) and Cardington, Bedfordshire (clay with flints).

At Kew Observatory, data are available from the old, long established site (A) and also from a new, more open site (B). The position of the old site (A) is shown in the *Observatories' Year Book*<sup>2</sup> for 1960, and the new site (B) is about 80 yards to the south-south-east. The old site is on freely drained disturbed soil with sandy loam (0–15 in.) quickly merging into rubble (composed of mortar, broken brick and tiles) with a layer of sandy clay-loam from 3 ft 6 in. down to at least 4 ft. The new site which has an impeded profile drainage is on alluvial soil, with sandy loam (0–6 in.) changing gradually to become clay loam and silty clay by 3 ft down to at least 4 ft.

The soil thermometers used are described in the *Handbook of meteorological instruments*.<sup>3</sup> Soil data for Kew (site A), Woburn, Rothamsted and Cardington are as indicated in Tables I, II and III. The programme at Kew (site B) from 14 February 1963 includes observations of soil surface temperature using a grass minimum thermometer placed on the bare ground. Surface temperatures over grass have been found to correspond to ground surface radiative temperatures.<sup>4,5</sup> When snow is lying the surface thermometer would normally be covered. It should be noted that the term 'bare soil' may include snow-covered soil as opposed to snow-covered grass.

Throughout this account soil at a temperature below 0°C will be referred to as frozen soil, notwithstanding that there may be a small depression of the freezing-point on account of dissolved materials in soil moisture. Values of maximum concentrations of soluble salts in soil, estimated from data given by Baver<sup>6</sup> and Harper,<sup>7</sup> suggest an effect on the freezing-point much below measurable limits. Furthermore, from atmospheric chemistry observations (see for example, tables in *Tellus*, 1959),<sup>8</sup> it is clear that the monthly mean total soluble salt concentration in rainwater, inland in England, never exceeds  $N/100$  (and rarely  $N/1000$ ), where  $N$  is the gram equivalent weight of salt per litre. Therefore any depression of the freezing-point of soil is neglected in the present calculations.

**Soil physics and soil freezing mechanism.**—The soil surface layer is heated or cooled by radiation and atmospheric advection, and heat is transmitted through the soil by conduction. Cooling by evaporation may be considerable but is usually very limited in midwinter in the British Isles; warming by condensation and deposition is normally small; the transfer of heat by sublimation may be important and is discussed later with the effects of snow cover. When the ground surface is warmer than the surrounding air, the effect of wind or turbulence is to remove heat from the surface layer and thereby to reduce any heat supply available for conduction downwards: that is, the stronger the wind, the less effective is the radiative heating of the soil surface during daylight—this is particularly noticeable during periods of sunshine.<sup>9</sup> Conversely, by night, air motion may inhibit surface cooling and consequently also the upward flux of soil heat. Thus wind speed as well as air temperature greatly influences the soil temperature régime.

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\*The air temperatures for Kew are those measured in the standard thermometer screen and not the 'North Wall' screen.

Temperatures at Woburn and Rothamsted were recorded in °F and so some main conversions to °C are shown in the Tables and text to allow direct comparison with Kew and Cardington data which are reported in °C. Similarly, snow depths in in. have been shown also in cm.

Soil temperature changes in a homogeneous soil may be described approximately by the well known equation:

$$\frac{\partial \theta}{\partial t} = a \frac{\partial^2 \theta}{\partial z^2}$$

where  $\theta$  is soil temperature at time  $t$  and depth  $z$ , and  $a$  is the coefficient of thermal diffusivity as defined by the formula

$$a = \text{thermal conductivity} / (\text{specific heat} \times \text{density})$$

where all terms refer to soil, and the thermal conductivity is assumed to be constant.

The general behaviour of soil temperature variation with depth may be explained by assuming that the thermal diffusivity is constant. However it has been shown<sup>10</sup> that diffusivity is not generally constant with depth, most especially in the top 10 cm where a tenfold variation may occur. The significant variation of diffusivity in the top soil layer is exhibited for example by data from a grass-covered clay site near Cambridge<sup>11</sup> and also by data given by Johnson and Davies<sup>12</sup> for natural grass-covered chalky soil in the area of Porton (Wiltshire).

The main cause of differences in thermal diffusivity can be attributed to varying water content. Moderately wet soil has much better thermal conductivity than dry soil. This leads to a greater thermal diffusivity because at lower water contents, soil density and specific heat increase much less rapidly with increase of moisture content.

The soil acts as a reservoir of heat and so, with the onset of autumn, there is an increase in mean temperature with depth and any freezing tends to penetrate gradually downwards. However, during marginal freezing weather, intermittent thawing may possibly occur at and near the surface, with a thawing at the bottom of the frozen layer. While the heavier, water-holding clay soils tend to be slow to change in temperature, on account of the high specific heat and latent heat of water (or ice), the better drained sandy soils may experience comparatively rapid changes in water content, and the transfer of heat by water percolation may be considerable. The degree of percolation is dependent not only on the soil type but also on drainage facilities: examples of sudden changes in soil temperatures and further discussion may be found elsewhere.<sup>13,14,15</sup>

From a study of Kew (site A) data, Wright<sup>16</sup> suggested that between depths of 10 cm and 20 cm, grass interfered with the normal course of heat conduction but that the annual variation of temperature between depths of 20 cm and 122 cm is in accordance with the simple theory of heat conduction. He compared data from the grass-covered sandy loam at Kew with data from bare sand at Potsdam, and found that at Potsdam (where one would expect the diffusivity to be higher) the average range of temperature at a depth of 10 cm was about twice that at Kew, and at a depth of 20 cm about three times. Wright found also that, at both these depths, maximum temperatures were reached about 1½ hours earlier at Potsdam and that diurnal variation extended to greater depths there.

**Soil thawing process.**—As with the freezing process, heavier soils tend to thaw more slowly. For example, at a depth of 4 ft, there is a tendency for later and even lower absolute minima than in better drained soils. Towards the end of winter, thaws are more liable to be rapid, with warming penetrating

quickly downwards from the surface. Rapid major thaws during midwinter in south-east England are normally associated with the advection of warmer air: indeed it is estimated that solar radiation without advective energy would be insufficient to effect such a change. However, when the surface warms slowly (e.g. in midwinter with limited advection and especially with thick snow cover), any downward heat flux is small and tends to be masked by the reversal of temperature gradient at lower levels and the tendency for an upward flux of terrestrial heat: under such conditions, there is no systematic downward penetration of thawing. As with freezing, thawing may be inhibited by snow cover (but see later).

**General weather near the ground during the winter 1962-63.**—Synoptic and general climatological details are published elsewhere, for example in the *Monthly Weather Report*\* (which includes monthly charts of 'Anomaly of mean 1 foot earth temperature in the U.K.'), the *Daily Weather Report*,\* *Daily Aerological Record*,\* and corresponding summaries, and in an assessment by Booth<sup>17</sup> of the winter of 1963 until mid-February. However it is useful here to summarize a few relevant details.

Snow was covering the ground at 0900 GMT on each day at Kew from 27 December 1962 to 27 January 1963, inclusive, and in February from the 1st-7th and on the 11th and 12th; there was no snow cover in March. At Cardington snow cover was rather more persistent, whereas at Rothamsted and Woburn generally deeper snow persisted continuously from 27 December 1962 until 2 March 1963, inclusive. In late December 1962, before the snow covered the ground, air temperatures at Kew were considerably below average and winds were mainly easterly with some strong or gale force gusts. January 1963 continued very cold with day maximum temperatures at Kew below freezing-point on the 1st, 11th-13th, 17th-24th, and with strong easterly or north-easterly winds from the 17th-21st. After a temporary warming towards the end of January (see Table III(b)—columns for air temperatures) the cold spell returned on the 30th and lasted until 6 February. Thereafter, until 23 February, air temperatures remained between  $-2.5^{\circ}\text{C}$  and  $+4.6^{\circ}\text{C}$  but from 24 February to 3 March, a further cold spell occurred with grass minima varying from  $-6$  to  $-11^{\circ}\text{C}$ . On 4 March, the onset of south-westerly winds marked the end of the cold spells of early 1963.

Similar changes of air temperature occurred at Woburn, Rothamsted and Cardington but at Cardington there were markedly lower minimum temperatures presumably caused by topographical effects.

**Soil freezing spells during the winter of 1962-63.**—During December 1962 there was only a temporary freezing at Kew to a depth of 4 in., and although late December and January were very cold with strong day-time winds, deep soil freezing was delayed till about mid-January because of the usual lag in change of soil temperature behind that of air temperature.

Soil freezing during early 1963 at Kew occurred mainly in two spells:

- (i) from about mid-January to about mid-February (though the peak in the fourth week of January was followed by a temporary and shallow thaw at the end of January), and

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\*Meteorological Office. *Monthly Weather Report*. London, HMSO.  
Meteorological Office. *Daily Weather Report*. London, HMSO.  
Meteorological Office. *Daily Aerological Record*. London, HMSO.

- (ii) a shorter and less severe spell during the last few days of February and the first few days of March.

Allowing for the natural lag, this sequence corresponds with that of the general weather. The Kew (site A) temperatures under grass showed a gradual penetration of freezing from 4 in. to 8 in. to 1 ft in January; however the thaw of mid-February was so gradual that downward progression was masked. Following the thaw in early March, temperatures at depths of 4 in., 8 in. and 1 ft rose rapidly, thus illustrating a seasonal singularity of soil climate.<sup>14</sup>

**Depth of freezing.**—According to a personal communication from H. H. Lamb, studies of old records indicate that the last winter with comparable soil temperature extremes was in the year 1684, but that winter was a little colder and also rather more prolonged and continued into March. In that year, which is believed to have been fairly snow free, it is estimated that in east Somerset (in the region of, but not actually on, the Mendip Hills) frost penetrated to a depth of 1.5 to 2 ft into dry ground and 3 to 4 ft into wet ground. It is reported that similar conditions occurred at two snow-cleared sites near London during the recent winter and that these conditions were confirmed by reports of freezing pipes at 3 to 4 ft below cleared ground.

The data are insufficient to define the extreme depth of freezing soil under natural snow cover during 1963, but a rough estimate may be obtained by extrapolation. It was found that during the anticyclonic conditions prevailing on 23 and 24 January 1963—at the climax of the 1963 cold spells—the 0900 GMT soil temperatures under grass at Kew (site A) were very similar to absolute minimum soil temperatures (see Table I(b)), and decreased linearly with depth from 4 in. to 1 ft. This 'linear' effect was previously found for 0900 temperatures following anticyclonic nights at Rothamsted, and has been demonstrated theoretically,<sup>9</sup> albeit in the absence of snow cover. In both situations, temperatures were therefore such as to satisfy the equation derived for general heat conductivity in soil under 'steady state' conditions:

$$a \frac{\partial^2 \theta}{\partial z^2} = 0 .$$

By linear extrapolation (and incidentally also by graphical interpolation with the 4 ft temperature), it is suggested that frost extended below the natural snow cover to a depth of about 1.5 ft under grass at Kew (site A) in early 1963, and probably to a depth of 1.5 to 2 ft under bare soil at this site.

During early 1963, freezing of heavy clay soils in south-east England probably did not extend beyond a depth of 1 ft: there was no evidence of freezing at a depth of 1 ft at the clay site at Rothamsted (Table I(c)) or even at the exposed though lower clay site of Cardington (Table I(d)) where the maximum depth of snow cover reported was 15 cm. However, at well drained sandy sites, the depth of freezing may well have exceeded that at Kew; the extreme temperatures at Woburn (sand) suggest a maximum depth of freezing similar to that at Kew, though the 'linear' effect at Woburn is not so marked, probably on account of the greater variation of thermal diffusivity with depth. The effect of soil type is further discussed in a later section.

**Effect of snow cover.**—Snow cover generally tends to inhibit change of soil temperature. Because of the snow's albedo, the absorption of solar radiation is restricted and surface temperatures tend to be low so that a steep temperature gradient is liable to be established in the snow layer. Under suitable

conditions this appears to be sufficient for appreciable changes in temperature below the snow cover. It is noteworthy that during the period of thick snow cover, 20–23 January 1963, the soil temperatures at Kew at depths of 4 in., 8 in. and 1 ft (under grass and under bare soil) continued to decrease generally, and that therefore penetration of frost probably continued under the snow. Details of soil and air temperatures and snow cover for Kew and other stations are given in Table III.

In a study of heat transfer in snow, Yen<sup>18</sup> concluded that vapour processes make a significant contribution to the process of heat transfer associated with a natural snow cover. Experimental work<sup>19</sup> on artificially compressed snow subjected to a temperature gradient of about 10°C (–1°C to –12°C) through a sample depth of about 50 cm, for a period of 5 days, showed that 0.135 gm/cm<sup>2</sup> of snow was transferred by sublimation from the portion of the sample at higher temperature to the portion at lower temperature. Yosida<sup>20</sup> calculated the heat transfer by diffusion of water vapour and found it to be  $2.2 \times 10^{-4} \times$  (temperature gradient) cal/cm<sup>2</sup>sec for snow at 0°C. Table III(b) gives some indication of the order of magnitude of the temperature gradient in snow at Kew: for example, on 23 January the 0900 GMT air (screen) minimum temperature was –12.1°C, the overnight grass<sup>21</sup> minimum temperature was –15.8°C, and with snow depth of 13 cm the 0900 GMT soil temperature was –2.6°C at a depth of 4 in. under grass. (The Table gives the soil temperature only for the 28th and the 24-hour changes during the previous week.)

It is interesting to note that, after freezing, soil temperatures at a depth of 4 in. under grass at Kew exceeded 0°C (at 1800 and 2100 GMT on 27 January 1963) when general snow cover (greater than half cover and depth 4 cm) was still being reported: at these times the soil was still frozen at 8 in. and 1 ft under grass and at 4 in. and 8 in. under bare soil. The occurrence of thawed top soil, at the end of the thaw of a thick snow layer, is not surprising in view of the increases of soil temperature associated with thawing snow (Table III and later sections refer).

**Effect of soil type and condition.**—The effect of soil type is shown clearly by a comparison of absolute minimum soil temperatures (see Tables I and II). In January 1963, the minimum at a depth of 4 in. under the bare loam at Kew (site A) is just midway between that for Woburn (sand) and that for Rothamsted (clay). This is comparable with what one would expect for the relation between grass minima on these types of soil. At a depth of 8 in. under bare soil and at 1 ft below grass, the minima for Kew and Woburn are very similar (Woburn being only slightly lower) and both are substantially below those for Rothamsted where no freezing was observed at a depth of 1 ft. At a depth of 4 ft, the January minima were very similar for all three sites, but it is interesting to note that for the quarter January–March 1963, the lowest temperature was recorded at Rothamsted, in March. Although snow cover had disappeared by the time of this minimum, the water-holding clay would be slower to warm up, and at a depth of 4 ft was still giving heat to colder layers above.

Equally marked were the differences in the rates of decrease of temperature (under snow cover) which preceded these absolute minima (see Tables I and III). For example, the maximum 24-hour (0900–0900 GMT) decreases of temperature at 4 in. and 8 in. under bare soil and 1 ft under grass (see Table

III(a), (b) and (c)) were greatest at Woburn (except at 8 in.) and least at Rothamsted. At Kew (site A), the corresponding changes were intermediate but at a depth of 8 in., the changes at Kew and Woburn were rather similar. The relation between these rates of decrease, at least at a depth of 4 in., may be considered typical of the soil types and to reflect their relative diffusivities. At lower depths, soil differences are masked by the normal damping of range of temperature with depth and by the general increase of water content.

The effect of soil type during the temporary warming of late January was similarly demonstrated (see Table III). The largest sustained increase of soil temperature at a depth of 4 in. under bare soil (due partly to percolation<sup>13,14</sup> of melted snow) occurred at the sandy site of Woburn while increases at the clay site of Rothamsted were the least conspicuous, the clay soil being impervious (at least at this time of the year when cracking would be absent) and also the warmest soil initially. Increases of soil temperature at a depth of 4 in. under the bare loam soil at Kew (site A) were generally intermediate between these extremes (though the largest single 24-hour (0900–0900 GMT) increase at a depth of 4 in. occurred at Kew). Even before the air temperature increase of 26 January, there were appreciable increases of soil temperature, especially at Woburn (see Table III(a)) where the higher diffusivity of the wet sand would be particularly favourable to the upward flux of terrestrial heat from below. The largest post-minimum increase (at a depth of 4 in.) occurred at Woburn in spite of the deeper snow layer there; deeper or more persistent snow cover is not unusual in sandier areas. At depths of 8 in. and 1 ft at Rothamsted, the rates of increase of soil temperature were small and distinctly less than at Kew and Woburn.

At Rothamsted under poor drainage conditions the maximum 24-hour (0900–0900 GMT) increase of soil temperature at a depth of 8 in. under bare soil in January 1963 occurred early in the month in non-freezing soil under 11 in. of snow. This maximum was presumably caused by the insulating effect of snow cover with a consequent restriction of radiation and convection losses, and by the upward flux of heat from below. There was a slight decrease in temperature at depths of 1, 2 and 4 ft.

The effect of soil type or condition on soil temperature is particularly complex during snow cover which itself partly depends on soil type and condition, and on ground cover. A most interesting example of the difference in persistence of snow cover over rough grass, rolled grass and bare soil was observed at Harpenden<sup>22</sup> during a previous winter. It appears that when the soil temperature at a depth of 4 in. exceeded the screen air temperature and melting depended more on the upward flux of soil heat, snow melted first where it was in better thermal contact with the ground, that is over rolled grass or bare soil: but when the air temperature exceeded the soil temperature at a depth of 4 in. (downward flux of heat), snow melted first from the rough grass where contact with and exchange of free air was greater. (The explanation for the latter, which is given in the original paper<sup>22</sup> does not appear to be acceptable.)

Rapid changes of soil temperature can occur only in well drained soils.<sup>13,14</sup> When a sandy soil becomes waterlogged because of bad drainage, or when it retains water because of a high humus content, such a soil will behave more like a heavy soil. In early 1963, the similar soil temperature minima at Woburn and Kew at 8 in. under bare soil and 1 ft under grass (Table I(a) and (b)) may well have been caused by a decrease with depth of drainage facilities at



Woburn or alternatively by the freely drained rubble subsoil at Kew (site A). The equalizing influence of high water content is well demonstrated by the relations found by Sarson<sup>23</sup> between rainfall and soil temperatures for clay and sandy soils. The monthly July rainfall at Woburn ( $R$ ) has a correlation of  $-0.69$  with the July monthly soil temperature excess ( $y$ ), of Woburn (sand) over Rothamsted (clay), for a depth of 1 ft under grass, for the period 1930–50. More generally  $R$  and  $y$  are related by the formula,<sup>23</sup>

$$y = 2.4 - 0.5954 (R - 2.31) - 0.0378 (T - 64.5)$$

with a multiple correlation coefficient of  $-0.68$ , where  $T$  is the July monthly mean temperature in  $^{\circ}\text{F}$  at a depth of 1 ft under grass at Woburn, and 2.31 and 64.5 are the July averages of rainfall in inches and soil temperature in  $^{\circ}\text{F}$  respectively, for the period 1930–50 at Woburn.

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**Note.**—Part II, to be published in February, will include the following topics: variation of soil temperatures over short distances; diurnal variation; differences between grass-covered and bare soil; and past climatological extremes of soil temperature.

TABLE II—LONG-PERIOD ABSOLUTE MINIMUM SOIL TEMPERATURES UNDER GRASS, AT 0900 GMT ‡

Station	Symons thermometer at 1 foot				Symons thermometer at 4 feet			
	Temperature $^{\circ}\text{F}$ $^{\circ}\text{C}$	Date(s)	Snow depth at 0900 GMT		Temperature $^{\circ}\text{F}$ $^{\circ}\text{C}$	Date(s)	Snow depth at 0900 GMT	
Woburn (sand)	29.0 $-1.7$	21 Jan. 1940	<6 in. (15 cm)		39.4    4.1	17–19 March 1947 inclusive	Nil†	
Kew (Site A) (loam etc.)	31.3 $-0.4$	21 Jan. 1940 24 Jan. 1940	Partial cover** ≤ 1 cm**		37.9    3.3	12 March 1947	Nil§§	
Rothamsted (clay)	32.0§    0.0	18–23 Feb. 1929 3 March 1929 21 Jan. 1940 22 Jan. 1940 25 Jan. 1940	Nil Nil 0.75 in. (2 cm) drifts drifts		36.3    2.4	19–22 March 1947 inclusive	Nil††	

Station	Period
Woburn	June 1918–Dec. 1962 inclusive*
Kew (Site A)	July 1903–Dec. 1962 inclusive
Rothamsted	May 1926–Dec. 1962 inclusive at 1 foot. Oct. 1945–Dec. 1962 inclusive at 4 feet.

\*Data for depth of 4 feet are not available from Oct. 1924–May 1926 inclusive, and for Jan. 1931. \*\*At 0700 GMT. †Up to 9 in. earlier in March and snow cover ( $\leq 6$  in.) throughout Feb. 1947. ††Up to 9 in. earlier in March and snow cover (up to 3–4 in.) throughout Feb. 1947, with drifts to greater depths. §At 1 foot under bare soil, absolute minimum temperature for period 1915–62 inclusive was  $30.8^{\circ}\text{F}$  ( $-0.7^{\circ}\text{C}$ ) on 21 Jan. 1940. §§Up to 10 cm earlier in March and snow cover (up to 13 cm but generally  $\leq 2$  cm) throughout Feb. 1947. ‡At 1000 GMT before 1915.

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TABLE 1—ABSOLUTE MINIMUM SOIL TEMPERATURES AND RATES OF CHANGE OF SOIL TEMPERATURE IN EARLY 1963

(a) WOBUEN EXPERIMENTAL STATION, (sand), 52°01'N, 0°35'W: 291 feet above M.S.L. JANUARY 1963

Type of soil cover	Bare soil		Grass	
Type of thermometer	Bent-stem*		Symons**	
Depth of thermometer	4 inches	8 inches	1 foot	2 feet
†Absolute minimum °F	22.4 -5.3 24th 7(18)	27.8 -2.3 24th 7(18)	29.4 -1.4 24th 7(18)	29.4 33.8 +1.0 28th, 29th, 30th 4(10) on 28th 3(8) on 29th 3(8) on 30th
Date of absolute minimum				
Snow depth at 0900 GMT on the same day in inches (cm)				4 feet 39.7 +4.3 31st 3(8)
Maximum 24-hour decrease (°F)	4.4	2.1	1.7	0.3
Initial temperature (°F), and date/time (GMT) of beginning of maximum 24-hour decrease.	29.4, 21/0900	30.0, 22/2100	31.1, 23/0900	various on several occasions
Maximum 6-hour decrease (°F)				
Initial temperature (°F), and date/time (GMT) of beginning of maximum 6-hour decrease.	≥ 1.5 ≤ 28.0 (between 21/2100 with 28.0°F and 22/0900 with 25.0°F)	1.0 28.0, 23/1500	** **	** **
Maximum 24-hour increase (°F)	4.8	1.8	0.8	Fairly steady decrease
Initial temperature (°F), and date/time GMT of beginning of maximum 24-hour increase.	24.1, 25/2100	28.2, 25/2100	29.8, 26/0900	
Maximum 6-hour increase (°F)				
Initial temperature (°F), and date/time (GMT) of beginning of maximum 6-hour increase.	2.8 22.4, 24/0900	0.8 29.2, 26/1500	** **	** **

\*Observations at 0900, 1500 and 2100 GMT only. \*\*Observations at 0900 GMT only.

†These values are also the absolute minima for the period January-March, inclusive, 1963 except as follows:

(i) At 2 ft, 33.7°F (0.9°C) on 5 March 1963, no snow. (ii) At 4 ft, 37.7°F (3.2°C) on 11 and 12 March 1963, no snow.

TABLE I—ABSOLUTE MINIMUM SOIL TEMPERATURES AND RATES OF CHANGE OF SOIL TEMPERATURE IN EARLY 1963—continued

(b) KEW OBSERVATORY (SITE A), (loam etc.), 51°28'N, 0°19'W: 18 feet above M.S.L. JANUARY 1963

Type of soil cover		Bare soil				Grass		Symons**	
Type of thermometer		Bent-stem*		Bent-stem*		Bent-stem*		Bent-stem*	
Depth of thermometer		8 inches		8 inches		8 inches		8 inches	
†Absolute minimum °C		4 inches		4 inches		4 inches		4 inches	
°F		2.8		2.7		2.7		2.7	
Date/time (GMT) of absolute minimum		23/0900		23/1500		23/1200		24/0900	
		23/1800		26/0600		24/0600		26/0900	
Snow depth at 0900 GMT on same day in cm.		13		13 on 23rd		13 on 23rd		13 on 24th	
		12 on 26th		13 on 24th		12		12 on 26th	
Maximum 24-hour decrease (°C)		1.6		1.0		0.6		0.5	
Initial temperature (°C), and date/time (GMT) of beginning of maximum 24-hour decrease.		-0.7, 18/1800		-1.2, 22/1500		various on several occasions		-0.6, 22/0900	
††Maximum 3-hour decrease (°C)		1.4		0.5		0.2		0.3	
Initial temperature (°C), and date/time (GMT) of beginning of maximum 3-hour decrease.		-0.9, 19/1500		-0.6, 19/1500		various on several occasions		+1.1, 11/0600	
Maximum 24-hour increase (°C)		2.0		1.6		1.5		0.8	
Initial temperature (°C), and date/time (GMT) of beginning of maximum 24-hour increase.		-2.4, 25/1800		-2.2, 26/0600		-2.1, 26/0600		-1.2, 26/0900	
		-2.3, 25/2100				-2.6, 26/0600		-1.1, 26/1500	
§Maximum 3-hour increase (°C)		0.7		0.5		0.4		0.2	
Initial temperature (°C), and date/time (GMT) of beginning of maximum 3-hour increase.		-0.6, 14/1200		-2.2, 23/1800		-2.7, 23/1200		various on several occasions	
		-2.8, 23/0900		-1.8, 26/1200		-1.9, 26/1200			
				-1.3, 26/1500		-1.5, 26/1500			

\*Observations at 0600, 0900, 1200, 1500, 1800 and 2100 GMT. \*\*Observations at 0900 GMT only.

†These values are also the absolute minima for the period January–March, inclusive, in 1963 except as follows: at 4 ft, 3.2°C (37.8°F) on 4.5.6 and 8 March.

††Maximum decreases in °C between 2100 and 0600 GMT are as follows: (i) At 4 in. and 8 in. under bare soil, 0.7 and 0.6 respectively.

(ii) At 4 in., 8 in. and 1 ft under grass, 1.0, 0.5 and 0.2 respectively.

§Maximum increases in °C between 2100 and 0600 GMT are as follows: (i) At 4 in. and 8 in. under bare soil, 0.2 and 0.4 respectively.

(ii) At 4 in., 8 in. and 1 ft under grass, 0.6, 0.3, and 0.2 respectively.

TABLE I—ABSOLUTE MINIMUM SOIL TEMPERATURES AND RATES OF CHANGE OF SOIL TEMPERATURE IN EARLY 1963—*continued*  
(c) ROTHAMSTED EXPERIMENTAL STATION, (clay), 51°48'N, 0°22'W; 420 feet above M.S.L.  
(i) JANUARY 1963

Type of soil cover		Bare soil			Grass		
Type of thermometer		Bent-stem		Symons	Bent-stem		Symons
Depth of thermometer		4 inches	8 inches	1 foot	4 inches	8 inches	2 feet
*Absolute minimum °F		31.2	32.8	32.9	30.6	31.8	36.0
		-0.4	+0.4	+0.5	-0.8	-0.1	+2.2
Date of absolute minimum		25th	26th and 27th	24th and 28th	25th	27th	26th
*Snow depth on same day, in inches (cm)		5(13)	4(10) on 26th 2(5) on 27th	5(13) on 24th 2(5) on 28th	5(13)	2(5)	4(10)
Maximum 24-hour decrease (°F)		0.7	0.2	0.5	1.2	0.7	0.3
Initial temperature (°F), and date of beginning of maximum 24-hour decrease.		32.5 on 23rd	33.6 on 12th 33.4 on 13th 33.2 on 22nd	33.5 on 22nd	32.2 on 22nd	33.0 on 23rd	36.5 on 23rd
Maximum 24-hour increase (°F)		0.8	0.5	0.4	1.0	0.6	0.2
Initial temperature (°F), and date of beginning of maximum 24-hour increase.		31.2 on 25th	33.4 on 4th	33.5 on 12th	31.1 on 26th	31.8 on 27th	36.6 on 17th
*Absolute minimum °F		28.9	32.0	32.1	30.2	31.8	34.9
Date of absolute minimum		1 March	1, 3-4 March	+0.1 4 March	-1.0 1 March	-0.1 27 Jan.	+1.6 4, 5, 6 March
*Snow depth on same day in inches (cm)		1(3)	1(3) on 1 March nil on 3, 4 March	Nil	1(3)	2(5)	Nil

\*Observations at 0900 GMT only.

TABLE 1—ABSOLUTE MINIMUM SOIL TEMPERATURES AND RATES OF CHANGE OF SOIL TEMPERATURE IN EARLY 1963—*continued*

(d) CARDINGTON, (clay), 52°06'N, 0°25'W: 93 feet above M.S.L. JANUARY 1963

Type of soil cover	2 inches	Bent-stem* 4 inches	8 inches	Grass Symons**
Type of thermometer				1 foot
Depth of thermometer				+0.1
†Absolute minimum °C	2.9 26.8	-2.6 27.3	-0.8 30.6	32.2
Date/time (GMT) of absolute minimum	24/0900 24/0900	24/0900	several occasions	25/0900, 26/0900 27/0900, 28/0900
Snow depth at 0900 GMT on the same day in cm.	15	15	Various	15 on 25th, 13 on 26th 5 on 27th, 1 on 28th
Maximum 24-hour decrease (°C)				
Initial temperature (°C), and date/time (GMT) of beginning of maximum 24-hour decrease.	1.2 -0.9, 10/0900	1.0 -0.4, 11/0900 -0.6, 11/0600	0.6 -0.2, 18/1200	0.3 +1.5, 9/0900
Maximum 3-hour decrease (°C)				
Initial temperature (°C), and date/time (GMT) of beginning of maximum 3-hour decrease.	0.7 -1.4, 11/2100	0.5 -2.1, 24/0600	0.7†† -0.1, 19/0900	** **
Maximum 24-hour increase (°C)				
Initial temperature (°C), and date/time (GMT) of beginning of maximum 24-hour increase.	1.9 -2.3, 25/2400	1.3 -1.9, 25/2400	0.6†† -0.8, 19/1200	0.1 various on several occasions
Maximum 3-hour increase (°C)				
Initial temperature (°C), and date/time (GMT) of beginning of maximum 3-hour increase.	0.7 -1.8, 12/1500 -2.2, 18/1200	0.4 -1.5, 12/1500 -2.6, 24/0900 -1.6, 26/0900	0.3 -0.6, 19/1500	** ** Fairly steady decrease

\*Observations at 0300, 0600, 0900, 1200, 1500, 1800, 2100, and 2400 GMT. \*\*Observations at 0900 GMT only.

†These values are also the absolute minima for the period January–March, inclusive, 1963 except as follows: at 4 ft, 2.4°C (36.3°F) on 8 March, no snow.

††Value of soil temperature at 1200 on 19 January suspect; next largest 3-hour decrease 0.2°C, and next largest 24-hour increase 0.5°C.

TABLE III—CHANGES IN SOIL TEMPERATURE AT VARIOUS DEPTHS IN LATE JANUARY 1963,  
WITH ASSOCIATED AIR TEMPERATURES AND SNOW DEPTHS

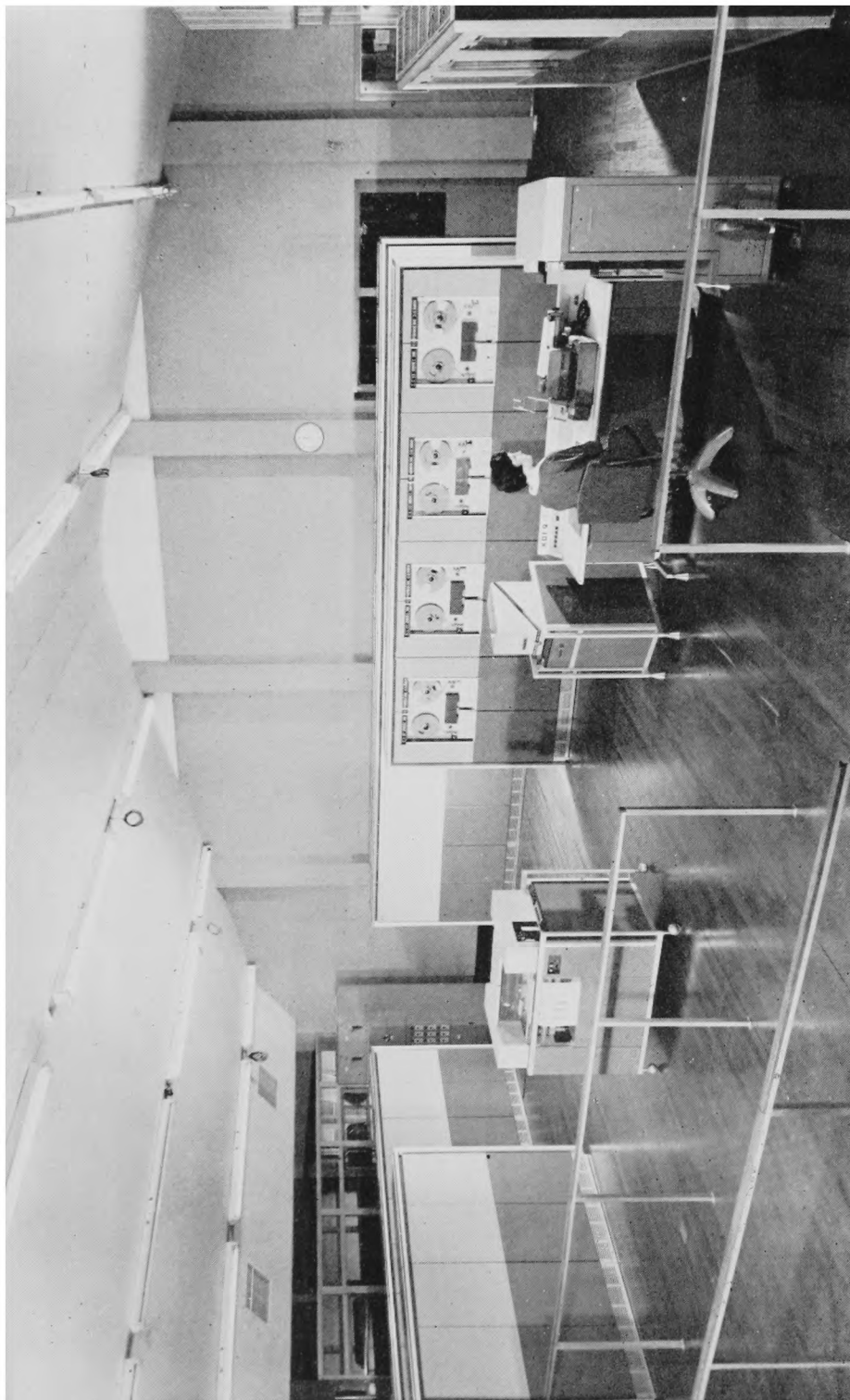
(a) WOBURN EXPERIMENTAL STATION

Type of soil cover Type of thermometer Depth of thermometer 24-hour period ending 0900 GMT on	24-hour change in soil temperature					Air screen temperature		**Grass thermometer temperature: overnight minimum	Snow depth at 0900 GMT at end of period inches centimetres				
	Bare soil		Grass		Minimum °F °C	Maximum °F °C		°F °C					
	Bent-stem		Symons										
	4 inches degrees Fahrenheit	8 inches degrees Fahrenheit	1 foot degrees Fahrenheit	2 feet degrees Fahrenheit						4 feet degrees Fahrenheit			
21st	-0.2	0.0	-0.1*	-0.2*	-0.1*	23	-5.0	29	-1.7	27	-2.8	8	20
22nd	-4.4	-0.9	-0.4	0.0*	-0.1*	-2	-18.9	28	-2.2	9	-12.8	8	20
23rd	-2.1	-1.0	-0.6	0.0*	-0.1*	-4	-20.0	23	-5.0	8	-13.3	8	20
24th	-0.5	-1.3	-1.7	-0.3*	-0.3*	-1	-18.3	25	-3.9	7	-13.9	7	18
25th	+1.6	+0.8	+0.3	0.0*	-0.1*	6	-14.4	21	-6.1	12	-11.1	7	18
26th	+3.0	+0.4	+0.1	-0.7*	-0.1*	11	-11.7	34	+1.1	13	-10.6	7	18
27th	+2.7	+1.2	+0.8	0.0*	-0.1*	32	0.0	38	+3.3	21	-6.1	6	15
28th	+1.4	+0.9	+0.5	-0.2*	-0.1*	33	+0.6	37	+2.8	31	-0.6	4	10
Temperature at 0900 GMT on 28th in °F °C	31.1 -0.5	31.1 -0.5	31.1 -0.5	33.8 1.0	39.9 4.4								

(b) KEW OBSERVATORY (SITE A)

Type of soil cover Type of thermometer Depth of thermometer 24-hour period ending 0900 GMT on	24-hour change in soil temperature							**Grass thermometer temperature: overnight minimum °C	Snow depth at 0900 GMT at end of period centimetres		
	Bare soil		Grass			Symons				Air screen temperature Minimum °C	Maximum °C
	Bent-stem		Bent-stem	Grass	1 foot	4 feet					
	4 inches degrees Celsius	8 inches degrees Celsius	4 inches	8 inches	1 foot degrees Celsius	4 feet					
21st	-0.4	+0.1	0.0	0.0	0.0	0.0*	0.0*	-3.0	-0.5	-5.2	14
22nd	-0.7	-0.5	-0.9	-0.5	-0.2	-0.1*	-0.1*	-7.1	-0.5	-12.3	14
23rd	-0.9	-0.7	-0.8	-0.6	-0.4	0.0*	0.0*	-12.1	-0.4	-15.8	13
24th	+0.6	-0.2	0.0	-0.1	-0.3	-0.1*	-0.1*	-10.7	-2.3	-12.0	13
25th	+0.1	+0.4	+0.5	+0.4	+0.2	-0.1*	-0.1*	-10.3	-4.3	-9.3	12
26th	+0.2	-0.2	-0.2	-0.4	-0.4	0.0*	0.0*	-10.3	+0.1	-12.6	12
27th	+1.8	+1.4	+1.9	+1.3	+0.8	-0.2*	-0.2*	-0.6	+7.4	-0.6	6
28th	+0.4*	+0.4	+0.7*	+0.7*	+0.2	+0.3	0.0*	+1.7	+3.9	+0.1	0
Temperature at 0900 GMT on 28th in °C	0.3	-0.1	0.3	0.2	-0.2	-0.1	3.9				

\*Final temperature was above freezing-point; with all other changes the final temperature was below freezing-point.  
\*\*Measurement taken on snow surface when snow was lying and thermometer kept free of snow if possible (see Observer's Handbook21).



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PLATE 1—PART OF THE KDF 9 INSTALLATION IN THE ENGLISH ELECTRIC-LEO  
BUREAU AT KIDSGROVE

See page 19

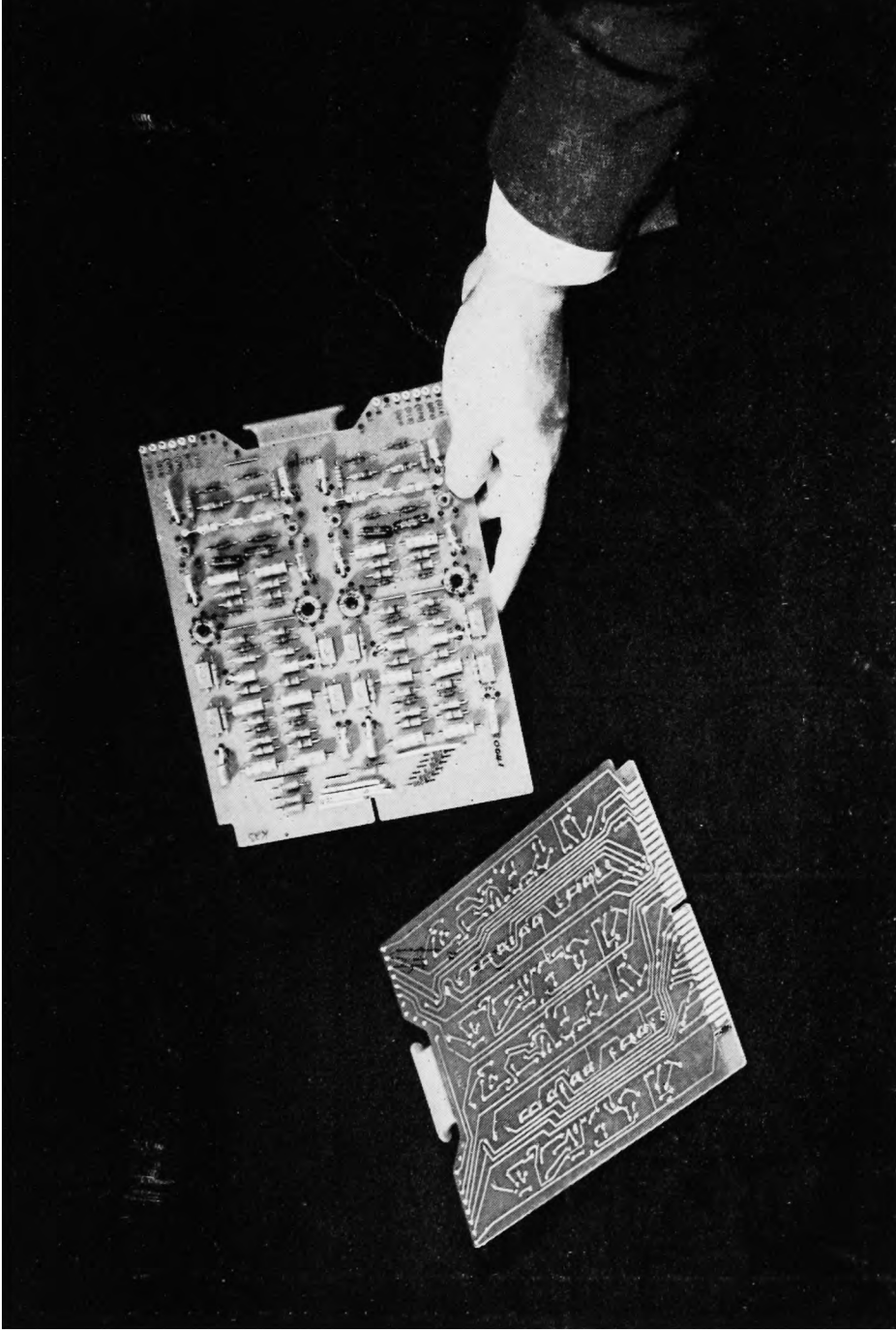


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PLATE II—PAPER TAPE PUNCH, CONTROL CONSOLE, AND PAPER TAPE READER  
OF THE KDF 9

See page 19

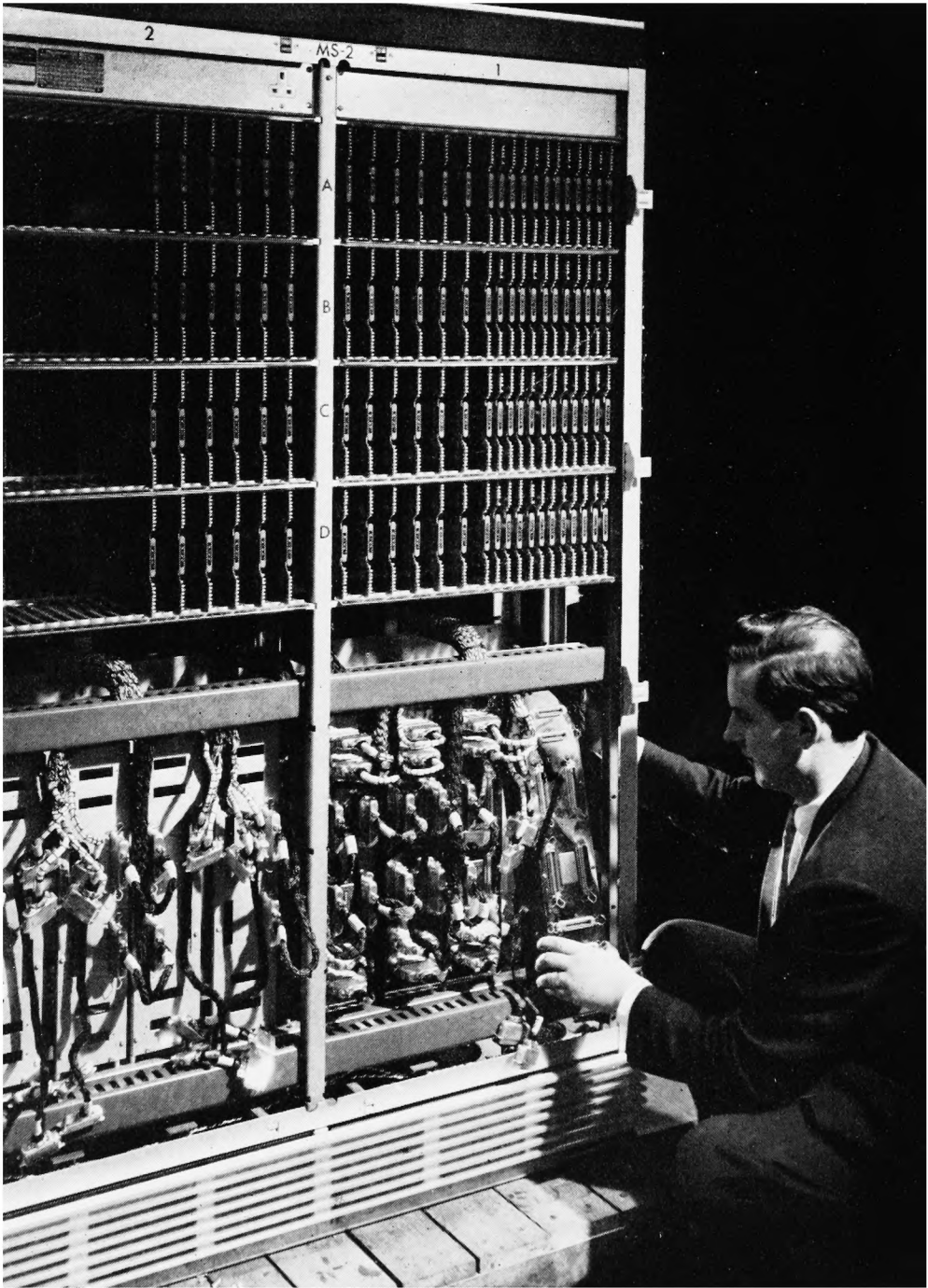




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PLATE III—'PULSE AMPLIFIER' PRINTED CIRCUIT PLUG-IN MODULE OF THE KDF 9

See page 19



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PLATE IV—ONE OF THE MAIN STORE RACKS OF THE KDF 9 SHOWING CORE MODULE  
BEING FITTED

See page 19

TABLE III—CHANGES IN SOIL TEMPERATURE AT VARIOUS DEPTHS IN LATE JANUARY 1963,  
WITH ASSOCIATED AIR TEMPERATURES AND SNOW DEPTHS—*continued*

**(c) ROTHAMSTED EXPERIMENTAL STATION**

24-hour change in soil temperature															
Type of soil cover Type of thermometer Depth of thermometer 24-hour period ending 0900 GMT on	Bare soil			Grass			Air screen temperature		**Grass thermometer temperature:		Snow depth at 0900 GMT at end of period inches centimetres				
	Bent-stem		Symons	Bent-stem		Symons	Minimum Maximum		°F °C						
	4 inches	8 inches	1 foot	4 inches	8 inches	1 foot	°F	°C	°F	°C					
21st	-0.1*	+0.1*	+0.2*	+0.6*	0.0*	0.0*	-0.1*	23	-5.0	29	-1.7	20	6.7	7	18
22nd	-0.4*	0.0*	-0.1*	-0.6*	0.0*	-0.1*	-0.2*	12	-11.1	27	-2.8	16	-8.9	6	15
23rd	0.0*	-0.2*	-0.5*	-1.2	0.0*	+0.1*	-0.1*	2	-16.7	27	-2.8	13	-10.6	6	15
24th	-0.7	0.0*	-0.1*	0.0	-0.7	-0.3*	-0.3*	4	-15.6	27	-2.8	12	-11.1	5	13
25th	-0.6	-0.1*	+0.1*	-0.4	-0.2*	-0.2*	0.0*	7	-13.9	23	-5.0	13	-10.6	5	13
26th	+0.8	-0.1*	0.0*	+0.5	0.0*	-0.1*	-0.2*	7	-13.9	33	+0.6	13	-10.6	4	10
27th	+0.1*	0.0*	0.0*	+1.0*	-0.3	+0.1*	+0.1*	31	-0.6	40	+4.4	29	-1.7	2	5
28th	0.0*	+0.1*	-0.1*	-0.1	+0.6*	+0.1*	+0.1	33	+0.6	36	+2.2	31	-0.5	2	5
Temperature at 0900 GMT on 28th in °F °C	32.1 0.1	32.9 0.5	32.9 0.5	32.0 0.0	32.4 0.2	33.4 0.8	36.2 2.3	39.4 4.1							

**(d) CARDINGTON**

24-hour change in soil temperature											
Type of soil cover	Grass					Symons 1 foot degrees Celsius	Symons 4 feet Celsius	Air screen temperature		**Grass thermometer temperature: overnight minimum °C	Snow depth at 0900 GMT at end of period centimetres
	2 inches	Bent-stem 4 inches degrees Celsius	8 inches	temperature							
				Minimum °C	Maximum °C						
Type of thermometer											
Depth of thermometer											
24-hour period											
ending 0900 GMT on											
21st	-0.2	-0.2	+0.2	0.0*	0.0*	0.0*	-7.2	-1.1	-10.8	15	
22nd	-1.0	-0.7	-0.2	0.0*	0.0*	0.0*	-17.1	-1.9	-20.3	15	
23rd	0.0	-0.1	-0.2	-0.1*	-0.1*	-0.1*	-16.1	-2.8	-20.4	15	
24th	-0.6	-0.8	0.0	-0.1*	-0.1*	-0.1*	-18.3	-6.2	-19.2	15	
25th	+0.7	+0.8	-0.2	0.0*	0.0*	0.0*	-12.4	-5.9	-11.4	15	
26th	+0.6	+0.2	+0.1	0.0*	0.0*	0.0*	-11.9	+0.6	-13.9	13	
27th	+1.3	+1.1	+0.3	-0.1*	-0.1*	-0.1*	-0.9	+5.1	-0.2	5	
28th	+0.2	+0.2	+0.1	0.0*	0.0*	0.0*	+1.4	+3.2	+0.6	1	
Temperature at 0900 GMT on 28th in °C	-0.1	-0.3	-0.3	0.1	0.1	3.5					

\*Final temperature was above freezing-point; with all other changes the final temperature was at or below freezing-point.

Final temperature was above freezing-point, with all other changes the final temperature was at or below freezing-point.

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## A NEW COMPUTER SYSTEM FOR THE METEOROLOGICAL OFFICE

By E. J. SUMNER, B.A.

**Introduction.**—The first Meteorological Office (MO) computer was delivered in the autumn of 1958 and became known in the office as METEOR. It was a *Ferranti Mercury* type, based on thermionic valves and operating solely from punched paper tape. It soon became evident that METEOR, although a very powerful tool for research as it was primarily intended to be, was not going to be fast enough or reliable enough for work that had to be carried out unfailingly to a tight schedule—operational numerical weather prediction, for example, employing the latest multi-layer, larger-area models of the atmosphere. Moreover it had neither the external facilities nor the control features necessary to undertake the data handling required in modern climatological services or in the automatic editing of telecommunication messages.

During recent years enormous strides have been made in computer manufacture which is now universally based on transistors and other improved components mounted on printed plug-in circuit boards. The improved manufacturing techniques have made it possible to construct faster, more complex, more versatile, and at the same time more compact and more reliable machines, controlling a large number of ancillary devices—entire electronic data-processing systems, in fact. The one chosen as a replacement for METEOR is the *English Electric-Leo* KDF 9 computer system which is to be installed in the meteorological headquarters, Bracknell, in the autumn of 1964, and will be called COMET.

This article describes the new system and, very briefly, the associated services that will be available to all branches of the Office. The reader is referred to a previous paper<sup>1</sup> for the background.

**The general system.**—Photographs of a typical KDF 9 installation are shown in Plates I and II. On view in the first plate are: a paper tape reader and punch (to the right and left of the operator's console, respectively), several magnetic tape units (immediately facing the operator), a line-printer (left foreground) and, in the background, various cabinets of the computer itself. The close-up on Plate II shows more details of the tape units and of the console, including the automatic typewriter for communication between the computer and the operator.

The storage capacity, operating speeds and ancillary equipment of the new Meteorological Office system are listed in Table I, side by side with comparative information for METEOR. KDF 9 is in all respects faster than METEOR, with a larger memory store and a wider range of input/output devices and operating media. Like all computers of its generation, it is built on a 'modular' or 'packaged' principle so that the number of external devices and the size of the internal memory can be increased later, within limits, with little interference with normal working.

Plate III shows back and front **views** of a typical printed circuit module, one of a hundred or so basic circuits from which the computer is assembled. The one in question is used to amplify the information pulses that pass to and fro within the computer. In Plate IV a memory unit is being fitted below racks of circuit boards.

The components of circuit modules are intrinsically very reliable but if one fails, the maintenance engineer, assisted by special diagnostic programmes and test equipment, has the relatively easy task of finding the module affected. A spare one can then be plugged in and the computer is ready for use again, while the faulty board is repaired at leisure.

As mentioned above, KDF 9 is faster than METEOR—it has a basic rhythm of 6 microseconds, that is ten times faster. However, for arithmetical processes, speeds are up by a larger factor (e.g. by a hundred for division) and so are magnetic tape reading and writing speeds, although for the other input/output devices the speed increases are only of the order of three to six times. Carrying out a full 'numerical prediction' run on METEOR takes 4 hours at present; it is estimated that this could be done in less than 20 minutes on KDF 9. However, in assessing the increased capacity for work of the new system as compared with the old, speed is not the only factor. There is also the increased reliability and the more efficient utilization arising from the fact that up to four different programmes may be run simultaneously on KDF 9 (see the section on time sharing, later). All things considered, its capacity for work will be of the order of twenty times that of METEOR.

Physically KDF9 is very little larger and the heat dissipation is only about half. However the air-conditioning requirements are much more stringent; dust and humidity control, as well as temperature control will have to be provided.

**Operating media.**—Whereas data from the meteorological library of some 30 million punched cards can only be made available to METEOR via

TABLE 1—KDF9 AND METEOR COMPARED  
KDF 9

ITEM	METEOR
Internal storage	
Main store	1024 40-bit words
Magnetic drum	16,384 40-bit words
Operating speeds	<i>microseconds</i>
Access to main store	120
Addition and subtraction—fixed-point*	—
floating-point	180**
Multiplication—fixed-point	—
floating-point	300**
Division—fixed- and floating-point	3800
Input/output equipment	
Paper tape readers	Speed
Paper tape punches	300 characters per second
Card readers	33 characters per second
Line printers	150 lines per minute
Magnetic tape units	(92 characters per line)
	Number
	1
	1
	0
	1
	0
	Speed
	1000 characters per second
	110 characters per second
	600 cards per minute
	1000 lines per minute
	(160 characters per line)
	40,000 characters per second
	Number
	3
	3
	1
	1
	6

\* See section on information representation for explanation of fixed- and floating-point.

\*\* Note: Arithmetic times on METEOR include the time of one transfer from the main store to the arithmetic unit, whereas those for KDF 9 do not.

special machines which first convert them to paper tape, KDF 9 will be capable of reading punched cards directly, at 600 cards per minute. Paper tape facilities are also provided, more abundantly in fact because so much more teleprinter data on tape will be handled in future, and because of the increased local production of punched tape (e.g. from digitizing equipment such as that installed at Kew Observatory to record radiation data). Both 5- and 8-channel tape, with different codes, will be in use, requiring that readers and punches should be quickly switchable from one mode to the other, as required.

For the first time, the MO will be equipped to deal with data recorded on magnetic tape, a most powerful medium in view of its high storage capacity (several hundred times that of cards) and its extremely high reading and recording speeds, viz. 40,000 characters (decimal or alphabetical) per second. A single reel of  $\frac{3}{4}$ -inch tape, 2400 feet long and about 10 inches in diameter, will hold more than 10 million characters, doubly recorded for reliability in binary code, in two 8-channel sets side by side. On input to the computer from magnetic tape, both copies of the data are scanned simultaneously; if either or both give a valid response the correct character is transferred into the main computer store. Double recording eliminates the more usual failure caused by a very local blemish on the tape or a particle of dust interposing itself between the reading head and the tape and affecting only a single channel.

Finally, there is the fast printer operating at 1000 lines per minute, each line containing up to 160 characters. This will have good registration so that results may be printed onto stationery on which map outlines or special lined formats have been pre-printed. Multiple copies may also be obtained by the usual methods.

**The information representation and memory stores.**—Numbers are stored within the memory of the computer as groups of 48 bits (binary digits), each group constituting a 'word' or 'register.' The number may be either in fixed-point or floating-point form. Briefly, in fixed-point arithmetic the programmer has to remember where the decimal point comes in the number whereas in floating-point this is automatically taken care of by the computer,\* but the price paid for this facility is slower working, especially for addition and subtraction. The floating-point representation also permits larger numbers to be handled, although with less precision.

Decimal or alphabetical characters are entered on tape in a 6-bit code and are therefore stored within the computer eight to a 'word.' Instructions on the other hand are made up of 8-bit 'syllables,' six to a 'word.' Some instructions (e.g. all of the arithmetic instructions) are only one-syllable; others are two or three (maximum). Whatever their length, they are strung together in the store in strict succession, overflowing from one register to the next if necessary. This makes for great economy of storage of programmes within the computer.

The MO computer will have three 4096-'word' modules of main storage, which can be expanded later to a maximum of eight (i.e. 32,768 'words') if required. Access to any 48-bit 'word,' containing data or instructions, in this store can be obtained in 12 microseconds, frequently less. Before arithmetic and other operations can be carried out on numbers in the main store, they have

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\*Numbers in floating-point are considered to be in the form  $m \times 2^n$  and the  $m$  and  $n$  are separately stored, 40 'bits' of a 'word' being reserved for the former and 8 for the latter.

first to be transferred to a special 'nesting' store of only 16 'words.' There are four such stores, one reserved for each possible programme. The stores operate on a 'first-in-last-out' principle, i.e. 'words' are inserted very much like the bullets in a rifle magazine, but the top three 'words' (or cells) may be rearranged cyclically. Once 'words' or numbers are in the nesting store, a variety of arithmetical and manipulative processes may be carried out on them at very high speed—often within 1–2 microseconds—without further (slower) reference to the main store. This mode of working is particularly efficient when repeated iterations on the same numbers have to be carried out, e.g. in evaluating a polynomial.

Another novel feature of KDF 9, conducive to faster working, is an 'advanced think' control unit by means of which transfers between the main and nesting stores take place in parallel with computing, whenever this can be arranged by the central control of the computer. In favourable circumstances access times to the main store may be effectively shortened from 12 to 2 microseconds (on average, to 7 microseconds).

Yet another store, which however is more of an external device than an internal memory, is the magnetic drum, capable of holding 40 'bands' each containing 1024 'words' of information. The drum rotates at about 3,000 rev/min, and access to each band takes about 10 *milliseconds* which is very slow by comparison with the maximum time of 12 *microseconds* quoted for access to the main store. However, if a long string of data is required in exactly the sequence it is stored on the drum, a continuous transfer rate to the main store (to which information must be transferred before use) of the order of half a million characters per second can be achieved.

**Programming.**—Instructions to the computer must be written out in a suitable language. The principal KDF9 programming language is called *User Code*; it is fairly self-evident in form and therefore easy to remember. For example, fixed-point arithmetic functions employ the usual mathematical symbols (+, −, ×, ÷), and floating-point is distinguished merely by the addition of the letter F. Thus  $\times F$ ; means: 'multiply two floating-point numbers in the top two cells of the nesting store together and store the result in the top cell.' (The semi-colon is written after *every* instruction as a terminator.)

Plain-language instructions like ERASE;, FINISH;, ZERO; and NEG; (negative) are used as well as equally obvious but more technical words such as DUP;, ROUND;, PERM;, AND;, OR; and NOT;. Then there is a host of instructions represented by initial letters, such as PR; or PW; (*paper tape read* or *write*, respectively), MRWD; (*magnetic tape rewind*), MBR; (*magnetic tape backward read*), LP; (*operate line printer*), etc.

Usually instructions are carried out in strict sequence, as they are written, but from time to time it is necessary to jump to some remote point in the programme depending on some criterion, e.g. whether a particular value is positive, negative or zero. For example, there is the instruction  $Jr \geq Z$ ; which is interpreted as: 'jump to the point in the programme labelled "r" (an integer) if the top cell of the nesting store is greater than or equal to zero, otherwise proceed to the next instruction in sequence.'

Obtaining access to data stored in the main store is particularly easy on KDF 9. Each main-store register must carry an 'address' to identify it. In one form of addressing, data registers are designated Y<sub>0</sub>, Y<sub>1</sub>, Y<sub>2</sub>,....etc. The



instruction  $Yr$ ; brings the word in main-store register  $r$  to the top cell of the nesting store (pushing all the other words in the nesting store down, one cell). The instruction  $=Yr$ ; transfers the word from the nesting store to the appropriate main-store register.

Thus in order to add together two floating-point numbers in the main-store locations  $Y_1$  and  $Y_2$  and store the result in  $Y_3$ , say, the programmer simply writes:

$Y_1; Y_2$ ; (the two numbers are now in the top two cells of the nesting store)  $+F$ ;  $= Y_3$ ; (the result is now stored away).

To form the fourth power of the product of these same two numbers, say, the instructions are:

$Y_1; Y_2; \times F; DUP; \times F; DUP; \times F; = Y_3$ ;

The first multiplication forms the product in the top cell of the nesting store. Then a copy of this is made in the second cell by means of the  $DUP$ ; instruction. The second multiplication then forms the square. Because of the next  $DUP$ ; this square is copied and the final multiplication gives the fourth power.

Programmes have to be punched character by character onto paper tape and then read into the computer under the control of a special translator or 'compiler' programme which carries out a conversion to the internal machine codes. (For various reasons the internal codes are quite different from those on tape.)

Apart from User Code there are several other programme languages which are even simpler. These include *Fortran* and *Algol* (algebraical languages), *Cobol* (almost basic English) and *Mercury Autocode*, which will be familiar to many users of METEOR. Programmes written in these languages will be shorter and easier to get right but will generally use the computer less efficiently. They make more concessions to the programmer and are more remote from the internal codes and mode of functioning than User Code. The translation process is thus more complex and the compiled programme (either on paper or magnetic tape), which is the one actually used at 'run time,' will usually take up more internal storage and use up more computer time.

It will therefore be politic to write programmes that have to be run many times in User Code whereas those intended for one-off jobs (e.g. answering a specific climatological inquiry) would be more expeditiously dealt with in one of the other languages. The choice of language depends on the sort of problem to be dealt with (Cobol, for example, is more adapted to business applications), although the personal background and taste of the programmer is not entirely to be discounted.

**Parallel processing and time sharing.**—One feature of electronic computers has always been the great disparity between the speeds at which they can accept information into the main store and the much lower speeds of peripheral devices (printers, readers, punches, etc.). This disparity has inevitably led to development of techniques for carrying out several input/output operations in parallel with each other and with internal processing operations.

KDF 9 is capable of operating up to 16 peripheral units simultaneously, subject only to a maximum combined transfer rate of  $1\frac{1}{3}$  million characters per second. All the units of the MO system can in fact be in operation at one

time without saturating the input/output control. Transfers can be in sizable data blocks and, once initiated, proceed to completion quite independently of central control which can be devoted to processing data already in the nesting store.

It is seldom however that any one programme will need all 16 peripheral units to itself, or can be written so as to keep central control busy all the time. Thus, provision is made for the computer to share its time between several programmes. The order of priority of time-shared programmes has to be laid down. The first-priority programme proceeds without interruption until it is held up because it needs to read in further data or print out intermediate results, say, or even because of a fault in one of the units it is using. In this event a second programme is automatically switched in until the first is ready to resume control or until it is itself held up for one reason or another, whereupon control passes to a possible third programme, and so on up to a maximum of four. While a particular programme is being dealt with, input/output transfers relevant to that and the other programmes may be proceeding quite independently, as previously explained.

The internal switching and general 'house-keeping' of all these activities is under the control of a master programme called the 'Time-sharing Director.' The programmer need not be concerned with this: he merely writes his programme as though it were the only one present. Information as to the memory and peripheral unit requirements of each programme has, of course, to be supplied to the console operator who has to ensure that the total requirements do not exceed those available to the system at the time.

The aim is to keep all internal circuitry and all ancillary devices as busy as possible in the interest of economy, although this may mean some sacrifice in the speed of execution of particular programmes. However if programmes are judiciously combined, e.g. if a heavy computing programme is run with one requiring a simple transfer, say, from tape to printer, then the hold up to either will be quite insignificant.

**Final remarks.**—KDF 9 will greatly increase the computing and data processing facilities available within the Office. It will introduce a new quality into the work of research and service branches alike, and make great demands on both. Added powers almost invariably bring added problems and responsibilities.

The actual day-to-day running and maintenance of so large and so sophisticated a system on a time-sharing basis will be quite a task in itself. So too will be the production and organization of the large ever-growing library of programmes and data, recorded in a variety of media, that will be required to feed it.

MO18c will be largely responsible for this as a central service and will also provide programming assistance on request. The more specialized programming of some research problems will, however, continue to be done by the branches concerned. Processing via conventional punched-card machines will probably diminish, although for smaller jobs it will be many years before they will be entirely superseded.

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# THE NATURE OF THE EARTH'S OUTER ATMOSPHERE (THE MAGNETOSPHERE) AND ITS POSSIBLE INFLUENCES ON METEOROLOGY

By F. D. STACEY, B.Sc., Ph.D.

**Introduction—the magnetosphere.**—The study of the very high atmosphere is now recognized as relevant to meteorology. Although at the present time the direct influences upon our weather of effects in the remote atmosphere appear mostly marginal or uncertain, this is probably due more to ignorance than to a lack of real connexions. Consequently the level to which meteorological research interests extend is continually rising and it is pertinent to consider whether we can really assign any upper limit to the atmosphere. The atmosphere is most satisfactorily defined as that gaseous envelope which travels with the earth in its orbit around the sun. Thus defined, the atmosphere extends to between 5 and 20 earth radii and is therefore very much more extensive than that considered in normal meteorology. By far the largest part of it consists of a tenuous, ionized gas or plasma, whose behaviour is directly controlled by the earth's magnetic field. For this reason it has been termed 'the magnetosphere' (Gold<sup>1</sup>).

At first sight it might appear that the geomagnetic field, being approximately dipolar, extends outwards into the interplanetary medium indefinitely, with strength decreasing as the cube of the distance from the earth, but this cannot be so. The field rotates with the earth and the electrically conducting plasma is carried around with it, because the currents induced in any plasma, which does not initially rotate with the field, would very rapidly compel it to do so. But the whole of interplanetary space cannot be rotating with the earth; the field at great distances would be too weak. Instead the more remote plasma prevents the penetration of the rotating field. The field itself is thus restricted to a limited volume (the magnetosphere), within which the plasma moves with the earth, and beyond which the field does not penetrate and the plasma moves independently of the earth. The geomagnetic field thus provides a giant magnetic bottle for the atmosphere and substantially isolates it from the interplanetary medium.

**Effect of the 'solar wind.'**—The emission by the sun of a more or less uniform stream of protons and electrons constitutes the 'solar wind,' which is continually 'blowing' past the earth. We may think of the wind as a moving plasma which tends to carry the earth's field with it, so that the magnetosphere is compressed on the sunlit side and extended on the dark side. The solar wind deforms the magnetospheric surface very much in the way one might expect an ordinary atmospheric wind to deform a flimsy balloon suspended from a fixed point in its interior by elastic bands to the surface. This is indicated in Figure 1, which is a diagrammatic representation of the internal structure of the magnetosphere. The general picture has now been established by satellite research, although many details are still not clear. An alternative approach to the problem of magnetospheric compression by the solar wind is to consider the motion of individual solar-wind particles approaching the earth. As they strike the magnetic field, protons are deflected one way and electrons the other. This charge separation constitutes an electric current in the magnetospheric surface, which has just such a magnitude and configuration as to cancel the field outside the surface. The probable structure of the magnetospheric surface is then more

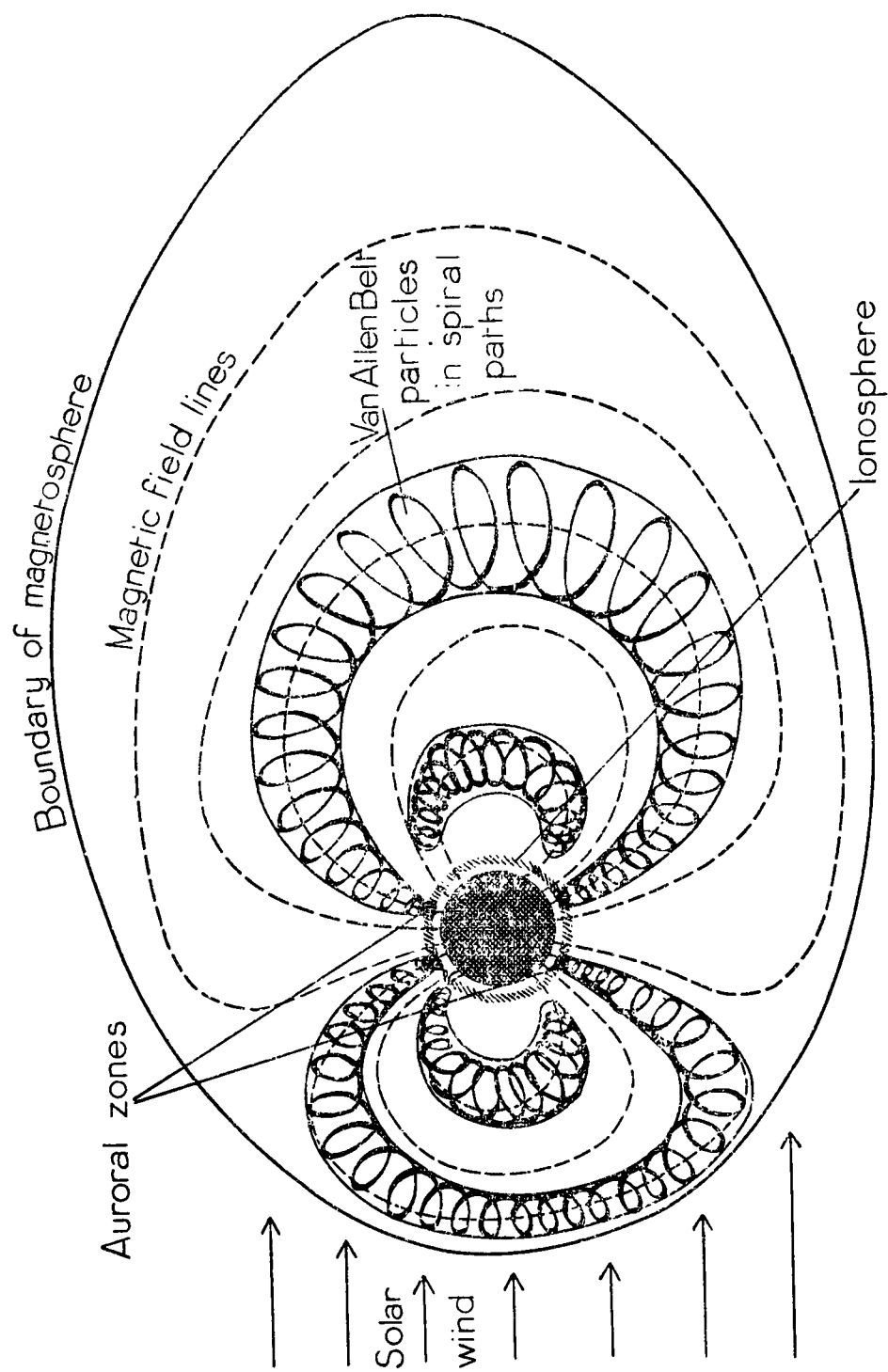


FIGURE 1—THE MAGNETOSPHERE

obvious because not all of the particles have the same initial momentum and they therefore penetrate the surface to different depths. For this reason the magnetospheric boundary is actually a transitional zone several hundred kilometres thick, in which there is a momentum exchange between the magnetospheric and interplanetary plasmas. Axford and Hines<sup>2</sup> have pointed out that this momentum exchange is equivalent to a frictional contact between the solar wind and the magnetospheric plasma, driving an internal convective motion of the magnetosphere with important consequences. Fejer<sup>3</sup> considers that rotation of the field within the magnetospheric boundary, as deformed by the solar wind, may constitute at least as important a driving mechanism for convection. Whatever its precise cause, the convection induces magnetospheric currents which are responsible for the regular diurnal geomagnetic variations and are most noticeable in the auroral zones where particularly intense currents flow at ionospheric heights.

**The radiation belts.**—Extensive regions within the magnetosphere contain intense fluxes of energetic particles whose velocities are such that they are ‘trapped’ by the magnetic field. They are commonly known by the name of their principal discoverer, J. A. Van Allen, and are disposed in the manner indicated in Figure 1. The development of our knowledge, particularly of the outer of the two main belts has been reviewed recently by Farley.<sup>4</sup>

We are still a long way short of a satisfactory detailed explanation for the origin and structure of the Van Allen belts but the elementary mechanical explanation of particle trapping is straightforward. The velocity of any particle may be resolved into two components, parallel and perpendicular to the magnetic field lines. The component along the field is unaffected by it but the perpendicular component is deflected so that the particle spirals about the field lines. Very energetic (cosmic ray) particles are only slightly deflected by the field; very low-energy particles are confined by the field to so small a space that they can be regarded as stationary (except when they are impelled by electric fields set up by the magnetospheric convection). Particles of moderate energy (important energies appear to be 0.1–1 mega electron-volt (MeV) for electrons, 0.5–5 MeV for protons) have spiral paths small compared with the size of the magnetosphere but are nevertheless sufficiently energetic to ignore (almost) the convective or tidal motions. They spiral about the magnetic field lines with the parallel component of their motion carrying them towards one of the auroral zones. As the field lines approach the earth they converge and this has two effects upon the particle motion, as shown in Figure 2. The spirals

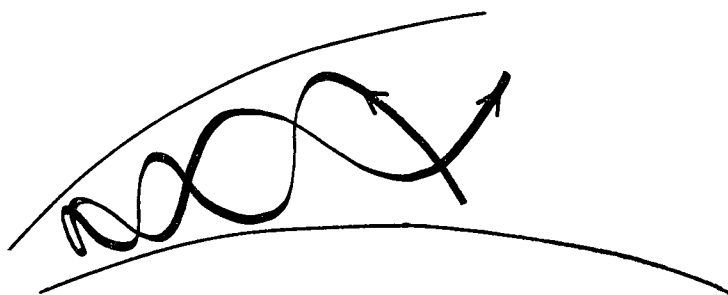


FIGURE 2—PATH OF A VAN ALLEN BELT PARTICLE REFLECTED FROM AN AURORAL ZONE BY CONVERGENCE OF THE MAGNETIC FIELD

become tighter in the stronger field and the parallel component of the motion is reversed by the convergence of the field lines. The particles are magnetically reflected from the auroral zones at each end of their paths.

Particles of both signs have superimposed drift motions, eastwards for electrons and westwards for protons, which constitute a 'ring current' (at a distance of several earth radii) whose strength changes substantially during magnetic storms, (Akasofu and Chapman<sup>5</sup>).

**Geomagnetic storms.**—At irregular intervals the sun ejects streams of charged particles with much higher velocities than those of the normal solar wind. The arrival of one of these streams at the magnetospheric surface is noticeable almost immediately in the records of magnetic observatories as a 'sudden commencement.' This is so called because it is a normal (although not necessary) precursor to a magnetic storm and because its suddenness in a previously 'quiet' record can be quite striking. A magnetogram or a record of a storm normally has a form which is represented somewhat diagrammatically in Figure 3, but wide ranges of variation are possible, depending upon the sequence of particle fluxes which reach the earth and the initial state of the magnetosphere.

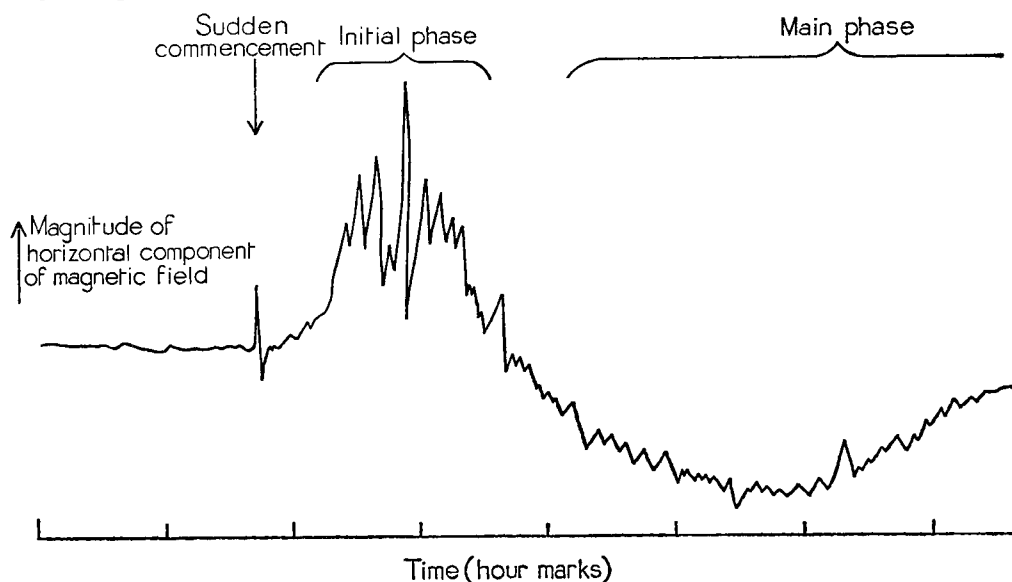


FIGURE 3—CHARACTERISTIC SEQUENCE OF CHANGES IN FIELD DURING A MAGNETIC STORM

The sudden commencement mechanism has been explained most satisfactorily by Wilson and Sugiura.<sup>6</sup> Particles striking the magnetospheric boundary generate hydromagnetic waves which are propagated to the earth as magnetic disturbances. Hydromagnetic waves may be regarded as electromagnetic waves in which the conducting plasma moves with the field lines and controls the wave motion. The waves are of two types, longitudinal and transverse with respect to the field. The simple classical picture of tubes of magnetic force with elastic properties describes the nature of these waves quite clearly. The transverse waves represent a compression of the tubes of force, which is propagated across the tubes and therefore strikes the earth principally in low latitudes where the geomagnetic field is nearly horizontal. The longitudinal waves may be regarded as 'kinks' which propagate along the tubes to high latitudes.

Following the sudden commencement of a magnetic storm there is normally an initial phase, lasting an hour or so, during which the field intensity at the earth's surface is increased by the continued compression of the magnetosphere. This is followed by a day or so of 'main phase' during which an enhancement of the ring current reduces the field at the surface. A well developed main phase is commonly accompanied by auroral displays at high latitudes. The connexion between aurorae and the ring current is readily understood although the mechanism has not been conclusively demonstrated. In magnetically disturbed conditions solar particles probably penetrate to the outer Van Allen belt where the increased particle density causes enhancement of the ring current. However, either the higher particle density is unstable or else the new particles have velocities unsuitable for permanent trapping. Some of the particles are 'dumped' into the ionosphere in the auroral zones, where the outer belt is terminated, and cause auroral displays.

**Space science and meteorology.**—The action of the geomagnetic field in directing particles towards high latitudes may apply to fine particulate matter, as well as to the protons and electrons of the Van Allen belts. Solid particles of diameter 100 ångström units (Å) approaching the earth with velocities of the order 10 km/sec and positively charged to about 10 volts by the photoelectric emission of electrons in the sun's ultra-violet and X-radiation, would have spiral paths of dimensions appreciably smaller than the magnetosphere and they would therefore spiral towards high latitudes. Larger particles behave similarly if they are more highly charged or approach the earth more slowly. Thus a significant proportion of the meteoritic dust reaching the lower atmosphere probably does so quite non-uniformly. Its subsequent redistribution therefore depends upon the circulation in the denser part of the atmosphere. If the ice nuclei necessary for rainfall depend for their formation at least partly upon the arrival of meteoritic dust, as Bowen<sup>7</sup> has been asserting for a number of years, then it would follow that rainfall is directly influenced by magnetospheric processes.

The suggestion that meteoritic dust is magnetically directed towards high latitudes may be relevant to the recent discovery by Hemenway *et al.*<sup>8</sup> that a noctilucent cloud, sampled by a rocket flight over Sweden, contained particles of nickel-iron in the size range 500Å–5000Å. Noctilucent clouds are observed at high latitudes in summer months, when the sun is below the horizon but sufficiently near to it to illuminate the clouds. They occur at very much higher altitudes (75 km in the Swedish observations) than normal clouds; so high that it is doubtful whether ordinary atmospheric moisture could be responsible. The nickel-iron composition is very suggestive indeed of meteoritic origin, since metallic nickel-iron is one of the important constituents of meteorites. It is therefore most reasonable to regard the noctilucent cloud material as meteoritic dust which has been precipitated through the magnetosphere. However, magnetic direction of particles in this size range requires that they be charged to several thousand volts. Secondary electron emission during bombardment by electrons of the inner Van Allen belt appears to be the most plausible mechanism for producing a charge with this potential.

The problem of moisture in noctilucent clouds still arises because the collected cloud particles appear to have had ice coatings. In contemplating the moisture content of the outer atmosphere it may be necessary to consider the exchange

of hydrogen with interplanetary space, and in particular the precipitation of protons by the solar wind. It is interesting (but possibly not significant) to note that a solar wind of  $5 \times 10^9$  protons/cm<sup>2</sup> sec (a figure obtained from Bierman's<sup>9</sup> deduction from the behaviour of comet tails) arriving at a hemispherical magnetospheric surface of radius 10 earth radii would, if entirely collected by the earth, accumulate in the whole of geological time to produce a volume of water approximately equal to that of the oceans.

Discussion of the role in meteorology of meteoritic matter has been renewed recently, particularly by Bowen,<sup>10</sup> Adderley<sup>11</sup> and Bigg.<sup>12,13</sup> Variations with lunar phase of rainfall, ice nucleus concentrations, ozone and geomagnetic storms are connected by strong implication with a lunar control on meteor arrival. If any or all of these correlations are real they may depend upon a modulation by the lunar gravitational field, of the interplanetary dust arriving at the earth, electric and magnetic effects being almost certainly much too small. Even so, it requires that the velocity of the dust relative to the earth-moon system be very small, in order that lunar gravity should be able to influence the orbits of dust particles sufficiently. In fact the particles must be in orbits around the sun, not very far removed from that of the earth.

A recent meteorological discovery which has attracted a good deal of attention from geophysicists concerned with problems of the very high atmosphere, is the 26-month cycle in equatorial stratospheric winds, discussed in detail by Veryard and Ebdon.<sup>14</sup> Available measurements indicate that the meridional winds reverse simultaneously all the way round the equator. The occurrence of a westerly wind of 20 knots or so, encircling the equator is not easily explained because it constitutes an air mass rotating faster than the earth, in the zone of the earth's maximum angular momentum. Stacey and Westcott<sup>15</sup> considered the possibility that the stratospheric air mass had been brought downwards by a vertical wind from ionospheric heights at which its electrical conductivity may have compelled it to rotate with the geomagnetic field. Such a mechanism allows the generation of a westerly wind by a simple conservation of angular momentum, but it requires a rather improbably strong vertical wind in the ionosphere. Nevertheless, Funk and Garnham<sup>16</sup> have reported a cycle of similar period in Australian ozone data, the phase coinciding very convincingly with that of the stratospheric wind if it is assumed that the westerly wind is in phase with the downward wind and that ozone is accumulated at lower than average altitudes by the downward wind and lags in phase by a quarter cycle, that is it represents an integration of the vertical wind. The implication that the 26-month periodicity may be evident at ionospheric heights led Stacey and Westcott<sup>15</sup> to examine geomagnetic and ionospheric data and they found peaks at 26 months in power spectra of monthly mean values of geomagnetic field at two equatorial stations. This particular analysis now appears to be suspect, but a more sensitive method of recognizing the 26-month periodicity in long series of geophysical data shows that sunspots, certain meteorological data and probably geomagnetic field all have a coherent cycle of small amplitude and a period of  $25.7 \pm 0.2$  months. It now seems most likely that the 25.7-month cycle in solar activity is ultimately responsible for all of the atmospheric effects with this periodic tendency, but the mechanism is not understood.

King-Hele<sup>17</sup> has reported the major changes in atmospheric density above



300 km, where satellite-drag data are available from 1957. Since the 1957-58 sunspot maximum, the average density has decreased by a factor of 5 at 400 km and 30 at 600 km. There is also a diurnal variation of a factor of 10, which is however less surprising than the long-term change. During enhanced solar activity the magnetosphere evidently increases in density simultaneously with its contraction in size. The magnitude of the changes makes it surprising that evidence of the 11-year solar cycle is so lacking in meteorological data.

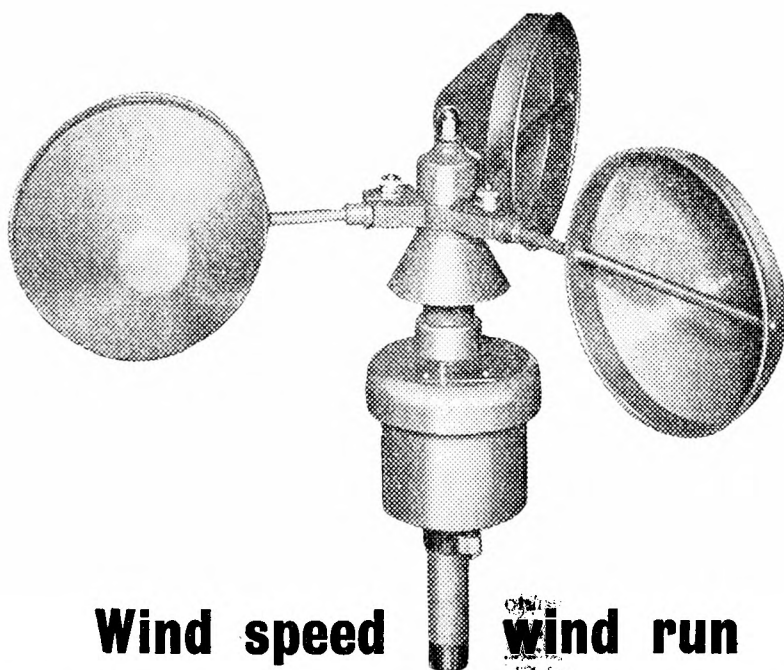
At the present time there is insufficient evidence for a satisfactory quantitative discussion of any of these problems. They represent a new frontier in meteorology and require new techniques for their investigation. Although satellite research is essential, conventional meteorology is by no means helpless and even existing records may contain unsuspected clues on magnetospheric control of the weather, such as the change in distribution of ozone (Kulkarni<sup>18</sup>) and even of the atmospheric circulation at 300 mb (Woodbridge *et al.*<sup>19</sup> and Macdonald and Roberts<sup>20</sup>) following magnetic storms.

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#### NOTES AND NEWS

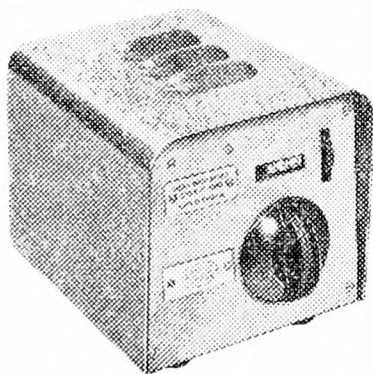
The new and more modern front cover design was prepared by Mr. D. W. H. Wigmore, Cartographic Section, Meteorological Office, with the close co-operation of HMSO Layout Section.



**Wind speed      wind run**

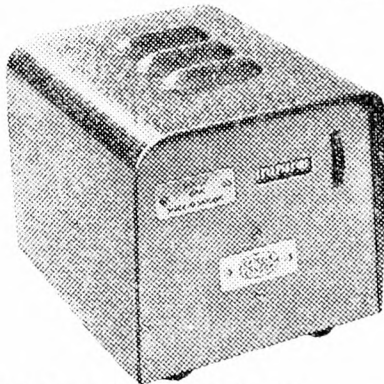
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## **A VISIT TO THE EXTENDED FORECAST BRANCH OF THE UNITED STATES WEATHER BUREAU**

By J. M. CRADDOCK

During the past ten years, while I have been engaged on research in the Meteorological Office into the possibilities of long-range weather forecasting, I have met and corresponded with a good many of the scientists engaged in similar work in other parts of the world. Among them was Mr. Jerome Namias, Chief of the Extended Forecast Branch of the United States Weather Bureau, and in May and June 1963 I was able to visit him on his home ground, and to see how the methods described in his published work are actually put into effect. Unfortunately, Mr. Namias himself was taken ill about a week after my arrival, and did not return to duty for over three months, so I had only a few discussions with him. However, I had conversations with nearly all his colleagues, and attended several conferences and was able to form a very clear impression of the Extended Forecast Branch at work.

It is worth remarking here that long-range weather prediction is an inherently more difficult problem than short-range forecasting which itself is difficult enough. Firstly our understanding of the principles involved is comparable with the understanding of the principles of short-range forecasting which existed at the time of Admiral FitzRoy before the advances made in the last 100 years. Secondly the meteorological data exchanged on the international communications network are intended mainly for the short-range forecaster, and are not arranged conveniently for use in long-range work and finally, because each large-scale development lasts a considerable time, the student of long-range changes cannot rely entirely on his own memory, but must supplement it by a library of relevant information in a form suitable for quick reference. Hence any unit intending to make real progress in this field must have three things: a general method of attack which, because of our imperfect understanding of the basic physics, must be capable of modification in the light of experience; an organization for sifting, averaging and otherwise processing the myriads of data intended for short-range purposes into a much smaller number of data which are or may be relevant to the long-range problem; and a versatile library of background information to serve as a long-range memory. To these might be added a sound procedure for checking and assessment.

The fulfilment of these requirements, particularly those for data processing and the background library, are beyond the resources of nearly all private individuals and most small meteorological services, and it is not surprising that the Extended Forecast Branch of the United States Weather Bureau should be one of the most active units in this field.

The physical location of the Extended Forecast Branch is at Suitland, Maryland, in one of a group of U.S. Government buildings on the outskirts of Washington, D.C. The building is shared with other branches of the Weather Bureau, including the main library and, most important, that part of the Joint Numerical Weather Prediction Unit which produces short-range forecasts by computer. As a result, the Extended Forecast Branch receives a large proportion of its working material in the form of punched cards and magnetic tapes, checked and ready for the computer, which are prepared originally for use in short-range forecasting. Further, the Branch has access to the very fast IBM7094 computer which is used for short-range numerical forecasting, and has exclusive use of two small IBM1401 computers. The facilities for data processing are therefore excellent.

The main work of the Extended Forecast Branch is the preparation of forecasts of the mean conditions for periods of 5 days and 30 days ahead, and the basic method consists in each case of the estimation of future changes from a series of northern hemisphere charts of the observed height of the 700 mb surface averaged over the same time interval. In other words, the averaging over 5 days or 30 days is intended to smooth the large, rapidly changing features which dominate the daily upper air chart while leaving the more lasting features which must change progressively into those of the chart for the forecast period. The experimental work on 90-day forecasts similarly makes use of 90-day mean charts but differs from the other procedures in laying more stress on correlations, contingencies and qualitative reasoning associated with interactions between the atmosphere and the underlying surface.

The choice of an upper air chart as the basic tool for long-range forecasting has the consequence that the period covered by the background library, or by the long-range memory, is comparatively short, since it is confined to the years for which realistic upper air charts can be drawn. Hence it is difficult to find good analogues for the current situation, although the library is well organized to make use of what material there is. Another consequence is that the forecast upper air chart, when it has been arrived at, has to be interpreted to give the real objects of interest for most consumers, namely, the anomalies of temperature and rainfall in different parts of the United States. For this purpose the national territory is divided into 40 districts, most of them coinciding with the individual states. A forecast of the anomalies of temperature and precipitation is produced by the Extended Forecast Branch and shows smooth variations over the whole of the United States. This forecast is sent to the District Forecast Centres where the forecasters interpret and sometimes modify it for their own uses.

The staff of the Extended Forecast Branch number about 40. Work on 30-day and seasonal forecasting, which is described later, is under the direct control of Mr. Namias. Subject to his general guidance, his scientific colleagues head the groups which carry out the rest of the work.

Five-day forecasting, which forms the largest activity, is carried out by a roster of six forecasters under Mr. Charles Woffinden. During my stay Mr. Woffinden was absent and his place was taken by Mr. James O'Connor. Three forecasts are issued each week, on Sundays, Tuesdays and Thursdays, and these are sent as guidance forecasts to the main forecasting centres in the United States. (They are also received overseas, for example, at Bracknell.) The forecast period starts at the time when a 48-hour outlook ends, so that if, for clarity, we designate the day the forecast is made by  $D$ , the forecast is of average conditions from  $D + 2$  up to  $D + 6$ , or a 5-day period centred on  $D + 4$ . The basic material is a series of 5-day mean charts for overlapping periods of which the most recent, based wholly on observed material, is centred at  $D - 3$ . Thus the forecaster has to extrapolate the changes on his series of observed charts for a further 7 days. To help him he has several auxiliary charts based partly on observed data and partly on short-range numerical forecasts. He also has an auxiliary chart based on the assumption that 5-day mean upper air features will be advected by barotropic processes on an unchanging 30-day mean pattern which characterizes the current state (and may be considerably different from the climatic normal).

Not only the chart analysis but also the chart drawing is carried out by computer. The IBM7094 has as one means of output a mechanical curve follower, which, once a blank chart is put in place, draws a set of isopleths far more smoothly and rapidly than can be done by hand. This facility is used to present the observations in every form which may be useful. For example, a northern hemisphere field of the 700 mb height may be charted directly as a departure from normal or as a tendency field from the preceding field. The same treatment is given to northern hemisphere charts of the air pressure at sea level. Similar representations are used for the fields of temperature and rainfall over the United States, and zonal indices are regularly calculated and displayed. The forecaster has to reconcile the various indications, and this he does on the basis of judgement and experience of 5-day mean charts gained during the last 10–15 years. His first essay at the forecast 700 mb northern hemisphere chart is translated in terms of temperature and rainfall anomalies in the United States, and these are compared with estimates made by statistical methods which have been developed by Mr. W. H. Klein. All the material is considered at a conference attended by scientists of the Branch, and the forecaster amends his preliminary forecast as far as he thinks necessary. The final forecast includes, not only the mean forecast 700 mb contour field for the northern hemisphere for the 5-day period, but a similar forecast of the mean pressure field at sea level and the distribution of temperature and rainfall anomalies over the United States. It also includes a separate pressure and frontal field for each of the 5 days, but these are to be looked on as showing the type of air mass and pressure change to be expected in each area rather than the actual weather systems.

A related activity is work on development and verification, which goes on under Mr. William H. Klein. Mr. Klein<sup>1</sup> has done a great deal of statistical groundwork on subjects such as depression tracks. In the last few years he has been dealing mostly with the development of objective numerical methods of forecasting the temperature, pressure or rainfall in each forecast area of the

United States in terms of predictors such as the 700 mb height at a grid of points over the northern hemisphere, measured either simultaneously or some days earlier. He uses the screening procedure, a variety of multiple regression analysis, which sets out to extract from a very large number of possible predictors a much smaller number of predictors which give almost as good results. The repetition of such an analysis for each of 40 forecast areas in the United States for each of several weather elements represents a very large effort in computation, which is practicable because of the availability of the 7094 computer. The method of approach makes possible the sifting of useful predictors from irrelevant ones, and while his results do something to confirm the use of an upper air chart as the basic tool for prediction, they also indicate the desirability of including additional predictors.

Working with Mr. Klein, Dr. Don Gilman is concerned with forecast verification. Five-day mean forecasts of 700 mb height are verified for a grid of points covering most of the northern hemisphere, while those of temperature and precipitation are verified for the United States only. Success in forecasting the change in 700 mb contour height is nearly everywhere positive, but is higher in some areas than in others, being higher, for example, over Great Britain and most of North America than it is over strongly baroclinic areas such as the Gulf of Alaska and the Atlantic off the eastern seaboard of America. Success in forecasting 5-day mean temperatures is generally higher than that of a control forecast based on a short-range forecast plus persistence. As regards 5-day rainfall, the forecasts seem to show success in all seasons except summer. The various methods of forecasting which go to make up the technique have been tested separately, and it is interesting that none of them are as successful as the official forecasts. It seems, therefore, that the judgement of the forecasters does make a positive contribution to the standard of the forecasts. Besides carrying out much other work on forecast verification and probability statements, Dr. Gilman is also examining the possibility of predicting 30-day mean temperatures and rainfall by statistical methods.

Research work in the Extended Forecast Branch, which is directed by Mr. Phil Clapp,<sup>2</sup> is mainly concerned with the development of a simplified atmospheric model proposed by Dr. Julian Adem.<sup>3</sup> The model is intended to have the same characteristics as regards heat exchange as the real atmosphere, but with the functions of dynamical process in effecting heat exchange being replaced by an Austausch coefficient. With this simplification, the mathematics become reasonably tractable, and it is hoped that the use of actual initial and boundary conditions will lead to predictions of the normal seasonal changes. There is a great deal of work to be done before it is clear whether the experiment is a success, but it is encouraging that work so far has shown the importance, under the assumptions made, of heat storage in the oceans.

The computer operations of the Extended Forecast Branch are carried out by a separate unit under the direction of Mr. Billy Lewis. Mr. Lewis is a trained meteorologist, but also an expert programmer who is able to relieve the other scientists of the Branch of all the specialized but essential work such as the preparation of data and the actual operation of the computer.

Work on 30-day and seasonal forecasting is carried out by Mr. Namias himself, or under his personal direction assisted especially by Mr. Klein and

Mr. Robert Dickson. The 30-day forecasts, which are issued at the beginning and middle of each month are produced by methods very similar to those used for 5-day forecasting, although of course the part played by short-range numerical forecasts is less. A full description of the method used ten years ago has been published by Namias in 1953<sup>4</sup> and the changes since then seem to be due more to the improvements in computer facilities and the availability of short-range numerical forecasts than to any major alteration of approach. However, feed-back phenomena from surface to atmosphere, such as sea surface temperature abnormalities, or snow cover, are considered to bolster or negate other indications. Namias<sup>5</sup> has illustrated an example. The first objective is the mean chart, for the forecast period, of the 700 mb contour heights over the northern hemisphere, and this is used to predict the broad distribution of above and below normal temperatures over the United States, and more roughly, over the rest of the northern hemisphere. To arrive at the first objective, several auxiliary charts are produced, each showing the expected position of the 700 mb troughs and ridges on some reasonable hypothesis, for example that the movements apparent on the most recent observed charts will be continued through the forecast period. Similar predictions are made of several zonal indices, and of the pressure distribution at sea level. However, if these auxiliary charts show disagreement, and they nearly always do, the task of reconciling them depends mainly on the judgement of the forecaster. He also has, for each forecast district in the United States, a number of contingency tables connecting the temperature and rainfall anomalies for different months, and if he knows, for example, that in a certain region a warm August has very rarely been followed by a cold September, he will be reluctant to make a September forecast of the 700 mb contour pattern with a cold trough in that region if August has been warm. Even when the mean 700 mb contours have been forecast, these have to be translated to give the expected anomalies of temperature and rainfall at the ground surface. The equations for doing so have been developed for forecast areas in the United States. For some purposes, those calculated for 5-day forecasting have been used and found satisfactory. For other parts of the northern hemisphere much cruder estimates are made, and unlike the forecasts for the United States, these are not checked after the event. There seems no doubt that the technique, as at present carried out, should show a higher standard of success over the United States than over any other part of the northern hemisphere. An official verification for the United States was published<sup>6</sup> in 1961.

Work on seasonal forecasting, which is mainly experimental, is similarly based on the use of time-mean charts, long-term relationships and contingency tables. However, it is still at an early stage.

The work of the Extended Forecast Branch also includes the routine production of 72-hour forecasts and descriptions of the past month's weather for the *Monthly Weather Review*. It therefore combines functions which in Britain are shared between several branches of the Meteorological Office.

This account falls far short of being a full description of the work of the Extended Forecast Branch, although I have tried to give a fair impression of the whole. I must, however, pay tribute to the scientists who so generously gave their time to discussions with me and to the friendliness with which I was received in America.

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## NOTE ON THE PROBABILITY DISTRIBUTION OF WIND DIRECTION WITH APPLICATIONS TO ERRORS OF FORECAST WINDS

By A. F. CROSSLEY, C. L. HAWSON and J. A. HARKER

When a family of vectors has a Gaussian distribution it can be completely expressed in terms of the mean vector  $\bar{\mathbf{V}}$  and the standard vector deviation  $\sigma$  of the individual vectors about the mean vector. The probability of the direction of any one of the vectors differing by not more than some specified angle  $\alpha$  from the direction of the mean vector can be derived from the two parameters  $\bar{\mathbf{V}}$  and  $\sigma$  as described below.

Let  $\mathbf{V}$  be a vector inclined at some angle to  $\bar{\mathbf{V}}$ , and let  $P(\alpha)$  be the probability of the direction of  $\mathbf{V}$  differing by not more than an angle  $\alpha$  from that of  $\bar{\mathbf{V}}$ . In Figure 1,  $\bar{\mathbf{V}}$  is represented by OA, OC makes an angle  $\alpha$  with OA,  $\mathbf{V}$  is

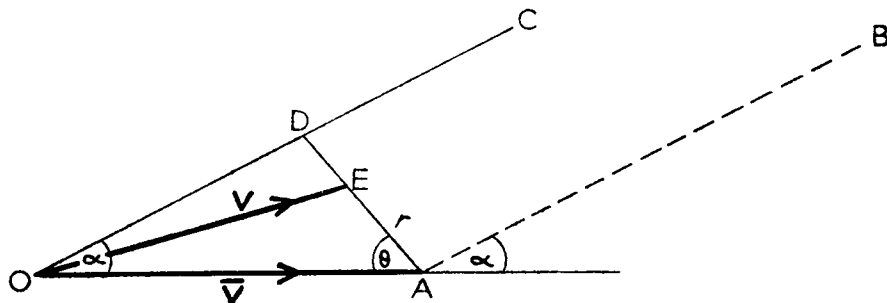


FIGURE 1—RELATIONSHIP BETWEEN VECTOR  $\mathbf{V}$  AND MEAN VECTOR  $\bar{\mathbf{V}}$

is represented by OE, and AE (produced if necessary) meets OC at D. Denote by  $r$  the distance AE and denote by  $\theta$  the angle between AO and AE. For a Gaussian distribution of  $\mathbf{V}$  about  $\bar{\mathbf{V}}$ ,<sup>1</sup>

$$P(\alpha) = \frac{1}{\pi\sigma^2} \iint r \exp\left(-\frac{r^2}{\sigma^2}\right) dr d\theta \quad \dots (1)$$

where  $\sigma$  is the standard vector deviation of  $\mathbf{V}$  about  $\bar{\mathbf{V}}$ ;  $r$  is the magnitude of the vector difference between  $\mathbf{V}$  and  $\bar{\mathbf{V}}$ ; and the integration is over the area enclosed between OA and OC both extended to infinity, and a similar area reflected in OA.



Construct AB parallel to OC. In the area enclosed between OC and AB, when the value of  $\theta$  is given,  $r$  ranges from 0 to AD, where

$$\frac{AD}{\sin \alpha} = \frac{|\nabla|}{\sin (\theta + \alpha)} \quad \dots (2)$$

and the contribution to (1) is

$$\frac{2}{\pi \sigma^2} \int_0^{\pi - \alpha} \int_0^{AD} r \exp \left( -\frac{r^2}{\sigma^2} \right) dr d\theta$$

which by use of (2) becomes

$$\frac{1}{\pi} \int_0^{\pi - \alpha} \left[ 1 - \exp \left( -\frac{|\nabla|^2}{\sigma^2} \frac{\sin^2 \alpha}{\sin^2 (\theta + \alpha)} \right) \right] d\theta \quad .$$

In the area enclosed between OA produced and AB,  $r$  is unrestricted and the contribution to (1) is simply  $\alpha/\pi$ .

Hence

$$P(\alpha) = 1 - \frac{1}{\pi} \int_0^{\pi - \alpha} \exp \left( -\frac{|\nabla|^2}{\sigma^2} \frac{\sin^2 \alpha}{\sin^2 (\theta + \alpha)} \right) d\theta \quad , \quad \dots (3)$$

an expression which is in agreement with one given without proof by P. Graystone.<sup>2</sup>

Values of  $P(\alpha)$  were determined from equation (3) on the Meteorological Office electronic computer METEOR for selected values of  $\alpha$  and the ratio  $|\nabla|/\sigma$  by use of Weddle's<sup>3</sup> formula with the range of integration divided (for the most part) into 90 equal segments. The results are shown in Table I and are plotted graphically in Figure 2. Tests using different numbers of sectors for the

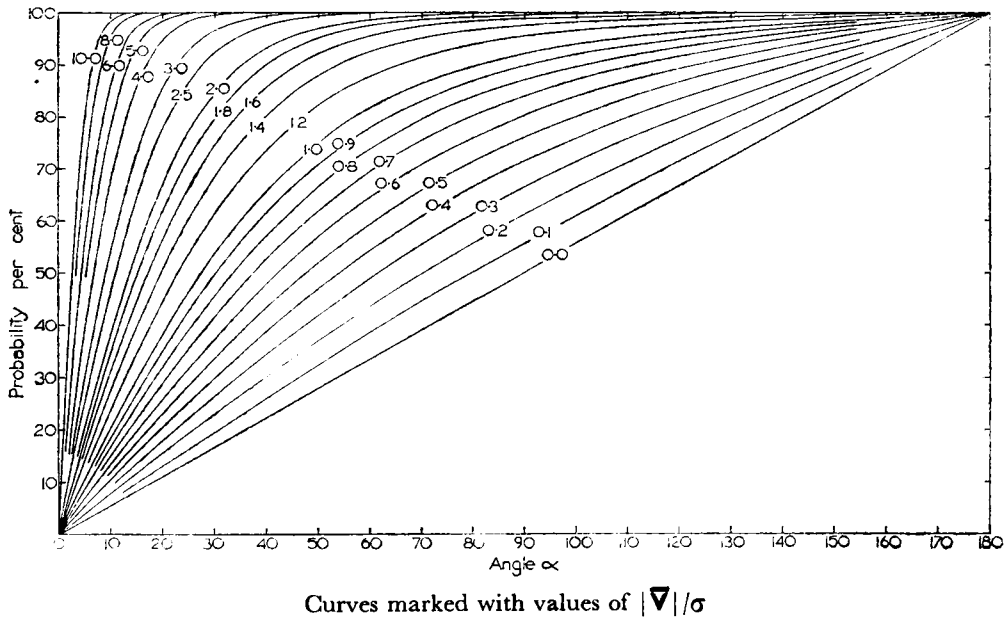


FIGURE 2—PROBABILITY DISTRIBUTION IN A GAUSSIAN FAMILY OF VECTORS

TABLE I—PROBABILITY DISTRIBUTION OF DIRECTION IN A GAUSSIAN FAMILY OF VECTORS

$ \nabla /\sigma$	Angle ( $\alpha$ ) between vector $\nabla$ and mean vector $\nabla$																	
	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
	Probability																	
0.0	0.028	0.056	0.083	0.111	0.139	0.167	0.194	0.222	0.250	0.278	0.306	0.333	0.361	0.389	0.417	0.444	0.472	0.500
0.1	0.033	0.065	0.098	0.132	0.165	0.197	0.229	0.260	0.291	0.322	0.353	0.383	0.413	0.443	0.472	0.500	0.529	0.556
0.2	0.037	0.077	0.116	0.154	0.191	0.228	0.265	0.301	0.336	0.370	0.403	0.436	0.467	0.498	0.527	0.556	0.584	0.611
0.3	0.044	0.090	0.134	0.178	0.221	0.263	0.304	0.343	0.382	0.419	0.454	0.489	0.521	0.553	0.583	0.611	0.638	0.664
0.4	0.052	0.103	0.154	0.204	0.252	0.299	0.345	0.388	0.430	0.469	0.507	0.542	0.575	0.607	0.636	0.664	0.690	0.714
0.5	0.060	0.117	0.175	0.231	0.285	0.337	0.387	0.434	0.478	0.520	0.558	0.594	0.628	0.659	0.687	0.713	0.738	0.760
0.6	0.067	0.132	0.197	0.260	0.319	0.376	0.430	0.480	0.527	0.570	0.609	0.645	0.678	0.708	0.735	0.759	0.782	0.802
0.7	0.075	0.148	0.220	0.289	0.355	0.416	0.474	0.526	0.575	0.618	0.658	0.693	0.725	0.753	0.778	0.801	0.821	0.839
0.8	0.083	0.165	0.244	0.320	0.391	0.457	0.517	0.572	0.621	0.665	0.704	0.738	0.768	0.794	0.818	0.838	0.855	0.871
0.9	0.092	0.182	0.268	0.350	0.427	0.497	0.560	0.616	0.666	0.709	0.747	0.779	0.807	0.831	0.852	0.870	0.885	0.898
1.0	0.100	0.199	0.293	0.382	0.463	0.536	0.601	0.658	0.708	0.750	0.786	0.817	0.842	0.864	0.882	0.897	0.910	0.921
1.2	0.119	0.234	0.343	0.444	0.533	0.612	0.679	0.736	0.783	0.822	0.853	0.878	0.899	0.915	0.928	0.939	0.948	0.955
1.4	0.137	0.270	0.394	0.504	0.601	0.682	0.749	0.802	0.845	0.878	0.904	0.924	0.939	0.950	0.959	0.966	0.972	0.976
1.6	0.157	0.306	0.443	0.562	0.663	0.744	0.808	0.857	0.893	0.920	0.940	0.955	0.965	0.973	0.978	0.983	0.986	0.988
1.8	0.176	0.342	0.490	0.617	0.719	0.798	0.857	0.899	0.929	0.950	0.965	0.975	0.981	0.986	0.989	0.992	0.993	0.995
2.0	0.195	0.377	0.536	0.667	0.768	0.843	0.896	0.931	0.955	0.970	0.980	0.987	0.991	0.993	0.995	1.000	1.000	1.000
2.5	0.242	0.461	0.640	0.773	0.865	0.923	0.957	0.977	0.988	0.993	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3.0	0.288	0.539	0.728	0.853	0.927	0.966	0.985	0.994	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
probability																		
3.0	0.117	0.233	0.343	0.445	0.539	0.622	0.695	0.758	0.810	0.853	0.888	0.916	0.937	0.954	0.966	0.987	0.992	0.995
4.0	0.156	0.307	0.446	0.569	0.674	0.760	0.829	0.881	0.920	0.947	0.966	0.979	0.987	0.992	0.996	1.000	1.000	1.000
5.0	0.195	0.378	0.540	0.675	0.781	0.858	0.913	0.949	0.971	0.984	0.992	0.996	1.000	1.000	1.000	1.000	1.000	1.000
6.0	0.233	0.446	0.625	0.762	0.859	0.922	0.960	0.981	0.991	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
7.0	0.270	0.510	0.699	0.832	0.914	0.960	0.983	0.994	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
8.0	0.307	0.570	0.763	0.885	0.951	0.981	0.994	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
9.0	0.343	0.625	0.817	0.924	0.973	0.992	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
10.0	0.378	0.676	0.861	0.951	0.986	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

TABLE I—PROBABILITY DISTRIBUTION OF DIRECTION IN A GAUSSIAN FAMILY OF VECTORS *continued*

$ \bar{\mathbf{V}} /\sigma$	Angle ( $\alpha$ ) between vector $\mathbf{V}$ and mean vector $\bar{\mathbf{V}}$															
	90°	95°	100°	105°	110°	115°	120°	125°	130°	135°	140°	145°	150°	155°	160°	175°
0.0	0.500	0.538	0.556	0.583	0.611	0.639	0.667	0.694	0.722	<i>probability</i>						
0.1	0.556	0.584	0.610	0.637	0.663	0.689	0.714	0.739	0.764	0.788	0.812	0.836	0.860	0.884	0.889	0.944
0.2	0.611	0.638	0.663	0.688	0.712	0.735	0.758	0.780	0.802	0.823	0.844	0.864	0.884	0.904	0.923	0.954
0.3	0.664	0.689	0.713	0.735	0.757	0.778	0.798	0.817	0.836	0.854	0.872	0.889	0.905	0.922	0.938	0.962
0.4	0.714	0.737	0.759	0.779	0.798	0.817	0.834	0.850	0.866	0.881	0.896	0.910	0.923	0.937	0.950	0.969
0.5	0.760	0.781	0.800	0.818	0.835	0.851	0.865	0.879	0.892	0.905	0.917	0.928	0.939	0.950	0.960	0.975
0.6	0.802	0.820	0.837	0.853	0.867	0.880	0.893	0.904	0.915	0.925	0.934	0.943	0.952	0.961	0.969	0.980
0.7	0.839	0.855	0.870	0.883	0.895	0.906	0.916	0.925	0.933	0.941	0.949	0.956	0.963	0.970	0.976	0.985
0.8	0.871	0.885	0.897	0.908	0.918	0.927	0.935	0.942	0.949	0.955	0.961	0.967	0.972	0.977	0.982	0.988
0.9	0.898	0.910	0.920	0.929	0.937	0.944	0.950	0.956	0.961	0.966	0.971	0.975	0.979	0.983	0.986	0.991
1.0	0.921	0.931	0.939	0.946	0.952	0.958	0.963	0.967	0.971	0.975	0.978	0.981	0.984	0.987	0.990	0.993
1.2	0.955	0.961	0.966	0.970	0.974	0.977	0.980	0.983	0.985	0.987	0.989	0.990	0.992	0.993	0.995	0.996
1.4	0.976	0.980	0.983	0.985	0.987	0.989	0.990	0.991	0.992	0.993	0.994	0.995	1.000	1.000	1.000	1.000
1.6	0.988	0.990	0.992	0.993	0.994	0.995	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.8	0.995	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Note:  $|\bar{\mathbf{V}}|/\sigma$  is the ratio of the magnitude of the mean vector to the standard vector deviation.

range of integration showed that the tabulated values of probability are not more than 0.001 in error, except that when a computed value exceeds 0.9950, giving an entry of 0.995 (rounded down) or greater, the remaining values for larger angles of  $\alpha$  in the same row are entered as 1.000. This device was adopted in order to economize the time required on the computer.

The tabulations, which can be applied to any family of vectors with a Gaussian distribution, have practical applications to problems involving winds.

Upper level winds away from the influence of surface features are often distributed about the vector mean wind very nearly in accordance with the Gaussian law of errors (see for example C. E. P. Brooks, C. S. Durst, N. Carruthers, D. Dewar and J. S. Sawyer<sup>1</sup>). If, for example, it is required to find the probability of the wind departing by more than say  $20^\circ$  from the mean wind direction during a season for which the mean vector wind is  $250^\circ$  32 knots and the standard vector deviation is 20 knots, simply determine the ratio  $|\bar{\mathbf{v}}|/\sigma = 32/20 = 1.6$  and extract the value of  $P(\alpha)$  appropriate to this ratio from the table for the required angular departure  $\alpha = 20^\circ$ . This gives  $P(20) = 0.56$ . Thus the probability of the wind direction being inclined at an angle greater than  $20^\circ$  from the mean wind direction at any time in this season is 44 per cent. Alternatively during this season the wind blows at an angle greater than  $20^\circ$  from the mean wind during 44 per cent of the time.

The distribution of errors in forecast winds at most levels is also likely to approximate to a Gaussian distribution provided that the forecaster does not introduce bias, e.g. by applying some safety factor such as increasing speeds for headwinds, or overdeepening of depressions. The theory of errors suggests that the more sources of error there are the more likely is the distribution to be Gaussian. Thus the likelihood of a Gaussian distribution for the errors increases with the number of levels involved in the forecast. Such circumstances arise in problems involving radio-active fallout when the probability of some specified angular error in the predicted wind direction is of great importance. The distribution of errors in the forecast winds can be represented by the root mean square vector difference,  $\sigma_f$ , between the true wind  $\mathbf{V}$  and the corresponding forecast wind  $\mathbf{V}_f$ . On those occasions when all the actual winds have the same value  $\mathbf{V}$ , the forecast winds  $\mathbf{V}_f$  can be regarded as distributed about  $\mathbf{V}$  with standard vector deviation  $\sigma_f$ ; and conversely if a large number of occasions are separated out on each of which the forecast wind has the same value  $\mathbf{V}_f$ , then the corresponding actual winds can be regarded as distributed about  $\mathbf{V}_f$  with the same standard vector deviation  $\sigma_f$ . Of course, for any particular forecast there will be only one result and consequently no error distribution; however, before the result is known the probability distribution enables the chance of this result lying within any specified range to be estimated. Thus for an individual forecast the probability distribution of the angular difference between the actual and forecast winds about the direction of the forecast wind can be obtained from the tables or graph and the ratio  $|\mathbf{V}_f|/\sigma_f$ . As an example suppose we require the probability of the actual wind direction lying between  $270^\circ$  and  $290^\circ$  when the forecast wind is  $250^\circ$  40 knots and the standard vector error of the forecast system is 20 knots. Then the ratio  $|\mathbf{V}_f|/\sigma_f = 40/20 = 2$  and for this ratio the probability of the actual wind direction lying between  $270^\circ$  and  $250^\circ$ , i.e. a veer of  $0^\circ$  to  $20^\circ$  from the forecast direction is

$\frac{1}{2}[P(20)] = \frac{1}{2}(0.67)$ , and similarly the probability of a wind between  $290^\circ$  and  $250^\circ$  is  $\frac{1}{2}[P(40)] = \frac{1}{2}(0.93)$ . Hence the probability of the wind direction lying between  $270^\circ$  and  $290^\circ$  is  $\frac{1}{2}(0.26) = 0.13$ .

It should be mentioned that in this type of problem  $\sigma$  is dependent on the time interval between the validity time and the time of the latest observations available to the forecaster, as well as on the forecast techniques, levels and season involved. As a further refinement it would be useful to investigate how the standard vector deviation of the forecast errors varies with the forecast wind and the synoptic situation. Although in the main the procedure outlined should provide a sound statistical method for the determination of the probability of any specified angular error in a wind forecast, a few occasions will arise when the forecaster is able to make a subjective assessment which will be better than this statistical estimate of the likely errors, because he can see that in the particular circumstances the probability distribution will not be normal, e.g. when a sharp trough separating two quite different wind régimes is forecast to be close to the location for which the forecast wind is given. In the circumstances of this example the probability distribution of the angular errors will be bimodal about the forecast directions of the two wind streams and not Gaussian about one of them.

**Note added in proof.**—Mr. E. Knighting has pointed out in a private communication that

$$P(\alpha) + P(\pi - \alpha) = 1 + \operatorname{erf} \left( \frac{|\mathbf{V}|}{\sigma} \sin \alpha \right)$$

As the error function  $\operatorname{erf} x$  is extensively tabulated, the range of integration required for the computation of  $P(\alpha)$  can be restricted to  $0 \leq \alpha \leq \pi/2$ , with consequential saving in time required on the computer.

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## SOIL TEMPERATURES DURING THE FROST OF EARLY 1963 IN SOUTH-EAST ENGLAND—PART II

By E. N. LAWRENCE, B.Sc.

**Summary.**—Variation of soil temperature over short distances and diurnal variation are discussed. Comparisons are made between soil temperatures under grass and under bare soil, and finally some past climatological extremes are considered. Part I of this article was published in January of this year.<sup>1</sup>

**Local or random site differences.**—Differences may arise between soil temperatures at nearby sites with apparently identical 'standard' exposures.<sup>2,3</sup> In a Kew experiment, soil temperatures (at 0930 and 1500 GMT) at a depth of 1 ft under level grass were measured at three sites within a radius of 20 yards and it was found that<sup>4</sup> "the standard deviation of the individual differences from the mean of the three readings was  $0.16^\circ\text{F}$ , and 96.4 per cent of the readings were within  $\pm 0.3^\circ\text{F}$  of the mean." Again, North American data<sup>4</sup> show differences on a summer day of up to about  $2^\circ\text{C}$  at a depth of 5.5 cm between sites within 20 metres, and over  $5^\circ\text{C}$  at a depth of 10 cm between sites 100–150 metres apart (albeit with different instrumentation). Thus a change of site is liable to be associated with differences in the soil temperature régime.

The new site (B) at Kew showed no freezing whatsoever in early 1963 at a depth of 1ft under grass (absolute minima  $0.4^{\circ}\text{C}$ , recorded with a Symons thermometer); indeed, absolute minima at this site were very similar to those for Rothamsted (clay). However, the soil temperature differences between sites A and B are probably the result of distinctly different exposures, soil types and conditions of soil (see introduction in Part I<sup>1</sup>). The somewhat artificial soil at site A is very different from that at site B which is distinctly heavier between depths of about 6in. and 3ft 6in. and only slightly disturbed (during the recent installation of soil thermometers). Also, site A has a free drainage while site B has an impeded drainage as evidenced by gleying\* and iron and manganese mottles within the profile, at all levels down to a depth of 4ft. Furthermore, at site B but not at site A, there is a surface organic mat ( $1\frac{1}{2}$  to 0 in.) which would act as a sponge under wet conditions but as an insulating layer when dry.

Site changes at Woburn are equally revealing. A reorganization at this station in October 1928 resulted in a marked change<sup>b</sup> at this time in the monthly deviations from the standard 1941–50 mean of the difference between earth temperatures at a depth of 1ft at Woburn (under grass) and at Rothamsted (under bare soil). The temperature excess of Woburn over Rothamsted changed from being a little greater in winter than in summer to distinctly greater in summer than in winter. The site change at Woburn resulted in distinctly lower temperature records in winter (by about  $1\frac{1}{2}^{\circ}\text{F}$ ) and higher temperature records in summer (by about  $2\frac{1}{2}^{\circ}\text{F}$ )—relative to Rothamsted. A further change of site in 1958 appears to have caused a reversion towards the original (pre-1928) conditions.

**Diurnal variation.**—Although diurnal changes are inhibited under snow-covered winter conditions, some diurnal variation was apparent during early 1963. At Kew (site A), Woburn and Cardington in January 1963 under thick snow (see Tables I and III<sup>†</sup> in Part I), the maximum variation was about  $\frac{1}{2}^{\circ}\text{C}$  at a depth of 4in. and probably about half this value at a depth of 8in. Even at a depth of 1ft at Kew (site A), the diurnal change of temperature during the general cooling period preceding the absolute minima of January was indicated by a levelling out from about 1500 to 2100 GMT.

Daily *minimum* soil surface temperatures with no snow cover at Kew (site B) in early 1963 were often considerably lower than the corresponding air (screen) temperature minima, but 3-hourly observations of surface temperature suggest that the *maxima* were not so different: for example, during the period 2100 GMT on 2 March to 2100 on 3 March, the air temperature varied from  $-5.6^{\circ}\text{C}$  to  $10.4^{\circ}\text{C}$ , while surface temperature varied from  $-8.8^{\circ}\text{C}$  (minimum) to  $9.5^{\circ}\text{C}$  (at 1500). This relationship between air and surface temperatures is presumably seasonal and caused at least partly by the cold, damp soil, and perhaps partly by site differences—and precedes the pronounced March rise of soil temperature<sup>c</sup> referred to in Part I.<sup>1</sup>

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\*Gley is a technical term used to describe the characteristics of an imperfectly or poorly drained soil. When the soil is saturated with water, intense reducing conditions are created which are characterized by the presence of the grey colorations of ferrous iron. On exposure to air, the grey colours commonly change to brown. In the zone of a fluctuating water table, rusty mottles and grey colours occur together. Gleying is the process by which gley occurs.

<sup>†</sup>Tables I (a), (b) and (c), II and III are published in Part I in the January 1963 issue of the *Meteorological Magazine*.

**Comparison of temperature under grass and under bare soil.**—The insulating effect of grass cover is shown by the tendency for grass minimum temperatures to be lower than minimum temperatures on a bare soil surface: for example, on the night of 2–3 March 1963, the grass minimum temperature (2100–0900) at Kew was  $-10.6^{\circ}\text{C}$  as compared with  $-8.8^{\circ}\text{C}$  on bare soil—though this difference may be caused partly by site differences.

At Kew (site A) in January 1963, at depths of 4in. and 8in., freezing occurred earlier and penetrated more quickly under bare soil than under grass: at a depth of 4in., freezing under grass occurred some 1–2 days later while at a depth of 8in. the lag was 2–3 days. Conversely, both in late January and early March 1963 (some Kew data for the time of the mid-February thaw being missing), at depths of 4in. and 8in., thawing occurred later under bare soil than under grass-covered soil—about one day later at 4in. and about 2 days later at 8in. in the thaw of early March. Both bare soil and grass-covered soil showed the tendency for freezing and thawing to penetrate downwards from 4in. to 8in. at Kew (site A) during January 1963. In contrast with Kew, Rothamsted data for depths of 4in. and 8in. showed no significant difference between grass-covered soil and bare soil for the dates of freezing and thawing, but in clay soil, changes are inhibited generally.

During January 1963 at Kew (site A), absolute minima were slightly lower under bare soil than under grass while maximum 3-hour increases of soil temperature, maximum 3-hour and 24-hour decreases were all slightly greater under bare soil than under grass (Table I(b)). Likewise at Rothamsted (Table I(c)) for the period January to March inclusive 1963, the absolute minimum temperature was lower under bare soil at a depth of 4in. However, at 8in. the bare soil temperature was slightly higher, and at both these levels the minima for January 1963 were higher under bare soil (Table I(c)); but higher absolute minimum temperatures under bare soil are abnormal, as judged from Rothamsted long-term data (Table II).

Though the differences at Kew during 1963 may be attributed mainly to a greater mean diffusivity under bare soil because of higher thermal conductivity, it is noteworthy that under grass at depths of 4in. and 8in., soil temperatures arrived simultaneously at  $0^{\circ}\text{C}$  at the end of the second freezing spell in early March, whereas under bare soil, temperatures (at least at the observing hours) did not show such a tendency. This suggests better drainage<sup>6,7</sup> and more effective percolation under grass.

**Past climatological extremes.**—Reports of the depth of freezing soil, already described, suggest that new long-term extremes of soil temperature minima were recorded during early 1963. However the following facts emerge when the present Kew data are compared with similar though limited past data for the same site for 0900 GMT (1000 GMT before 1915):

- (i) *Absolute* minimum soil temperatures for the recent winter are the lowest since records began, in July 1903; the previous record occurred in January 1940 (at 1ft under grass) and in March 1947 (at 4ft under grass) (Tables I(b) and II).
- (ii) With reference to minimum *monthly mean* temperatures at Kew, also since July 1903, the lowest values occurred in February 1963 ( $32^{\circ}\text{F}$ ) and January 1963 ( $32.2^{\circ}\text{F}$ ,  $0.1^{\circ}\text{C}$ ) at a depth of 1ft under grass, and in

February 1963 (38.1°F, 3.4°C) at a depth of 4ft under grass; the next lowest monthly mean values at Kew occurred in January 1940 (33.1°F, 0.6°C) at 1ft, and in February 1940 (39.2°F, 4.0°C) at 4ft.

However, at Regent's Park (0900 GMT observations for the period 1884-1910) there were even lower absolute minimum temperatures and lower monthly mean temperatures, namely in February 1895: 28.2°F (-2.1°C) and 30.9°F (-0.6°C) respectively, at 1ft under grass, and 34.8°F (1.6°C) and 36.7°F (2.6°C) respectively, at 4ft under grass. These were record values for Regent's Park except that the minimum monthly mean temperature at 4ft under grass reached 36.5°F (2.5°C) in January 1891: but during these earlier winters at Regent's Park there was probably less protective snow cover<sup>8,9,10</sup> and less warming by artificial (urban) sources. All the data under discussion here seem to confirm that the period 1896 to 1937 was a period of exceptional immunity from difficult winter conditions.<sup>11</sup>

It may be seen from Table I (columns for depths of 1ft and 4ft, under grass) and Table II that in early 1963, a new extreme of soil temperature was recorded at a depth of 4ft at Woburn though not at a depth of 1ft where lower temperatures were recorded in January 1940. The lower soil temperature at a depth of 1ft during 1940 may well be due to changes of site at this station, described in an earlier section, and also to rather less protective snow cover in that year.

At Rothamsted (Tables I and II), absolute minimum temperatures at depths of 1ft and 4ft under grass during early 1963 were within 1°F of the long-period absolute extremes, which were recorded in the years 1929 and 1940 (at 1ft) and 1947 (at 4ft), but there was less protective snow cover during these years.

Past meteorological data in general are not sufficiently detailed to allow calculations of the extreme depths of frost penetration into soil, since the depth of freezing depends not only on air temperature but also on wind velocities, solar radiation and especially on snow cover; soil temperature at, say, a depth of 1ft may be regarded as the integrated effect of these variables. Soil temperature at a depth of 1ft together with details of snow cover provide a good indication of winter severity and discomfort.

**Acknowledgements.**—The author is indebted to the Director, Lawes Agricultural Trust, Rothamsted Experimental Station and to Mr. C. A. Thorold, B.Sc., Lawes Agricultural Trust, Woburn Experimental Station for the supply of special data used in this investigation, and to Mr. B. Wilkinson, M.Sc., Regional Soil Chemist, South-east Region, National Agricultural Advisory Service, Ministry of Agriculture, Fisheries and Food for the soil morphological data and much useful discussion, particularly on soluble salt content of soils.

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## THE HASTINGS AIRCRAFT OF THE METEOROLOGICAL RESEARCH FLIGHT

By D. R. GRANT

**Introduction.**—Since September 1950 the Meteorological Research Flight (MRF) has been carrying out experiments in the atmosphere at heights up to 20,000 feet in a Hastings C Mark I aircraft (Plate II). During this time many instruments had been fitted and subsequently removed after completion of the experiment for which they had been designed. Many of the cables and much obsolete bracketry remained and much of the equipment still in use did not comply with the latest safety regulations. It was, therefore, decided that a major re-design of the inside of the aircraft was required. At the same time it was planned to fit a number of new radio and navigational aids and some new meteorological equipment.

Preparations for the refitting went on for a number of months and the work on the aircraft was started in July 1962. By February 1963 the work had been completed, and after flight tests the aircraft was available for experimental work early in March 1963.

**Re-design of interior.**—The galley has been removed and the signaller's position has been moved to the rear of the fuselage. All the radio and navigational equipment is now housed in a specially built rack on the starboard side. Electrical supplies for radio and experimental equipment and a small amount of meteorological instrumentation are also installed on the starboard side (Plate III). The whole of the port side from behind the first pilot to the main door (Plate IV) is available for meteorological instruments and observers, apart from one seat occupied by the signaller.

Immediately behind the first pilot there is a forward facing seat which is occupied by the officer in charge of the experiment. Behind this seat are the instrument exposure positions. All instruments to be exposed in the airstream are mounted at the end of 1½-inch diameter steel tubes about 3 feet in length. These tubes are clamped to ramps inside the aircraft and the instruments can be moved out to a distance of about 2 feet through portholes in the side (Plate V). At least three instruments may be exposed simultaneously. Behind the ramps there is a seat for the observer operating them, and then come five tables, each with two seats for observers. All seats are fitted with intercommunication with a switch to select any of about 5 channels. One of these channels is reserved for the exclusive use of the observers and they can talk

freely without interruptions by aircrew communications. All tables are similarly supplied with power, viz. 28V d.c. aircraft supply, 24V d.c. stable battery supply, 115V 400 c/s 3 phase, and 230V 50 c/s single phase.

**Meteorological instrumentation.**—Temperature is still measured with the standard Meteorological Office (MO) electrical resistance thermometer. The element is fitted under the wing. Two standard instruments are fitted on the aircraft and three additional elements are installed one of which has a blanked-off front to protect it from precipitation and improve its performance in cloud. One of the other two is used for supplying a continuous temperature record to a multi-channel galvanometer recorder, and the other is connected to a self balancing bridge which has recently been developed and which is at present undergoing tests. On this instrument no manual balancing of the bridge is necessary and the temperature is displayed on a counter.

The lag coefficient of this thermometer element is about 8 seconds which means that it is insensitive to small-scale variations. For experiments in which detailed temperature structure is required, an ultra rapid thermometer can be fitted to one of the booms and its output is connected via an amplifier to the galvanometer recorder. Using this instrument, temperature changes can be recorded of  $0.05^{\circ}\text{C}$  occurring in  $1/10$  sec (i.e. in a distance flown of about 25 feet).

The MO frost-point hygrometer is available for measuring dew- and frost-points. As a reading on this instrument takes at least 30 seconds it is again unsuitable for measuring small-scale variations. For this purpose a micro-wave radio refractometer is used to measure the refractive index of the air. It is known that

$$(n - 1) \times 10^8 = \frac{77.6p}{T} + \frac{3.735 \times 10^5 e}{T^2} \quad \text{where}$$

$n$  is the refractive index,  $p$  (mb) the atmospheric pressure,  $e$  the vapour pressure (mb) and  $T$  is the air temperature in  $^{\circ}\text{K}$ . Thus if pressure and temperature are known, the vapour pressure can be obtained from the refractive index. The radio refractometer is not an absolute instrument and is also subject to zero drift, but its sensitivity is constant. Occasional simultaneous readings of  $p$ ,  $T$  and  $e$  must be taken by standard instruments to establish the absolute value of refractive index at one or two points on the record. The speed of response of the radio refractometer is about the same as that of the ultra rapid thermometer.

No entirely satisfactory instruments have yet been developed to measure cloud and raindrop size distribution and liquid water content. On the Hastings a magnesium oxide impactor is used to measure cloud droplet size distribution. A slide coated with magnesium oxide is exposed for about  $1/100$  of a second and the cloud droplets make impressions in the oxide film. These are photographed under a microscope after the flight. A chronotron is used to measure the time of exposure. For raindrops the impressions are made in aluminium foil. A hot wire liquid water content meter is also fitted. This measures the reduction in resistance of a hot nickel wire when rain or cloud drops impinge on it. The accuracy of the calibrations of the magnesium oxide impactor and the hot wire water content meter is in doubt and the calibrations are at present under investigation.



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PLATE I—MAJOR K. J. GROVES PRESENTING THE MEMORIAL PRIZE FOR METEOROLOGY  
TO MR. T. H. KIRK

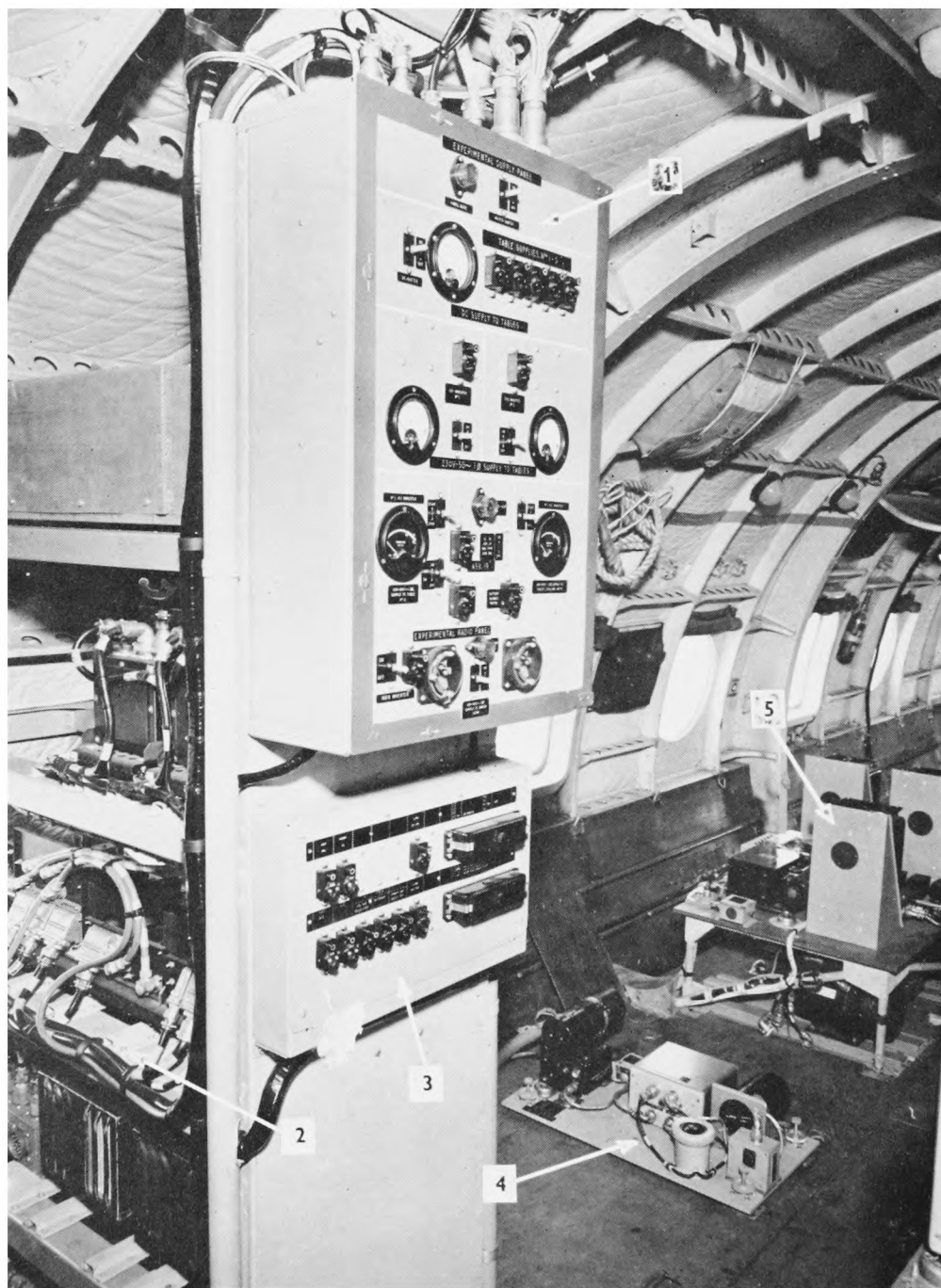
See page 62



*Crown copyright*

PLATE II—THE HASTINGS AIRCRAFT OF THE METEOROLOGICAL RESEARCH FLIGHT  
FLYING OFF THE ISLE OF WIGHT

The cloud warning radar is in the pod under the nose. See page 47

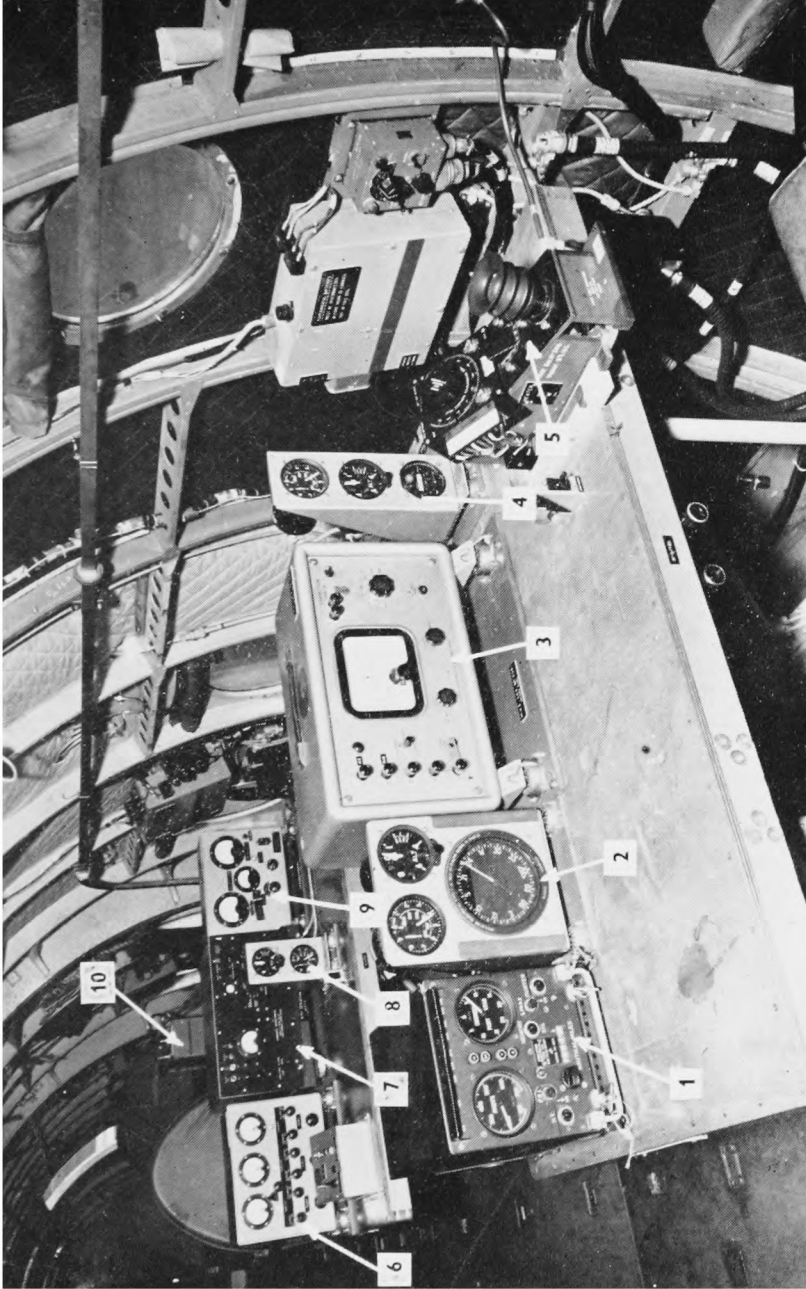


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PLATE III—THE STARBOARD SIDE OF THE HASTINGS OF THE METEOROLOGICAL  
RESEARCH FLIGHT

1. Experimental power supplies switch panel. 2. Radio and navigational equipment. 3. Radio  
power supplies switch panel. 4. Vertical current measuring equipment. 5. A.c. power supplies.

See page 47.



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PLATE IV—THE PORT SIDE OF THE HASTINGS AIRCRAFT OF THE METEOROLOGICAL  
RESEARCH FLIGHT

1. Doppler radar control unit. 2. Airspeed indicator, altimeter, and compass repeater. 3. Chronometer. 4. Airspeed indicator, altimeter and self-balancing bridge indicator. 5. Hygrometer and balanced-bridge temperature indicator. 6. Ultra rapid thermometer amplifiers. 7. Radio refractometer. 8. Altimeter and airspeed indicator. 9. Hot wire water content meter. 10. Multi-channel galvanometer recorder. See page 47.





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PLATE V—EXTERNAL VIEW OF INSTRUMENT EXPOSURE POSITION

From top to bottom, radio refractometer cavity, angle of incidence wind vane, and magnesium oxide impactor. See page 47.

Chloride particles can be collected on a slide coated with gelatin impregnated with silver nitrate solution. The diameter of the stain caused by the reaction of the chloride with the nitrate and the subsequent reduction of the silver chloride to metallic silver enables estimates to be made of the masses of the chloride particles.

For detection of particles of precipitation size a 3-cm radar is now available.

Winds can be measured using a Doppler radar. This displays instantaneous readings of ground speed, drift and heading, and if simultaneous readings of airspeed are taken the wind can be calculated. The error in winds obtained by this method is more than 5 knots. Greater accuracy can be obtained by flying for a short time and comparing changes in ground position and air position. A ground position indicator (which is operated by the Doppler radar) and an air position indicator are fitted for this purpose. To obtain the highest possible accuracy the output from the ground position indicator is fed into repeater boxes which indicate changes in ground position to the nearest 0.02 nautical miles in the north and south direction, and the output from the air position indicator is fed into a wind finding attachment with a similar accuracy. With a time interval of one minute, wind errors are then reduced to about 2 knots.

Vertical air currents of a scale encountered in cumulus clouds are obtained by measuring (i) the vertical velocity of the aircraft relative to the ground (by integration of an accelerometer) and (ii) the vertical velocity of the air relative to the aircraft, and adding (i) and (ii) to obtain the vertical velocity of the air relative to the ground. The component (ii) is obtained by a wind vane which measures the angle of incidence of the air relative to a fixed axis on the aircraft, a pitch gyro which measures the angle of this axis relative to the ground (this angle changes due to pitching of the aircraft), and the true airspeed of the aircraft. Small corrections have to be applied to some of the measurements for angle of roll and rate of pitch. Many measurements have therefore to be made at a very high frequency to obtain vertical currents by this method.

All instruments are either read by an observer in the air or are recorded on a multi-channel galvanometer recorder. The latter is used if readings are required at a high frequency. At present the following observations can be recorded on film moving at speeds up to 15 cm/sec:

Time (in seconds)	Liquid water content
Airspeed	Pitch angle
Temperature (standard element)	Roll angle
Ultra rapid temperature	Rate of pitch (or roll)
Radio refractive index	Vertical acceleration of aircraft
	Angle of incidence of wind

ICAO (International Civil Aviation Organization) height.

An example of a record of a flight in turbulent conditions with some of these instruments in operation is shown in Figure 1.

**Layout of equipment.**—The officer in charge of the flight has a good view in the forward direction. He has control of the 3-cm radar equipment and can therefore tell whether a cloud ahead contains precipitation particles. He also has a thermometer on which he can read air temperature.

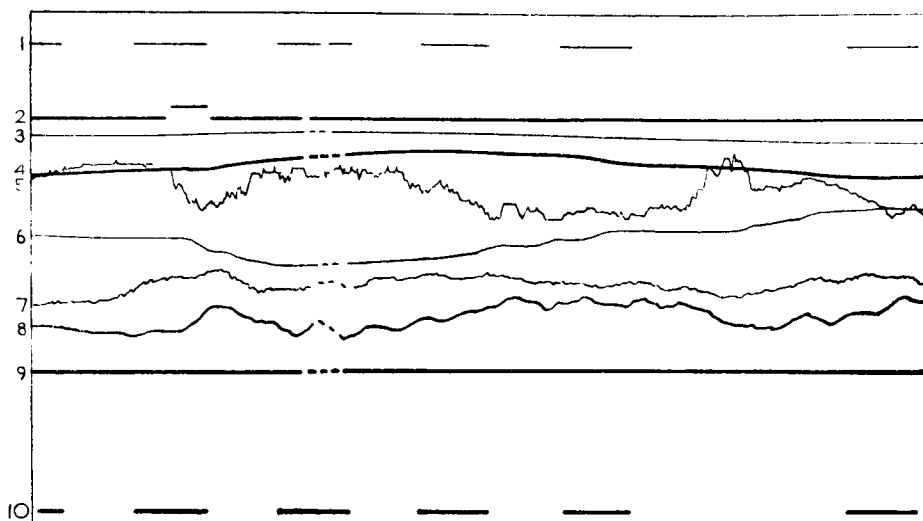


FIGURE 1—AN EXAMPLE OF A RECORD OF A FLIGHT IN TURBULENT CONDITIONS

1. Half-second time marks; 2. Event marker; 3. Coarse airspeed; 4. Sensitive height; 5. Wind vane; 6. Sensitive airspeed 7. Rate of pitch; 8. Vertical accelerometer; 9. Coarse height; 10. Half-second time marks.

On the first table behind the ramps there are seats for two observers. At one position indicators of ground speed, airspeed, drift heading and height are available. These observations are made when spot winds are required. At the other position temperature, frost-point, airspeed and height can be read. On this table there is also the chronotron for measuring the time of exposure of the magnesium oxide slides in cloud.

At the next table there is the radio refractometer, ultra rapid thermometer and hot wire water content meter, and on the third table there is the recorder and the ground position repeater box. Two other tables are available, one of which has the self balancing bridge and the other has the signaller's equipment. There is ample space on these tables for future developments.

On each table and at the officer-in-charge's position there are switches for putting event marks on the recorder to indicate the occurrence of something of interest, e.g. entry into cloud, passing through haze top, etc.

The layout of the equipment has been arranged to reduce to a minimum the number of observers carried on each experimental flight. The number required varies from one to four depending on the project.

**Navigational aids.**—The Hastings is now equipped with most of the latest navigational aids and can be operated in any part of the world. A detachment to El Adem has already been made and further overseas flights are being considered.

**Projects.**—There are many projects assigned to MRF on the research programme of the Meteorological Research Committee, but only a few can be worked on at any one time. At present a large effort is being put into the



instrumentation. The equipment for vertical current measurement is being improved and consideration is being given to recording the output of all instruments in digital form on magnetic tape in a form suitable for feeding directly into a *Mercury* computer. The very tedious work of reading film records will then be eliminated. A study of the accuracy of wind measurement is being made to see if the divergence of wind within a closed area can be measured with sufficient accuracy to deduce from it vertical currents on a much larger horizontal scale than that of an individual cumulus cloud. Calibration of the cloud-physics instruments is proving to be a very difficult problem, but it is hoped that progress will be made using a spinning disk to generate a cloud of drops of known size and projecting through it a magnesium oxide coated slide mounted on a bullet fired from an air gun designed by the Royal Aircraft Establishment.

Concurrently with this instrumental work (which itself requires a large amount of flying) a number of other flying projects are in progress using the Hastings. The instruments with high response speeds are being used in a study of convection and the recent detachment to El Adem combined a study of convection over the desert with some measurements in sea-breeze conditions. Flights are being made in frontal rain using the aluminium foil impactor to study the variation of precipitation intensity with height.

**Conclusions.**—There is no doubt that experimental work in the Hastings is greatly facilitated by its refitting and re-equipment. All the modifications to the aircraft were done by the Experimental Aircraft Services Department of the Royal Aircraft Establishment and we are grateful to them for the speed and efficiency with which they planned and executed the project.

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## A DIAGRAM TO ASSESS THE TIME OF FOG CLEARANCE

By J. A. BARTHRAM

**Introduction.**—Radiation fog is normally expected to clear when insolation has caused the temperature to rise sufficiently to give at least a saturated lapse rate from the surface to the fog top. To forecast the time when the required surface temperature (the 'clearance temperature') will be reached, an estimate has to be made of the insolation necessary to raise the temperature of the air to the required level, plus that needed to warm and evaporate the water droplets of the fog. Kennington<sup>1</sup> has shown that the extra insolation required for the water content can be taken into account by increasing the insolation needed for air by a simple factor. This factor is dependent only on the dawn temperature and the clearance temperature. He has also given an estimate of the total insolation received at the top of a fog and available for dispersing it. The present paper puts his results in a form readily usable by a forecaster, and includes a set of diagrams from which the fog clearance time can be quickly assessed.

**Basis of the diagram.**—Figure 1 shows a frequent type of ascent curve at the end of a night during which radiation fog has formed. Taking the surface temperature at dawn as  $T_1$ , the clearance temperature as  $T_2$ , and the fog top as A, then for practical purposes the heat required to raise the temperature of the air from  $T_1$  to  $T_2$  is proportional to the area of the triangle  $T_1 T_2 A$ .

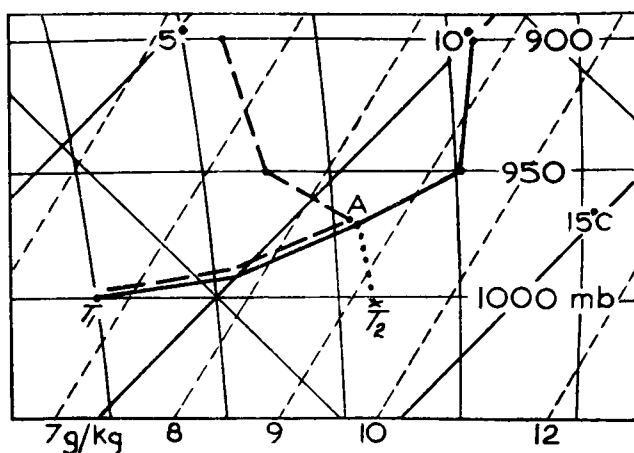


FIGURE 1—ASCENT CURVE ON NIGHT OF FOG

— dry-bulb temperature, - - - dew-point temperature,  
 $T_1$  dawn temperature,  $T_2$  fog clearance temperature,  
 'A' indicates fog top.

On the large-scale inset tephigram of Meteorological Office Form 2810A (1956 edition), at pressures and temperatures likely to be experienced in radiation fog,  $1^\circ\text{C} = 0.7 \text{ cm}$ ,  $10 \text{ mb} = 0.28 \text{ cm}$ , and  $1 \text{ cm}^2$  represents an energy of  $12.5 \text{ gm cal/cm}^2$ . Thus the insolation,  $H$ , required to raise the temperature of air from  $T_1$  to  $T_2$  is given by

$$H = \frac{1}{2} (T_2 - T_1) \times 0.7 \times D \times 0.028 \times 12.5 \text{ gm cal/cm}^2$$

where  $D$  is the depth of fog in mb.

Kennington<sup>1</sup> showed that in order to warm and evaporate the liquid water, the insolation  $H$  must be increased by a factor  $F$  given by

$$F = \frac{T_1 + T_2}{60} + \frac{2}{3}$$

where the temperatures are in Fahrenheit. Figure 2 was drawn to obtain  $F$  when temperatures are in degrees Fahrenheit or Celsius.

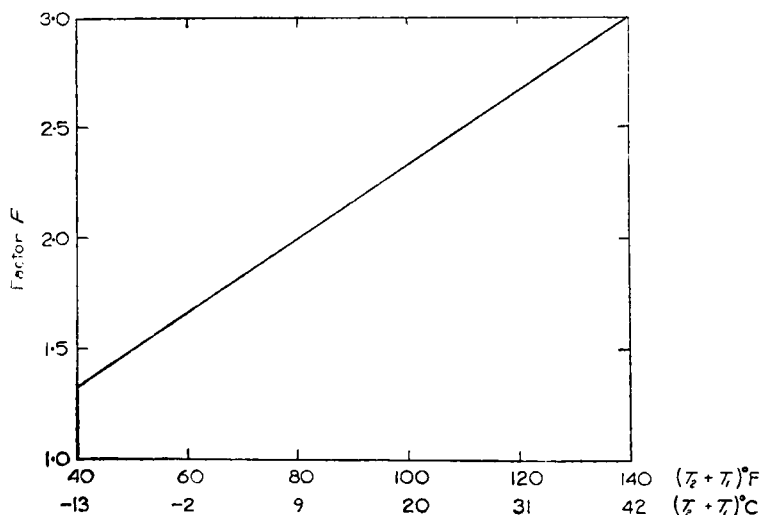


FIGURE 2—GRAPH TO DETERMINE FACTOR  $F$  USING FAHRENHEIT OR CELSIUS SCALES

Figure 3 shows selected lines of constant values of  $H$  for temperature differences up to  $10^{\circ}\text{C}$  and fog depths up to 60 mb.

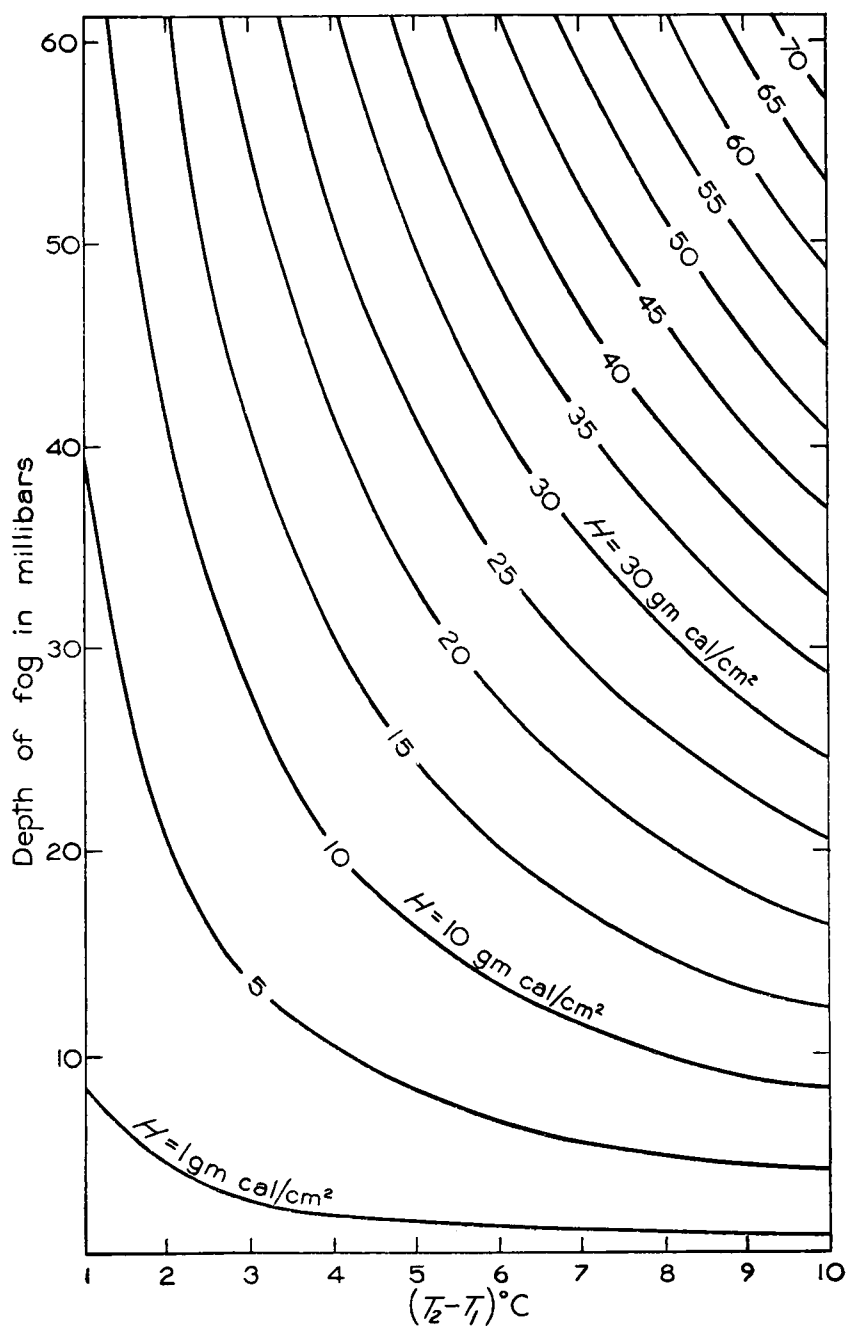


FIGURE 3—INSOLATION,  $H$ , REQUIRED TO WARM A LAYER OF DRY AIR  
 $T_1$  temperature in  $^{\circ}\text{C}$  at dawn,  $T_2$  fog clearance temperature.

The insolation values of Figure 3 were then multiplied by the values of  $F$  obtained from Figure 2, thereby finding the total insolation required to disperse the fog. Selected lines of constant values of this total insolation were drawn to produce Figure 4.

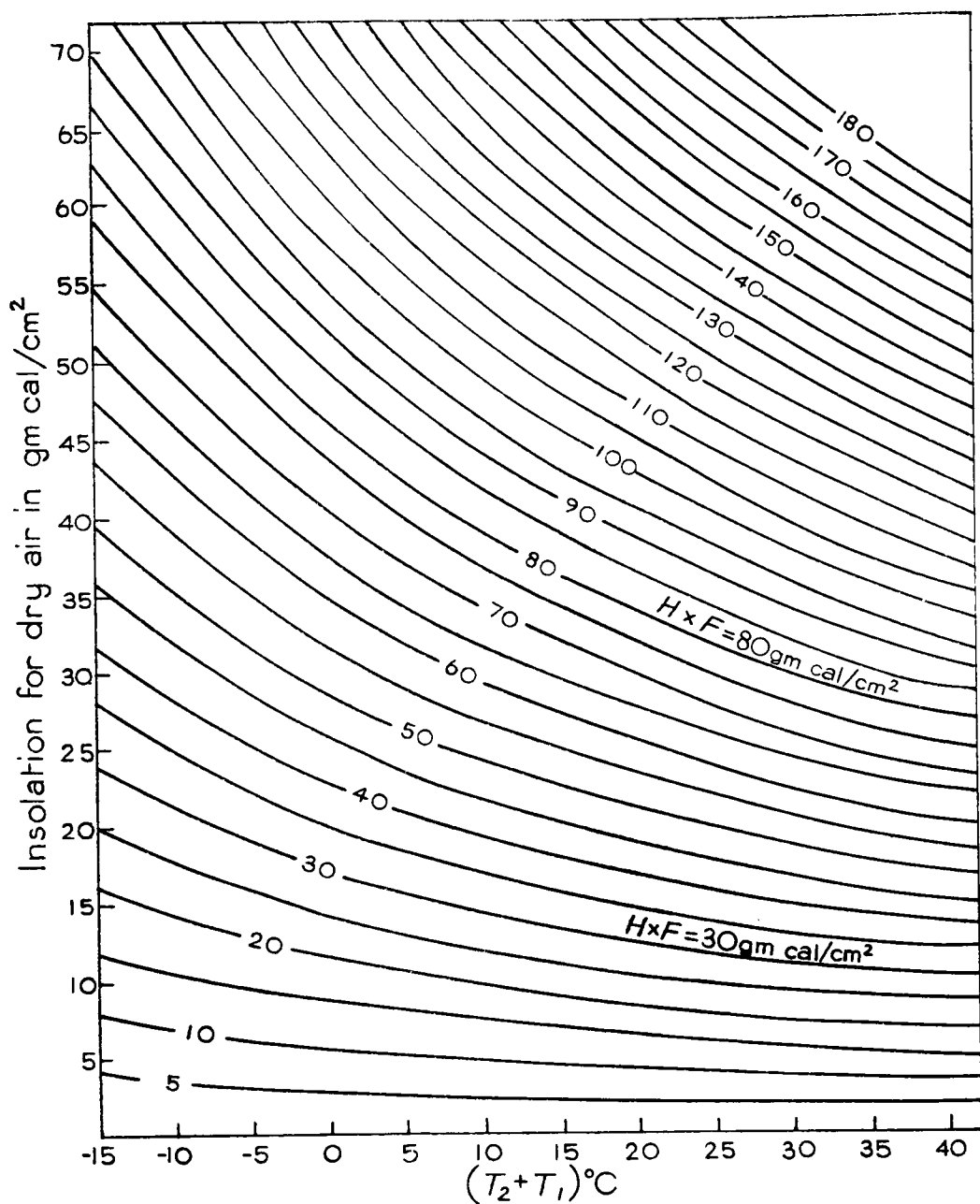


FIGURE 4—TOTAL INSOLATION,  $(H \times F)$  REQUIRED TO WARM A LAYER OF FOGGY  
AIR  
 $T_1$  temperature at dawn in °C,  $T_2$  fog clearance temperature.

Figure 5 shows in a graphical form the time by which the insolation available to disperse thick fog will have been received. The lines are based on Table III of Kennington's paper,<sup>1</sup> on the assumption that the figures given there refer to the middle of the month at the Greenwich meridian. Months have been grouped where this did not produce an error of more than 15 minutes in the time by which a given insolation was received. For a thin fog Kennington suggests that the insolation available for dispersal of fog is increased by half. No definition of a thin fog was given by Kennington, but experience has pointed to a visibility of not less than 600 yards.

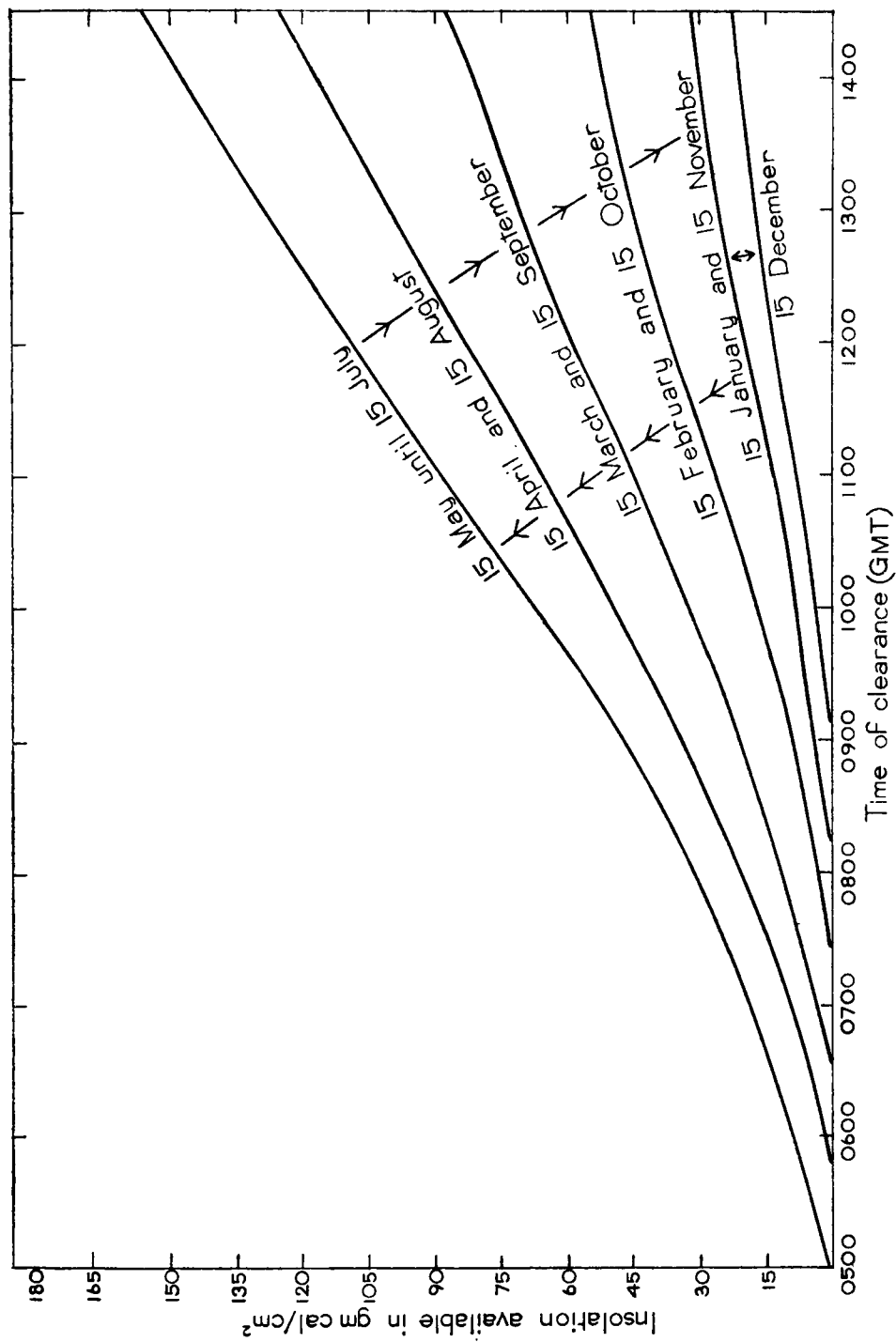


FIGURE 5—INSOLATION AVAILABLE BY VARIOUS TIMES

**Method of use of the fog clearance diagram.**—Firstly a forecast is required of the clearance temperature ( $T_2^\circ\text{C}$ ) by any preferred method, also the value of the dawn temperature ( $T_1^\circ\text{C}$ ) and the fog depth in millibars must be known or estimated. On Figure 3 plot the temperature difference  $T_2 - T_1$  against the depth of fog. Read off the value of the insolation required to warm a layer of dry air, and plot this on Figure 4 against the value of  $T_1 + T_2$ . Read off the value of the total insolation required to warm a layer of foggy air, and then find from Figure 5, for the appropriate month and date, the time when this amount of insolation will be available, i.e. the time of clearance of the fog.

For cases of thin fog (visibility over 600 yards) only two-thirds of the total insolation value obtained from Figure 3 should be used.

**Discussion.**—The major unknown in using the diagram is usually the depth of fog. A midnight radiosonde ascent will give a useful guide, but it may be that the depth of fog has increased by 5 to 15 mb by dawn. Unless the depth of fog is known, it is probably best to take likely upper and lower figures and calculate the range of clearance times. This range is unlikely to be excessive, and will be sufficiently accurate for most purposes. The diagram gives a useful indication of winter days when a fog may persist. The times of Figure 5 must be amended for stations at significant distances from the Greenwich meridian.

The author has mounted the Figures 3, 4 and 5 under clear plastic as three diagrams side by side with a common base line. The various readings can then be traced out by chinagraph as in Figure 6 without having to read and replot

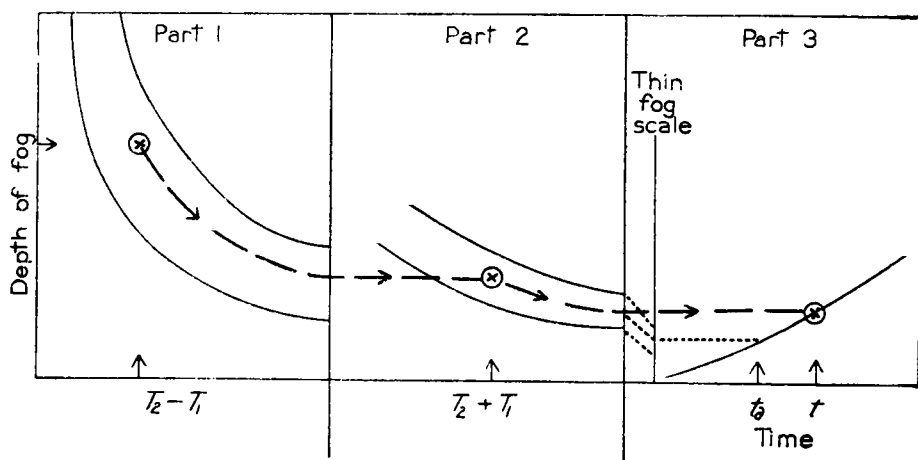


FIGURE 6—METHOD OF USE OF FOG CLEARANCE DIAGRAMS SHOWN IN FIGURES 3, 4, AND 5

$T_1$  temperature at dawn in  $^\circ\text{C}$ .  $T_2$  fog clearance temperature,  
 $t$  is time of fog clearance,  $t_a$  is time of thin fog clearance.

insolation values. For cases of thin fog a system of dotted lines can be used to lead into a special scale two-thirds of the main vertical scale of the third part of the figure.

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## THE FIFTH INTERNATIONAL SYMPOSIUM ON CONDENSATION NUCLEI

By J. B. STEWART, B.Sc., D.I.C.

The symposium took place from 13 to 17 May 1963. The first half, comprising three sessions on ice nuclei, was held at Clermont-Ferrand and the second, of five sessions on condensation nuclei, at Toulouse, at the invitation of the Universities of Clermont-Ferrand and Toulouse respectively.

The programme of the symposium and abstracts of the papers appeared in the *Journal de Recherches Atmosphériques*,<sup>1</sup> (this journal replaces the *Bulletin de l'Observatoire du Puy de Dôme*). Full papers are published in the next edition of the same journal. Of the thirty papers presented, about a third were of direct interest to the cloud physicist and are summarized here.

The first lecture was given by V. J. Schaefer (U.S.A.) who used slides and a film to describe some of the studies and observations made in the geyser and hot springs area of Yellowstone Park.<sup>2</sup> Since the air in this area contains very few nuclei—about 50 particles per cubic centimetre—it can be used as a natural laboratory to study conditions of high supersaturation and supercooling. For example the film showed the dramatic effect of burning pine cones to provide a source of condensation nuclei upwind of one of the hot pools. When nuclei were supplied, a thick plume of condensed water drops was formed, whereas before there had been only a slight haze over the pool. Particularly striking were the photographs which were shown of optical phenomena—haloes, mock suns, arcs etc.—produced by ice clouds formed by artificial seeding. This was in contrast to the complete absence of optical phenomena when ice clouds occurred naturally at temperatures below  $-40^{\circ}\text{C}$ .

H. W. Georgii (Germany) gave the results of experiments of the effects of trace gases on ice nuclei. He found that sulphur dioxide had a negligible effect on the ice nucleating power and similarly for ammonia, unless the concentration of ammonia was much greater than occurs in the atmosphere. In the discussion that followed Dr. Georgii agreed with Dr. Soulage (France) that the lowered nucleating power of ice nuclei in polluted air was due to coagulation with other particles rather than poisoning by industrial gases.

H. R. Pruppacher (U.S.A.) presented a paper on the effects of soluble salts on the supercooling of water droplets. To resolve the discrepancy between theory and experiments of earlier workers, further experiments were carried out. Pruppacher found that drops of a solution with a concentration of more than  $10^{-2}$  mole per litre had a lower mean freezing temperature than drops of pure water. He has also shown that in the previous experiments, large numbers of nuclei were added with the salt and so the freezing-point of the drops of solution was higher than that of the pure water drops.

A film by R. Serpolay and Mlle M.-J. Toye (France) showed the growth of ice 'whiskers' from a nucleus, viewed through a microscope. The 'whiskers' were less than  $10\ \mu$  thick, but grew to about a millimetre long.

J. A. Day read a paper by N. Fukuta (Japan) and B. J. Mason (U.K.) on the epitaxial growth of ice on organic crystals. They found that of the substances tested, the most effective were the stearoids. On several of these, ice crystals would grow at temperatures only one or two degrees below  $0^{\circ}\text{C}$ . The nucleating

power of these compounds is not caused by similarity of their crystal structure to that of ice, but by the presence and arrangement of certain groups in their molecules, which form bonds with the water molecules and so facilitate the phase change.

J. Podzimek (Czechoslovakia) presented calculations which showed that water-vapour pressure gradients near condensing droplets are sufficiently great to make diffusiophoresis—transport down the water-vapour pressure gradient—important in the capture of insoluble particles by condensing cloud drops. This result is in conflict with recent work reported by Goldsmith.<sup>3</sup>

J. P. Lodge (U.S.A.) described further work that he and H. A. Bravo (U.S.A.) have carried out using Millipore filters to measure ice nucleus concentrations.<sup>4</sup> They used this method to test organic materials such as those studied by Fukuta and Mason. For inorganic materials and natural aerosols, the Millipore filter method agrees very well with other methods, but the agreement is poor for organic substances. Thus for cholesterol the threshold temperature given by the Millipore filter method was  $-14^{\circ}\text{C}$ , compared to  $-1^{\circ}\text{C}$  as found by Fukuta and Mason. Lodge and Bravo have also collected snow flakes on Millipore filters, which were then warmed to evaporate the snow flakes and the residues tested to find the temperature of ice formation. With natural snow it was found that none of the residues was active at  $-15^{\circ}\text{C}$ , whereas with snow formed by seeding with silver iodide, every residue was active at  $-15^{\circ}\text{C}$ . Thus it may be possible, the authors suggest, to detect silver iodide in ice crystals.

The rest of the symposium dealt with condensation nuclei.

S. Twomey (U.S.A.) described measurements of the concentration of particles on which drops form in natural clouds. It is known that only a small number of the available nuclei grow into cloud droplets and that the supersaturation is very rarely greater than one per cent. Also it has been shown that to grow a drop of  $5\text{ }\mu$  radius takes some seconds at one per cent supersaturation and about 40 seconds at 0.1 per cent supersaturation. To be able to measure the concentration of nuclei forming drops in natural clouds, Twomey used a thermal diffusion chamber to give steady supersaturations at values down to 0.1 per cent. His results, obtained with this apparatus suggest, that the major source of the nuclei effective in cloud formation is the continents, but the nuclei are not man-made. He found little difference between the concentrations of such nuclei in the air at the surface in Washington, D.C. and at 10,000 feet.

Mlle M. Deloncle (France) described observations of particles up to  $10\text{ }\mu$  diameter in a fog near Paris, when the relative humidity was as low as 70 per cent. She suggested that this was caused by the presence of sulphur dioxide and sulphur trioxide.

J. A. Day (U.S.A.) described his experiments and results on the formation of small drops by the rupture of air-bubble films. By allowing the bubble to burst in a highly supersaturated environment, the droplets grew sufficiently to be photographed with a cine-camera and counted. He found that the number of droplets increased as the bubble diameter increased—this disagrees with Mason's results,<sup>5</sup> which suggested that the number of droplets was independent of the bubble diameter. Day found that in distilled water, a bubble of 2.2 mm diameter gave about 30 droplets, and in three per cent saline solution about 100 droplets.



D. C. Blanchard (U.S.A.) described some of his experiments into the origin of condensation nuclei. He has shown that no nuclei were produced when an air-borne drop of sea water crystallizes. In experiments on the rupture of air-bubble films, Blanchard found that the number of droplets produced was comparable with that found by Day and also was dependent on the diameter of the bursting bubble. However, if there was surface-active contamination present, no droplets were formed when the bubble burst at the surface.

On the last day of the symposium the participants were taken to the Lanne-mezan plain—75 miles west-south-west of Toulouse—to see the Météotron in operation. The Météotron consists of a large number of oil burners, which consume a ton of fuel per minute, arranged in the shape of a hexagon. When the Météotron is working the heat from the burners produces an artificial thermal, which is made visible by the smoke carried up with it. Unfortunately the demonstration was not wholly successful, partly because the meteorological conditions were unfavourable—low humidity at the surface, and a 6/8 layer of stratocumulus with its base at about 6000 ft—and partly because the equipment was not fully serviceable. It was impossible to say whether the Météotron produced any cloud.

The general impression of the symposium was one of a useful exchange of ideas in a particularly pleasant and informal atmosphere, owing not a little to the excellent arrangements made by Professor H. Dessens and his colleagues. Much of the benefit of the symposium came from discussions held after the formal proceedings were over, both in the conference hall and out of it.

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3. SCHAEFER, V. J.; Condensed water in the free atmosphere in air colder than  $-40^{\circ}\text{C}$ . *J. appl. Met., Lancaster, Pa.*, **1**, 1962, p. 481.
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#### REVIEWS

*Mean monthly temperature and salinity of the surface layer of the North Sea and adjacent waters from 1905 to 1954*, prepared and published by the Conseil Permanent International pour l'Exploration de la Mer, Service Hydrographique, Charlottenlund Slot, Denmark, preface by G. Dietrich.  $14\frac{1}{2}\text{in.} \times 13\frac{1}{4}\text{in.}$ , illus., pp. 318, 1962. Price: DK 45.

This beautifully printed and produced atlas gives monthly average maps of sea surface temperature (isotherms at intervals of half a degree Celsius), for each month of the year for the 50-year period 1905–54 for the waters surrounding the British Isles between  $47\frac{1}{2}$  and  $63^{\circ}\text{N}$ ,  $11^{\circ}\text{E}$  and  $21^{\circ}\text{W}$ , including inshore waters. There are corresponding maps of salinity for each month—the isopleth interval is not uniform but all lines are clearly labelled. It is the first time that maps of both items over this whole region have been published for the same period of years—a small but important detail which one should be scrupulous

about because of the well known warming trend during much of the last half-century. It was already known that water temperatures in the English Channel averaged  $0.6^{\circ}\text{C}$  higher in 1928–51 than in 1903–27.

Sources of data used include British lightships and coastal stations, the lightships of other neighbouring countries, Danish, Dutch and German merchant vessels and various research ship observations from the archives of the International Council for the Exploration of the Sea. The observations from research ships were compared with those from merchant vessels but the comparison suggested no noteworthy systematic discrepancies between the work of the two classes of vessel. All the observations were made at less than 5 metres depth.

The  $1\frac{1}{3}$  million temperature observations and 400,000 odd salinity observations available were unevenly divided over the area and in time, values for the years 1940–45 being particularly scarce. This meant that considerable skill had to be used in arriving at the isopleth analysis, when covering sparse areas, where the few observations available might have been made on unrepresentative occasions. In order to avoid any possibility of the analyst's personal bias misleading the user it was decided to publish not only the maps, but also tables giving monthly mean values and the number of available observations in every month of every year for each of 293 sea areas. This additional material makes up the main weight of the book. It is an addition of very great value for a number of purposes besides the one stated.

Ever since the publication of monthly mean values year by year over long periods of years for land stations all over the world in *World Weather Records* (the original volume being published by the Smithsonian Institution in 1927,<sup>1</sup> the latest volume (observations to 1950) by the U.S. Weather Bureau in 1959<sup>2</sup>), meteorologists—concerned with long-term variations and trends, or with the interactions between atmosphere and ocean—have wished to see similar long series of values of ocean surface temperature, at least for a few positions in the ocean representative of the main water bodies. There has been a plan in the Meteorological Office for some time past to produce such series for a few particular points in the world's oceans for use in research on climatic variations and long-range forecasting. Long-range weather forecasters anywhere in Europe, seeking to identify analogous situations in past years, are sure to make frequent reference to the tables now provided in this atlas.

The 293 areas for which mean values are given month by month over the 50 years comprise 46 four-degree "squares", 114 one-degree "squares", 71 quarter-degree "squares" and a remainder of intermediate sizes. Unfortunately it is only a minority of these areas for which the series are anything like complete, chiefly "squares" along the main shipping routes to the south-west and west about latitudes  $50$  and  $57^{\circ}\text{N}$  and the Faeroes–Iceland route. This distribution brings home the sad lack in our arrangements for collecting information from ships in the central North Sea and indeed in many other areas between the Western Approaches and the ports. Some important areas could perhaps be covered some day by automatic floating weather stations.

Even a cursory examination of the maps brings out many points which are not generally familiar. The warmest waters at the time of the annual maximum in August are along the Dutch and German coasts and (though this is not

specifically shown) in the inner reaches of Oslofjord. On average the coasts of Brittany and Cornwall are 2°C cooler. The warmest waters in summer near this country are off the Thames and Essex, approached by those off Sussex and Hampshire, in the Bristol Channel and Cardigan Bay and bordering the Lancashire coasts. The coldest waters in February are in the coastal shallows and show an obvious relation to the regions of low salinity—Oslofjord, the German Bight, the Dutch coast, the Wash, the Lancashire coast and innermost Moray Firth (in ascending order of average temperature). Seasonal warming and cooling is particularly rapid in some of these areas. The tables of monthly values will facilitate the reckoning of standard deviations which also promise to hold some interesting lessons. Variability from year to year seems higher in the North Sea than in the broad waters of the North Atlantic drift, but appears to be high in the prominent tongue of cold water which approaches the Faeroe Islands from the north. Evidently the east Iceland arm of the Greenland current, with which this tongue is presumably connected, is one of the most variable features near enough home to effect British weather.

The applications of this very practical and yet very scientifically produced work clearly range from fisheries and marine biology to tourism and bathing, as well as to the growing meteorological effort on long-range weather forecasting and climatic trends. This atlas should find a place in a number of commercial and industrial offices as well as in scientific laboratories. It should also serve as a model for further enterprises.

H. H. LAMB

#### REFERENCES

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*Boletín de estadística meteorológica e hidrográfica, No. 1 and 2*, Ministerio de Agricultura, Servicio de Agrometeorología e Hidrología. 8½in. × 11in., pp. 40, Pacific Press, S.A., Av. Brasil 537, Lima, Peru, 1962.

These two publications are the first of a series which will eventually give Peruvian meteorological and hydrological data, grouped according to river basins. It will be interesting to see how quickly the whole country is covered, and how data for succeeding years can be added to the present publications. In some cases the layout seems wasteful unless a standard form is deemed essential for the future. No information is given concerning how the observations are made—particularly important in the case of evaporation data. The plan seems a promising one although it is difficult to judge on the basis of the first publications in the series. (Statistics are now published for at least 19 river basins.)

A. BLEASDALE

#### HONOUR

The following award was announced in the New Year Honours List, 1964:

M.B.E.

J. Bell, B.Sc., Senior Experimental Officer, Meteorological Office, Bracknell.

## **AWARDS**

### **L. G. Groves Memorial Prizes and Awards**

The presentation of the L. G. Groves Memorial Prizes and Awards for 1963 was made by Major K. J. Groves in the Air Historic Room at Air Ministry, Whitehall, on 15 November 1963. These annual awards were instituted by Major and Mrs. K. J. Groves in memory of their son Sergeant L. G. Groves, RAFVR, who was killed on a meteorological sortie in 1945.

The Memorial Prize for Aircraft Safety was awarded to Flight Lieutenant A. W. Price of RAF Coningsby, who perfected a device which enables survivors from crashed aircraft, on land or sea, to be spotted on the radar of searching aircraft or ships at long range, and which can be carried in dinghy survival packs. It is called 'R.I.T.A.' (Reflecting Indicator for Aircrew). Flight Lieutenant Price donated the greater part of his award to charity.

Mr. T. H. Kirk of the Meteorological Office, Bracknell, received the Memorial Prize for Meteorology, for his work on duties in Malta, and for his 'exceptional interest' in the scientific problems of weather forecasting. Among scientific papers he has had published are detailed reports on a tornado, low-level turbulence, pressure jumps, and other features of climatic conditions in Malta. (See Plate I.)

The Air Meteorological Observers' Award, presented to a member of aircrew employed on meteorological observer or other flying duties relating to meteorology for meritorious work and devotion to duty, was won by Flight Lieutenant D. H. Gannon, of RAF Farnborough. He has for four years flown as a navigator on meteorological research flights, showing the highest efficiency and completing 350 sorties in more than 900 hours flying in Canberra, Hastings and Varsity aircraft. Flight Lieutenant Gannon was navigator in the RAF Canberra which won the 1953 England to New Zealand Air Race.

Finally the Second Memorial Award, for meritorious work in any of the fields covered by the other three prizes, was won by Chief Technician J. Mulholland, of RAF Binbrook. He designed a portable set for making regular and careful pre-flight checks at forward landing strips to ensure the correct and safe operation of the complex flying clothing and equipment used in the RAF.

## **NOTES AND NEWS**

### **Conference on Atmospheric Radiation, 1964**

The International Radiation Commission of the International Association of Meteorology and Atmospheric Physics of the International Union of Geodesy and Geophysics is having a conference at Leningrad, from 10-15 August 1964. There will be both invited and contributed papers on a wide variety of topics of current interest in the field of Atmospheric Radiation.

Further information may be obtained from: Professor J. London, Department of Astrophysics and the Atmospheric Sciences, University of Colorado, Boulder, Colorado, U.S.A., and Professor M. I. Budyko, The Main Geophysical Laboratory, M. Spasskoya 7, Leningrad K-18, U.S.S.R.

### **Conference on Radio Meteorology, 1964**

The Inter Union Committee on Radio Meteorology (of the International Scientific Radio Union and the International Union of Geodesy and Geophysics) is arranging a conference at Boulder, Colorado from 14–18 September 1964. The symposium will cover all aspects of Radio Meteorology and will incorporate the eleventh Weather Radar Conference sponsored by the American Meteorological Society.

The organizing committee would like to hear now from all those interested in attending and participating in the conference. Contributed papers will be reproduced, and then distributed a month or more before the conference to allow the necessary thorough reading by all participants.

Correspondence should be addressed to Mr. J. W. Herbstreit, Program Committee, 1964 World Conference on Radio Meteorology, Central Radio Propagation Laboratory, National Bureau of Standards, Boulder, Colorado, U.S.A.

### **CORRIGENDA**

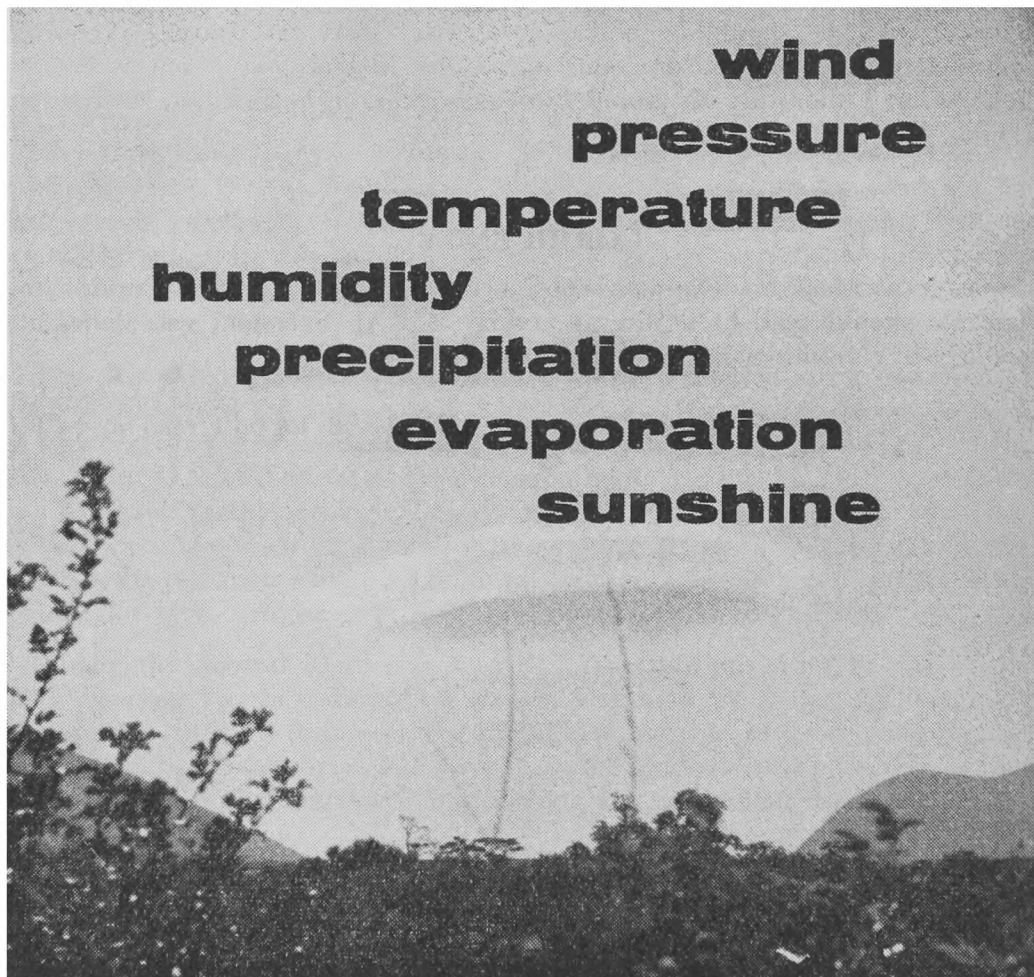
*Meteorological Magazine*. October, 1963, between pages 302, 303. Caption to Plate IV should read 'The aircraft, based at RAF Syerston, was flying at 7000 feet in cumulus-type cloud above Cottesmore.'

*Meteorological Magazine*, October 1963, page 339, line 28: for 69°F read 69–73°F.

# **METEOROLOGICAL INSTRUMENTS**

**for  
measuring**

**wind  
pressure  
temperature  
humidity  
precipitation  
evaporation  
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## THE ACCURACY OF RAIN-GAUGES

By E. R. C. REYNOLDS, Ph.D.

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**Purposes of rain-gauge comparisons.**—There is considerable variation of the efficiency with which different designs of rain-gauge collect precipitation. It is the aim of rain-gauge comparisons to assess these differences of behaviour. So variable is the efficiency of rain-gauges that their design, installation and siting is strictly stipulated by the individual meteorological organizations in an attempt to unify national networks. International comparisons have been initiated by the World Meteorological Organization<sup>1</sup> in an attempt to provide information to unify the data from the various national networks. However, rain-gauge efficiency is not a constant quantity, but is dependent upon the nature of the precipitation and other climatic factors, both during the storm, and in the interval between the storm and the measurement of the collected water. Thus, although it is an easy matter to obtain reduction coefficients between gauge types used together over an extended period (a year is commonly adopted), these are dependent on the unique combination of climatic factors affecting the efficiency throughout the period. Poncelet<sup>2</sup> in Belgium has shown that such coefficients become reasonably steady only if the period is as long as five years. In using such coefficients, it must be remembered that they are validly applied only to data comparable with those from which they were derived.

It often happens that rainfall measurement is imperative in places where the conditions depart seriously from national standard conditions. When studying the water balances of forests,<sup>3,4</sup> it has been found necessary to measure the rainfall above the trees. Such measurements have also been made by the author in Bagley Wood, near Oxford, and for some time now records from fifteen gauges above the trees have been collected. Several kinds of wind shield and gauge have been employed: the aim of the comparison in this case has been to define the most efficient rain-gauge in this situation. The experience from this installation and from the treatment of the data has been incorporated into this paper.

### **Experimental methods of comparison.**—

(i) *Design of the rain-gauge network.*—The site for the comparison need not be sheltered, but it should be sufficiently uniform to prevent the effects of the location of the individual gauges from obscuring the differences between the instruments themselves. In fact, an exposed site would allow of a comparison

under a wider range of wind conditions, but the area is likely to be less uniform than a sheltered one. The *design of the array* of gauges should be such as to overcome location effects within the site rather than to demonstrate these as did Poncelet.<sup>2</sup> The account of his field comparison of rain-gauges has previously been reviewed,<sup>5</sup> when the value of duplicating each gauge type was discussed. Allis *et al.*<sup>6</sup> recognized that their comparisons suffered from a lack of replication of gauges. Replication is a precaution against any unsuspected lack of uniformity over the site; the greater the likelihood of variability, the larger should be the number of similar gauges. To reduce the replication necessary, and yet minimize the effects of site variability, the gauges could be moved every time a certain number of showers have been recorded, following the method used to overcome rainfall variability beneath trees.<sup>7</sup> The systematic arrangement of the compared gauges (for example, by Poncelet<sup>2</sup>) normally results in the differences caused by instrument design being confounded with any systematic variability across the site. The instruments therefore should be placed at random over the area,<sup>8</sup> the only restriction being that they must not be so closely spaced as to disturb one another's behaviour.

(ii) *Additional instrumentation.*—Various rain-gauge designs differ in the degree to which they are subject to errors caused by evaporation from the funnel or the container, splashing out of the funnel, splashing into the gauge from the ground or a wind shield, condensation in the funnel, and aerodynamic effects. According to the resources of the station, as many as possible of the primary causes of these effects should be measured, although the Belgian work illustrates how much can be done when only approximate data are available.<sup>2</sup>

Of the greatest value is a *rainfall recorder* on the site for assessing the rainfall intensity (mean intensity over the total record, or short-period maximal intensity), the number of showers contributing to a record (and thus the number of wetting and drying cycles to which the gauges are subject) and the time of the rain, for the purpose of synchronization with other environmental measurements. A simple *directional rain-gauge* has been found very valuable in the comparison of rain-gauges at Oxford. It serves as a useful check on the freedom of the individual gauges from anomalous location effects. The angle of incidence of the rain (a function of raindrop size and wind speed) can be computed from the directional gauge<sup>8</sup> to assist in interpreting the differences between gauge types. *Recording anemometers* are valuable in assessing the varying efficiency between the instruments in overcoming aerodynamic errors. While the wind speed ought to be measured at the height of the gauges on the site, some important information might be obtained in a detailed study of the wind speed around the individual instruments. Other factors associated with evaporation can be measured with a *thermohygrograph* and a *solarimeter*, while the temperature of the rain-gauge surface might also be recorded.

#### **Treatment of data.—**

(i) *Form of basic data.*—Reading the rain-gauges at intervals shorter than 24 hours increases the information yielded by the installation.<sup>2</sup>

Splashing and aerodynamic factors are operative only during the time of rainfall; evaporation takes place after the rainfall as well. To utilize the environmental information it is necessary to integrate the readings separately for each of these two periods. The integration may be manual, from the recorder charts, or automatic, by modifying the recording instruments. There is obviously



considerable scope for ingenuity in designing a meteorological station such that the information is collected in the most relevant form, provided that the comparison of rain-gauges is sufficiently important to warrant such development. For example, the integration of the information collected during rainfall ought probably to be weighted according to the rain intensity. It is to be noted that the directional rain-gauge in fact does this. It would be of considerable assistance to the subsequent analysis of the data if as much as possible was recorded directly in a form suitable for a computer.

(ii) *Classified ratios of rain-gauge catches.*—The ratios between the total catches of different instruments over a lengthy period allow of very little interpretation of the differences unless climatically distinct seasons are compared. It is more informative to classify the data according to the climatic conditions associated with each record, and then to compare the ratios between gauge collections in each class. Poncelet<sup>2</sup> has demonstrated this method, and has shown that the various gauge designs conform with the relationships of the classified results. A synopsis of the classification has been given, and the limitations of the method discussed.<sup>5</sup>

(iii) *Correlation of relative catches.*—A better method is to adopt a multiple regression approach (first suggested by Riesbol<sup>6</sup>) since this allows of simultaneous variation among the environmental variables. Furthermore, the effect of interaction between the environmental variables on the relationship between gauges may be defined, and the arbitrary limits of the classes in Poncelet's method are removed. Three types of regression have been used in the treatment of the data from the gauge comparison at Oxford. They are illustrated by the following equations, where  $R_1$  and  $R_2$  are the catches of the compared rain-gauges (or the mean catch where replication is employed), and  $x_1, x_2$  etc., are environmental variables:

$$R_1 - R_2 = a + bx_1 + cx_2 + dx_1x_2 \dots \dots (1)$$

$$R_1/R_2 = a' + b'x_1 + cx'_2 + d'x_1x_2 \dots \dots (2)$$

$$R_1 = A + BR_2 + CR_2x_1 + Dx_1 + ER_2x_1x_2 + Fx_1x_2 + Gx_2 \dots \dots (3)$$

Equation (1) reveals the relationship between the absolute differences in catch and the environment, irrespective of the size of record. This is suitable for analysing the differences between gauges due to 'end losses' caused by wetting and retention. Equation (2) is useful to interpret cumulative differences dependent on the size of the catch. Equation (3) allows of insertion of wetting differences and cumulative differences at the same time, interactions on the right-hand side involving  $R_2$  representing cumulative effects, and those without  $R_2$  the 'end effects.' Seventy per cent or more of the variability (expressed as the sum of squares) between the tree-top gauges at Oxford has been shown to be correlated with environmental factors by such equations. The form of the functions of the environmental factors as inserted in the regression should follow, as far as possible, the form in which they are known to affect the physical processes which govern rain-gauge efficiency. Where this is not yet known, the form of the functions should be as rational as possible.

Where the 'independent' variables are known to be highly correlated among themselves as in the case of those which condition gauge behaviour, the statistical significance attaching to each of the partial regression coefficients is considerably determined by the inclusion or exclusion of related variables. A better form of statistical analysis in this case is multivariate analysis.

**Application of derived relationships.**—With the improvements outlined above, the conventional method of assessing the accuracy of rain-gauges by the comparison of instruments in the field is eminently suited to climatological studies. Despite the different gauge designs employed in the different countries, such a procedure could lead to the unification of the data from the various national networks.<sup>1</sup> The relationships between gauges defined in terms of the prevailing climatic environment, are applicable within the range of conditions under which they are derived, and not only to the unique climatic combination of the site over a period. The relationships are thus similar to Poncelet's *Interpolation coefficients*<sup>2</sup> for the application of the results of gauge comparisons to areas where no comparison has been conducted, solely by reference to the climate of these areas. The regression equations are applicable to individual storms unlike simple coefficients from gauges compared for lengthy periods.

Using these field methods the causes of the differences between gauge types can be analysed, in so far as correlations can be interpreted to distinguish cause and effect. The defects and merits of the different instruments can be defined, and this would lead naturally to improved designs.

**Limitations of field comparisons of rain-gauges.**—It is important to point out that this method necessarily gives only the relative accuracy of each gauge. Even with the most advanced field methods and data treatment, there seems no prospect of assessing the absolute accuracy of rain-gauges in this way. For instance, the measurements of rainfall above the trees in Bagley Wood gave surprisingly consistent records and statistically reliable estimates for the mean rainfall.<sup>10</sup> However, since the water balance of the plantation is being assessed, it is necessary to know the absolute accuracy of these estimates; unfortunately the installation provides no information on this. Allis *et al.*<sup>6</sup> reached a similar conclusion from their comparisons. In other situations where the object of using rain-gauges is the assessment of the total quantity of precipitation over an area, comparative estimates of gauge efficiency are inadequate. Those people concerned with water supply, water yield, urban or rural drainage, flood prevention and forecasting, river works, and water balance studies for biological or hydrological purposes are particularly troubled by the problem of the accuracy of rain-gauges. In these fields, for adequate sampling, the gauges may have to be sited in exposed places such as on hillsides or above trees, instead of adhering to the national standards. Errors associated with such gauges may be particularly high.

**The absolute accuracy of rain-gauges.**—To emphasize the importance of defining the absolute errors of rain-gauges, Table I is reproduced as an example of a tentative estimation of their size.

These errors need to be quantitatively assessed for each type of gauge in relation to the prevailing conditions. There follows a consideration of some ways of achieving such an assessment.

TABLE I—APPROXIMATE ERRORS OF RAIN-GAUGES (AFTER KURTYKA<sup>11</sup>)

Source of error	Size of error per cent
Evaporation	-1.0
Adhesion	-0.5
Colour	-0.5
Inclination	-0.5
Splash	1.0
Exposure (wind)	-5 to -80

(i) *Weighed lysimeters*.—The suggestion was made by Harrold and Dreibelbis<sup>12</sup> that constantly weighed blocks of vegetated soil are more accurate and more sensitive than rain-gauges, for the measurement of precipitation. The average annual excess of such a weighed lysimeter compared with a U.S. Weather Bureau Fergusson gauge was 4.38 inches at Coshocton, Ohio, with a mean annual precipitation of about 45 inches. Most of this difference occurred in the collection of snow or light rain. Weighed lysimeters present no aerodynamic differences from the surrounding ground. Splashing onto or off the lysimeter should not affect the accuracy of a carefully designed installation. However, weighed lysimeters are subject to evaporation and transpiration during rainfall which would produce errors in the measurement of precipitation and detract from their value as standards with which to compare rain-gauges. Weighed lysimeters record the condensation of water in and on the soil and on the vegetation. In the work of Harrold and Dreibelbis this was admittedly overestimated;<sup>13</sup> although the source and the quantity of this water is greatly dependent on the height and density of the vegetation,<sup>14</sup> it probably constitutes an error in rain-gauging. Nevertheless, in common with other ground-level gauges (see, for example, Bleasdale<sup>15</sup>) which are also subject to evaporation and condensation errors,<sup>2</sup> weighed lysimeters do minimize the Jevons' wind effect which is probably the largest source of error in rainfall measurement (see Table I).

(ii) *Stroboscopic and filming methods*.—Ideally, a standard against which conventional rain-gauges could be compared, would present no obstruction to the wind, no gains or losses by splashing, no thermal sink or store which would condense or evaporate water before measurement, and no surface which must be wetted and thus retain some unmeasured water. This could be achieved if the vertical component of the rate of fall and the quantity of water involved could be measured with a beam of light. This might be possible using a reflected stroboscopic beam with frequency scanning, measurement of the transmission, and appropriate orientation with respect to the direction of the falling raindrops.

Alternatively, electronic scanning of successive high-speed photographs of the falling raindrops might be developed to measure the quantity of rainfall.

(iii) *Simulated rainfall*.—It is conceivable that the production of uniform simulated rainfall (cf. Childs<sup>16</sup>) over rain-gauges in the field would be a feasible proposition for evaluating their efficiency. The true rainfall being known, the true accuracy of the gauges under measured climatic conditions could then be assessed.

(iv) *Controlled environment*.—Perhaps the most profitable way to estimate the absolute accuracy of rain-gauges would be to examine the aerodynamic effects by measuring the characteristics of air movement around gauges in a wind tunnel, and to determine the fate of raindrops theoretically. The thermodynamic relations of the gauges might be used to estimate condensation and evaporation errors. The assessment of splashing errors too might be approached fundamentally. Poncelet<sup>17</sup> has promised a theoretical estimation of the errors of rain-gauges which should at least reveal the possibilities of this method.

**Conclusions.**—Many scientists and engineers rely upon the accuracy of rain-gauges, but most have neither the time nor the facilities to estimate the absolute efficiency of gauges to sample rainfall correctly. They require information in one of two forms: either a statement of the conditions under which the

various gauges function with a known and tolerable efficiency, or the corrections to be applied to rain-gauge catch according to the prevailing climate. In any event, it is a matter of considerable urgency that the absolute accuracy of rain-gauges currently in use be established, even although this involves an extensive programme of research.

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## PERIODIC AND RANDOM FLUCTUATIONS OF THE WIND AT ADEN

By G. A. TUNNELL

**Introduction.**—Three-hourly wind observations over a seven-year period have been analysed and reveal very interesting periodic and random fluctuations in the wind in the Gulf of Aden. The record was obtained from an unobstructed cup anemometer and wind vane set up at a height of 41 feet at Khormaksar airfield on the narrow isthmus that runs 3 to 4 miles north and south connecting Aden to the mainland of Arabia. Figure 1 shows a map of the area.

**General analysis of the observations.**—The monthly mean of wind at a specific hour over the seven-year period is denoted by vector  $\mathbf{V}_m$ . The average of the values of  $\mathbf{V}_m$  for the eight three-hourly observations during each 24 hours is taken as the general monsoon wind for the month and is denoted by  $\mathbf{V}_M$ . The difference  $\mathbf{V}_m - \mathbf{V}_M$  is considered to be a diurnal variation in the wind and is

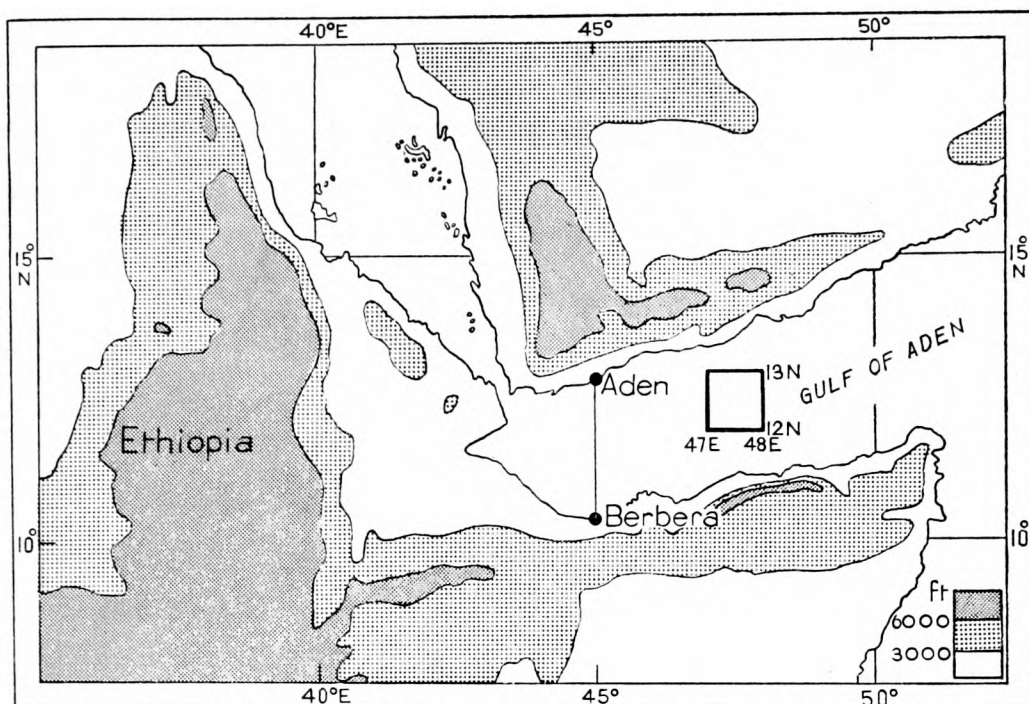


FIGURE 1—MAP OF THE AREA

denoted by  $\mathbf{V}_d$ . If the actual wind is  $\mathbf{V}$  then the difference  $\mathbf{V} - \mathbf{V}_m$  is considered to be a random variation  $\mathbf{V}_R$  produced either locally or from fluctuations in the general circulation by transitory systems of varying sizes.

The surface wind  $\mathbf{V}$  at any time may then be taken to consist of the general monsoon wind for the month, plus a diurnal variation from the mean, plus a random variation component. Thus

$$\mathbf{V} = \mathbf{V}_M + \mathbf{V}_d + \mathbf{V}_R.$$

It is found convenient to resolve the various vectors into components perpendicular to and parallel to the general direction of the coastline of Arabia at Aden, so that

$$\mathbf{V} = u\mathbf{n} + v\mathbf{c}$$

where  $\mathbf{c}$  is a unit vector pointing along the coast ( $065^\circ$  from north),  $\mathbf{n}$  is a unit vector pointing inland and perpendicular to  $\mathbf{c}$ , and  $u, v$  are the magnitudes of the components of  $\mathbf{V}$  in directions of  $\mathbf{n}$  and  $\mathbf{c}$  respectively.

$$\text{Similarly } \mathbf{V}_m = u_m\mathbf{n} + v_m\mathbf{c}$$

$$\mathbf{V}_M = u_M\mathbf{n} + v_M\mathbf{c}$$

$$\mathbf{V}_d = (u_m - u_M)\mathbf{n} + (v_m - v_M)\mathbf{c}$$

$$\mathbf{V}_R = (u - u_m)\mathbf{n} + (v - v_m)\mathbf{c}.$$

**Regular variations of the wind.**—Aden experiences two distinct climatic seasons: (i) that of the south-west monsoon during July and August, and (ii) the remainder of the year when the north-east monsoon predominates,<sup>1</sup> though there are transitional months.

Table I gives for each month the strength and direction of the monsoon winds which are remarkably constant during each of the two monsoon periods. The mean wind  $\mathbf{V}_M$  during the north-east monsoon is  $095^\circ$  6 metres per second, while during the south-west monsoon it is  $225^\circ$  3 metres per second.

TABLE I—MONTHLY MEAN WIND AT ADEN AND THE DIURNAL VARIATION

Diurnal variation ( $V_m - V_M$ ) for varying hours (LMT)																										
Month	Monthly mean wind		0000		0300		0600		0900		1200		1500		1800		2100									
	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec								
Jan.	095	6.0	331	0.9	340	1.1	328	1.3	005	0.9	102	1.3	165	2.3	188	1.5	297	0.3								
Feb.	096	6.1	002	0.9	344	1.1	323	1.4	005	1.0	109	1.2	171	2.6	192	1.6	341	0.5								
Mar.	095	6.2	020	0.8	329	0.9	326	1.3	001	0.6	136	1.1	173	2.7	196	0.9	002	1.1								
Apr.	098	5.3	342	0.9	328	1.3	320	1.5	015	0.4	142	1.7	167	2.8	172	0.8	003	1.3								
May	104	3.4	350	1.1	343	0.9	327	1.7	009	0.5	145	2.2	172	2.9	173	0.7	344	1.4								
June	194	1.5	043	1.8	029	1.0	354	1.5	031	0.4	211	2.7	222	3.8	158	0.7	049	2.6								
July	225	2.7	056	3.2	058	2.4	038	1.2	235	1.2	240	4.7	238	5.2	113	0.5	062	4.1								
Aug.	225	2.7	054	3.3	063	1.8	020	0.6	250	0.5	239	3.8	237	5.1	198	0.4	062	4.2								
Sept.	164	1.5	035	2.0	037	0.9	351	1.3	320	0.3	199	2.2	211	3.4	226	0.8	045	2.5								
Oct.	100	3.6	340	2.2	327	2.1	323	2.8	050	0.8	147	3.5	166	4.1	170	1.3	356	1.6								
Nov.	091	5.2	342	1.6	318	2.4	315	2.4	041	1.2	129	2.4	162	3.3	176	1.7	358	0.6								
Dec.	094	6.0	353	0.8	340	1.3	324	2.0	020	1.5	120	1.4	169	2.7	193	1.8	282	0.1								

There are however striking seasonal changes shown in the tabulations of the diurnal variation ( $V_d$ ). During the north-east monsoon the wind increases and declines daily along an axis perpendicular to the coast, while during the south-west monsoon it increases and declines along an axis parallel to the coast. This is illustrated in Figure 2 which gives  $V_m$  and  $V_d$  for January and July.

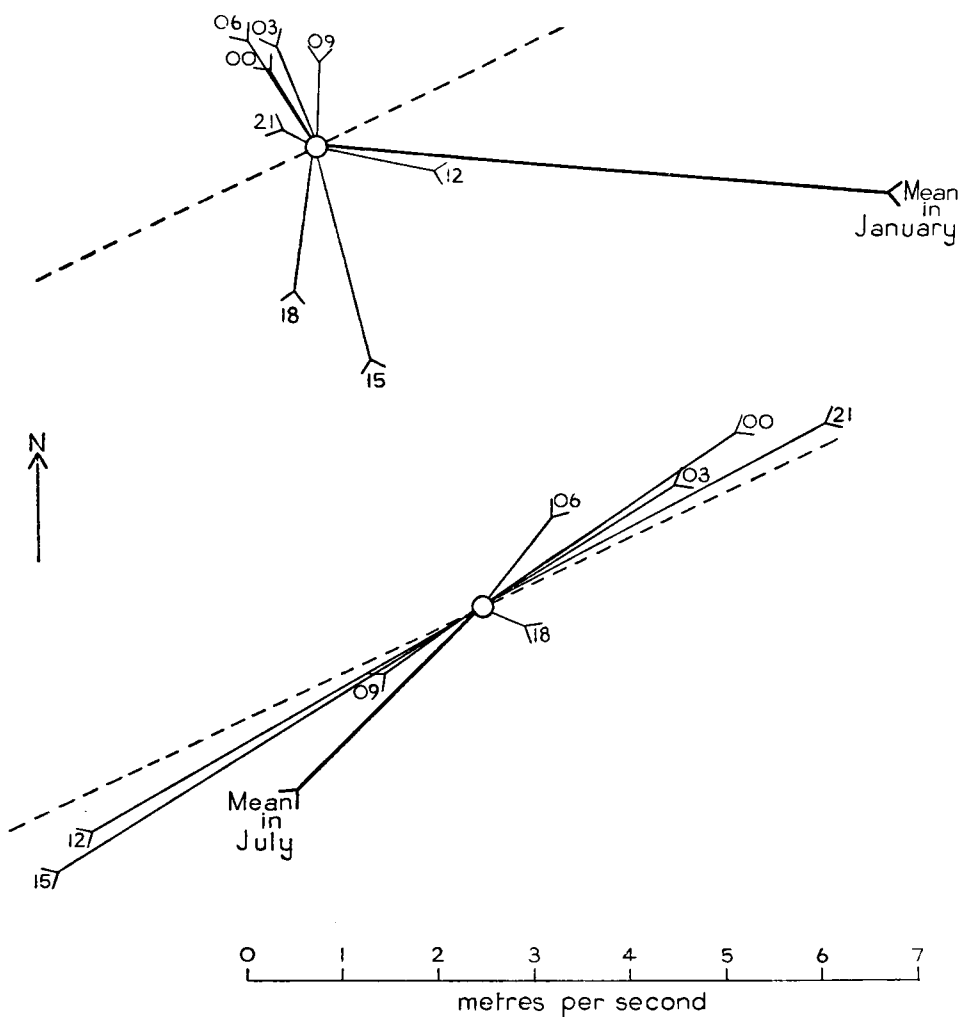


FIGURE 2—DIURNAL VARIATION ( $V_m - V_M$ ) AT ADEN IN JANUARY AND JULY  
 Winds are drawn as vectors measured towards the station position according to the scale shown. Times of observations (LMT) are entered in the arrow tail.  
 --- Coastline, ——— monthly mean wind, ——— diurnal difference from the mean.

The character of these changes is revealed more clearly by the variation in the onshore and coastwise components of  $V_d$ . The variation of the onshore component during the day and night has the character of a sea and land breeze and varies with the inland atmospheric surface temperature, with a minimum towards dawn. Figure 3 shows the onshore component in January. Secondary maxima and minima appear frequently after midnight (local time) during the months of the north-east monsoon when the diurnal variation of either component is sufficiently small.

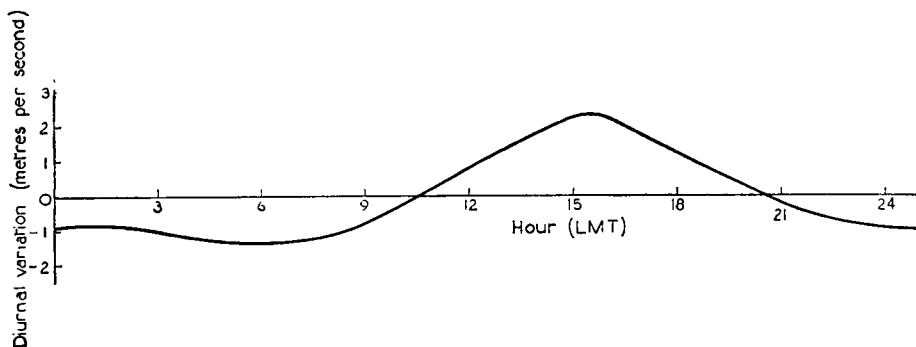


FIGURE 3—ONSHORE COMPONENT ( $u_m - u_M$ ) OF THE DIURNAL VARIATION AT ADEN IN JULY

During the north-east monsoon the amplitude of the mainly onshore variation of  $V_d$  increases with the mean daily maximum temperature, but during July and August—the months of the south-west monsoon—the predominance of the sea-breeze cycle is replaced by a mainly coastwise variation. The coastwise component ( $v_m - v_M$ ) of the diurnal variation in July at Aden is included in Figure 5. During July and August the coastwise component reaches its maximum from the south-west between 1200 and 1500 Local Mean Time (LMT) but its minimum is towards 2100 LMT many hours earlier than dawn which is the time of minimum temperature inland.

**Harmonic analysis of the components of diurnal variation ( $V_d$ ).**—The components of the diurnal variation may each be represented by first and second harmonic terms (the diurnal and semi-diurnal terms) in the form:

$$A_1 \cos \frac{\pi}{12} (h - T_{m1}) + A_2 \cos \frac{\pi}{6} (h - T_{m2})$$

where  $h$  is the hour of observation in Local Mean Time; and amplitude  $A_1$  and time of maximum  $T_{m1}$  refer to the diurnal term while  $A_2$  and  $T_{m2}$  refer to the semi-diurnal term.

TABLE II—HARMONIC COMPONENTS OF THE DIURNAL VARIATION AT ADEN

Month	Onshore				Coastwise			
	First harmonic	Second harmonic	First harmonic	Second harmonic	First harmonic	Second harmonic	First harmonic	Second harmonic
	Amplitude m/sec Time of maximum LMT	Amplitude m/sec Time of maximum LMT	Amplitude m/sec Time of maximum LMT	Amplitude m/sec Time of maximum LMT	Amplitude m/sec Time of maximum LMT	Amplitude m/sec Time of maximum LMT	Amplitude m/sec Time of maximum LMT	Amplitude m/sec Time of maximum LMT
Jan.	1.60	15.8	0.55	3.1	0.47	20.6	0.52	5.4
Feb.	1.67	15.7	0.69	2.9	0.41	18.3	0.68	5.2
Mar.	1.50	14.9	0.81	2.4	0.29*	14.7	0.61	4.6
Apr.	1.86	14.5	0.82	2.1	0.07*	9.7	0.49	4.1
May	1.93	14.2	1.08	2.0	0.21*	15.5	0.41	4.4
June	1.29	14.6	0.60	1.6	2.19	12.9	1.42	2.6
July	0.57	14.2	0.08*	2.5	4.25	12.5	1.59	2.1
Aug.	0.49	14.3	0.22	3.3	3.82	12.6	1.74	2.8
Sept.	1.30	15.2	1.11	2.3	1.96	13.0	1.10	3.3
Oct.	3.30	14.3	1.12	1.8	0.06*	19.8	0.71	4.2
Nov.	2.73	15.0	0.62	2.0	0.42	23.7	0.91	4.6
Dec.	1.98	16.0	0.65	2.2	0.57	19.5	0.73	5.0

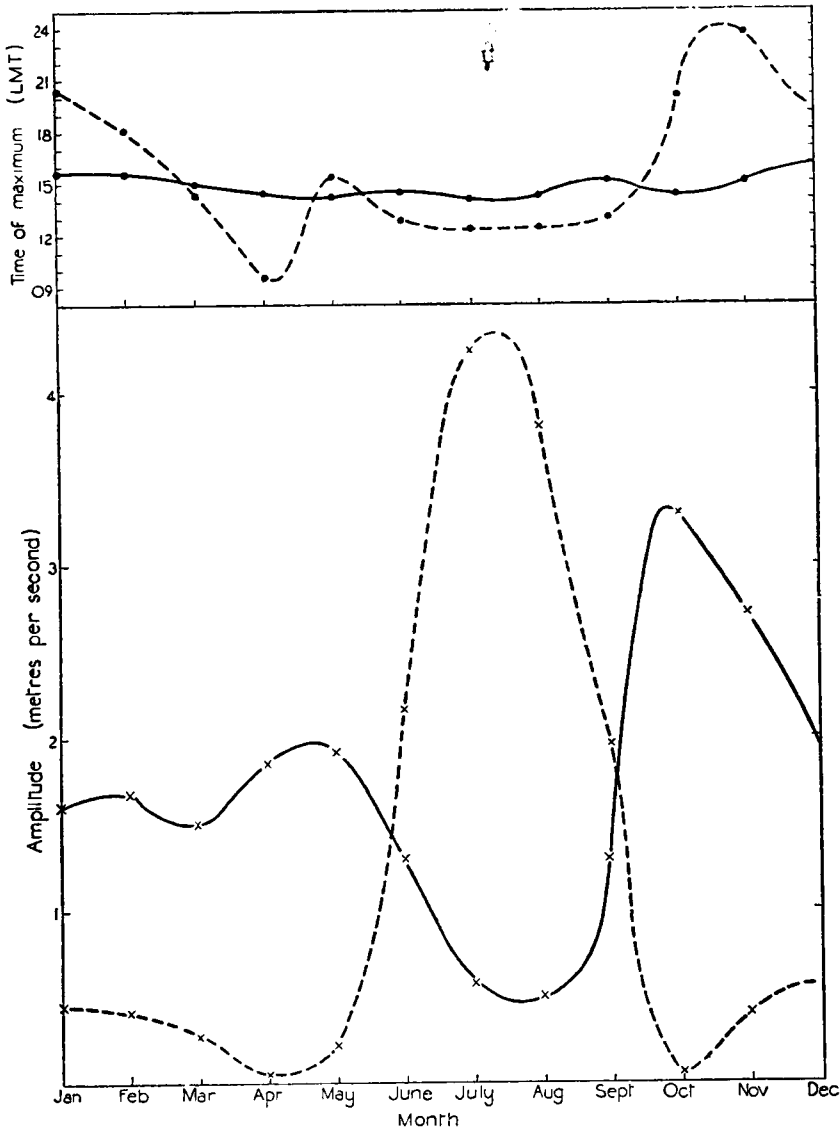
\*Not statistically significant

Table II gives the amplitudes and times of maxima for the diurnal and semi-diurnal terms of the onshore and coastwise components of the diurnal



variation ( $V_d$ ). All these amplitudes are significant according to the criterion for significance used by Brooks and Carruthers,<sup>2</sup> but some are found to be not significant when the more stringent criterion of Chapman and Bartels<sup>3</sup> is applied. Amplitudes that do not meet this criterion are marked by an asterisk. (The criterion of Chapman and Bartels allows for the increased probability of accidental harmonic terms when consecutive observations are not statistically independent, and makes use of the concept of the equivalent number of independent days. This concept is considered more fully later since like most climatic statistics it has a physical significance.)

The seasonal variation of amplitude, and of the time of maxima of the first harmonic terms of the diurnal variations from the mean are illustrated in Figure 4. They suggest that there are three distinct daily variations in the wind.



**FIGURE 4—SEASONAL CHANGE IN AMPLITUDE AND TIME OF MAXIMUM OF THE FIRST HARMONIC OF THE DIURNAL VARIATION AT ADEN**  
 .——. Time of maximum of onshore component, - - - time of maximum of coastwise component.  
 x——x Amplitude of onshore component, x- - -x amplitude of coastwise component.

- (i) During the north-east monsoon, a diurnal oscillation of the component normal to the coast predominates. The time of maximum is approximately that of the maximum surface temperature inland apart from there being a small seasonal variation from just after 1400 LMT in the warmest month to 1600 LMT in the coolest.
- (ii) During July and August there is a mainly coastwise variation with amplitude about twice the magnitude of the mean rate of flow ( $V_M$ ) with a constant time of maximum of about 1230 LMT two hours earlier than that of the thermal maximum inland.
- (iii) During the north-east monsoon a weak daily coastwise oscillation occurs simultaneously with the predominating oscillation but disappears when the latter is at its strongest. The most striking characteristic of the coastwise oscillation is a large seasonal variation in the time of maximum which gets steadily earlier, from 0000 LMT in November to 1000 LMT in April. It then gets later but is suddenly interrupted by the strong oscillation described at (ii) above with its constant time of maximum.

Oscillation (i) is probably the normal sea breeze flowing almost perpendicular to the coast, as the geostrophic term in the wind equation at this latitude is small. The weak coastwise oscillation under (iii) above appears to be closely associated with the sea breeze. In the warmest month its time of maximum (i.e. time of weakest easterly flow) is consistent with the flow of the north-easterlies being diverted from the Gulf towards the hot interior of Arabia crossing the coast east of Aden, where the mountains are lower (see Figure 1). During the coldest months the time of maximum at midnight is consistent with a minimum in the hottest part of the day when there is a strong easterly wind towards Africa.

Oscillation (ii) above appears to be a daily variation in the south-west monsoon accentuated by the topography of the Gulf of Aden. Its time of maximum is in phase with the thermal maximum at 30 to 40°E, i.e. over northern India. (There is also a strong semi-diurnal term which produces the minimum between 1800 and 2100 LMT. See Figure 5.)

To find out whether there is a general diurnal variation in the surface atmospheric flow towards India during the south-west monsoon, the diurnal variation of the rate of flow in the direction of mean flow is derived for Habbaniya, for a 1° sea square in the Gulf of Aden and for a 5° sea square in the Arabian Sea for July and August and for January (for comparison). The results are set out in Table III which also gives details of any regular daily variation perpendicular to the direction of the mean flow (again for comparison). During July and August there is a maximum flow in the south-west monsoon at all these places within half an hour of 9.3 hours GMT. The greatest amplitudes occur at Aden, over the Gulf of Aden and at Habbaniya where the flow is concentrated by wide valleys between blocks of mountains. Southwards over the Arabian Sea towards the subtropical high the daily cycle is much less strong. However in general there is evidence of a daily fluctuation in the south-west monsoon which could be responsible for the coastwise fluctuation of the wind at Aden in July and August.

**Second harmonics or semi-diurnal terms of the daily variation.**—The amplitudes of the second harmonics vary as those of the first. However they never fall below a half a metre per second even when for example the

TABLE III—AMPLITUDE AND TIME OF MAXIMUM OF THE FIRST HARMONICS OF THE COMPONENTS OF THE DIURNAL VARIATION

Place	Month	Mean flow		First Harmonic		Period	Number of observations used
		deg	m/sec	Parallel to mean flow Amplitude m/sec	*Perpendicular to mean flow Time of maximum GMT		
Aden (12°50'N, 45°01'E)	July	225	2.7	4.26	9.5	1949-55	8 per day
	August	225	2.7	3.82	9.6	1949-55	8 per day
	January	095	6.0	0.47	17.6	1949-55	8 per day
Habbaniya (33°22'N, 43°34'E)	July	313	4.0	1.90	8.9	1949-56	8 per day
	August	316	3.2	1.69	9.4	1949-56	8 per day
	January	288	0.5	0.68	8.5	1949-56	8 per day
1-degree sea square in the Gulf of Aden (12-13°N, 47-48°E)	July	233	4.7	2.40	9.3	1945-59	562
	August						
	January	077	4.7	0.20	16.4	1945-59	278
5-degree sea square in the Arabian Sea (10-15°N, 60-65°E)	July	229	11.0	0.38	9.8	1945-59	669
	August	229	9.2	0.53	9.1	1945-59	607
	January	034	5.4	0.43	9.7	1945-59	609
Berbera (10°27'N, 45°02'E)	July	216	7.1	3.96	5.2	1931-32	24 per day
	August	229	5.2	4.19	4.9	1931-32	24 per day
	January	044	2.9	2.77	3.5	1932-33	24 per day

\* Onshore components for Aden and Berbera, otherwise 90° anticlockwise from mean flow.

first harmonic of the coastwise variation is zero. This is probably due to the presence of the semi-diurnal atmospheric tide which according to atmospheric pressure observations is very strong at this latitude. Theory suggests<sup>4</sup> that the coastwise semi-diurnal tidal oscillation should be 3 hours ahead of the onshore oscillation but there is no simple relation between the time of maximum of pressure and that of either of the wind components. Table II shows that during the north-east monsoon the second harmonic of the coastwise wind oscillation is 2 to 3 hours ahead of the onshore wind oscillation. However, there is a seasonal variation in both the time of maximum wind and its amplitude which follows those of the first harmonics, consistent with the supposition that the semi-diurnal terms during the north-east monsoon are a combination of atmospheric tide and the second harmonics of the daily variation from the mean. There is however no evidence of the atmospheric tide during the south-west monsoon.

**Abnormal diurnal variation of wind at Berbera.**—Table III shows that at Berbera, due south of Aden on the opposite side of the Gulf, mean winds are consistent with the north-east monsoon and south-west monsoon when they predominate but the diurnal variation  $V_d$  differs from that at all other locations in having a very large onshore and coastwise variation of wind, probably caused by convergence towards the large areas of intense rain over mountains to the east, south and west of Berbera, particularly over Ethiopia in July and August. During these months Figure 5 shows that there is a minimum in the coastwise flow<sup>5</sup> just before 1900 LMT probably associated with rain

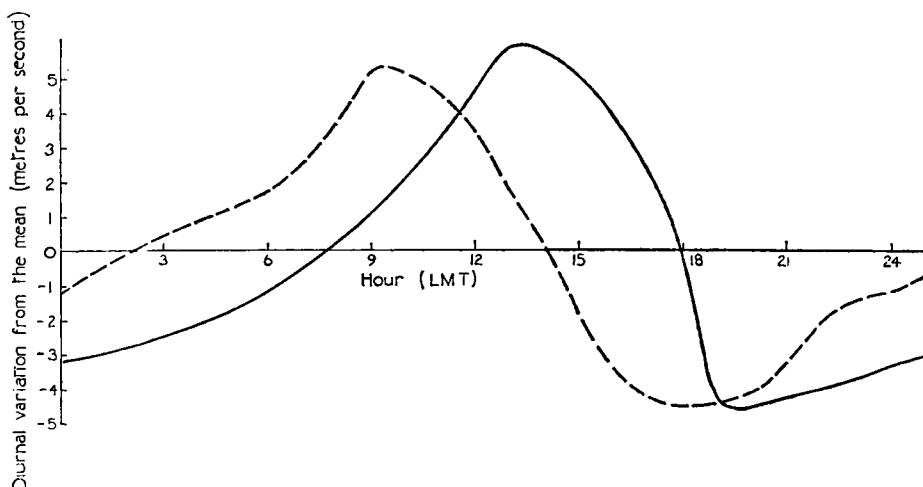


FIGURE 5—COASTWISE COMPONENT ( $v_m - v_M$ ) OF THE DIURNAL VARIATION IN JULY AT ADEN AND BERBERA  
 — Aden, - - Berbera.

areas over Ethiopia to the west. This compares with a similar sharp minimum experienced just before 2000 LMT at the same time of the year at Aden. It is therefore probable that the large coastwise variation in wind at Aden during July and August is caused not only by a daily maximum in the flow of the south-west monsoon towards 1230 LMT but also to a weakening of the flow due

to the Ethiopian rains towards 1900 LMT. This is confirmed by the great magnitude at this time of the variance of the coastwise random fluctuation described below (see Figure 6), and more directly by the relatively low mean wind  $\mathbf{V}_M$  in July and August (see Table I).

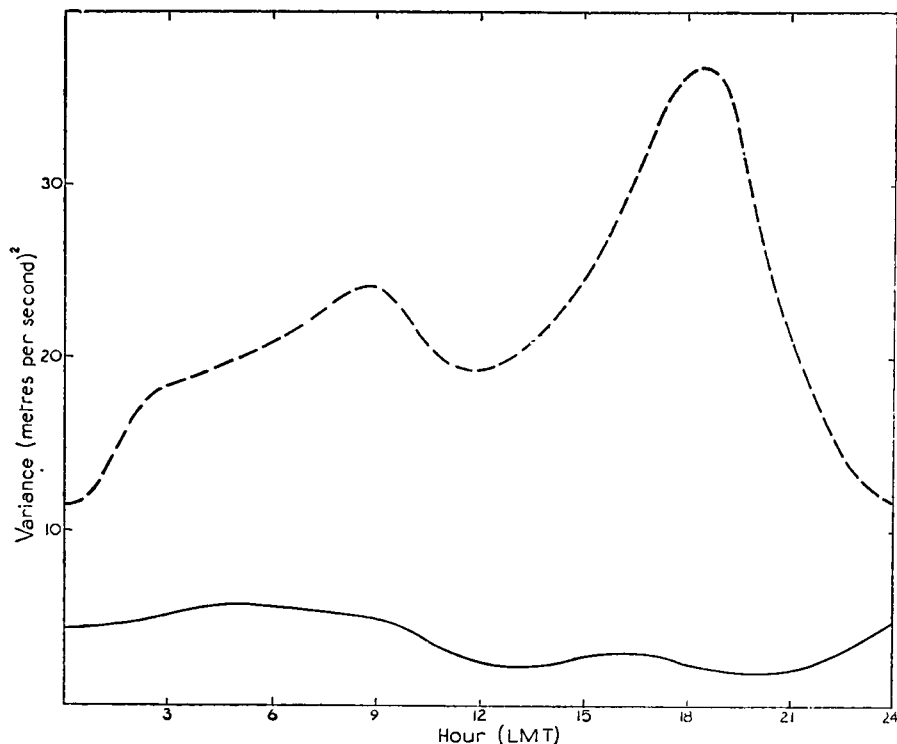


FIGURE 6—VARIANCE OF THE RANDOM FLUCTUATIONS AT ADEN

— Onshore component in January, - - - coastwise component in July.

**Random fluctuations of the wind at Aden.**—This section considers the random difference of the observed wind from the monthly mean of wind at that hour i.e.  $\mathbf{V}-\mathbf{V}_m$ , and considers the magnitude of the onshore and coastwise components  $u-u_m$  and  $v-v_m$ . The variance ( $\sigma_n^2$ ) of the onshore components is proportional to the energy of the onshore component of the random difference. Thus

$$\sigma_n^2 = \Sigma \frac{(u - u_m)^2}{N}$$

where  $N$  is the number of observations and similarly, for the coastwise components

$$\sigma_c^2 = \Sigma \frac{(v - v_m)^2}{N} .$$

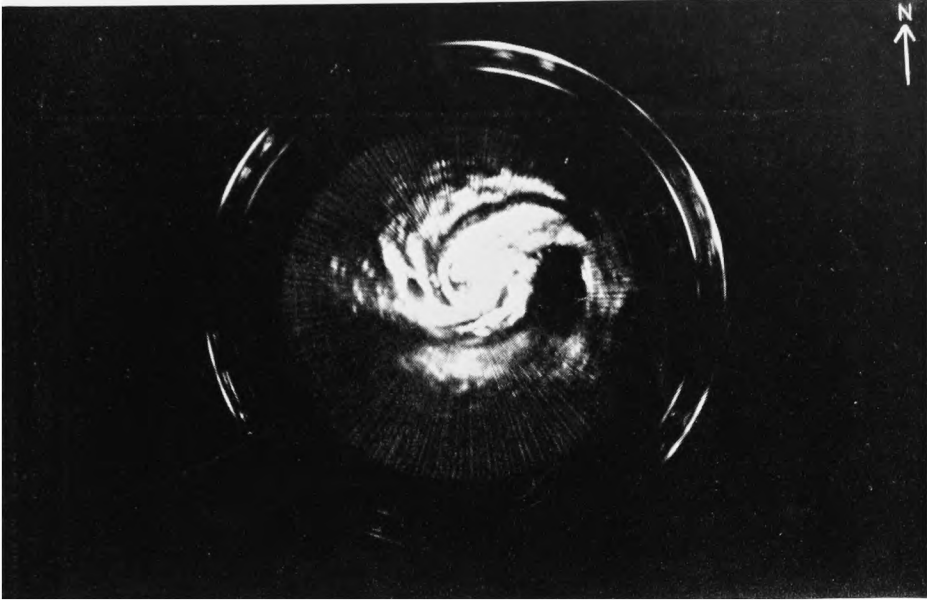
The correlation  $r_{nc}$  between the onshore and coastwise components is tabulated in Table IV along with the variance for each hour of observation.

For many hours of the day the components are statistically almost independent, but at times there is a high correlation suggesting physical association. Finally the equivalent number of independent days is used as a simple measure of the duration in time of the predominating fluctuations. Variations are from day to day and do not include microclimatic fluctuations over a few hours or

TABLE IV—VARIANCE OF AND CORRELATION BETWEEN COASTWISE AND ONSHORE RANDOM FLUCTUATIONS OF THE WIND AT ADEN,  
WITH THE EQUIVALENT NUMBER OF INDEPENDENT DAYS PER MONTH

	Local Mean Time												Number of independent days per month													
	0000			0300			0600			0900			1200			1500			1800			2100			Onshore component 13	Coastwise component 8
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C			
Jan.	4.5	6.7-0.5	5.2	9.1-0.7	5.7	8.1	-0.7	5.0	7.0-0.4	2.5	7.3	-0.1	2.7	6.2+0.3	2.3	4.8+0.1	1.9	5.7-0.2								
Feb.	4.1	6.2-0.5	4.3	7.1-0.6	6.5	7.9	-0.6	4.3	6.7-0.4	2.4	5.6	-0.1	2.7	4.6+0.3	2.1	4.5+0.3	2.4	5.0-0.3								
Mar.	3.5	8.1-0.5	3.7	7.8-0.6	5.3	8.3	-0.7	3.5	7.5-0.3	3.3	7.7+0.1	3.6	8.0+0.3	2.2	6.6	0.0	2.9	5.9-0.2								
Apr.	3.3	6.7-0.4	2.0	7.3-0.3	4.5	7.7	-0.7	2.3	8.9-0.5	3.8	6.4+0.2	2.8	5.7+0.1	2.3	5.5	-0.1	2.6	5.4-0.1	19						11	
May	2.7	6.1-0.5	5.2	7.1-0.4	5.1	6.3	-0.5	2.9	11.5-0.5	3.7	14.0	-0.5	4.3	14.9	-0.4	3.2	11.6	-0.4	1.8	5.0-0.4						
June	2.5	4.3-0.3	4.7	10.0-0.1	4.9	13.9+0.1	3.0	21.9-0.3	7.0	23.9	-0.8	7.7	21.5	-0.8	4.3	16.2	-0.5	2.9	5.8-0.3							
July	4.4	11.8-0.2	4.5	18.4-0.2	3.4	20.9	0.0	3.2	24.1-0.3	2.8	19.5	-0.6	3.3	24.5	-0.5	10.5	36.5	-0.2	4.8	21.3	0.0				16	10
Aug.	4.0	10.9-0.1	3.7	13.7-0.1	3.2	21.0	0.0	2.9	23.6-0.2	6.0	26.5	-0.6	3.8	23.0	-0.6	10.7	32.4	-0.2	4.4	11.5	-0.2					
Sept.	2.5	8.6-0.3	4.4	11.3-0.4	5.4	11.8	-0.2	4.5	21.4-0.4	7.3	30.0	-0.7	8.1	28.9	-0.8	6.6	20.4	-0.3	2.7	6.8-0.3						
Oct.	4.4	5.8-0.6	4.1	6.9-0.4	5.3	7.1	-0.5	3.6	8.4-0.2	3.3	7.3+0.3	4.2	8.1	-0.2	2.8	6.2	-0.1	2.8	5.8-0.4	20					21	
Nov.	7.7	7.7-0.7	8.2	9.5-0.7	7.6	9.1	-0.7	3.8	5.7-0.4	2.6	5.6+0.4	2.8	6.0+0.3	1.9	4.5+0.1	3.1	4.6-0.5									
Dec.	4.9	6.8-0.5	6.6	7.4-0.6	7.5	6.9	-0.6	4.5	5.7-0.2	3.5	5.9+0.2	2.9	4.5+0.2	2.2	4.5+0.1	1.7	4.9-0.4									

A =  $\sigma_n^2$  in (metres per second)<sup>2</sup>, B =  $\sigma_e^2$ , C =  $r_{nc}$ .



*Photograph by R. H. Brass*

PLATE I—PHOTOGRAPH OF THE PPI RADAR DISPLAY TAKEN ON BOARD THE  
WEATHER REPORTER AT 1100 GMT ON 14 OCTOBER 1963

The radius of the display is 75 nautical miles with range markers every 10 nautical miles,  
(See page 90).



*Photograph by M. G. Habberley*

PLATE II—CLOUD FORMING OVER THE COASTLINE BETWEEN SALALAH AND CAPE  
FARTAK ON THE SOUTH-EAST ARABIAN COAST ABOUT 1600 LOCAL MEAN TIME  
ON 23 SEPTEMBER 1963

Surface winds were light at the time and this cloud was the result of the local sea breeze.



*Photograph by G. J. Jefferson*

PLATE III—CLOUD FORMATION ASSOCIATED WITH A JET STREAM AT 1820 GMT ON

22 JUNE 1963

The photograph was taken looking towards a direction of 220 degrees (see p. 91).



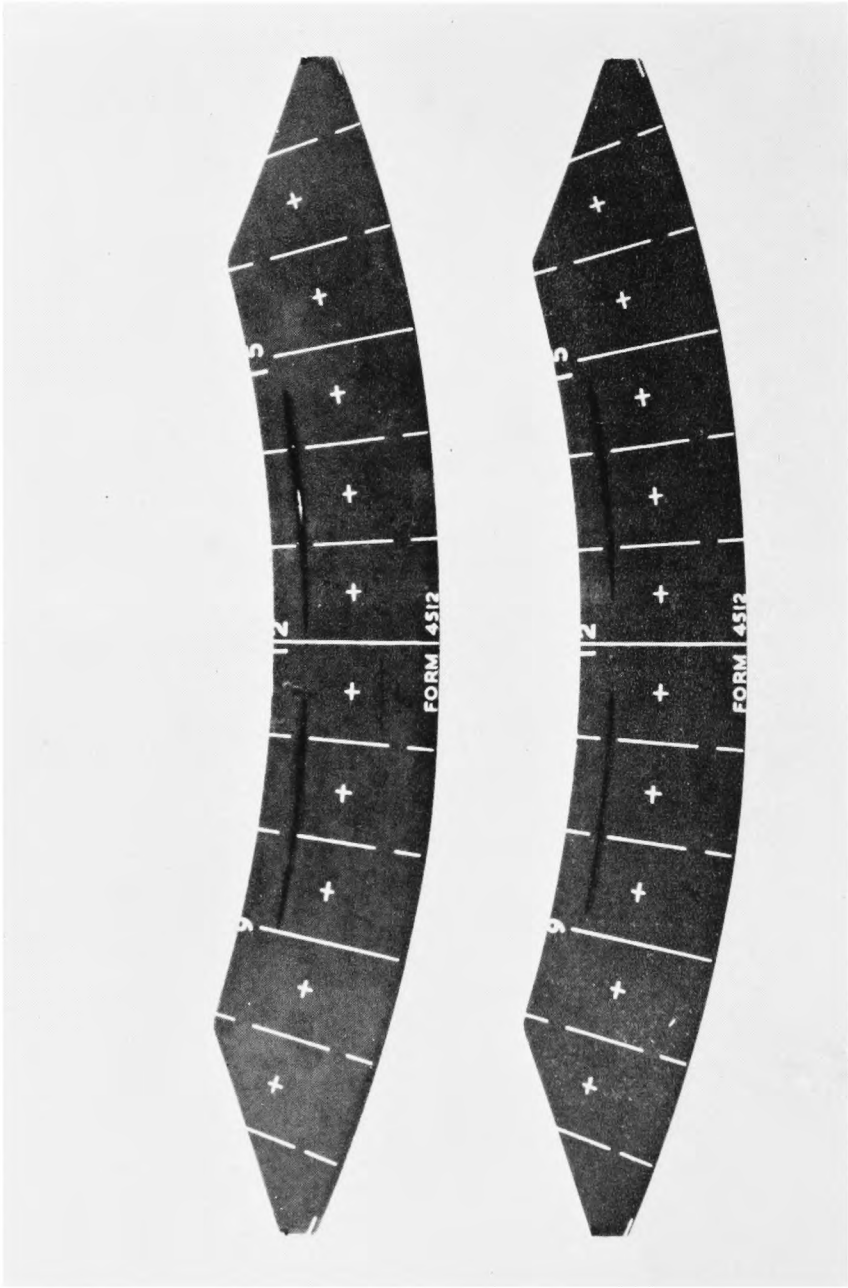


*Photograph by G. J. Jefferson*

PLATE IV—CLOUD FORMATION ASSOCIATED WITH A JET STREAM AT 1820 GMT ON

22 JUNE 1963

The photograph was taken looking towards a direction of 270 degrees (see p. 92).



*Crown copyright*

PLATE V—SUNSHINE CARDS FOR 10 JANUARY 1963  
Manchester Weather Centre above, Manchester College of Science and Technology below,  
(see page 91).

less. For non-overlapping samples of  $N$  consecutive observations at a fixed hour with a standard deviation of  $\sigma$ , the standard deviation  $\sigma_a$  of the averages of the samples is

$$\sigma_a = \sigma / \sqrt{N_1} ,$$

where  $N_1$  is the number of independent observations equivalent to the  $N$  actual observations.

If all consecutive observations are independent then  $N = N_1$  but if fluctuations tend to persist longer than a day then  $N_1 < N$ . The greater the duration of the predominating fluctuations the smaller will be  $N_1$ . In the present work samples contain the observations at a fixed hour for all days of the month, and from the samples the equivalent number of independent days per month is derived. Since the number of years is small, a mean is taken of values derived from four observational hours.

At the surface the air tends to flow mainly along the Gulf of Aden (Figure 1) rather than up over the mountain rim. This is confirmed not only by the direction of the mean wind but also by the upper air wet-bulb and dry-bulb temperatures below 20,000 feet which exhibit subsidence (anticyclonic subsidence during the north-east monsoon and orographic subsidence during the south-west monsoon). Any extensive atmospheric exchanges over the mountain rim north and south of the Gulf would need forces sufficient to overcome the high stability of the atmosphere. Large-scale fluctuations of the monsoon winds are therefore more likely to affect coastwise flow along the Gulf than onshore flow. Transient fluctuations produced by local variations on the scale of land and sea breezes would however affect both coastwise and onshore components of the random fluctuation ( $\mathbf{V}_R$ ).

Thus in Table IV the energy of the coastwise component of random fluctuation, represented by the variance ( $\sigma_c^2$ ), is frequently almost twice as great as that for the onshore component. In addition, the duration of coastwise fluctuation is greater because the equivalent number of independent days per month is about half the number for onshore fluctuations (except in October). Finally there is high negative correlation between coastwise and onshore fluctuations at night during the north-east monsoon particularly towards dawn, but during the day in the south-west monsoon. Abnormally strong nocturnal winds are thus associated with a weak north-east monsoon, and strong sea breezes with a weak south-west monsoon. In contrast, sea breezes during the north-east monsoon and nocturnal winds during the south-west monsoon are statistically less associated with and at times independent of the strength of the monsoon winds.

In the late afternoon and evening during the south-west monsoon when the random fluctuations are exceptionally high, there is low correlation between onshore and coastwise fluctuations. This low correlation suggests that it is unlikely that the random fluctuations are produced by local sea-breeze effects. Figure 6 shows the daily variation of the variance of the coastwise component of the random fluctuation in July. The maximum occurs about the time of the minima of the coastwise component of the diurnal variation ( $\mathbf{V}_d$ ) at Berbera and Aden in July (Figure 5), i.e. at the time of weakening in the general south-west monsoon wind. The random fluctuation is therefore not of local origin but may be linked with a large-scale feature such as the formation of

storm centres over Ethiopia. For comparison the variance of the onshore component in January is also shown in Figure 6 and shows the relative steadiness of the wind in January and the low energy of any random fluctuation.

**Conclusions.**—The periodic variation of wind at Aden is controlled largely by climatic systems on a continental scale like the Indian south-west monsoon, the north-east monsoon, and the rains of East Africa. Flow associated with these is constrained by topography to flow along the Gulf of Aden. Periodic fluctuations from systems on the scale of sea breezes are also experienced causing variations normal to the coastline. It is also apparent that the climatic controls that cause the periodic variations also closely control the magnitude and duration of random fluctuations of wind.

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551.515.4:551.553.11:551.558.1

## THE SEA BREEZE AND INLAND CONVECTION—AN EXAMPLE OF THEIR INTERRELATION

By J. FINDLATER

**Introduction.**—Cumulus and cumulonimbus often appear to develop at random overland in unstable airstreams. This analysis however shows an example of convective storms which developed in association with meso-scale features readily identifiable some hours before the first development of showers and thunderstorms. Some detailed observations in a sea-breeze convergence zone are described also.

**Analysis of surface charts.**—The synoptic chart for 0600 GMT on 12 June 1963 revealed a light westerly airstream over most of England with a minor trough just discernible in the isobars from the Wash to Hampshire. On the 0900 GMT chart isobars drawn at half-millibar intervals showed consistent distortions near the trough. The whole of southern, central and eastern England was free of low and medium cloud but large amounts of thin cirrus lay over the western half of the country in association with a slow-moving occlusion which was orientated north to south over the Irish Sea. Sea fog in the English Channel affected the southernmost parts of the south coast but strong surface heating and generally light winds precluded any advance inland.

Surface winds reported at 0900 GMT were mostly of about 5 knots from variable directions. A streamline analysis of the surface wind field revealed two well marked convergence zones, one associated with the weak isobaric trough and the other with the onset of the sea breeze from the south coast over parts of West Sussex. Figure 1(a) shows these features as they appeared at 0900 GMT. Subsequent hourly charts were also analysed by streamlines for convergence zones and the amount of convection cloud, and a selection of the resulting analyses is shown in Figures 1(b)–(d).\*

\*Errata—in Figures 1, 2 and 3, 50°N should read 51°N.

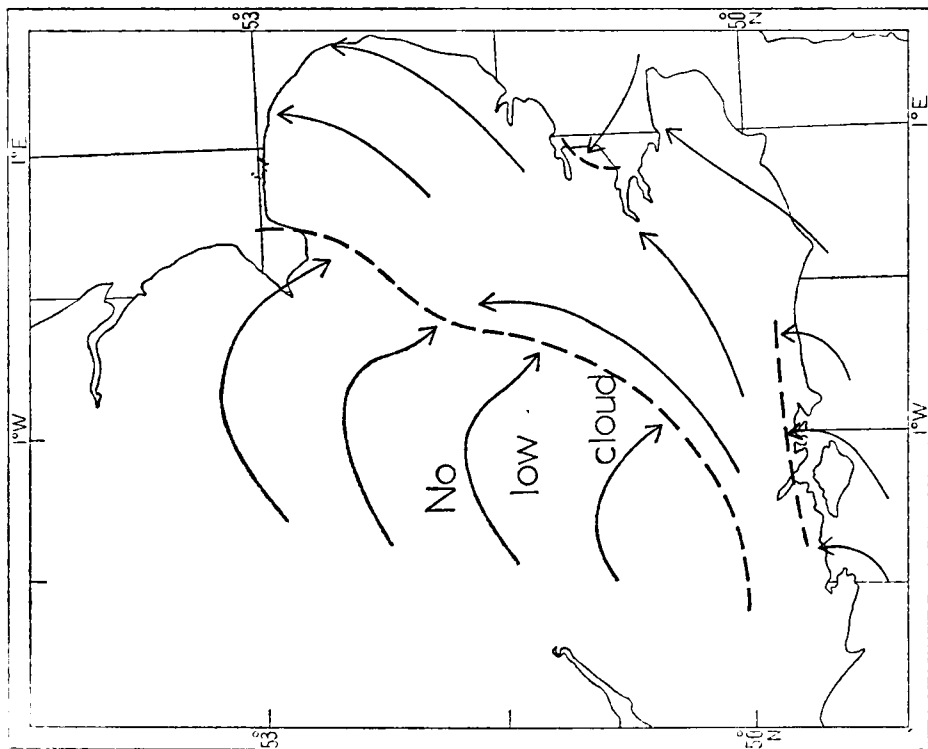


FIGURE 1 (a)—STREAMLINES AND CONVERGENCE ZONES

AT 0900 GMT, 12 JUNE 1963

Arrowed lines are streamlines, — — — convergence zones.

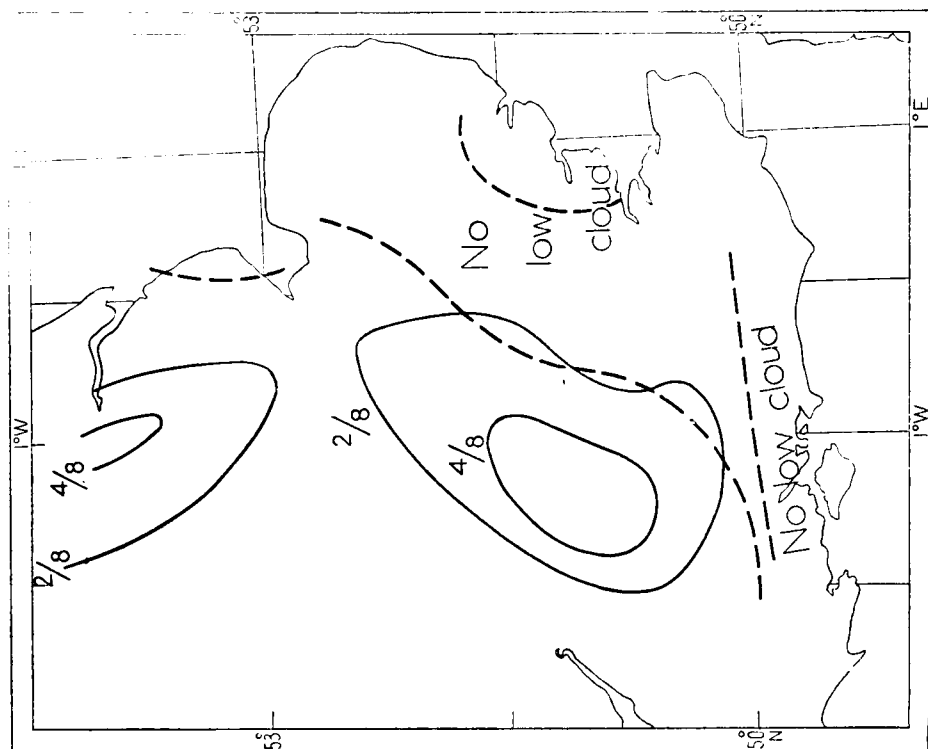


FIGURE 1 (b)—CONVERGENCE ZONES AND AMOUNTS OF

CUMULUS AT 1100 GMT, 12 JUNE 1963

— — — Convergence zones, ——— isopleths of cloud amount.

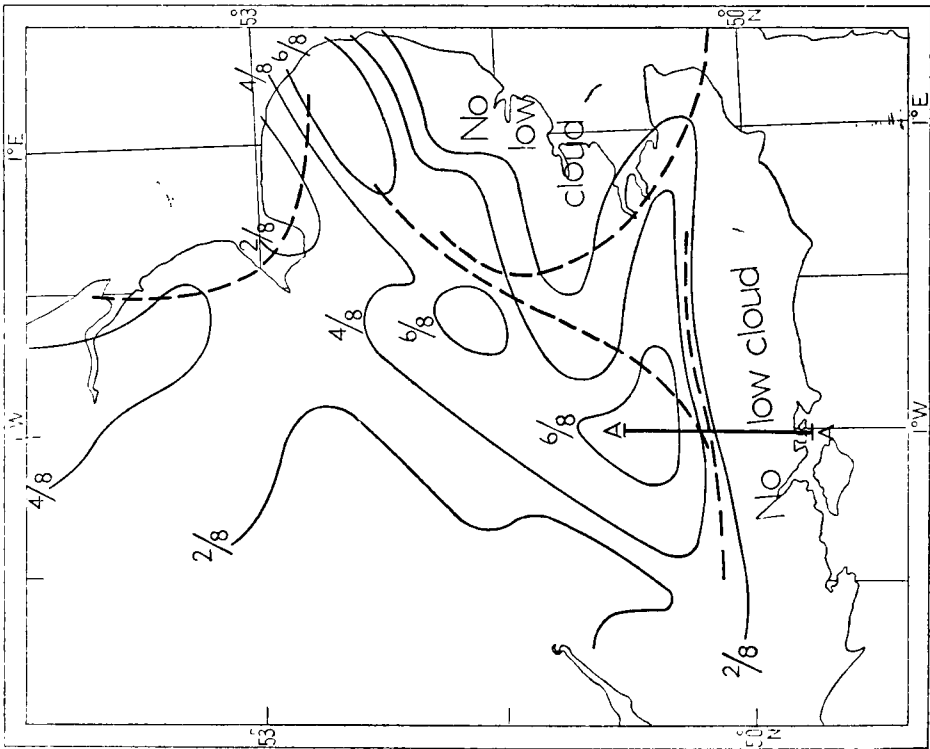


FIGURE 1(c)—CONVERGENCE ZONES AND AMOUNTS OF CUMULUS AT 1300 GMT, 12 JUNE 1963  
 --- Convergence zones, ---- isopleths of cloud amount.  
 A—A is the line of cross-section shown in Figure 4.

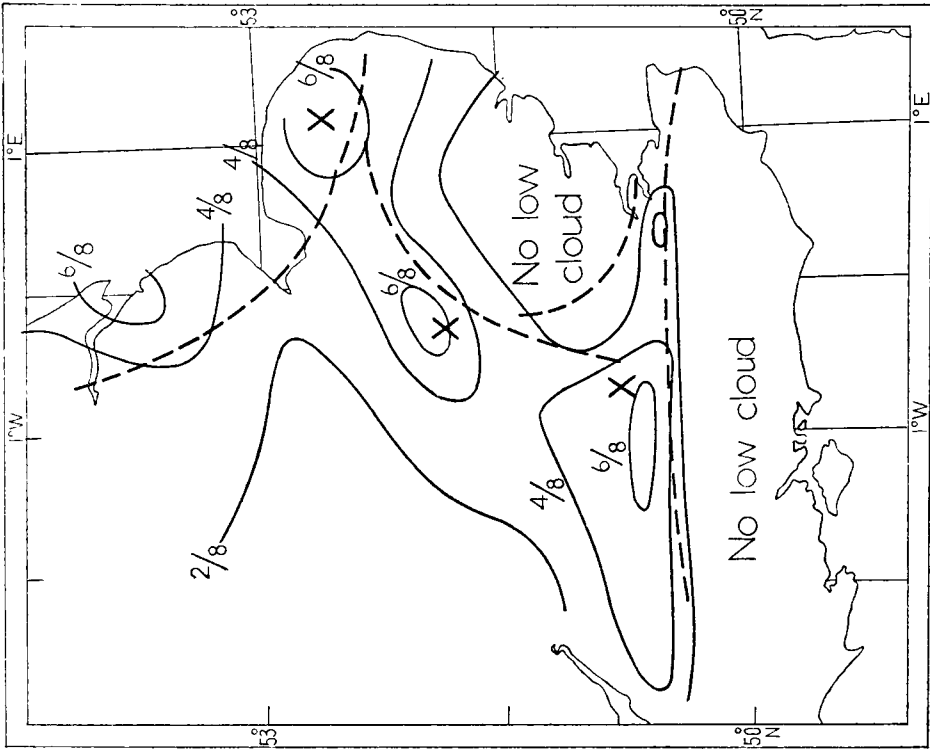


FIGURE 1(d)—CONVERGENCE ZONES AND AMOUNTS OF CUMULUS AND CUMULONIMBUS AT 1500 GMT, 12 JUNE 1963  
 --- Convergence zones, ---- isopleths of cloud amount.  
 X Positions at which thunderstorms occurred at 1400 GMT.

Cumulus formed by 1000 GMT and by 1100 two distinct convection systems had become established, both of them just to the west of the main convergence zone. One centre of activity lay near Oxford and the other near Doncaster. At 1200 GMT the southernmost cloud system began extending quickly eastwards to the south of the Thames valley as sea breezes formed convergence zones which moved inland from the south coast of Hampshire and Sussex, and from the north coast of Kent. A sea breeze had also become established on the coast of Lincolnshire, parts of south Yorkshire, and most probably on the north coast of Norfolk. Figure 2 shows the pattern of isobars, streamlines and convergence zones at 1200 GMT. On this chart the relation between the surface-wind

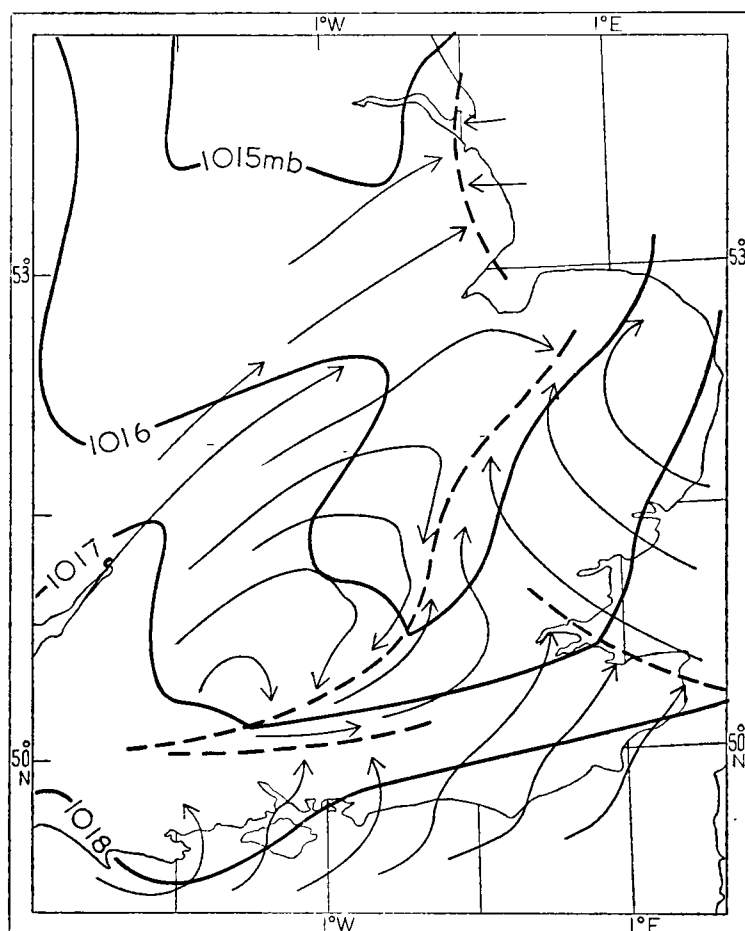


FIGURE 2—ANALYSIS OF SURFACE-WIND STREAMLINES AND ISOBARS AT 1200 GMT,  
12 JUNE 1963

--- Convergence zones, — isobars. Arrowed lines are streamlines.

streamlines and the isobars is of particular interest over Essex and Suffolk, and also just to the north of the convergence zone west of London. At this time also a new centre of convective activity appeared over central Norfolk—at about the same time as the sea breeze would be becoming established on the north coast of Norfolk. By 1300 GMT maximum amounts of cumulus (or cumulonimbus) south of the Wash had become organized into three areas; these were near Farnborough, Cranfield and Thetford, and one hour later thunderstorms were reported from these areas (see Figure 1(d)).

It is noteworthy that in each of the three areas where convection led to thunderstorms a convergence zone due to a sea breeze closely approached the pre-existing convergence zone located on charts earlier in the day. In another area near the North Downs, where convergence zones associated with the south coast and the Thames estuary sea breezes approached each other, an isolated area of large cumulus developed at 1600 GMT. Six oktas of large cumulus were reported from Gravesend and subsequently a thunderstorm moving north affected Stansted between 1700 and 1800 GMT. During the next few hours the storms drifted northwards leaving in their wake skies clear of low cloud.

Figure 3 shows the positions of the various convergence zones at two-hourly intervals from 0900 GMT and the location of the four storm areas which developed by 1600–1700 GMT.

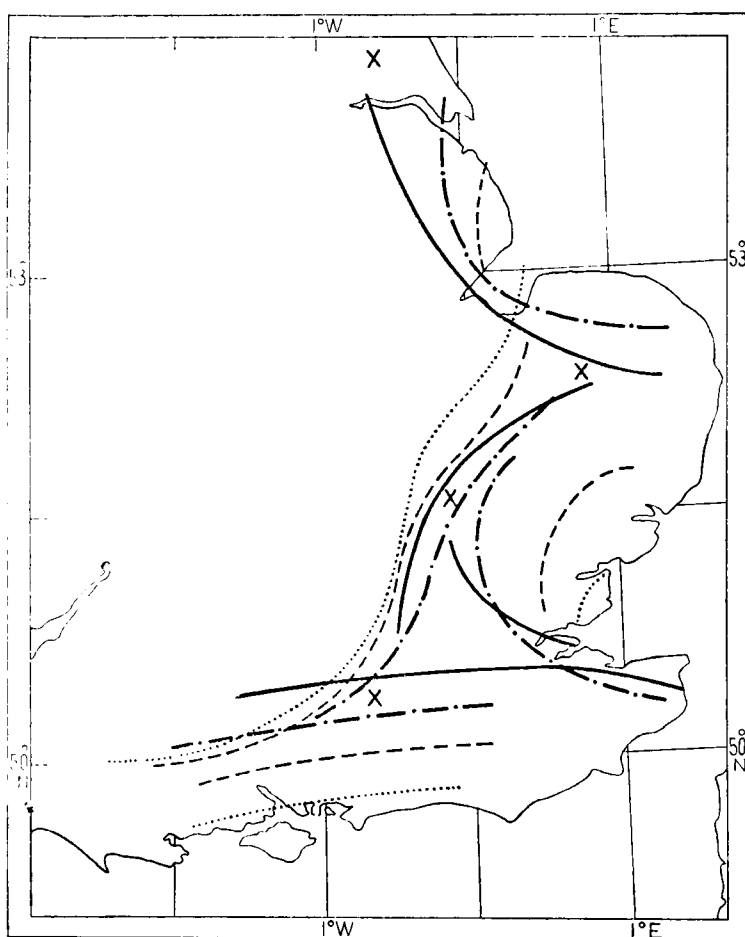


FIGURE 3—SUCCESSIVE POSITIONS OF CONVERGENCE ZONES, 12 JUNE 1963  
 .... 0900, - - - 1100, - · - · - 1300, ——— 1500 GMT.  
 X Positions of storm centres which had developed by 1600–1700 GMT.

The analysis of surface charts, of scale  $1:2 \times 10^6$ , described in the foregoing section was carried out using only the information available from the Channel One teleprinter broadcast from the Central Forecasting Office, Bracknell.



**Structure of the southern convergence zone.**—From Figure 3 it is obvious that the sea air from the English Channel moved quickly inland early in the day which is much earlier than the usual time for that part of the country, e.g. Simpson<sup>1</sup> quotes 1645 GMT as being a normal time for the sea breeze to reach Lasham, Hampshire, during the summer of 1962 and Wallington,<sup>2</sup> has shown two examples of the breeze reaching Lasham at about 1730 GMT—a value which corresponds closely to general experience in that area, although much earlier arrivals have been known.

On this day it was possible to make some detailed observations in the convergence zone, although its arrival was unexpectedly early. At 1326 GMT the author, piloting a Skylark 2 glider, took off from Lasham on tow behind a powered aircraft when the surface wind was westerly at 5 knots. The sky was mostly covered by 6/8 large cumulus which was building quickly to become cumulus congestus. The aircraft and glider combination climbed to the west into thick smoke haze below a group of dark-based cumuli at a considerably lower level (2500–3000 feet) than that at which cumulus for some hours earlier had been based (4000 feet). At 2600 feet above M.S.L. the glider released from the tug aircraft which returned and landed at Lasham at 1334 GMT, by which time the surface wind had changed suddenly to southerly 10–12 knots, necessitating a change of landing run. At this time the sky at Lasham was clearing quickly from the south.

The glider, after gaining about a hundred feet in very weak lift in the smoke haze, turned to the south and flew out of a well marked haze wall into air which was clear and with no cumulus visible to the south. The structure of cloud and haze was indicative of a sea-breeze convergence zone, whose characteristics have been described elsewhere,<sup>2,3,4</sup> so a return was made to the wall of haze to seek rising air. Height could be maintained in weak lift to the north of the haze wall, but none could be gained. The system was moving to the north at 5–7 knots and when repeated re-positioning failed to produce a gain of height the search was discontinued and the return flight to Lasham made through air devoid of cloud and thermals. During traverses of the convergence zone readings of airspeed and vertical velocity of the glider were noted, the latter being taken from a direct-reading variometer and also recorded on a barograph. Readings of vertical velocity have been corrected for the sinking speed of the glider at known forward airspeeds to yield smoothed values for the vertical velocity of the air in the vicinity of the convergence zone.

A cross-section through the convergence zone has been built up and is shown in Figure 4. The region to the north of the haze wall was one in which gliders had been soaring from low level up to cloud base at 4000 feet above M.S.L. until the arrival of the sea air. It can be assumed, therefore, that apart from a slight superadiabatic lapse rate close to the surface, say up to about 1000 feet above ground, the lapse rate approximated to a dry adiabatic. The convective condensational level of the surface air, marked on the cross-section as  $C_1$ , agreed well with the observed cloud base. Within the haze wall the characteristics of the rising air were different from those in thermals; a narrow belt of rising air lay on the north side of the haze wall with an equally narrow zone of sinking air on the southern side. The approximate width of these zones and the vertical velocities within them are shown in Figure 5.



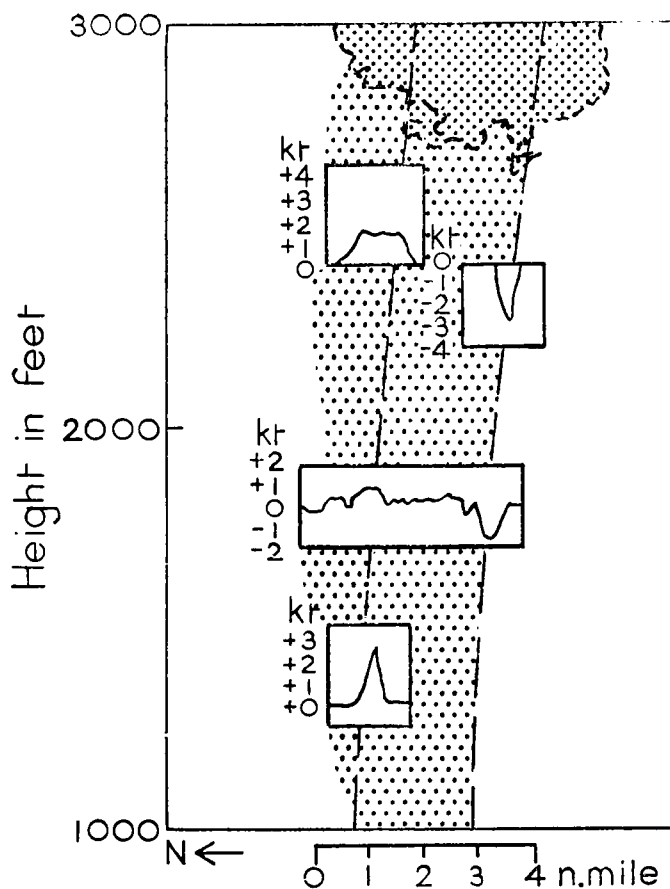


FIGURE 5—VERTICAL VELOCITIES IN THE  
CONVERGENCE ZONE  
For legend see Figure 4.

During the afternoon at Lasham the wall of cumulus could be seen receding to the north and although general tops were estimated at about 10,000 feet a massive flat-topped cumulus extending to about 15,000 feet could be seen in the vicinity of Farnborough at 1400 GMT. This was the cloud which gave rise to the thunderstorm in association with the southern convergence zone.

**Conclusions.**—This analysis, and others of the same kind which have been carried out, indicate that on some occasions preferred areas for convective development can be identified early in the day by meso-scale analysis, using routine hourly reports. Once the system was recognized only abbreviated charts were required to track it from hour to hour.

The structure of the sea-breeze convergence zone from the south coast on an occasion of deep convection forms a useful addition to the series recently reported<sup>4</sup> and, although no new characteristic was located, the way in which the south coast sea breeze fits into the pattern of convective development overland is indicative of their interrelation.

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## RADAR PHOTOGRAPH OF A DEEP DEPRESSION

The photograph of the PPI radar display reproduced in Plate I was taken on board the *Weather Reporter* at station 'A' ( $62^{\circ}\text{N}$ ,  $32.7^{\circ}\text{W}$ ) at 1100 GMT on 14 October 1963. It shows the echoes from precipitation around the centre of a deep depression which passed very close to the weather ship at that time. The synoptic situation at 1200 GMT, and observations from the weather ship at other hours are shown in Figure 1.

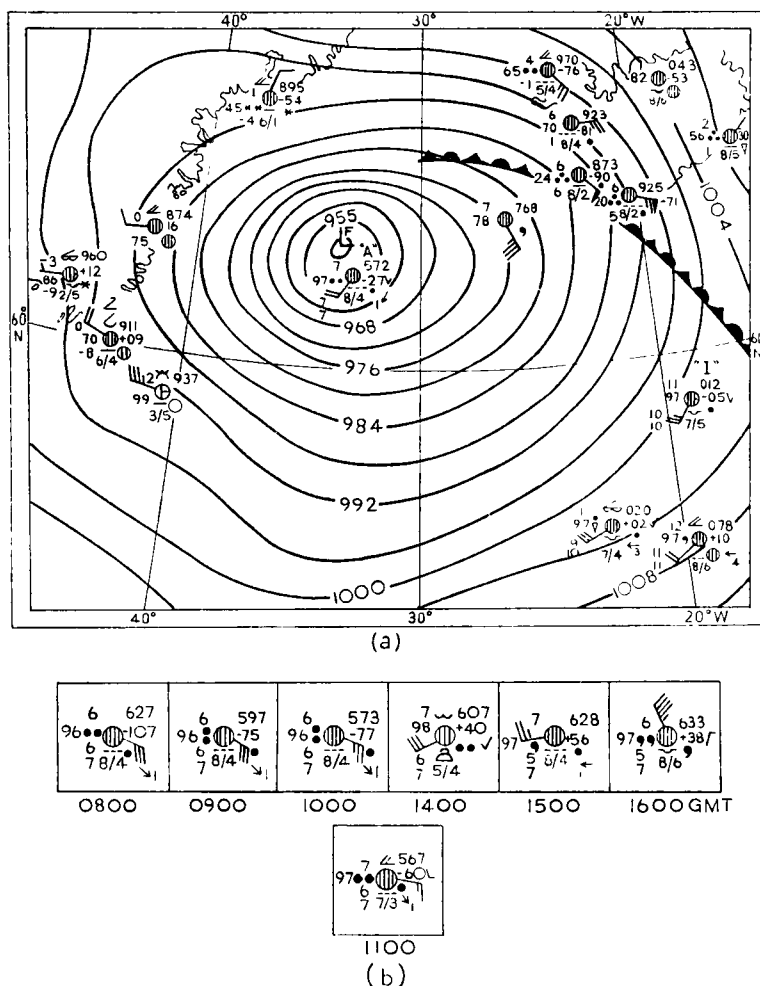


FIGURE 1—DEEP DEPRESSION NEAR WEATHER STATION 'A' ON 14 OCTOBER 1963  
(a) Synoptic situation at 1200 GMT, (b) observations from *Weather Reporter* between 0800 and 1600 GMT.

The depression concerned originated as a tropical cyclone in the central Atlantic and moved northwards east of Bermuda on 11 October. Polar air masses became engaged in the circulation of the storm and its structure became generally similar to that of an extratropical storm.

Spiral bands such as are seen in Plate I are a recognized feature of the radar echoes from tropical cyclones<sup>1</sup> but satellite photographs also show that a spiral structure of the cloud masses is normal in an occluded depression.<sup>2</sup> The reason for the spiral structure is not fully understood but it has provided a valuable method of identifying depressions from satellite observations.

The photograph is of considerable interest as showing the spiral organization in the radar echoes near the centre of a deep depression. It is rather unlikely that the spiral bands are directly related to the tropical origin of the depression, but the matter must remain uncertain in the absence of further radar observations from intense, symmetrical, mature extratropical depressions.

J.S.S.

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### EFFECT OF SMOKE ON RECORDED SUNSHINE

By J. E. B. RAYBOULD, B.Sc.

An interesting example of the effect of smoke on recorded sunshine occurred in Manchester on 10 January 1963. Factories and commercial firms in controlled zones, adjacent to smokeless zones, are allowed to discharge smoke and gases from their chimneys for a period of 10 minutes every 8 hours and the common practice in Manchester seems to be to exercise this right around midday. The effect of this discharge can be observed from the sunshine cards for Manchester Weather Centre and Manchester College of Science and Technology reproduced in Plate V. On this particular day the sky was cloudless and the wind easterly 6 to 8 knots, so that the loss of recorded sunshine of 0.5 hours at the Weather Centre and 0.9 at the College of Science and Technology was entirely due to smoke.

551.557.5:551.576.11:77

### PHOTOGRAPHS OF JET-STREAM CLOUDS

By G. J. JEFFERSON, M.Sc.

It is well known that jet streams, although commonly occurring in clear air, are at times accompanied by cloud. This has been shown statistically by Sawyer and Ilett.<sup>1</sup> Since the neighbourhood of jet streams, especially the entrance and exit regions or where the jet is intensifying or declining, is an area of ageostrophic motion, it follows that vertical motion is common. Where the motion is upward, cloud formation will occur when the air is sufficiently moist. Schaefer<sup>2</sup> discusses and illustrates the cloud types which are associated with jet streams and Schaefer and Hubert<sup>3</sup> discuss an actual occurrence of cloud associated with a jet stream over Schenectady, New York. Frost<sup>4,5,6</sup> in three illustrated articles describes, from an airline captain's view-point, the types of cloud which occur with jet streams and his findings are very similar to those of Schaefer. The main features are cirrus streamers of great complexity, showing long tufted streaks and complex shear lines. The bands of cloud lie along the jet, sometimes for great distances together with cross striation and at times tufted cirrus with long streamers ('fallstreifen') beneath. Frost mentions an occasion on which a line of thin cloud associated with a jet stream was followed for 1700 miles across the Atlantic until the aircraft's track left the line of the jet core. At lower levels, lines of altocumulus along the wind direction show billow or wave formation at right angles to it.

The two accompanying photographs, which were taken at Uxbridge, Middlesex, at 1820 GMT on 22 June 1963 illustrate clouds of these types associated with a jet stream. Plate III which was taken with the camera pointing approximately in a direction of 220 degrees shows that the main banding of

cloud was in a direction of about 240-060 degrees. Plate IV was taken in a direction of 270 degrees and again shows the main banding of the cloud with some signs of tufted cirrus and fallstreifen.

Figure 1 shows the maximum wind from a number of stations in north-west Europe at 1800 GMT on 22 June 1963 while Figure 2 shows the maximum winds at 0000 GMT on the 23rd. On Figure 2 the pecked line shows the analysed

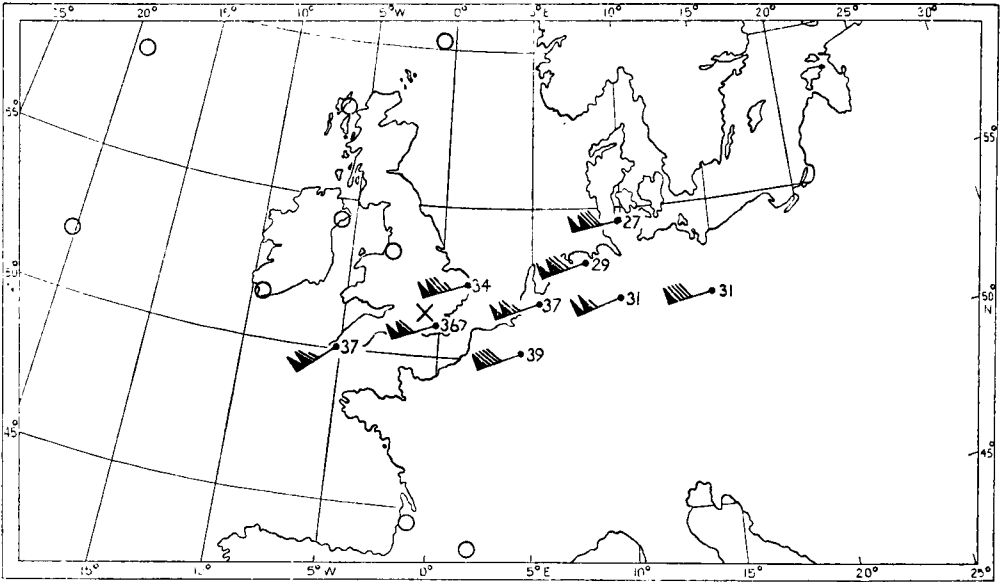


FIGURE 1—MAXIMUM WINDS OVER NORTH-WEST EUROPE AT 1800 GMT ON 22 JUNE 1963

X Position where photograph was taken.

O Stations where the maximum wind was less than 80 knots.

Figures on the right of the station circle give the height of the maximum wind in thousands of feet.

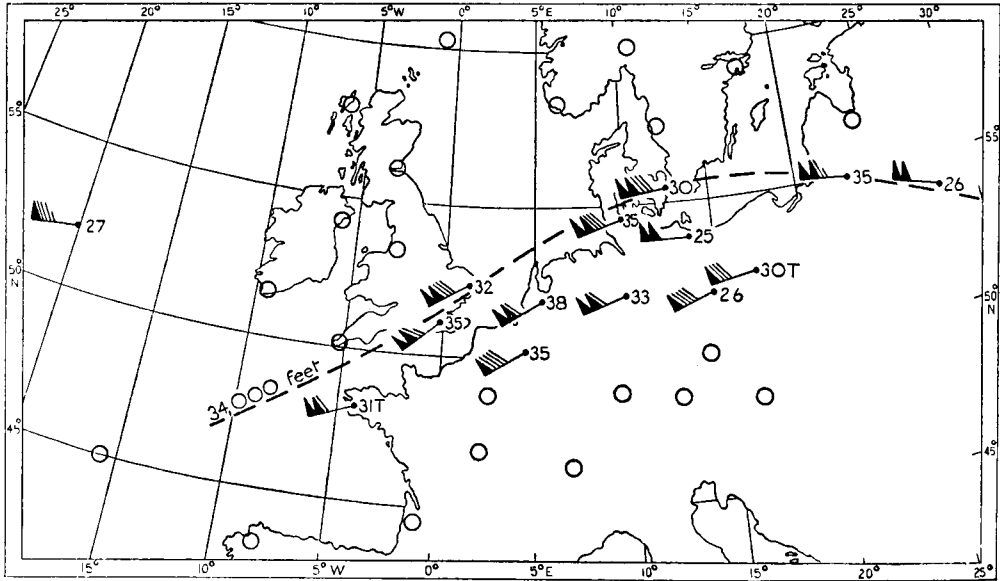


FIGURE 2—MAXIMUM WINDS AND JET-CORE POSITION OVER NORTH-WEST EUROPE AT 0000 GMT ON 23 JUNE 1963

O Stations where the maximum wind was less than 80 knots.

Figures on the right of the station circle give the height of the maximum wind in thousands of feet. T indicates that the maximum occurred at the highest point reached by the balloon.

--- Jet-core position.

jet-core position and height taken from the working charts at London (Heathrow) Airport Meteorological Office. It can be seen that the jet core lay from the west of the English Channel across East Anglia to Copenhagen and was placed at a height of 34,000 feet. Furthermore there appears to be some increase of wind speed downwind. The place where the photographs were taken thus lay just to the warm side of a weak jet entrance, a region where some upward motion is to be expected below the level of the jet. It thus appears probable that the clouds photographed were a little below 34,000 feet.

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551.507:352:551.515.827:551.578.11

### METEOROLOGICAL OFFICE DISCUSSION

#### The investigation of frontal rain by aircraft

At the first Meteorological Office discussion of the winter, held at the Royal Society of Arts on 21 October 1963, the subject was 'The investigation of frontal rain by aircraft.'

Mr. S. G. Cornford described how aircraft of the Meteorological Research Flight had flown in frontal layer cloud over southern England in winter to measure the concentration and size distribution of precipitation particles using the aluminium-foil technique. The results were used to calculate precipitation rates at heights up to 20,000 feet and showed that much of the precipitation was generated low in the cloud. On occasions when the nimbostratus extended well above the 0°C level the Bergeron process contributed less than half the rain which fell at the ground.

A novel feature was a layer 1000–2000 feet deep near the nimbostratus cloud base (which was usually at or below 2000 feet), in which the precipitation rate was several times that at the ground. The loss was too great to attribute to evaporation. The only explanation so far advanced was that raindrops shattered near the cloud base with an appreciable proportion of their water forming droplets of cloud droplet size. As it was borne upwards on the weak updraught, which must be present if rain is to be generated continuously, cloud water would be swept through by the next generation of raindrops so that they would grow and at the same time maintain a strong gradient of cloud water content in the upper side of the rainy layer. The water budget is balanced because in the presence of this gradient the updraught effects a net import of cloud water into the upper side of the layer and together with the condensing water vapour provides water for the net export of rain. As many of the raindrops shatter again much of the water begins another cycle within the layer.

Dr. Caton then explained how at the Meteorological Research Unit at Malvern he was able to measure precipitation particle concentrations and sizes at many levels in the free air by means of a vertically pointing 3-cm

Doppler radar. The measurements made so far were unreliable below 2200 feet, but above that height amongst 60 observations made on 8 days he could find nothing to support the idea of the existence of the rainy layer.

The discussion then centred on sampling errors, calibration of the aluminium-foil instrument and some of the implications of the existence of the layer.

Closing the discussion the Director-General said that there was evidence to show that the phenomenon described was a fact and no doubt practical applications would emerge. The need now was to reconcile the results of the radar and sampling techniques.

## REVIEW

*Tropical meteorology in Africa. Proceedings of the symposium jointly sponsored by the World Meteorological Organization and the Munitalp Foundation.* Edited by D. J. Bargman. 9½ in. × 7 in., pp. xv + 446, Munitalp Foundation, Nairobi, 1960. Price: S.F.20.

This book contains the papers presented at the symposium on Tropical Meteorology held at Nairobi in December 1959. Delay in publication, caused by the ill-health of the Editor, David J. Bargman, has not seriously detracted from its usefulness.

The symposium was attended by meteorologists from twenty-one African countries and by several well known scientists from Europe and the United States of America. The international character of the symposium as well as the quality of the main participants made this symposium an outstanding landmark in the history of meteorology in Africa. A wide field is covered by the recorded proceedings with the emphasis on practical applications both in synoptic meteorology and climatology. However, papers on various aspects of synoptic meteorology tend to dominate the book.

There are six excellent articles of a survey type on general synoptic problems including synoptic analysis and synoptic models, by N. E. La Seur and A. G. Forsdyke, and H. Flohn covers a variety of topics in five articles, for example, 'Multiple tropopause above the equatorial Pacific,' and 'The structure of the intertropical convergence zone.'

Amongst the other papers with a synoptic basis, perhaps the more interesting are 'Forecasting research in East Africa' by D. H. Johnson and H. T. Mörth, 'Generalized gradient wind equations and contour analysis in the tropics' by E. Kruger and 'Some streamlines and contours over the equator' by J. Cochemé. The contribution of Johnson and Mörth is particularly notable in emphasizing the usefulness of upper air contour charts in the equatorial zone by stressing the dynamical interpretation of contour and wind patterns, especially in relation to rainfall. Previously most meteorologists were sceptical of the value of upper air contour charts owing to the weakness of the geostrophic relationship in very low latitudes quite apart from the scarcity of reliable observations. However Johnson and Mörth give a broadly adequate theory supported by persuasive synoptic examples over Africa of their basic synoptic models, namely the Duct, the Drift and the Bridge. The papers by Johnson and Mörth, Kruger and Cochemé all highlight the necessity for an improved upper air network over Africa, and the need for more stations as well as more frequent and reliable observations.



Rainfall plays a vital role in the life of all African countries and its fundamental importance is reflected in such papers as 'On the global water vapour balance and the hydrological cycle' by J. P. Peixoto, 'The application of weather radar to hydrological problems' by V. D. Rockney, 'Cotton crop potential and rainfall expectation in Uganda' by H. L. Manning and 'Les campagnes de pluie artificielle du Nord-Cameroun' by R. Du Chaxel. These are all of a high standard.

The diversity of subjects treated at the symposium is illustrated further by papers on 'The agricultural uses of meteorological data' by E. W. Russell, 'Applications of synoptic meteorology to problems of locust control: some recent findings' by R. C. Rainey and 'The possibilities for utilization of wind power in tropical Africa' by E. W. Golding.

No doubt a case could have been made out for cutting down the size of this book of 446 pages, by drastic pruning of many papers or even by the omission of some of them. However it was probably wise to record the entire proceedings in view of the rarity of such meetings in Africa, and the need for periodical stock-taking.

R. MURRAY

## LETTER TO THE EDITOR

### An occurrence of 'ball lightning'

On the evening of Wednesday, 6 November 1963, at approximately 11.5 p.m., my father saw in his bedroom, in the centre of the room, a small, egg-shaped ball of brilliant light. Within the space of a few seconds, this small ball of light spread itself to form a sheet of darkish green light as wide as the room itself (approximately 12 feet). This curtain of light then moved towards my father and turned greyish colour. The whole sight then vanished as suddenly as it appeared, with a very loud bang, similar to the report from a rifle. The light was witnessed only by my father but the bang was heard by both my brother, from a neighbouring bedroom and my mother, who was downstairs in the kitchen. The bedroom light was on and it was raining at the time. We would not believe that this phenomenon had occurred if it were not for the fact that the very loud bang was heard by three people who were each in different rooms at the time.

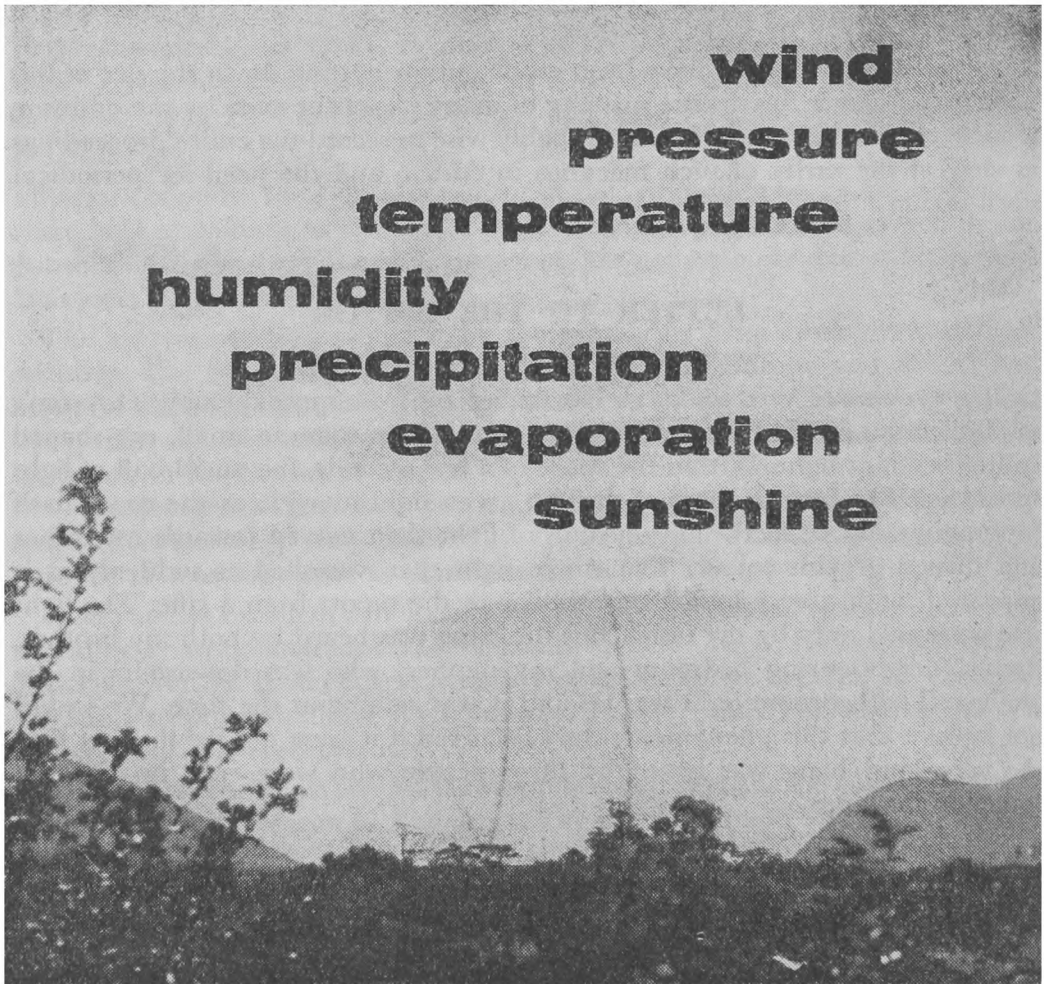
5 Hillside Avenue, Mapperley, Nottingham

M. F. FALKNER

[Other accounts of ball lightning appear in *Nature, London*, Vol. 198, 1963, p. 745, and *Zeitschrift für Meteorologie, Berlin*, Vol. 8, 1954, p. 27. Ed. M.M.]

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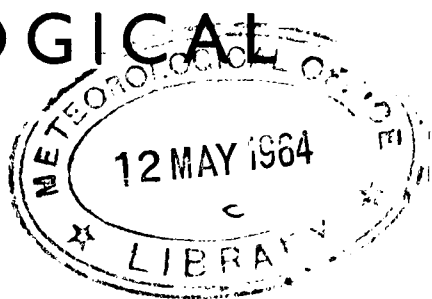
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# THE METEOROLOGICAL MAGAZINE

Vol. 93, No. 1101, April 1964



## **ARCHIBALD HAYMAN ROBERTSON GOLDIE, C.B.E., D.Sc., F.R.S.E.**

The news of the death of Dr. Goldie at Stirling on 24 January 1964, at the age of 75, came as a great shock to past and present members of the Office who knew him. Soon after his retirement nearly eleven years ago he moved back to the land of his birth and his many friends hoped he would find contentment there for many years to come. Unfortunately the later years of his retirement were marred by ill-health and that this should eventually have led to his death is, indeed, very sad.

Dr. Goldie joined the Meteorological Office as a Junior Professional Assistant in August 1913 and during his first two years in the Office he served at Falmouth Observatory, at South Farnborough and at Eskdalemuir Observatory. In September 1915 he was commissioned in the Meteorological Section of the Royal Engineers in which he served for four years and attained the rank of Major. He returned to the Office in 1919 and spent the next four years as Superintendent of the Local Services Division which catered primarily for the needs of the RAF. Then followed fourteen years as Superintendent of the Meteorological Office, Edinburgh, and nine years as Assistant Director responsible for research and in charge of the Marine, Climatological and Instrument branches. Finally, for the last five of his forty years' service he was Deputy Director for Research. A more detailed account of his career in the Office was published in the Meteorological Magazine for June 1953, shortly after his retirement.

Dr. Goldie was a good example of that comparatively rare combination of research scientist and sound administrator. He was thus well suited for the task of organizing research within the Office and for the official administration of the Meteorological Research Committee; but in addition to the work that this entailed he undertook personal research of high quality. His published papers cover a wide variety of important subjects, such as the general circulation of the atmosphere, the physics of the formation of condensation trails (of great importance during the Second World War), and the electrical conditions in the high atmosphere producing geomagnetic storms.

By nature Dr. Goldie was a quiet and friendly man who was highly esteemed by all who worked with and for him. When he took charge of the Marine, Climatological and Instrument branches on their evacuation to Stonehouse, Gloucestershire, he and his first wife, formerly Miss Marion Wilson of the staff of the Meteorological Office, Edinburgh, devoted much effort to ensure the

welfare of all members of the staff under the difficulties of living and working as evacuees. Many must look back with nostalgia at the pleasant Sunday afternoon gatherings at the old Cotswold house which the Goldies temporarily occupied at Woodchester. The news of Mrs. Goldie's death in 1948 came as a great sorrow.

In 1952, to the great pleasure of all their colleagues, Dr. Goldie married Miss Helen Carruthers who was on the scientific staff of the Climatology Division. The deep sympathy of those of the Office who knew her husband goes to Mrs. Goldie in her sad bereavement.

F. J. SCRASE

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## **METEOROLOGICAL OFFICE DISCUSSION**

### **Longe-range weather forecasting in Great Britain**

By J. M. CRADDOCK

The 3rd Monday Discussion of the 1963/64 season was held in the rooms of the Royal Society of Arts on 20 January 1964 under the Chairmanship of Dr. R. C. Sutcliffe. Mr. J. M. Craddock presented the following account of work on long-range forecasting which has taken place in the Meteorological Office since 1953.

**Introduction.**—Research work concerned with the slower changes in the atmosphere is at the stage typified by Kepler rather than Newton, in that its main task is that of assembling facts and recognizing regularities and patterns rather than seeking explanations. The phenomena considered are long lasting and cover wide geographical areas, while meteorological observations on a corresponding scale are comparatively recent, with the result that the number of adequately documented cases is far less than the number required as the basis for firm conclusions. Even when the utmost use is made of the incomplete observations made since the earliest times, the most serious restriction on the intending long-range forecaster is the shortage, not of ideas, but of information.

**The general approach.**—Our general meteorological experience leads us to the view that the large-scale processes control the smaller, and that our future weather depends, not so much on past and present conditions in Great Britain, as on the large-scale workings of the general atmospheric circulation. We must be prepared to study changes over an area at least as large as that used by the short-range forecaster, but unlike him we must average or filter our data to minimize the short-lived features which dominate the daily synoptic chart while preserving the more lasting though often smaller features which may persist further into the future. This involves a routine of rather mechanical calculation.

Once we have our current data prepared in a way which emphasizes the more lasting features, we require a library of past cases prepared in the same way, for use directly as analogues of the current situation, or indirectly to find rules and patterns of behaviour which may be applied to the future. In any case, the value of our conclusions will be in proportion to the size, relevance and comprehensiveness of our backing library. Often a suggestion which looks reasonable on theoretical grounds, or by reference to a small selection of past cases, can be seen at once to be unjustified when considered in the light of a comprehensive library of past cases. The assembly of the best possible library

is a very large task, entailing the collection and collation of data from many sources, and their presentation in a form suitable for ready reference and easy assimilation.

**Theoretical considerations.**—Any attempt to treat the slower atmospheric processes from general physical principles must take account of the thermodynamic processes which result in heat received from the sun near the equator being transferred polewards to balance radiative losses in high latitudes. While attempts at a theoretical solution have been made, e.g. by Smagorinsky<sup>1</sup> and Adem<sup>2</sup> it is doubtful whether present knowledge can yet produce a model which is simple enough for regular use but complicated enough to be realistic. In any case our observations are so incomplete, particularly in the tropics and in and over the oceans, that I doubt whether we can specify the initial conditions accurately enough to start a thermodynamic model on the right lines. An approach from direct physical principles is for the future rather than the present.

On the other hand, a purely statistical approach has to deal with material which does not conform to any of the familiar statistical patterns. Most meteorological variables show some periodic variations related to a basic period of a year. The periodic component can be estimated in advance from past values of the variable concerned, and this estimate which may be called the normal, or climatic expectation, is generally taken as a first approximation to a future value. The long-range forecaster has to try to improve on this by forecasting the departure from normal in the individual year in terms of observed departures from normal up to the time the forecast is made. If these departures from normal are measured, say at daily intervals, it generally appears that they do not occur haphazardly, but on the other hand they do not follow any regular periodic pattern. They usually form a coherent, vaguely oscillatory time series; a time series, moreover, in which the statistical characteristics are liable to vary with time, either erratically, or in a manner depending on the time of year.

These departures from normal are also subject to spatial correlations and geographical constraints in a way which is familiar to meteorologists but less so to most statisticians. Often, when data are arrayed for use in a table or chart, the number of data required for adequate representation is far greater than the number of effectively independent data, so that statistics calculated from such a field appear to be far more reliable than they really are.

These remarks help to show why simple statistical methods of the kind used extensively by Sir Gilbert Walker<sup>3</sup> have almost always produced disappointing results.

Having mentioned these difficulties, which render the field an unattractive one to many scientists, we must remember that many operations of agriculture and industry have to be planned well in advance in the light of the expected weather, which in the absence of any long-range forecast will be assumed to be the climatic normal. Any system of long-range forecasting will be useful provided that the errors of the forecasts are on average less than those which result from using the climatic normal on every occasion.

In these circumstances our object has been to develop a series of techniques, each with some physical argument in its favour, and supported by the fullest possible backing library of past instances. Now, although no one method

produces useful indications all the time, we sometimes get strong indications from several methods suggesting a departure from normal in a particular direction. On other occasions the indications may be so weak and conflicting that we can only forecast the climatic normal.

**Temperature anomaly patterns.**—Our first experiment consisted of the preparation as a routine of 5-day mean charts of the anomaly of air temperature at the earth's surface over an area of the northern hemisphere extending from the Rocky Mountains to beyond the Urals. The groundwork leading to the estimation of the normals from which these anomalies are measured has been described by Craddock<sup>4</sup> and the first 5-day mean temperature anomaly chart was for 1 to 5 May 1955. From 1957 pressure anomaly charts were produced as well, and both the series were continued until Autumn 1963, when they were superseded by charts—covering a larger area—of the 5-day mean anomalies of 1000-500 mb thickness and 1000 mb contour height.

Examination of the large-scale patterns of temperature anomaly showed that these were surprisingly well marked and persistent, and furthermore that they agreed with few exceptions with the anomalies of thickness of the 1000-500 mb layer. Since these anomalies are strongly correlated with those of the 500 mb airflow, we may be able to use the pattern of the anomalies of air temperature near the earth's surface as an indicator of the state of the circulation in the upper troposphere. If the present state of the circulation in the upper troposphere is any indication of the future, then cases which are similar in their large-scale patterns of temperature anomaly should tend to evolve in the same way. This hypothesis has provided our first experimental method for long-range forecasting, described in detail by Craddock.<sup>5</sup> The essentials are that our current 5-day mean charts are averaged towards the end of each month, to provide an approximation to the temperature anomaly pattern for that month. This pattern is compared with similar patterns for the same calendar month for all past years back to 1881, the most similar patterns are chosen as analogues, and the actual developments in the analogue years are used as basis for a forecast for the month to come, with more or less confidence depending on the agreement found between the sequels in the various analogue years.

We soon found that a large-scale similarity in the temperature anomaly fields is not in itself enough to produce a reliable basis for prediction, and we added the further conditions that there must be some agreement in the neighbourhood of the British Isles and in the sequence of weather types affecting the same limited area. With these additions, the technique is still in use, and is indeed, the only technique which has been used for long enough to enable us to get any real knowledge of its performance. It appears to work best in summer and worst in spring and autumn; it has had runs of months showing an encouraging standard of success but also, in 1959, a long run of almost unmitigated failure, and it appears, going over past results, that the standard of success would have been higher if, instead of forecasting for every month, we had only made forecasts in those months, amounting to perhaps one third of the total, in which the indications before the event seemed strongest.

The fact that it took us eight years to find the field of usefulness of this one technique emphasizes the point that this is a subject on which knowledge will grow very slowly as long as every new idea has to be tested against future

data. If new ideas can be tested against past data we can decide more quickly if they are useful. Tests of this kind have been carried out by ourselves, by Šiškov<sup>6</sup> in the U.S.S.R. and by other workers elsewhere. However, because a single forecast, made by a particular technique, occupies a panel of human forecasters for two or three hours, it is difficult to stage an experiment for testing the method on past data on a scale large enough to be really convincing.

It is worth mentioning that the staging of this experiment entailed the preparation of a backing library of about 1000 charts, each plotted with perhaps 200 temperature anomalies, one chart for each month from January 1881 up to date. A similar experiment could be based on charts of the monthly mean pressure anomaly pattern, but this would require another backing library of about the same size. We have made some progress towards this, because we have obtained from German and American sources photographic copies of charts of the monthly mean pressure for each month from January 1873 up to date, and of the pressure anomaly for each month of the years 1901 to 1937. Further, for the months of January and July only we have the use of pressure charts since 1750 produced by Mr. H. H. Lamb<sup>7</sup> for use in the study of climatic change. The conversion of these charts to a scale and projection comparable with our current working charts is an example of the time-consuming operations which must be carried out before full use can be made of our current data.

**Analogues by computer.**—The development and testing of forecasting methods can be enormously accelerated if instead of carrying out the processes of analogue selection by hand, we can perform the process on an electronic computer. Moreover, since the selection techniques are embodied in fixed, numerical rules, they are quite objective and free from the variations in standard which human forecasters find so hard to avoid. On the other hand, the computer has no commonsense and can only follow instructions, so that we must make very sure that we provide for every eventuality, and that we understand the full import of each instruction we give. This involves testing each step carefully before going on to the next.

From the time in 1957 when we knew the Meteorological Office was going to have a computer we started to build up a backing library on paper tape which could be fed into the computer. Many data we acquired from the meteorological services of the United States and Western Germany in the form of punched cards. Other data, including most of the Smithsonian *World Weather Records* were punched on to cards by other branches of the British Government Service. These all had to be converted to paper tape by means of a mechanical converter. We also punched data direct on to tape for ourselves. In spite of delays, we have built up over the years an impressive library of data in a form suitable for input to the computer.

Programming for the computer was shared by Mr. M. Grimmer and myself and nearly all the work on the matching of temperature anomaly patterns by computer was carried out by him. The first problem is to decide on a method of measuring the similarity between two charts which gives sensible results. Assuming each chart is represented by the values at a fixed grid of points (78 in our case) we have somehow to sum the discrepancies at all the points to measure the overall discrepancy. Then we can match the current chart against each of those for the same month in earlier years, and choose the most similar. The methods of matching used were the mean square discrepancy, the mean Bagrov index (see Bagrov and Morskoj<sup>8</sup>), the correlation coefficient, a measure

of agreement in sign, and a system in which all anomalies are classified into five categories and more marks are given the closer the corresponding values are to each other. None of these always gave sensible results, but an analogue selected by several methods is more likely to appear good to a human observer than one selected by one method only, and what is more important, it seems to have an above average chance of producing a good forecast. Another method of analogue selection depends on representing each chart by means of empirical orthogonal functions, in the way described by Grimmer.<sup>9</sup> The analogues chosen are the cases which show best agreement in the coefficients of the more important functions. Lists of analogues produced by several variants of these objective methods are produced by computer every month, and form part of the evidence considered by the panels of forecasters who actually do our long-range forecasting.

These objective methods are, of course, excellent for trial on past data, and Mr. Grimmer did in fact carry out several very large experiments to find the best methods of application. This work is still incomplete, and I need only say the standard of success may be highly significant, or it may be negligible, depending on the conditions of the experiment.

At the same time I was examining the conditions under which the temperature anomaly in one month provides valid evidence about the anomaly to be expected in another. This work has been described by Craddock and Ward<sup>10</sup> and the results occasionally provide a useful indication to the long-range forecaster.

**Sequence analogues.**—About this time the transfer of the long-range unit to the Climatological Research Branch, which took place as soon as the two units were moved to the new headquarters building at Bracknell, led to an influx of new material and new ideas, largely contributed by Mr. H. H. Lamb. The most important source of material is a classification (as yet unpublished), made by Mr. Lamb or his assistants, of the weather type over the British Isles for each day of each year from 1873 up to date. Using this valuable addition to our backing library, it is possible to select subjectively the weather sequences in past months or other periods which most resemble those of the period just completed, and this method of selecting analogues was at once included in our monthly routine.

The next stage was to select sequence analogues by computer. Before this could be done we translated Lamb's classification into a letter code in which each weather type is represented by one letter, so that, for example, a group of 31 letters will represent unambiguously the weather of each day of a 31-day month. This translation made it easy to read the data into the computer, and incidentally, made it possible to produce copies of the classification on the teleprinter. The task of devising an objective method of matching coded weather sequences proved less formidable than I had expected, and analogues selected by three objective methods of comparison are also included in our monthly routine.

While this was being done, Mr. R. Ward set out to produce his own classification of the daily and 5-day mean weather at London from 1873 up till now. This has a more local application than Lamb's classification, as the weather types are based on the direction of the geostrophic airflow in the 1000 miles before it passed over London, and on the pressure level at London.



This classification has also been coded for the computer and is used to produce objective lists of analogues. These methods of sequence matching can be carried out for periods longer or shorter than the calendar month, or for a 30-day period starting in mid-month, and are indeed our most useful tools for the production of forecasts starting in mid-month.

**Forecasting routine.**—The most recent charts of temperature and pressure anomaly are considered towards the end of each month by a panel of forecasters who select a group of analogues subjectively by comparison with the charts for the same calendar month since 1881 for temperature and since 1873 for pressure. Sequence analogues are chosen from the years since 1873. These lists are then compared with similar lists produced objectively by computer, and differences between the lists are reconsidered. The object of the list is to discover several past years which are similar to the present year under several headings, rather than years showing strong resemblance under one heading but little under any other. The selected years usually number from four to eight and the daily charts for the appropriate month in these years are re-examined by two pairs of forecasters working independently, and compared with the charts for the current month. This examination may result in some years being thrown out and often results in the analogue years being put in a different order of preference. This conference occupies the greater part of a working day.

A second conference is held, which is intended to take account of any and every other piece of evidence which may be relevant to the issue. It includes consideration of the state of the Arctic ice, the extent of snow cover, and the field of sea temperature anomaly in the North Atlantic and also items such as the forecasting rules proposed by Dr. F. Baur<sup>11</sup> and the month-to-month temperature relationships already mentioned. These arguments do not often by themselves lead to a definite forecast, but they may provide valuable indications when taken in conjunction with the analogues.

The conclusions reached at these conferences are presented at a final conference which normally takes place on the morning of the last day of the month. This conference, at which the final decisions are taken, is attended by officers senior to those who carry out the earlier work; the various indications are reviewed and discussed, and general agreement reached about what conclusions can be justified by the evidence. The final stages include the drafting of the forecast and the routine for printing and dispatch.

A similar but somewhat simpler routine is carried out at mid-month, to produce a forecast running to the middle of the following month.

**Verification and checking.**—A forecast based on a selection of analogues as indicated above may be in quite general terms (for example that a month is expected to be changeable, but predominantly cold and rainy) which give a clear picture, but are not easy to check. Partly to provide figures for checking, partly to clarify the indications to be drawn from a given group of analogues, Mr. R. Ward and his assistants have carried out the task of classifying the weather elements for a selection of British stations into deciles of the appropriate distribution. These decile values may show, for example, that in each of several analogue months the rainfall was high in the south-east and low in the north-west, or alternatively, that no obvious pattern existed, and the forecast can be phrased to take account of this. For checking purposes the

decile values are grouped in pairs into quintiles, and the mark given depends on the difference between the forecast and the observed quintile value at each station. This marking system can be adjusted to suit special requirements, and the version we use is designed so that a forecaster who does not know and is forecasting at random will secure no advantage by forecasting the normal. Another system which we use for comparative markings of our own forecasts and those received from overseas, is a five-point letter marking, from A which means 'no serious discrepancy between forecast and event,' and B 'good agreement,' down to E 'no real resemblance.'

The standard of success achieved depends partly on the checking system, and in view of the radical expansion of our methods during the last 2 years, it is difficult to say what it is. However, each of the main methods used would have had better than chance success if it had been used on each of the appropriate occasions in the last 8 years.

**Recent developments.**—The severe winter of 1962/63 emphasized the desirability of our being able to draw analogues not only from the recent years which mostly form a relatively mild epoch, but also from the earlier period in which severe winters were more frequent. Fortunately a good deal of work had already been done on the availability and interpretation of early data, by Mr. H. H. Lamb in the study of climatic change and by Craddock and Ward.<sup>10</sup> We found that we have enough data to determine the monthly mean temperature anomaly patterns over a useful area in western and central Europe for any month back to 1770, and the work of extending our reference library backwards from 1881 is now in progress.

The success of the Extended Forecast Branch of the U.S. Weather Bureau in forecasting for the winter of 1962/63 received wide publicity in Great Britain, and in May 1963 I visited Mr. Namias at his Office near Washington to gain first hand acquaintance with his methods. I have already given a full account of my visit (see Craddock<sup>12</sup>), so I need not repeat it now, but one conclusion I reached was that their treatment, based on circumpolar charts which covered all longitudes of the northern hemisphere, might easily discover indications which would be missed from our view-point, which had been confined to the Atlantic sector. On my return we considered the possibility of including 5-day mean upper air charts in our working material, and soon found that if we carried out our calculations by computer we would be able to display our material better and effect a saving in manpower.

So in August 1963 we decided to make a major change in our routine; to abandon our 5-day mean charts of temperature and pressure anomaly, which had to be produced by hand, and to use instead charts of the anomaly of 1000–500 mb thickness, 1000 mb contour height and 500 mb contour height, which could be produced by computer. Thanks to efficient use of the computer and outstanding diligence on the part of our staff, the change was completed in something over 2 months.

The value of our new 5-day mean upper air charts will be much increased when we have a library of similar charts for past years for comparison. The production of such a library from daily data would be a colossal task, but we are able to make use of a valuable pack of punched cards received from the West German Meteorological Service. These data are being averaged and rearranged by computer, so that from packs of daily upper air heights arranged

by circles of longitude there emerge 5-day mean heights in proper order for plotting on a circumpolar chart. The work, which is still in progress, illustrates the power of the computer at compressing within a few months work which could have taken half a lifetime.

**Conclusions.**—In the interests of brevity I have not mentioned our own fundamental researches and have said little of the interchange of ideas, forecasts and material which has gone on with meteorological services overseas. In fact the German methods, based on those of Dr. F. Baur (see, e.g. Baur<sup>11</sup>), the American methods described by Mr. J. Namias<sup>13</sup> and the Russian work based on and extending the ideas of B. Multanovskij<sup>14</sup> have all been given a good deal of attention. Work in these countries is proceeding actively, and often with a method of approach not unlike our own.

However, the features of our own work to which I attach most importance are these: firstly, our insistence on the use of objective, computer methods of selection as well as subjective methods; secondly, our use of panels of scientists rather than individuals to take the inescapable subjective decisions, and thirdly, the importance we attach to a comprehensive library of past cases, which enables us to match the current situation from many aspects and to select the best all round precedents rather than cases which are similar only in one respect. Finally I should mention the use of the computer, as a powerful and flexible tool with very varied applications.

In conclusion, our organization for collecting facts relevant to future weather sequences and drawing useful inferences from them will bear comparison with any similar organization in the world, and while I will not speculate on what the attainable standard of success in long-range forecasting may be, I do claim that few organizations have as good a prospect of reaching it as our own.

In the discussion which followed, Mr. R. F. M. Hay produced some results suggesting the possibility of predicting the summer temperatures in Great Britain from spring temperatures in North America and Russia, and Mr. N. E. Davis urged the prognostic value of the 100 mb chart. Mr. H. H. Lamb emphasized the importance of understanding the physical processes involved and the contribution which could be made by climatology. Lively exchanges followed in which several speakers commented favourably on the clarity of the official forecasts, and urged that they never be allowed to lapse into vagueness. Dr. Sutcliffe, in thanking the speakers, said that besides the unit engaged in producing the official long-range forecasts another strongly staffed unit had been formed to explore by more mathematical and theoretical methods the thermodynamic and other processes affecting the slower atmospheric changes.

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## A NOTABLE CASE OF DUST IN SUSPENSION OVER CYPRUS

By J. C. GORDON AND R. MURRAY

**Introduction.**—The thick dust which affected Cyprus for some 12 hours of the night of 18 to 19 December 1962 was of outstanding interest to the professional forecaster in Cyprus as well as to the man in the street. No one could remember a previous occasion with such a prolonged spell of thick dust in suspension in the lower atmosphere. Most professional forecasters would perhaps have been less surprised if the widespread dust had occurred in the late winter or spring, when Saharan depressions have their greatest frequency, rather than in December.

The air circulations leading up to and associated with the widespread dust of this occasion are discussed in this note, as well as some statistics of other occurrences of dust in suspension over Cyprus. As regards the case of dust on 18 to 19 December 1962, no very surprising or inexplicable features come to light, once the synoptic developments were set in train. Indeed the 'reasonableness' of both the synoptic developments and the occurrence of extensive dust in association with the synoptic situation is itself noteworthy. Why similar occurrences are not more frequent is another question to which a satisfactory answer is not given.

**General synoptic situation.**—The birth-place of the depressions with which the dust over Cyprus was associated was the western Sahara. In this region, some hundreds of miles south of the Atlas Mountains, several days beforehand there were already symptoms of cyclonic development which typically occur whenever cold upper troughs extend southwards over Algeria. The major cold outbreak over the British Isles on 12 December 1962 spread south-south-east to Algeria on 13 and 14 December. During the next day or two the relaxing upper trough moved eastwards over the Mediterranean leaving a cut-off depression in low latitudes near southern Algeria. Subsequently this cut-off low and the associated surface features moved north-eastwards roughly as indicated by the track of the 700 mb low, shown in Figure 1. In the meantime the upper trough, which had been moving eastwards and relaxing, was re-established over Europe and the central Mediterranean as the result of another cold outbreak spreading southwards over Europe.

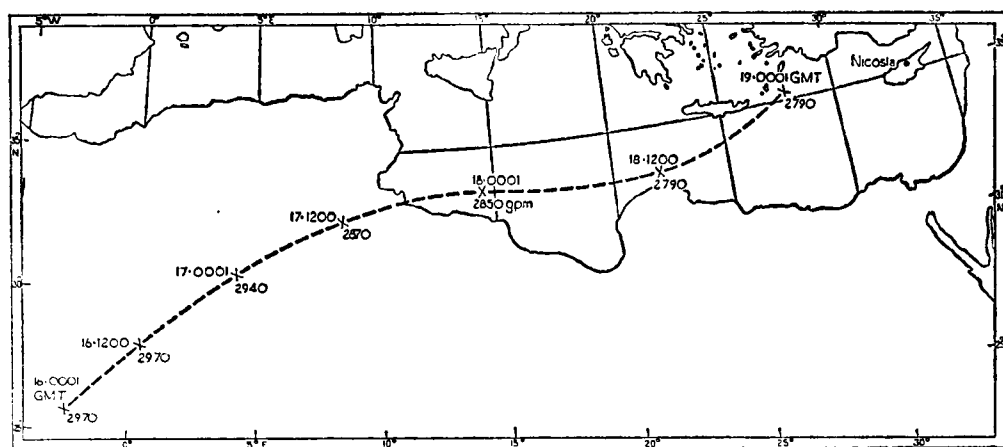


FIGURE 1—TRACK OF LOW AT 700 MB

Position given at 12-hourly intervals from 0001 GMT, 16 December 1962 to 0001 GMT, 19 December 1962. Contour heights at centre in geopotential metres.

The individual synoptic features of relevance were quite firmly in evidence on 17 December 1962. Figure 2 shows the surface chart and 1000–500 mb thickness lines for midday on 17 December 1962. The three frontal systems (A, B and C) had already a fairly long history, and they were maintained on subsequent charts even though some of the fronts, particularly the B system, became very weak and ill-defined. Lows LA and LB which were ahead of the thermal trough on 17 December (Figure 2), were favourably located for development and north-eastwards movement. During the next 24 hours rapid

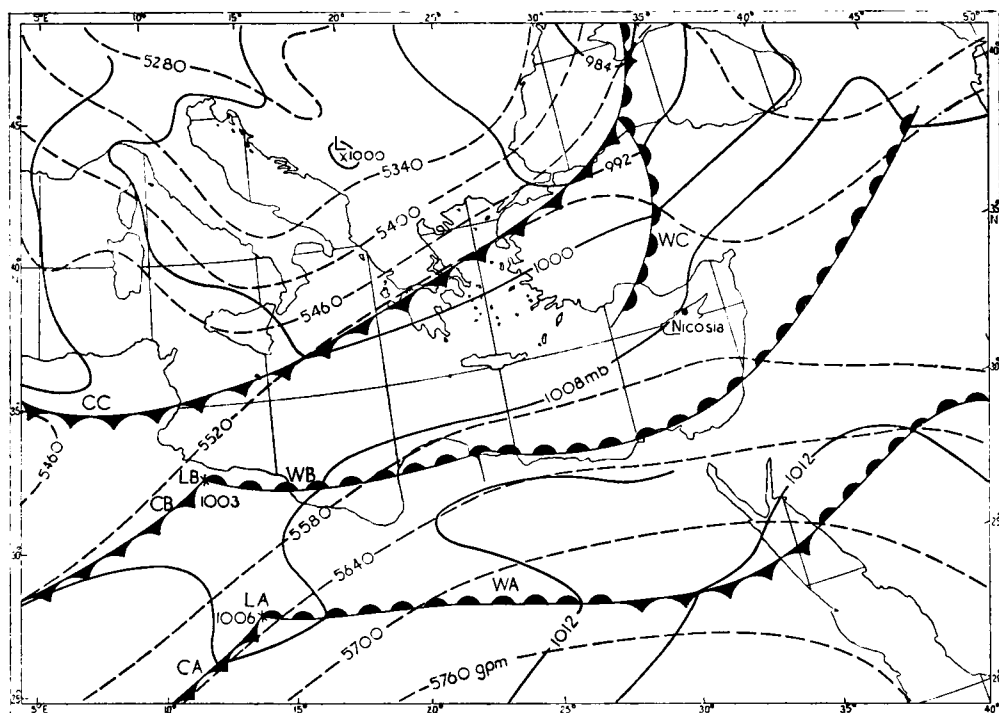


FIGURE 2—SURFACE CHART AND 1000–500 MB THICKNESS LINES FOR 1200 GMT, 17 DECEMBER 1962

—— Isobars, - - - thickness lines.

deepening and movement of LA and LB did in fact occur in association with characteristic distortion of the thickness pattern. At midday on 18 December 1962 (see Figure 3) a vigorous depression was near Crete (actually two centres  $LB_1$  and  $LB_2$  with lowest pressure 983 mb), whilst wave LA was some 70 miles north-west of Alexandria and significant front WA, which had moved quickly

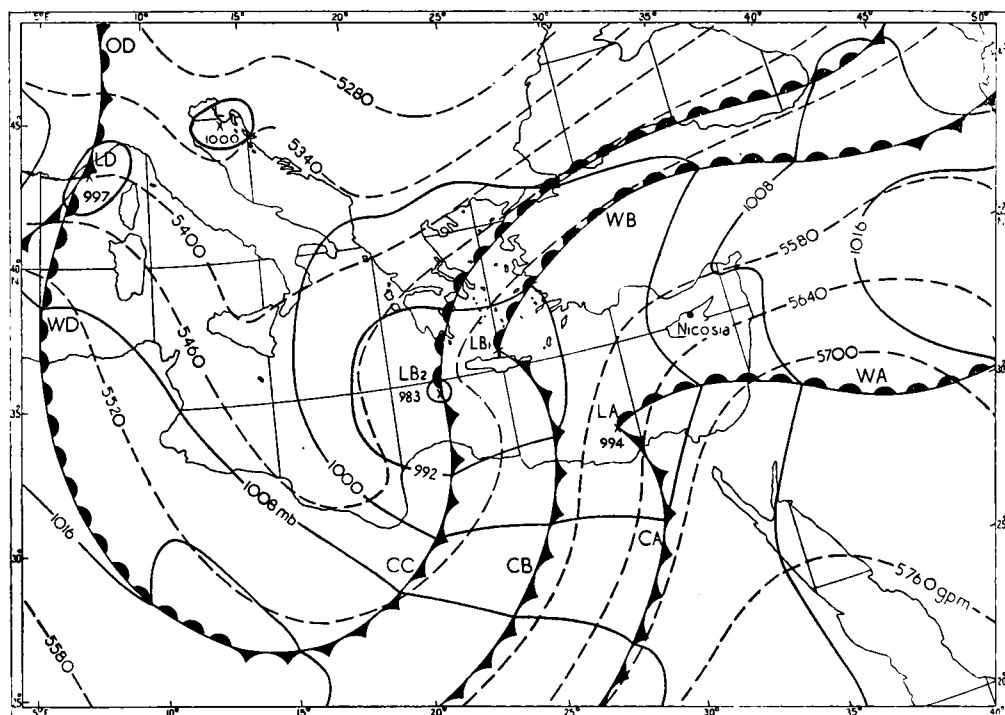


FIGURE 3—SURFACE CHART AND 1000-500 MB THICKNESS LINES FOR 1200 GMT, 18 DECEMBER 1962

—— Isobars, - - - thickness lines.

northwards, was midway between Cyprus and the Egyptian coast. Subsequently the B system moved over Turkey and the mobile wave LA travelled rapidly north-eastwards off the west coast of Cyprus. Front WA moved quickly northwards across Cyprus during the evening of 18 December, followed by dusty air which did not clear significantly until cold front CC swept eastwards across the island during the morning of 19 December. Figure 4 shows the synoptic chart at 1200 GMT, 19 December 1962, and Figure 5 gives the tracks of the main fronts of significance (i.e. WA and CC) at 6-hourly intervals from 1200 GMT, 18 December 1962 to 1200 GMT, 19 December 1962.

**Arrival of the dust.**—Early on 18 December duststorms were reported at a few places over Cyrenaica. By midday (Figure 3) surface winds had strengthened over an extensive area from Cyrenaica to Egypt, with gale force locally, and widespread duststorms were observed from the African coast to some 300 miles inland. For example, duststorms were reported at 1200 GMT on 18 December at stations El Adem (62063), Gialo (62161), Alexandria (62318), Port Said (62333), Cairo (62366), Minya (62387) and Manqabad (62393). At this time visibility was very good in Cyprus, but pressure was falling sharply and the surface wind was freshening from the south-east in advance of warm front WA (see Figure 3).

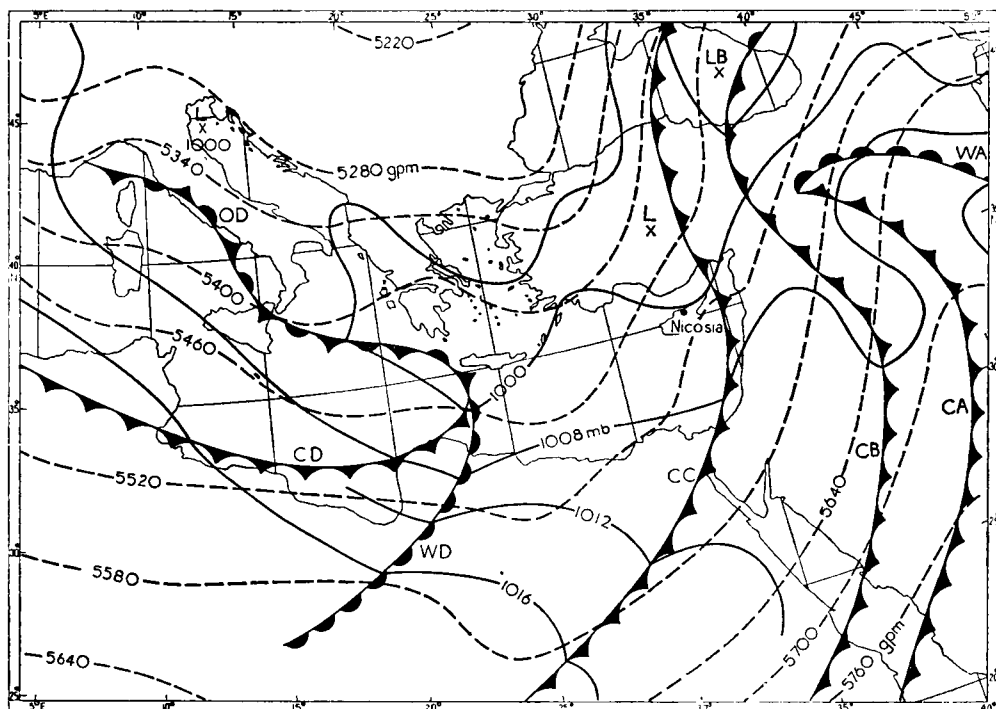


FIGURE 4—SURFACE CHART AND 1000-500 MB THICKNESS LINES FOR 1200 GMT,  
19 DECEMBER 1962  
—— Isobars, - - - thickness lines.

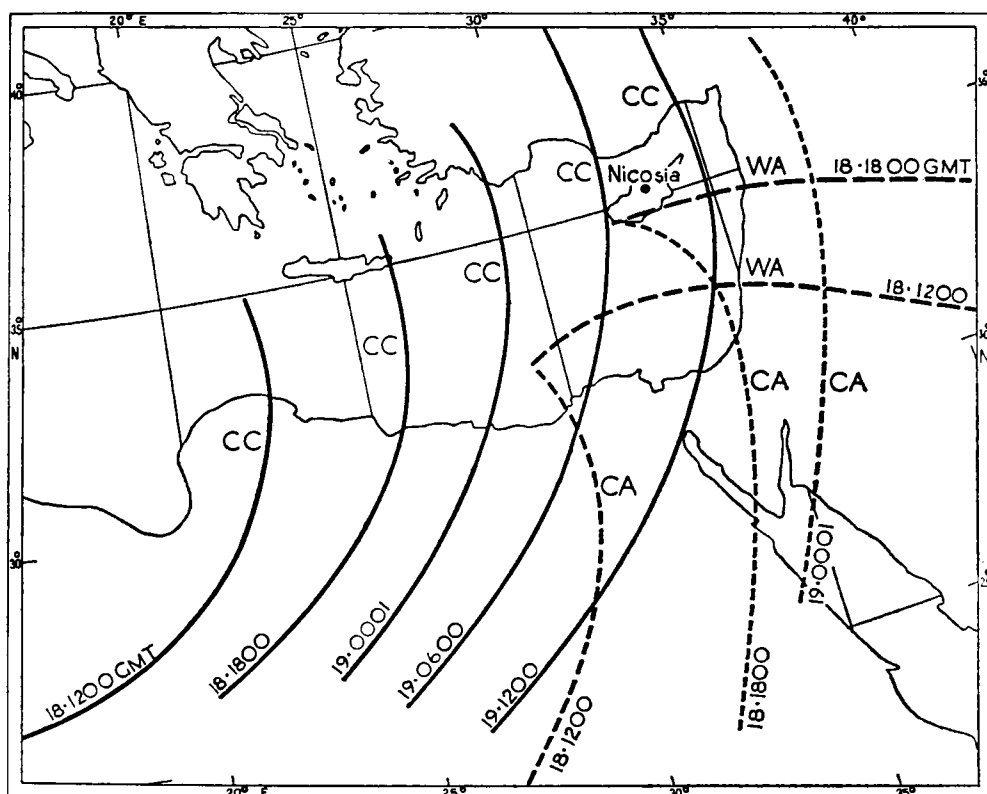


FIGURE 5—SUCCESSIVE POSITIONS OF FRONTS WA, CA AND CC  
The date and time (GMT) are shown against the positions of each front.

At Akrotiri on the south coast of Cyprus the passage of front WA about 1827 GMT was marked by a wind veer to 200 degrees 20 knots, a fall in humidity from 75 to 50 per cent, the occurrence of the maximum temperature of the day of 22.2°C (at 3½ hours after sunset) and a drop in visibility to 4 miles. The duty forecaster at Meteorological Office, Akrotiri, reported that "The air was filled with fine dust about the colour and size of face powder. By 1855 GMT the visibility was down to 2000 yards. The cloud structure before the front consisted of broken layers of Sc and Ac but after 1830 GMT the sky was virtually obscured." A further wind veer to 230 degrees 25 knots, with gusts to 34 knots about 1855 GMT was associated with the weak cold front CA.

At Nicosia in the central plain of Cyprus the dusty air was clearly brought in with the passage of the frontal trough about 1945 GMT. About this time the wind veered from 120 degrees 10 knots to 220 degrees 28 knots, with gusts to 38 knots, and visibility dropped from 10 miles to 770 yards. At Nicosia the main wind change occurred during a period of a few minutes, indicating that fronts WA and CA were occluded.

The dusty air which arrived at Nicosia at 1945 GMT on 18 December 1962 was tracked back in time, using quasi-geostrophic trajectories at 3000 feet and 850 mb. At the lower level the surface synoptic charts and 3000-foot wind observations were employed in tracking the air; at the upper level the 850 mb charts and the 850 mb winds were used. It should be noted that the Nicosia upper air sounding at 0001 GMT, 19 December 1962 (see Figure 6) showed a pronounced inversion at 750 mb: below this inversion it is evident that the dusty air was thoroughly mixed in the strong winds. Incidentally, at the same time the sounding at Helwan (near Cairo) gave the base of the stable layer at 870 mb.

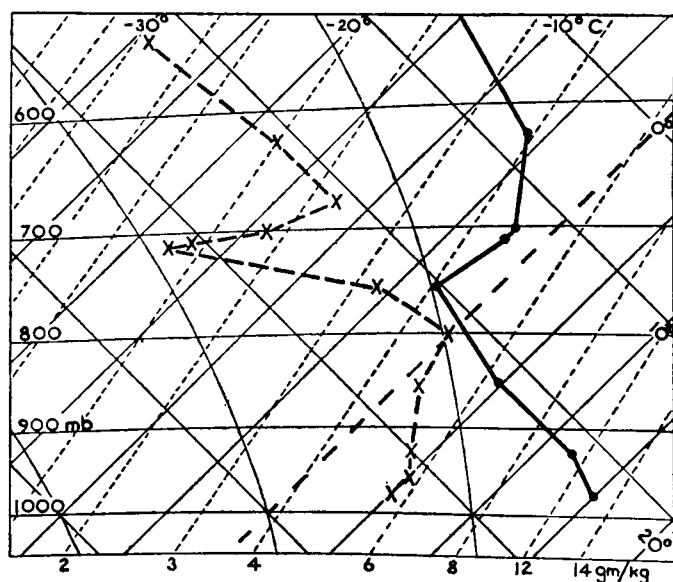


FIGURE 6—TEPHIGRAM FOR NICOSIA FOR 0001 GMT, 19 DECEMBER 1962

———— Dry-bulb temperatures, - - - dew-point temperatures.

Figure 7 gives the track of the air at the two levels. These tracks show clearly that (a) the air set out from Egypt where simultaneously duststorms were reported widely, and (b) the 'transit' time over the sea from the Egyptian



coast to Nicosia was only about 9 hours. Furthermore, it is significant that there were no reports of rain along the track of the dusty air. Thus the air which reached Nicosia at 1945 GMT on 18 December 1962 first traversed a part of Egypt where there was a plentiful supply of dust raised by the strong turbulent winds; then the dusty air moved across the sea to Cyprus with rather little fallout of dust owing to the rapidity of travel and the lack of precipitation.

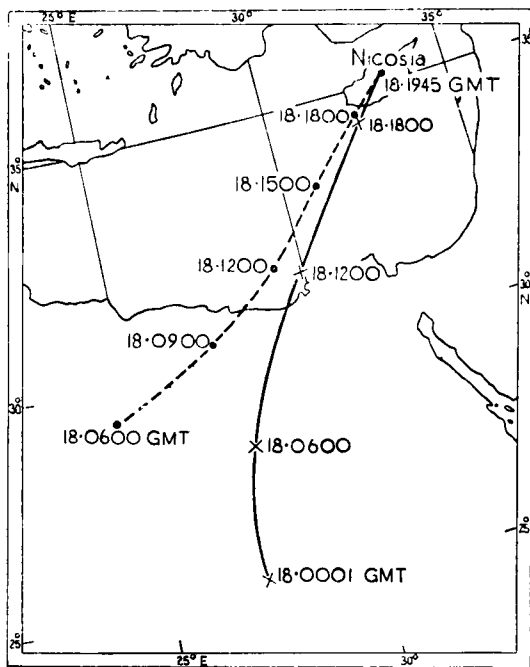


FIGURE 7—TRAJECTORIES OF AIR REACHING NICOSIA AT 1945 GMT, 18 DECEMBER 1962

-- Trajectory at 3000 feet, — trajectory at 850 mb.

**The dusty interlude over Cyprus.**—At Akrotiri, which was the first place affected by the dust, strong south-westerly winds persisted throughout the night, with a maximum gust of 41 knots, and visibility remained very poor, mostly between 1000 and 2000 yards. Visibility decreased to 300 yards about dawn on 19 December 1962 when intermittent slight rain fell. During the night after about 2300 GMT on 18 December there were outbreaks of slight rain (1.2 mm in all) which “fell as drops of thin mud but did not improve the visibility.” In fact the visibility at Akrotiri and at other stations in Cyprus decreased even further when muddy rain fell.

Following the arrival of the dusty air at Nicosia the visibility remained generally poor throughout the night for some 12 hours, with a minimum visibility of 660 yards about 2100 GMT on 18 December.

The dust was reported from other parts of the island during the night. For example the visibility dropped to 770 yards in association with rain at Paphos immediately in advance of front CC. The minimum visibility was 1400 yards at Morphou Bay near the north-west coast and it was 1700 yards at Ayios Nicolaos near Famagusta on the east coast. Many motorists noted, in the morning, that their cars were spattered with a thin sand-coloured mud. Actually there was little or no rain for the greater part of the dusty interlude,

but some rain fell in most places, almost exclusively with the approach of front CC on the morning of 19 December. Examples of rainfall amounts for the 12-hour period ending at 0600 GMT on 19 December are as follows: trace at Nicosia, 1.2 mm at Akrotiri, 3.7 mm at Paphos, 0.4 mm at Morphou Bay and 5.6 mm at Ayios Nicolaos.

The air at low levels over Cyprus during the night and early morning had undoubtedly been advected from Egypt or Cyrenaica in the strong south-west winds. For instance the dusty air over Nicosia at 0001 GMT 19 December almost certainly left the Egyptian coast between Salloum and El Alamein around 1200 GMT 18 December, at which time duststorms were widely reported over Cyrenaica and Egypt from El Adem to Port Said. Figure 8, which shows the approximate trajectories of air at 3000 feet and 850 mb, is relevant.

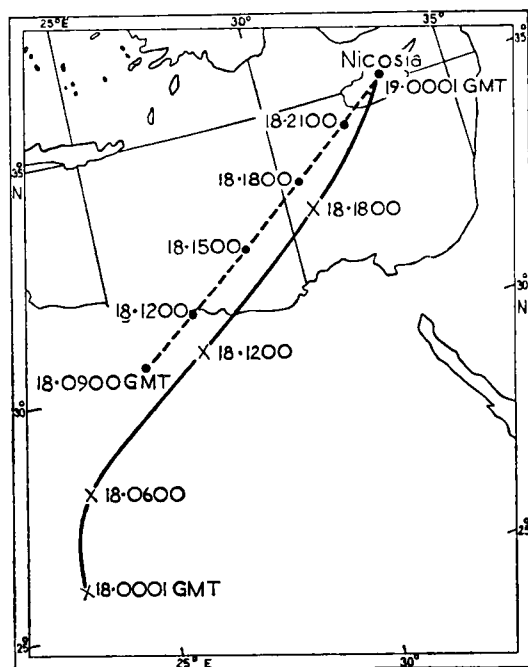


FIGURE 8—TRAJECTORIES OF AIR REACHING NICOSIA AT 0001 GMT, 19 DECEMBER 1962

-- Trajectory at 3000 feet, ——— trajectory at 850 mb.

It is noteworthy that over the source of the dust in Egypt and eastern Cyrenaica the surface air was very dry on 18 and 19 December; and the weak cold fronts which swept eastwards across this region gave virtually no rain east of about El Adem. There was probably little or no rain along the track of the dusty air until near Cyprus and even then mainly with the approach of front CC rather late in the period of roughly 12 hours of dust over Cyprus. Thus there was evidently insignificant washing out of dust by rain in the rather short transit time from the source of extensive duststorms.

**Clearance of the dust.**—The main clearance of the dusty air over Cyprus took place with the eastwards passage of cold front CC (see Figure 5). For instance, at Nicosia the frontal trough passed by at 0745 GMT on 19 December with an almost immediate improvement of visibility to 4 miles; whereas at Akrotiri, where the frontal passage was a little earlier, the visibility improved to  $3\frac{3}{4}$  miles at 0710 GMT and to 10 miles by 0800 GMT. Westwards of cold front CC the visibility over Cyprus was generally good or very good on 19 December.



*Photograph by P. A. Richards*

**PLATE I—LENTICULAR LEE-WAVE CLOUD OVER SIGNY ISLAND ON 30 MARCH 1958**

The photograph was taken looking west from the base hut shown in Figure 1 on page 118.



*Photograph by A. Stemmler*

PLATE II—DAMAGE RESULTING FROM A TORNADO AT LABUAN ON 25 JULY 1963  
A wooden hut was moved bodily 10-15 yards and disintegrated. The remnants of a coconut palm can be seen at the corner of the concrete base of the hut. (see page 120).

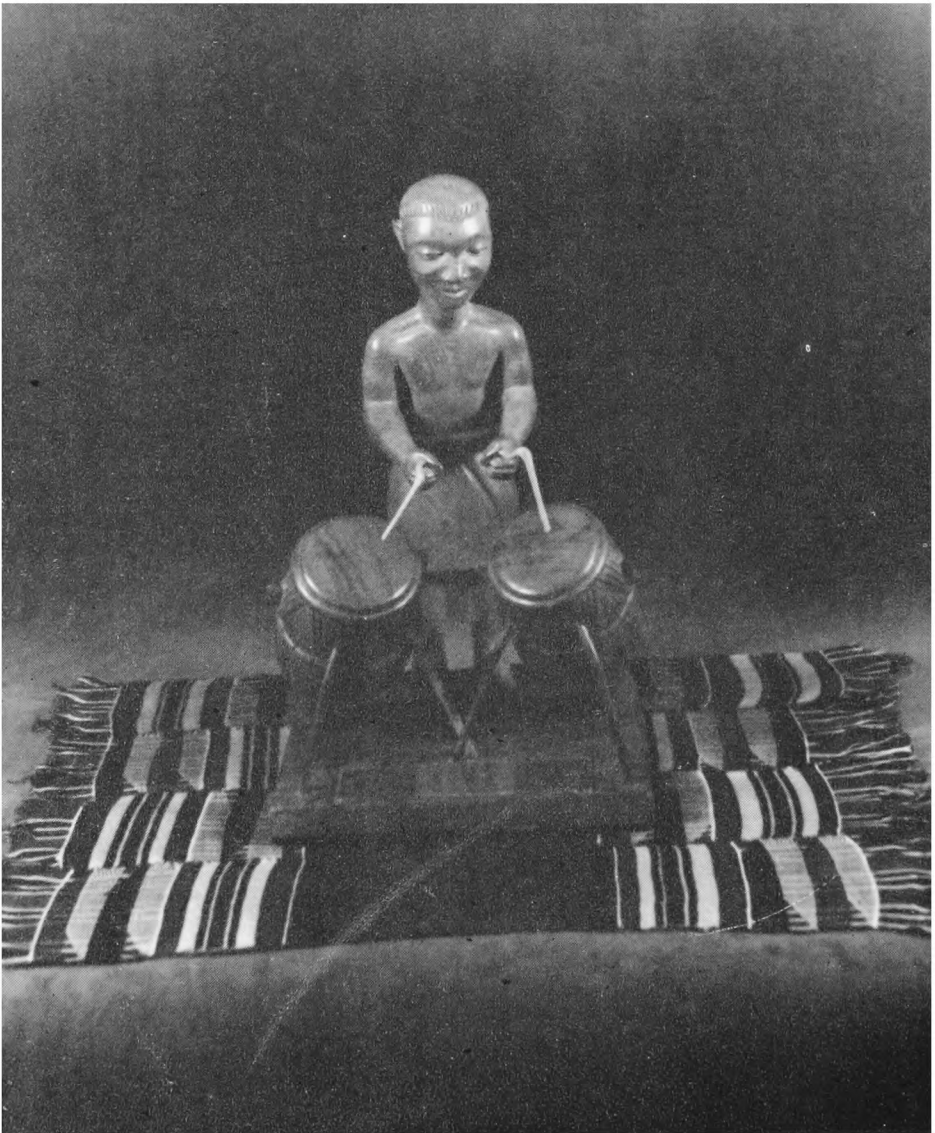


*Photograph by A. Stemmler*

**PLATE III—DAMAGE RESULTING FROM A TORNADO AT LABUAN ON 25 JULY 1963**

When an iron-roofed long house was completely wrecked, some of the corrugated iron was twisted and screwed up like waste paper, (see page 120).

*To face p. 113*



*Crown copyright*

PLATE IV —GIFT FROM THE GHANA METEOROLOGICAL SERVICES

See page 126.

The air which reached Nicosia at low levels about 0745 GMT in the rear of front CC was tracked back. Figure 9 shows the approximate trajectories. The air at 3000 feet appears to have been near Athens at 1200 GMT 18 December, near south Crete at 1800 GMT 18 December and then to have travelled eastwards to Cyprus. It was not possible to track the air beyond the Athens area

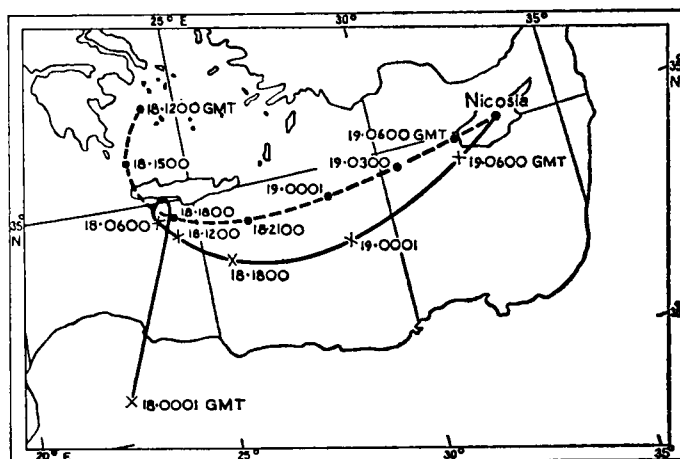


FIGURE 9—TRAJECTORIES OF AIR REACHING NICOSIA AT 0745 GMT, 19 DECEMBER 1962

- - - Trajectory at 3000 feet, ——— trajectory at 850 mb.

with any confidence. However it is probable that the air which reached Nicosia at 850 mb at 0745 GMT 19 December 1962 left Cyrenaica soon after 0001 GMT 18 December. This air almost certainly moved northwards from Cyrenaica to near Crete, then, after some hours of partial stagnation, eastwards to Cyprus. Even if the air at 850 mb originated over Africa, it must have travelled for at least 24 hours over the sea along a track where considerable precipitation fell and where the lower troposphere became increasingly unstable. Thus there was ample time for the concentration of dust originally in suspension to be significantly diminished by two processes, namely, (a) washing out by falling rain and (b) dispersion upwards in the fairly unstable air.

**Other occasions of dust over Cyprus.**—As a basis for comparison with the dust of 18–19 December 1962 the records for Nicosia for the years 1953–62 inclusive were scrutinized for other occasions of dust in suspension.

Surprisingly, there were only 3 occasions of significant dust haze at Nicosia during the period 1953–1957 and on none of these was the visibility seriously reduced. Synoptic charts were not available at Nicosia for this period.

During the subsequent 5-year period there were 23 instances of dust haze, excluding the case on 18–19 December 1962. While the majority of the extreme deteriorations in visibility due to dust lay in the 2–5 miles range, there were a number of instances when visibilities were lower than this and on one occasion the minimum visibility recorded was 1500 yards. This should be compared with a minimum visibility of 660 yards at Nicosia (and 300 yards in dust and rain at Akrotiri) in the case of 18–19 December 1962. Incidentally rain was reported on only 3 occasions during the dusty periods and the minimum visibility in rain was 2000 yards (this does not include the occasion of 18–19 December 1962). The average duration of the dust was about 11 hours though

the actual periods varied from about 1 hour to 41 hours. It is noteworthy that prior to all the instances of dust haze the surface wind at Nicosia was persistently easterly or south-easterly. However, the actual onset of the dust and the subsequent occurrence of the dust were associated with surface winds at Nicosia from a variety of directions; indeed on about one-third of occasions the surface wind was from a westerly point. On the other hand the clearance of the dust at Nicosia was generally associated with surface winds between south-west and north-west.

The 24 instances of dust occurred from November to May, with a maximum frequency in March; none occurred from June to October.

These cases were further examined to find the sources and synoptic situations associated with the dust over Cyprus. On all but two of the times the source of the dust was North Africa. On the other two occasions the dust originated over the Arabian peninsula and Iraq.

Of the 24 cases of dust only 16 were really distinct. For example dust was reported for varying periods on 13, 14, 16, 17, 18 and 19 January 1960 (the visibility on 14 January was actually reduced to 1500 yards for 8 hours), thus giving 6 instances. However, the synoptic pattern for the whole of the period from 13 to 19 January 1962 consisted of a series of cold fronts moving from west to east across North Africa and the central and eastern Mediterranean in association with a family of depressions moving east across central Italy and then north-east to the north of the Black Sea. The final clearance of the dust was brought about by a rise of pressure over Algeria and Tripolitania, resulting in the maintenance of north-westerly surface winds over Cyprus.

Examination of the dusty periods of 1958–62 suggests that there are three typical synoptic situations which give rise to dust over Cyprus. These are as follows:

(i) An intense depression is situated over the central Mediterranean with associated cold fronts moving eastwards over North Africa.

Widespread rising sand can occur both ahead of and behind the fronts. The widespread dust in suspension normally arrives over Cyprus in south or south-east winds and clears with the passage of the final cold front, usually in association with the build-up of an anticyclone over Algeria, Libya and the central Mediterranean and the movement north-eastwards of the main low centres.

(ii) Depressions which move from North Africa.

There are several variations. Depressions may move eastwards from the semi-permanent low pressure area over central Algeria following a fresh burst of cold air from the north. Depressions may originate over Libya and move eastwards or secondary depressions may form in the circulation of an intense depression over the central Mediterranean. For these lows to bring dust over Cyprus it seems that they should have a fairly intense circulation and the tracks of their movement should lie within the belt shown in Figure 10. There were no cases of dust reported at Nicosia with centres passing south of the belt shown in the figure. Furthermore, the dust frequently arrives over Cyprus in surface winds between south-west and north-west. The average duration of the dust is 5 or 6 hours but on one occasion it persisted for 16 hours.

(iii) A stationary or slow-moving depression is situated over the extreme south-east Mediterranean or over Saudi Arabia with a strong circulation on its eastern side.



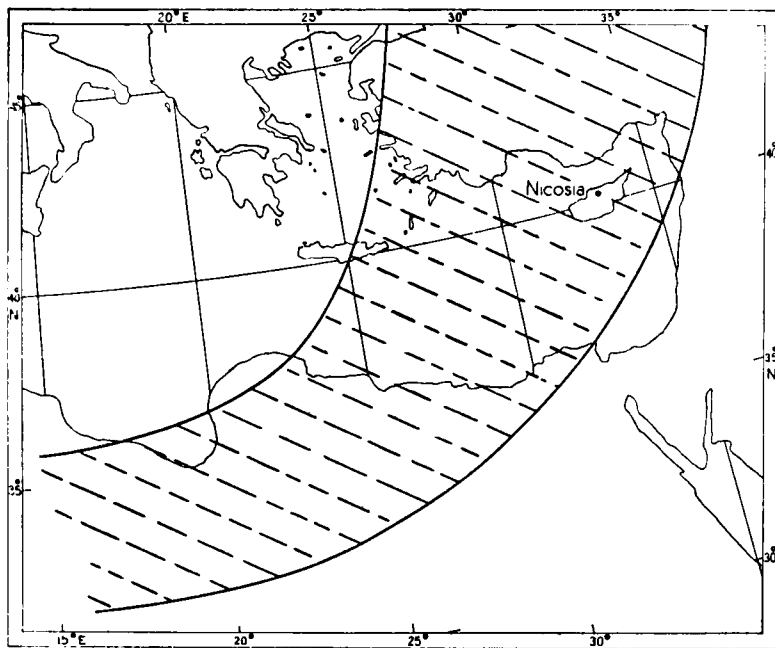


FIGURE 10—AREA ENCLOSING TRACKS OF AFRICA LOWS WHICH MAY BRING DUST TO CYPRUS

Errata: all latitudes are 5° too large

In this case dust may reach Cyprus from Saudi Arabia, Iraq or Syria and it may persist for quite considerable periods. The clearance is again associated with the build-up of pressure over the central and eastern Mediterranean.

Within the limitations of the data examined, it appears that types (i) and (ii) are about equally frequent and type (iii) is rather uncommon.

The existence of synoptic situations similar to those indicated as types (i), (ii) and (iii) is not of course a sufficient reason for the occurrence of widespread dust over Cyprus. There should additionally be a fairly low inversion (at about 850–700 mb) to restrict the vertical dispersion of the sand or dust, marked instability below the inversion, a minimum of precipitation so that the dust is not washed out and a minimum trajectory (in time) of the dust-bearing air between the source region and Cyprus. These additional factors were all present to a marked extent in the outstanding case of 18–19 December 1962.

551.5:061.3:550.3

# **INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS THIRTEENTH GENERAL ASSEMBLY, BERKELEY, CALIFORNIA, 1963**

By E. KNIGHTING

The Thirteenth General Assembly of the International Union of Geodesy and Geophysics (UGGI) was held at the University of California, Berkeley from 19–31 August 1963. All seven of the International Associations held their own meetings concurrently and there were a number of joint symposia such as those on Evaporation (International Associations of Meteorology and Atmospheric Physics, IAMAP, and of Scientific Hydrology, IASH,) and Ocean–Atmosphere Interaction (Association of Physical Oceanography, IAPO, and IAMAP).

The papers read in IAMAP were mainly divided into symposia on subjects such as meteorology of the upper atmosphere, interaction between ocean and atmosphere (with IAPO), radio meteorology, atmospheric and space electricity (with the Association of Geomagnetism and Aeronomy, IAGA,\*), atmospheric turbulence, evaporation, with other shorter symposia. Several of these symposia overlapped so that no one could attend all the meetings, but the lecture halls were sufficiently close to make it possible to hear papers first from one and then another session. The total number of papers almost reached two hundred, at least a fifty per cent increase on the number read at Helsinki<sup>1</sup> three years ago; over forty papers were read in the symposia on meteorology of the upper atmosphere. Dynamical meteorology and the general circulation were deliberately excluded because the International Commission on Dynamical Meteorology was to hold a special symposium on dynamical meteorology at Boulder immediately after the UGGI General Assembly.

Interest in the upper atmosphere has been steadily increasing over the last decade because the instruments for making observations have multiplied and revealed the intrinsic interest and importance of the region, and also because there is the practical problem of determining where the products of nuclear devices will be found at later times. Observations cover a wide variety of atmospheric substances such as water vapour, ozone, atomic oxygen and nuclear tracers as well as the more conventional winds and temperatures and in some cases information exists to levels above 100 km; further observational material is accumulating rapidly and is so diversified that workers in the field must have a detailed knowledge of the specialized physics and chemistry of this region as well as being dynamical meteorologists. A number of papers dealt with the observational material and its qualitative explanation in terms of upper atmospheric circulations, others dealt with the energy exchange processes in the upper atmosphere and there was occasional recourse to the electronic computer to carry out computations of possible circulations. The views held by the various speakers are still diverse and it is fair to say that as yet there is no agreed interpretation of many aspects of the observational evidence; nevertheless it is clear that progress has been rapid in the last few years and a coherent picture of the upper atmosphere will eventually emerge. A few papers dealt directly or indirectly with ozone measurements, particularly valuable because of all the upper atmospheric constituents ozone is perhaps the best understood and most widely observed and a wealth of data from the International Geophysical Year remains to be dealt with. Among other interesting papers (which included some on radiation in the upper atmosphere) were a few offering further data and tentative hypotheses about the 26-month oscillation in the tropical stratosphere, but the mystery remains.

The interaction between the oceans and the atmosphere must be as important as any other factor in determining the atmospheric circulations which exist and in attempting to make predictions over periods longer than a few days; it is equally important to the oceanographer and perhaps the stress in the joint symposia with IAPO was in his direction. It seems that at present the oceanographer is better able to make use of observed winds to explain the oceanic circulations than is the meteorologist to use oceanographic observations to explain atmospheric circulations. Perhaps more joint research is required

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\*The remaining three associations are the International Associations of Geodesy (IAG), of Seismology and Physics of the Earth's Interior (IASPEI) and of Volcanology (IAV).

before meteorologists can get the help that they need to remove the gross assumptions that are commonly made at sea level in their atmospheric models. On the other hand radio and radar experts seem to have more to offer to meteorology than they receive although many obscurities still remain and it appears that the theory of superrefraction still has to be agreed. The shorter symposia all had papers of interest, e.g. the observational material obtained from satellites was well discussed although its full impact on meteorology is yet to be felt.

The very large number of papers presented suggests that the amount of research work in meteorology is greater than ever before, especially if it is remembered that only certain facets of the research were presented at Berkeley, and it is certainly true that the volume of published papers is increasing as is the number of meteorological reports which do not appear in the established journals. With so much research going on it is almost inevitable that symposia as presently organized are made up of papers read by specialists in a rather narrow field and hence lack cohesion, however the organizers may try to achieve it. There is much to be said for IAMAP meetings being devoted to a series of carefully prepared review papers in the various branches of the subject, leaving the specialists to read their papers at the meetings organized by the International Commissions. At least, each symposium should commence with an adequate review to set the stage for the subsequent papers.

The setting of the meetings could scarcely be bettered, for the Berkeley campus is a very fine one with a more than adequate supply of good lecture theatres. The reception committee had done its work well and provided all the facilities that were needed for transport and accommodation and in the glorious weather we were all made very comfortable indeed.

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551.558.21:551.576.11

### LENTICULAR LEE-WAVE CLOUD AT SIGNY ISLAND

By P. A. RICHARDS

The following notes were compiled from observations made at Signy Island (60°43'S, 45°36'W) in the South Orkneys during 1958 and 1959.

The Pomona Plateau (general height 1500–1700 feet) situated at the western end of Coronation Island (Figure 1) appears to form standing waves under certain conditions giving rise to a series of lenticular lee-wave clouds. These form at right angles to the flow of the upper winds and have a base at about 6000 feet. The waves set up appear to have greatest amplitude at the position of the second wave, as on several occasions this was the only position where cloud formed. The wavelength between each cloud was  $3\frac{1}{2}$  miles, the clouds being 5–8 miles in length (Figure 1 and Plate I). The cloud formed only in the summer months on days when the surface temperature was above 0°C.

G. A. Corby\* gives three conditions suitable for the formation of waves:

- (i) Marked stable layer, approaching the isothermal, or an inversion, through some layer below 10,000 feet;
- (ii) Wind direction fairly constant with height;
- (iii) Wind speed increasing with height.

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\*CORBY, G. A.; Air flow over mountains. *Met. Rep., London*, No. 18, 1957, p. 36.

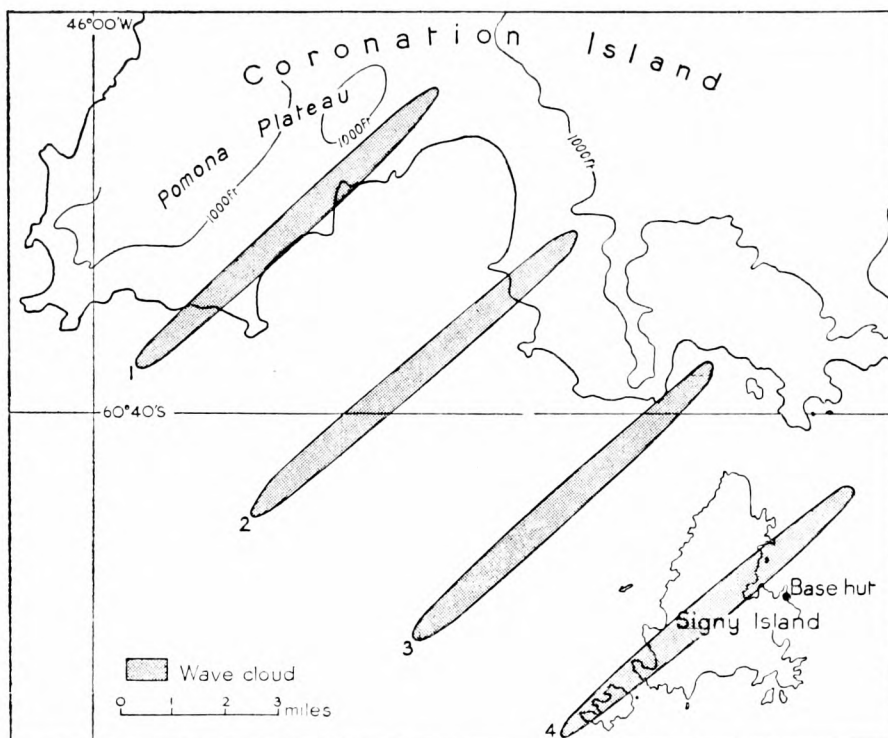


FIGURE 1—MAP OF THE AREA AND POSITIONS OF FOUR OF THE LEE-WAVE CLOUDS  
Wave clouds are numbered 1 to 4.

Owing to lack of information nothing is known of the upper air temperatures when cloud formed, but on all occasions the area was in a ridge of high pressure with slight barometric tendencies indicating stable conditions.

On the eight occasions when upper winds were obtained when wave clouds were present, the wind direction between the surface and 8000 feet never varied more than a few degrees ( $270^{\circ}$ – $310^{\circ}$ ) (see Table I). It will be seen that the strongest upper winds were recorded on 10 October 1958, the day on which the greatest number of wave clouds (6) was observed.

TABLE I—UPPER WINDS RECORDED ON OCCASIONS WHEN WAVE CLOUDS WERE PRESENT

Date	Time GMT	Height in feet								Position number of wave cloud* (see Figure 1)
		1000	2000	3000	4000	5000	6000	7000	8000	
		Direction and speed of wind <i>degrees/knots</i>								
1958										
30 Mar.	1715	290/31	300/27	320/32	290/21	280/13	290/20	290/35	280/35	1,2,3
4 Apr.	1700	290/11	300/15	290/23	280/22					1,2,3,4 at 8000 ft: 3
6 Apr.	1700	300/12	280/20	280/24	270/26	290/28	280/32	280/31	290/44	2
9 Apr.	1500	300/25	290/39	290/40	290/35	290/30	280/36	280/46	290/52	2
25 Apr.	1700	290/14	280/27	280/25	270/16	280/21	290/24	280/28	270/24	2,3
10 Oct.	1200	300/19	290/21	300/32	300/48	290/58	280/38	290/37		1,2,3,4,5,6
25 Nov.	1700	300/19	310/18	290/17	290/25	280/26	280/25	280/21	280/29	2,3
1959										
29 Mar.	1400	310/15	300/18	270/18	270/14	290/29	290/43	290/40	280/23	2 (occasionally sign of cloud at 1)

**Acknowledgement.**—The author was working for the British Antarctic Survey at the time of these observations and wishes to thank it for agreeing to publication of the article.

551.515.33

## TORNADO AT LABUAN—25 JULY 1963

By A. STEMMLER and P. M. BATE

The following report of a tornado may be of interest. It occurred about 1745 local time on 25 July 1963 over Labuan Island off the coast of North Borneo, approximately 5 degrees north of the equator. Figure 1 shows the track of the tornado near the airfield, and where the main damage occurred. The tornado was observed to have a counter-clockwise rotation and a path width of about

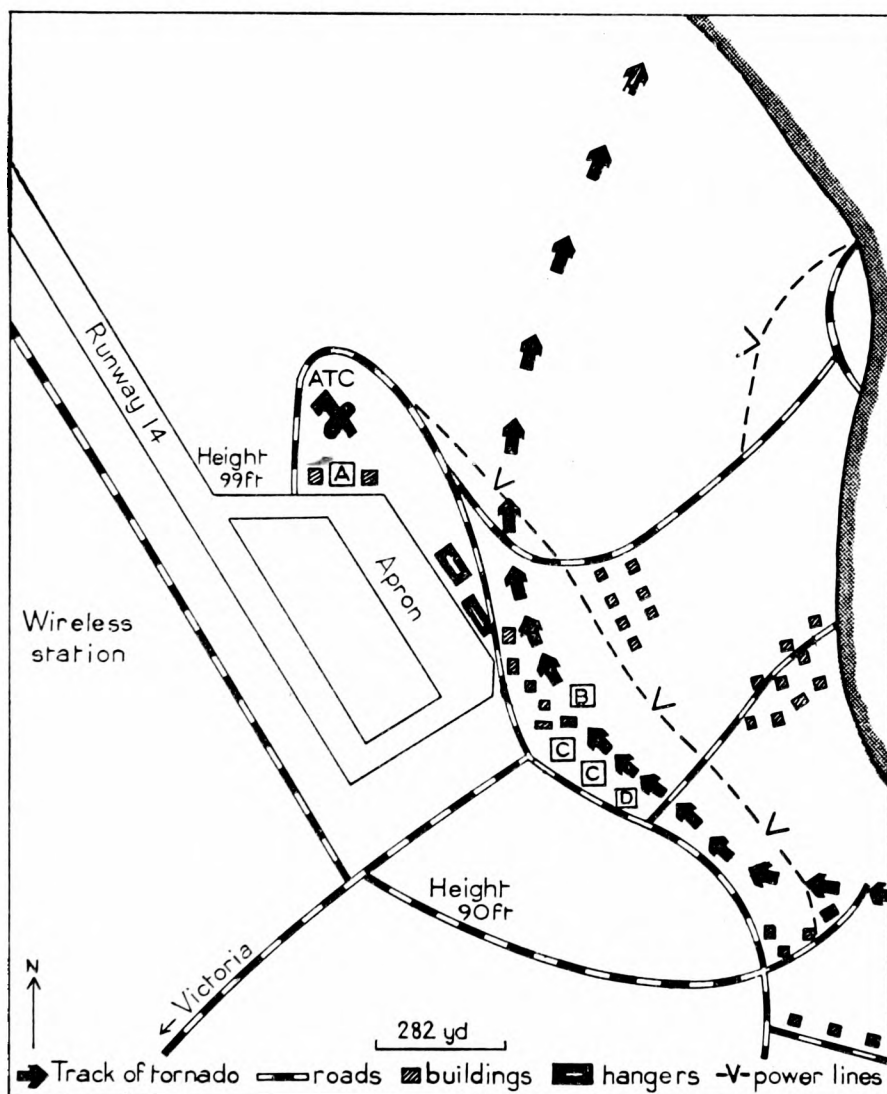


FIGURE 1—TRACK OF TORNADO ON LABUAN ISLAND, 25 JULY 1963

A—Pressure-tube anemograph;  
 B—Demolished hut and two radio masts;  
 C—Derofed corrugated-iron long houses; D—Uprooted tree.

10 to 20 yards. It was seen to move initially to the north-west with a speed of about 20 to 25 knots, and then it recurved to the north-east. During its passage pieces of corrugated iron (6 feet by 4 feet) were whirled around at about 800 feet above the eastern edge of the airfield and carried half a mile before being deposited on the ground, whilst two large corrugated-iron 'long houses' were completely deroofed and the iron wrapped round the power lines nearby, cutting off the electricity supply to the Labuan Hotel, the airfield and nearby houses. In addition a large tree near the site of the long houses was uprooted, a Valetta aircraft parked on the apron was revolved through 180 degrees without damage, one small wooden hut was moved about 100 yards and demolished and two small wooden houses were almost demolished. The gutters of most stone-built houses in the area were ripped off and two large wireless aerials were carried away—half of one was never recovered. Some of the damage is shown in Plates II and III.

The weather leading up to the tornado was as follows. During the early afternoon of the 25th, the usual large cumulonimbus cloud formed near Mount Kinabalu (see Figure 2). A large anvil developed by 1500 local time

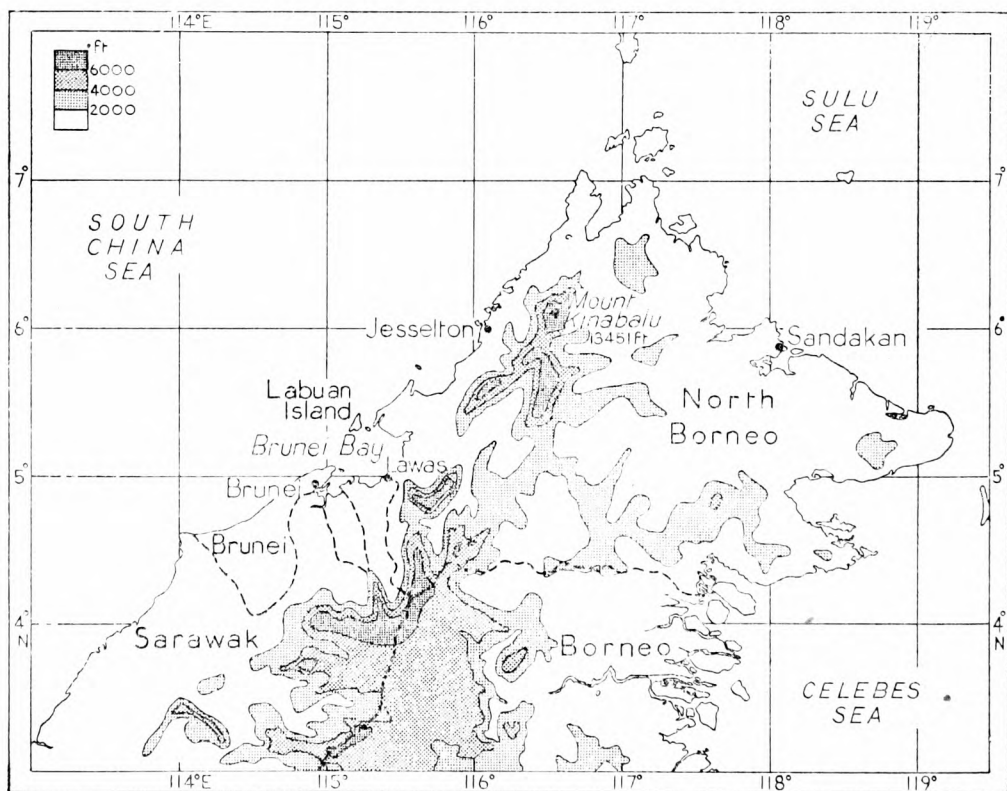


FIGURE 2—MAP OF THE AREA

and a cirrus canopy streamed downwind with the upper-level winds in the direction of Labuan Island. The main cloud appeared to be propagating south-south-westwards towards Lawas and Brunei and some high ground was covered in cloud. Otherwise the predominating cloud was cumulus mediocris until about 1600 local time, when another cumulonimbus developed over Brunei to the south-west of Labuan and amalgamated with the one formed earlier.

By 1700 local time a solid wall of cumulonimbus cloud had developed to the south of Labuan with almost 8/8 of anvil cirrus and by 1730 the now solid mass of dark cloud was only a few miles to the south of the airfield. Even at this time there was no real evidence of any particularly unusual phenomenon approaching, nor was a funnel cloud observed, but at 1745 the westerly sea breeze of 11 to 14 knots changed rapidly to 150 degrees and a sustained squall of 36 knots was registered on the anemograph. It is thought that this reading was a serious underestimation of the true wind because the anemometer was obstructed by trees. The Air Traffic Controller and the local meteorological observer estimated that the maximum gusts near the air traffic control building exceeded 60 knots. There was some suggestion that a line-squall moved from the south-west, because at 1750 local time the hygrograph showed a marked rise in humidity from 76 to 92 per cent whilst the thermograph showed a fall from 86 to 79°F. Little or no rain fell until 1800 local time but by 2000 1.4 inches of rain had been recorded with 1 inch falling between 1900 and 2000.

551.593.653:551.594.5

## **NOCTILUCENT CLOUD AND AURORA**

By F. D. BYRNE

It is not often that noctilucent cloud is visible at the same time as an aurora. Paton reports (with photographs) such an observation on 24–25 July 1950<sup>1</sup> at Abernethy, Perthshire, and I was fortunate to see this rare occurrence at Lerwick during the night of 30–31 July 1963.

The noctilucent cloud was first visible at 2245 GMT towards the west-north-west, extending from an elevation of 18° in the north-west to 26° in the west, and covering about 1/16 of the sky. It was silvery white in colour and very clear, with traces of normal cirrus, appearing dark, below it. As the sun descended lower below the horizon the noctilucent cloud lost much of its luminosity, and at midnight was barely discernible, but by then an auroral arc was also visible towards north-north-east, at a maximum elevation of 6°. This arc was faintly red in the north becoming yellow green in the north-east, bright but inactive. At 0030 the auroral arc was red at the base and yellow-green at the top, now with rays of moderate brightness, and the noctilucent cloud was becoming brighter.

Between 0030 and 0130 GMT the noctilucent cloud became brighter, and the aurora apparently weaker as the sunlight increased in the north-north-east sector. The noctilucent cloud was in almost the same position as at 2245, but it had become more patchy and less fibrous than before. By 0215 it had spread or increased to south of west and extended from approximately north-west to west-south-west, still at the same elevation, and still less than 1/8 in amount.

Auroral arcs are usually seen from Lerwick in a direction slightly west of north, but in this direction there may have been too much light for it to be visible, and only the eastern section was sufficiently bright to be seen. The Lerwick magnetograms indicate that the aurora probably began at midnight, reached its maximum around 0045 GMT and decreased slowly afterwards.

The best time for observing noctilucent cloud is when the sun is 6° to 7½° below the horizon. At this time, around 0230 GMT, the amount of cloud appeared to increase until the amount was at least 1/8, and it resembled a mixture of

cirrus and cirrocumulus: it was very distinctive and extended from north-west to west-south-west. Thereafter as the sun rose the cloud seemed to lose its texture and the impression of great height, until by 0330 it was no longer distinguishable from ordinary cirrus.

Those of us who have definitely observed noctilucent cloud this summer realize that we have probably seen it previously, and reported it as cirrus type cloud without really knowing what it was. If there is no moon it is not difficult to recognize, because noctilucent cloud appears bright against a darker sky, while lower cloud appears dark against a brighter sky. Our attention was drawn to these clouds by an excellent account of noctilucent cloud in the *Scientific American* by R. K. Soberman.<sup>2</sup>

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2. SOBERMAN, R. K.; Noctilucent clouds. *Sci. Amer., New York*, **208**, 1963, p. 50.

#### REVIEWS

*Experimentelle Untersuchungen mit Hilfe von ionisierenden Strahlen und Neutronen zur Bestimmung der witterungsbedingten Wachstumsintensität von Kulturpflanzen am natürlichen Standort*, by Kurt Unger. 9½ in. × 6 in., pp. 75, illus., Akademische Verlagsgesellschaft Geest & Portig K. -G., Leipzig, 1963. Price: DM 12.

The relationship between plant development and environment is of great theoretical and practical importance but in spite of much effort our present knowledge is very sketchy. This is largely because the problem has been examined in very general terms; meteorological parameters have been compared with total yields or with the development of the plants to certain specified phenological stages. Now that more sophisticated instruments permit a detailed recording of the micrometeorology of a crop stand, any improvements in the recording of plant growth should lead to a rapid extension of our knowledge of the relation between the two. So far, the only practicable method of estimating the increase in the mass of a plant has been to uproot and to weigh it. The removal of plants from a stand leads to changes in the environment and it is therefore most desirable that the growth be estimated *in situ*.

This publication is largely devoted to a description of instruments which can be used for this purpose. These are based on the principle that the attenuation of  $\beta$ -,  $\gamma$ -, and X-rays can be used as an estimate of the mass of material through which they are transmitted. Two types of apparatus are described; the first is used in estimating the development of individual plants which have a closed head, such as a lettuce or cabbage. This consists of a portable bow-shaped apparatus which is placed over the plant so that the radio-active source is on one side of the plant and the detector on the other. Two methods have been used to estimate the growth rate of plant stands. In one, a circular field was divided into 12 sectors, each containing a crop; at the centre <sup>60</sup>Co (a radio-active isotope of cobalt) was used as a source of  $\gamma$ -rays; the transmitted radiation was measured on a scintillation counter which could easily be moved round the edges of the various plots. The second method involved the construction of a bridge over the stand; this moved along rails on each side of the stand, with the source and detector at stand level. The results from these types of measurement are normally expressed in mass per unit area. When



these were compared with a system of growth recording depending on the number of internodes (in peas) the correlation coefficient was as high as 0.825 and significant at the 1 per cent level.

Measurements of plant development have now been made for some years at Quedlinburg in Saxony for comparison with the micrometeorological records of temperature, evaporation, global radiation and soil moisture. The last named has been measured by neutron scattering. These measurements will be published in due course, but examples of the relationships which can be derived from them are given in this publication. Briefly it may be stated that the effect on growth of temperature and evaporation may be represented by cubic polynomials, and the effect of soil moisture and radiation by linear regressions. The four elements together can give a reasonable estimate of growth; the multiple correlation coefficient between observed growth and the theoretical growth due to these environmental factors is 0.83 and is significant at the 5 per cent level. Thus 69 per cent of the variation in growth can be accounted for by four environmental factors; the remainder is due presumably to other factors or to experimental error.

This publication is of interest mainly to those concerned with the principles of the instrumentation involved in the detailed estimation of the variations in growth rate during the life of individual plants or stands of plants. Those who are more interested in the results of measurements already made will look forward to their appearance.

W. H. HOGG

*The physical geography of the sea and its meteorology*, by M. F. Maury. Edited by John Leighly, 9 $\frac{1}{4}$  in.  $\times$  6 in., pp. xxx + 445, *illus.*, Harvard University Press, Cambridge, Mass. Price: 68s.

The modern layout and excellent standard of production of this book make it necessary to emphasize at once that it was originally published more than a century ago and that it is now being republished for its historical interest—its ideas are not all acceptable today. However, it was written with the persuasive enthusiasm of a pioneering personality, and is very readable as an interesting piece of writing from the past, reflecting the interest and methods of an age twenty years before the Challenger Expedition of 1873–76.

The original book is no doubt available in various libraries but it has been chosen for republication as one of the John Harvard Library series which is financed by a permanent trust fund set up by Waldron Phoenix Belknap, Jr. The series is intended to make rare books and documents about the American cultural past more readily available to scholars and the general reader at a reasonable price.

This reissue of Maury's book will appeal to the historian or librarian of science, to all who are interested in American cultural history, and to the meteorologist or oceanographer with time for leisure reading. Such is made clear in an admirable 30-page introduction by the editor, John Leighly, Emeritus Professor of Geography, University of California, Berkeley. In this introduction is an account of the origin of the book, a summary of the reviews made in the years when the book was new, and a modern appraisal which makes the reader aware of the major criticisms of the scientific content of the book.

The following useful background to the book is based on Professor Leighly's introduction. From 1842 to 1861 Matthew Fontaine Maury was superintendent of the United States Navy Depot of Charts and Instruments (later called the Naval Observatory and Hydrographical Office). He arranged to extract observations from log-books of Naval vessels and in 1847 he issued the first of his 'Wind and Current Charts' for use in the navigation of sailing ships. The average time for a voyage from England to Australia was reduced from 124 days to 97 days when these charts were used, and therefore navigators were keen to co-operate when he made arrangements for special charts and forms to be used on board ship for recording observations. Maury played a leading part at an international maritime conference in 1853 at Brussels whereby ship observations were organized on a world wide basis. From this conference arose the official weather services of many countries including the British Meteorological Office under Admiral FitzRoy who had considerable correspondence with Maury. The 'Wind and Current Charts' were augmented by 'Explanations and Sailing Directions,' which also contained various articles written by Maury. The 'Sailing Directions' grew larger with every edition and eventually, for copyright protection, some of the contents were published in 1855 as '*The Physical Geography of the Sea.*' Many editions followed, both in America and elsewhere. The eighth and last American edition of 1861 is used for this republication in 1963. (In the Meteorological Office Library there is a copy of an English edition of 1855—'second edition enlarged and improved'—issued by the authorized British publishers, Sampson Low, Son and Co. The Library also possesses a set of the 'Wind and Current Charts' and an edition of the 'Sailing Directions'.)

The book itself is described in Maury's own introduction as being concerned with presenting, in an interesting and instructive manner, "a philosophical account of the winds and currents of the sea, of the circulation of the atmosphere and ocean, of the temperature and depths of the sea, of the wonders that lie hidden in its depths, and of the phenomena that display themselves at its surface.... its salts, its waters, its climates and its inhabitants, and of whatever there may be of general interest in its commercial uses or industrial pursuits".

The twenty-two chapters often seem haphazard but are packed with information and comment about the ocean and the atmosphere above it. After an introductory chapter on the sea and the atmosphere there are two chapters on the Gulf Stream—"the weather breeder". It is interesting to find that Dr. Franklin proposed to use sea temperature as a navigational aid, especially in the Gulf Stream area near the American coast, and that Rhode Island captains, by knowing how to avoid the Gulf Stream, were able to make better east-west Atlantic crossings than English captains. The currents of the atmosphere (trade winds, calm belts, and land and sea breezes) are then described and discussed at length in several chapters, although not always correctly. It is interesting to see red dust from the desert being quoted as a, "tally of the invisible air". The currents of the sea are next discussed, with an interesting account of the specific gravity of the sea, the salts of the sea, icebergs, whales and microscopic animalcules. Chapters on cloud at sea and on the interaction of winds and land masses are then followed by an account of the difficulties of deep sea soundings and the practical means of overcoming them. There are also descriptions of the types of minute shells obtained from the depths, and their

microscopic examination. (At one time Maury had in mind a 'picture chapter of the sea' and published drawings of microscopic organisms in the 7th and 8th editions of the *Sailing Directions*.)

Winds over sea routes and monsoons are then treated; with chapters also on sea temperatures and tide rips. Sperm whales are associated with warm water currents as shown on a chart of 'Sea drift and Whales,' while the right whale is found in cold water. Storms, hurricanes and typhoons are then discussed; some of the last chapters deal with winds in the southern hemisphere, and the climate of Antarctic regions. The book concludes with a chapter on temperature at different depths.

Professor Leighly points out that Maury presents in convenient form a map of the temperature of the surface water of the Atlantic (Figure 9) and also a map of the relief of the bottom of the Atlantic. Such maps were produced from original material prepared under Maury's direction for the 'Wind and Current Charts' and the 'Sailing Directions,' and represented an important step forward in the knowledge of the sea. Important information is also given on the sediments of the deep sea as shown in samples brought up by Brooke's sounding apparatus. The scientific weaknesses of the book lie in the more general speculations and hypotheses, and there the reader must weigh each paragraph carefully and distinguish fact from fancy. Thus an American meteorologist Frank Waldo said in 1893, "Maury showed his strength by collecting and mapping the normal winds of the oceans but shows his weakness in speculating on a philosophy of their origin". Although as a scientific treatise the *Physical Geography* fell below the level of the best contemporary knowledge, the rhetorical devices of popular writing made it a readable book for many. Its Biblical quotations and its many references to natural phenomena as examples of divine design even resulted in a favourable review in the *Christian Examiner* of 1856.

The original book contained several maps and tables and these have been well reproduced in this edition—in some cases in a slightly smaller form than the original to avoid 'fold out' maps. A useful index has been added by the editor who has also explained the minor changes which he has made to help the reader of today. The book can be recommended as an authoritative republication of a work by a famous American pioneer of oceanography and meteorology.

W.S.G.

## HONOUR

H.M. The Queen has approved the award of the Polar Medal to Mr. M. J. Blackwell for service as Senior Scientific Officer with the British Antarctic Survey during the 1959–60 season.

## METEOROLOGICAL OFFICE NEWS

### **Gift from the Ghana Meteorological Services to the Meteorological Office**

The Meteorological Office has received from the Ghana Meteorological Services, through the Office of the High Commissioner for Ghana in London, a gift of a wood carving of a drummer and talking drums, together with a strip of 'Kente' cloth, the Ghana national costume. The carving, which is about 10 inches high, is illustrated in Plate IV.

This gift has been made in appreciation of the services of the Meteorological Office Training School to the Ghana Meteorological Services in recent years and to mark the occurrence in 1960 of the 25th anniversary of the Training School.

In the letter accompanying the gift, Mr. F. A. A. Acquah, the Director of the Ghana Meteorological Services, says "The talking drums, by tradition, are used both as means of communication and on festive occasions in Ghana. It is my sincere wish that the sound of these drums and the bright colours of the 'Kente' perpetuate the close, warm and fruitful relations that exist between the United Kingdom Meteorological Office and the Ghana Meteorological Services."

I have accepted this gracious gift on behalf of the Office and I reciprocate the good wishes of the Ghana Meteorological Services. This splendid work of art will form a unique addition to our collection of historic objects and will be put on display, at first in the Headquarters at Bracknell and later at the Training School.

O. G. SUTTON

**Retirement.**—The Director-General records his appreciation of the services of:

Mr. H. L. Wright who retired from the Meteorological Office on 30 November 1963 after more than 36 years service. He was educated at Roborough School, Eastbourne and Kings College, London. After leaving Kings College with a first class honours degree in mathematics and a Drew gold medal he joined the Meteorological Office in 1927. Here he developed an interest in suspensoids in the atmosphere and their effect upon visibility. From Kew he was posted first to Eskdalemuir and then to Larkhill. His interest in visibility continued and led to a number of important papers. For this work he received the Buchan Prize of the Royal Meteorological Society in 1941.

In 1936 he was posted to Iraq where he served for two years. Following some short spells of duty with the Admiralty, the outbreak of war led to his return to the Middle East in 1940 where he served at various places until 1945, first as a civilian and later as a Squadron Leader. He was mentioned in dispatches in 1945. During this Middle East tour Mr. Wright was, for a time, Director of the Palestine Meteorological Service.

On return to the United Kingdom he was placed in charge of the branch responsible for supervising the upper air stations. This posting lasted for nearly three years and was followed by a spell of nearly the same length in the personnel branch. There followed two years in charge of one of the branches serving the Royal Air Force. In 1952 Mr. Wright again went abroad, this time as Chief Meteorological Officer at SHAPE (Supreme Headquarters Allied

Powers in Europe). On completion of the normal two year tour in that post he returned to this country with promotion to Senior Principal Scientific Officer to fill the post of Assistant Director (Staff and General). His last posting came with the reorganization of the Office in 1957 when he was placed in charge of Techniques and Training. It was fitting that after a career in which the early years were distinguished by his personal contributions to the science of meteorology his final post should have seen him in charge of the technical education of the younger members of the Office. His final year of service also saw him elected as a Vice-President of the Royal Meteorological Society in recognition of his services as Editor of *Weather*.

Throughout his career as a professional meteorologist 'Lionel' (I never heard him addressed by his first name) maintained an unruffled and urbane exterior. He was always ready to assist others. He has elected to retire from the Office at an earlier age than most and his many friends and colleagues will hope that he will enjoy a long and happy retirement.

A.C.B.

### CORRIGENDA

*Meteorological Magazine*, January 1964, page 8, line 24: for 'decreased' read 'increased'; page 12, Table I (a), line 6: delete 'Date of absolute minimum' and insert 'Date/time (GMT) of absolute minimum'; under columns headed '4 inches' and 8 'inches' after '24th' add '0900'.

*Meteorological Magazine*, March, 1964, page 74: under Figure 3, for 'July' read 'January'.

### OFFICIAL PUBLICATION

#### SCIENTIFIC PAPER

No. 18—*Airflow around a model of the Rock of Gibraltar*, by J. Briggs, B.A.

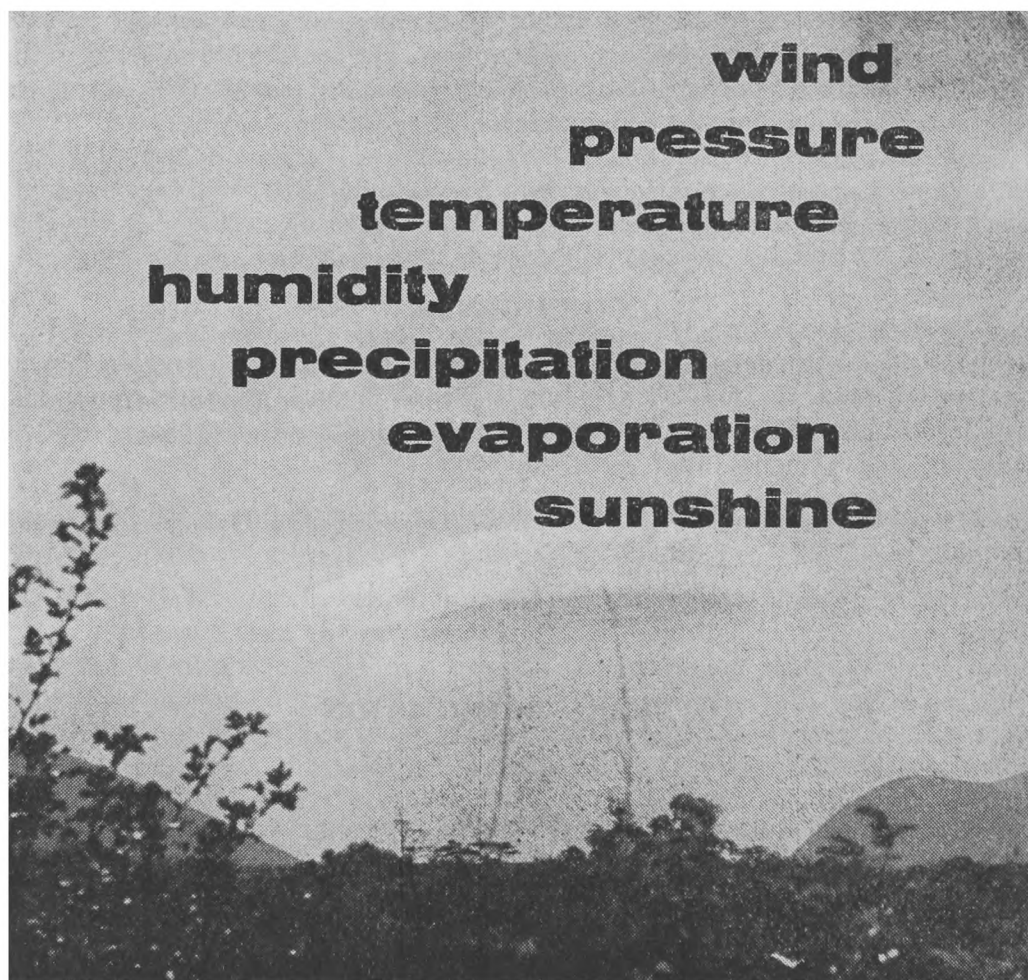
For certain adverse winds, those from south-east through south to south-west, severe turbulence in the lee of the Rock of Gibraltar can affect the runway at North Front, and also the approaches to the runway. This paper gives an account of wind-tunnel work designed to map out the areas of strong turbulence near the runway for these adverse winds.

Diagrams are presented which indicate the likely areas of rough and smooth air, at heights between 500 and 3500 feet and for winds between south-east and south-west, near the runway. The diagrams are based on observations of the fluctuations of smoke in the airflow around a scale model of the Rock.

A theoretical discussion of the relation of model airflow to real airflow suggests that the diagrams can give useful indication of the turbulent areas in the lee of the actual Rock.

# **METEOROLOGICAL INSTRUMENTS**

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# THE METEOROLOGICAL MAGAZINE

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## FREQUENCY OF DENSE AND THICK FOG IN CENTRAL LONDON AS COMPARED WITH FREQUENCY IN OUTER LONDON

By J. H. BRAZELL, M.Sc.

**Summary.**—Tables are given comparing fog frequencies for central London (Kingsway) with those for outer London (Kew, Heathrow and Croydon) over a period from 1947 to 1962. In general, it was confirmed that dense and thick fog occurred less frequently in central London than in the suburbs because of the heating effect of the heavily built-up area. The dates of the introduction of smoke control in various boroughs indicate that smoke abatement may be a factor contributing to the marked decrease in the frequency of dense fog in central London over the period.

**Introduction.**—By international agreement fog is defined as visibility below 1100 yd but, in general, it does not become a major hindrance or nuisance to the public until the visibility falls below 220 yd. Therefore, discussion in this note is confined to thick fog, defined as visibility less than 220 yd, and dense fog, defined as visibility less than 55 yd. In 1938 Bilham<sup>1</sup> pointed out that during foggy weather visibility is often better in the centre of a large city than it is in the adjacent suburban and rural districts, and he attributed this effect to the fact that large buildings in a built-up area act as a source of heat and tend to reduce radiation from the ground. In 1959 Shellard<sup>2</sup> showed that the frequency of visibility below 220 yd, during the decade 1947–56, was less at Croydon than it was at Kingsway, but that the Kingsway frequency was much less than the frequency at either Kew or London (Heathrow) Airport. The object of this note is to examine the relative frequency of dense and thick fog in central and outer London in more detail and over a longer period than was done by Shellard.

**Data.**—Table I gives the annual number of hours of dense and thick fog at Kingsway, London (Heathrow) Airport and Kew during the 16-year period 1947–62 and at Croydon during the 12 years 1947–58. The frequencies for Heathrow (1947–62) and Croydon (1947–56) are based on hourly observations but the Kingsway figures (1947–62) are based on 3-hourly observations only, assuming, as Shellard did, that each observation represents 3 hours of fog in the same range. Doubts may be expressed about the validity of this assumption, but Kelly<sup>3</sup> has shown that the error introduced by using 3-hourly observations to estimate the total number of hours of persistent fog is an over-estimation of only about 4 per cent, and Shellard has demonstrated that

TABLE I—ANNUAL NUMBER OF HOURS OF DENSE AND THICK FOG AT KINGSWAY, LONDON (HEATHROW) AIRPORT AND KEW 1947-62, AND AT CROYDON 1947-58

Year	Kingsway		Annual number of hours of fog Heathrow		Kew		Croydon	
	Dense	Thick	Dense	Thick	Dense	Thick	Dense	Thick
1947	24	81	48	195	84	180	21	61
1948	36	126	61	263	126	300	90	175
1949	15	51	61	206	156	282	3	65
1950	30	57	52	164	138	234	16	65
1951	12	51	55	163	78	234	40	117
1952	75	99	88	193	102	204	38	111
1953	24	69	77	337	54	396	44	177
1954	3	12	12	96	24	102	16	43
1955	6	33	29	152	42	102	15	54
1956	27	90	68	206	84	198	39	122
1957	9	27	40	120	54	126	18	42
1958	9	36	51	243	54	258	72	312
1959	21	99	98	254	132	270		
1960	6	27	21	110	24	132		
1961	0	27	40	147	24	144		
1962	30	78	84	183	174	282		
Period								
Average annual number of hours of fog								
1947-50	26	79	55	207	126	249	33	91
1951-54	29	58	58	197	65	234	35	112
1955-58	13	47	47	180	59	171	36	133
1959-62	14	58	61	173	89	207		
1947-56	25	67	55	197	89	223	32	99

Note: Heights above mean sea level are: Kingsway 65 feet, Heathrow 80 feet, Kew 18 feet, Croydon 217 feet.

a very good estimate of annual fog frequency can be obtained from 6-hourly observations. Using the method adopted by Shellard, the annual frequencies of thick and dense fog at Kew, and at Croydon during the years 1957 and 1958 were obtained from the available fog frequencies for the four hours 0300, 0900, 1500 and 2100 GMT published in the annual summary to the *Monthly Weather Report*.\* (The 0300 GMT fog frequencies for Kew, and for Croydon during the year 1958 were not available and had to be estimated by multiplying the appropriate 0900 GMT frequencies by the ratio between the 0300 and 0900 GMT frequencies for Heathrow in the case of Kew, and South Farnborough in the case of Croydon.) It must be pointed out that the frequencies of dense fog at Kew for the period 1949-62 and at Croydon for the years 1957 and 1958 refer to visibility below 44 yd.

Table II shows that the 1947-56 average annual frequencies of dense and thick fog at Heathrow and Croydon, based on hourly observations, agree very well with Shellard's frequencies which were based on observations at the four standard hours 0300, 0900, 1500 and 2100 GMT. The reason for the slight variation in the figures for Kew is that Heathrow observations were used to estimate the Kew 0300 GMT frequencies for this article whereas Shellard used the Croydon observations. It is considered that Heathrow is more representative than Croydon of conditions at Kew. Allowing for the different visibility

\* Meteorological Office. *Monthly Weather Report. Summary for the Year*. London, HMSO.



TABLE II—COMPARISON OF TABLE I FIGURES FOR 1947–56 WITH PREVIOUS WORK

Visibility in yards, less than	Kingsway		Heathrow		Kew		Croydon	
	55	220	55	220	44	220	55	220
	<i>Average annual number of hours of fog</i>							
1947–56 (See Table I)	25	67	55	197	89	223	32	99
Visibility in yards, less than	44	220	44	220	44	220	44	220
	<i>Average annual number of hours of fog</i>							
1947–56 (See Shellard <sup>2</sup> )	19	126	46	209	79	213	25	104

limits used and the slightly different period, the average annual frequency of dense fog at Kingsway during the decade 1947–56 agrees with that given by Shellard, but there is a marked disagreement in the frequency of thick fog. The frequency quoted by Shellard is based on information extracted from the Kingsway observation registers by an outside body. A comparison of the information extracted by this unit with the observation registers showed that, presumably because of a misunderstanding of the visibility code, they had included a large number of occasions of visibility equal to 220 yd (or between 220 yd and the next higher limit) in their frequencies of visibility below 220 yd for the period 1947–54. As a result the 1947–56 average annual frequency of visibility below 220 yd given by Shellard is much too high.

**Discussion.**—Table I shows that in every year from 1947 to 1962 the frequency of dense fog, and of thick fog, was less at Kingsway than it was at either Heathrow or Kew. During the period 1947–58, the frequency of thick fog at Kingsway was less than it was at Croydon in 11 years out of 12, and Kingsway had less dense fog than Croydon in 8 years out of 12. The lower frequency of dense and thick fog at Croydon compared with Heathrow and Kew is probably due to Croydon's higher altitude. It is interesting to note that, apart from a slight increase in the frequency of dense fog at Kingsway and Heathrow between 1947–50 and 1951–54, the 4-year means (Table I) show a continual decrease in the frequency of dense and thick fog at Kingsway, Heathrow and Kew during the period 1947–58 compared with a steady increase at Croydon.

Table III gives the average annual frequencies of dense and thick fog at Kingsway, Heathrow and Kew for the two 8-year periods 1947–54 and 1955–62. Comparison of these two 8-year means shows a decrease in the frequency of

TABLE III—AVERAGE ANNUAL NUMBER OF HOURS OF DENSE AND THICK FOG AT KINGSWAY, HEATHROW AND KEW DURING 1947–54 AND 1955–62 AND THE PERCENTAGE DECREASE

		Average annual number of hours of fog		Decrease per cent
		1947–54	1955–62	
Dense fog	Kingsway	27	13	52
	Heathrow	57	54	5
	Kew	95	73	23
Thick fog	Kingsway	68	52	24
	Heathrow	202	177	12
	Kew	241	189	22

thick fog of 24 per cent at Kingsway, 22 per cent at Kew and 12 per cent at Heathrow. However, the decrease in the frequency of dense fog is 52 per cent at Kingsway compared with 23 per cent at Kew and only 5 per cent at Heathrow. The lower frequency of fog in the centre of London, compared with the outskirts, is attributed to the heating effect of the heavily built-up central area, but it is extremely unlikely that an increase in this heating effect was the reason for the marked decrease in the frequency of dense fog at Kingsway for the period 1955-62.

Comparing the two 8-year periods 1947-54 and 1955-62, Table IV shows that there was no change in this heating effect during the winter 6 months as measured by the difference in mean temperature between St. James's Park and Heathrow, while the difference in mean temperature between Kingsway and Heathrow displayed an apparent decrease in the heating effect. However, the Kingsway observation site was moved in September 1959 from the roof of Victory House, where the thermometer screen was located in the centre of a cluster of buildings, to the roof of Princes House where the screen was placed on the edge of the building overlooking Kingsway. This change of site may be the main reason for the apparent decrease in the heating effect.

TABLE IV—COMPARISON OF MEAN TEMPERATURES FOR TWO 8-YEAR PERIODS

	Jan.	Feb.	Mar.	Oct.	Nov.	Dec.	Average of the six months
	<i>degrees Fahrenheit</i>						
1947-54							
Heathrow	39.4	39.2	44.0	52.0	45.2	41.7	43.6
St. James's Park	40.6	40.3	44.9	53.3	46.2	43.0	44.7
Kingsway	42.4	41.6	46.0	54.2	48.3	44.9	46.2
Difference (St. James's Park—Heathrow)	1.2	1.1	0.9	1.3	1.0	1.3	1.1
Difference (Kingsway —Heathrow)	3.0	2.4	2.0	2.2	3.1	3.2	2.6
1955-62							
Heathrow	39.5	40.1	44.0	52.5	44.8	40.9	43.6
St. James's Park	40.6	41.0	45.0	53.6	46.0	42.2	44.7
Kingsway	42.0	42.1	45.6	54.4	47.1	43.7	45.8
Difference (St. James's Park—Heathrow)	1.1	0.9	1.0	1.1	1.2	1.3	1.1
Difference (Kingsway —Heathrow)	2.5	2.0	1.6	1.9	2.3	2.8	2.2

The marked decrease in the frequency of dense fog at Kingsway compared with Kew and Heathrow may be due to a decrease in smoke pollution in the centre of London; 65 per cent of the observations of dense fog at Kingsway during the period 1947-62 were associated with calm conditions, and the wind was only 1 knot or less on 77 per cent of the reports of dense fog, which suggests that locally produced pollution may be more important than drifting pollution from outside the centre of the city. In this connexion, two factors must be considered, namely population changes and smoke control. During the post-war years many people have moved from central to outer London but the estimated decrease in population from 1947 to 1960 was only 4 per cent in the region within 2 miles' radius of Kingsway and only 3 per cent in the region within 4 miles. This slight decrease in population would probably have little effect on smoke pollution. The power to control smoke was given to local authorities in the Clean Air Act of 1956, but the City of London already possessed this power under the City of London (Various Powers) Act of 1954.

Table V gives the date when smoke control commenced, and the percentage number of premises and dwellings covered by smoke control at the end of 1958, 1961 and 1962 for the Local Authorities within a 3-mile radius of Kingsway, Kew and Heathrow. In the case of Local Authorities who only partly fall within one of these circular areas, a rough indication of the percentage of the borough or district within the area is given in Table V, but Local Authorities with less than a quarter of their region within one of the circular areas have been excluded. Table V shows that, in general, smoke control commenced earlier and progressed faster in the regions around Kingsway than it did in the regions around Kew and Heathrow. Kingsway is situated near the boundaries separating the City of London, Westminster and Holborn; the City was a smokeless zone by October 1955 and smoke control commenced in October 1958 in Westminster and in September 1959 in Holborn, so that by the end of 1962 Holborn and about 40 per cent of Westminster were also smokeless zones. Kew is situated in the borough of Richmond close to the boundaries with the boroughs of Twickenham and Heston and Isleworth; in two of these boroughs smoke control commenced in 1960 but in Twickenham it did not commence until May 1961. By the end of 1962, only 25 per cent of Richmond,

TABLE V—PROGRESS OF SMOKE CONTROL IN GREATER LONDON

Local authority	Smoke control commenced	Percentage number of premises and dwellings covered by smoke control by:		
	date	end of 1958	end of 1961	end of 1962
<i>3-mile radius of Kingsway</i>				
City of London*	1 Oct. 1955	100	100	100
Holborn	1 Sept. 1959	nil	71	100
Westminster	1 Oct. 1958	1	17	41
Southwark	1 Nov. 1961	nil	5	11
Lambeth (40)†	1 Oct. 1959	nil	3	8
St. Marylebone	1 Oct. 1958	8	53	67
St. Pancras (70)	1 Sept. 1959	nil	11	11
Finsbury	1 June 1962	nil	nil	9
Shoreditch	1 Sept. 1959	nil	18	37
Bethnal Green (60)	1 Dec. 1960	nil	33	62
Stepney (45)	1 Nov. 1960	nil	9	20
Bermondsey (55)	1 Oct. 1958	1	11	27
Chelsea (70)	1 Nov. 1960	nil	21	41
Paddington (50)	31 Oct. 1959	nil	18	33
Islington (60)	1 Sept. 1960	nil	4	8
<i>3-mile radius of Kew</i>				
Richmond	1960	nil	2	25
Twickenham (45)	9 May 1961	nil	nil	6
Heston and Isleworth (60)	1 Oct. 1960	nil	8	14
Ealing (25)	1 July 1960	nil	11	20
Brentford and Chiswick	1 May 1960	nil	12	12
Barnes (75)	1 Nov. 1961	nil	12	22
<i>3-mile radius of Heathrow</i>				
Feltham (75)	1 Nov. 1961	nil	14	20
Staines (45)	1 Dec. 1960	nil	18	26
Yiewsley and West Drayton (90)	1 Dec. 1960	nil	19	37
Hayes and Harlington (55)	1 June 1958	1	39	51
Heston and Isleworth (45)	1 Oct. 1960	nil	8	14

\*The Port of London is not a smokeless zone, but "The Dark Smoke (Permitted Periods) (Vessels) Regulations" have been applied since 1 June 1958.

†The figures in brackets in the first column are the approximate percentages of the boroughs or districts within the 3-mile radius.

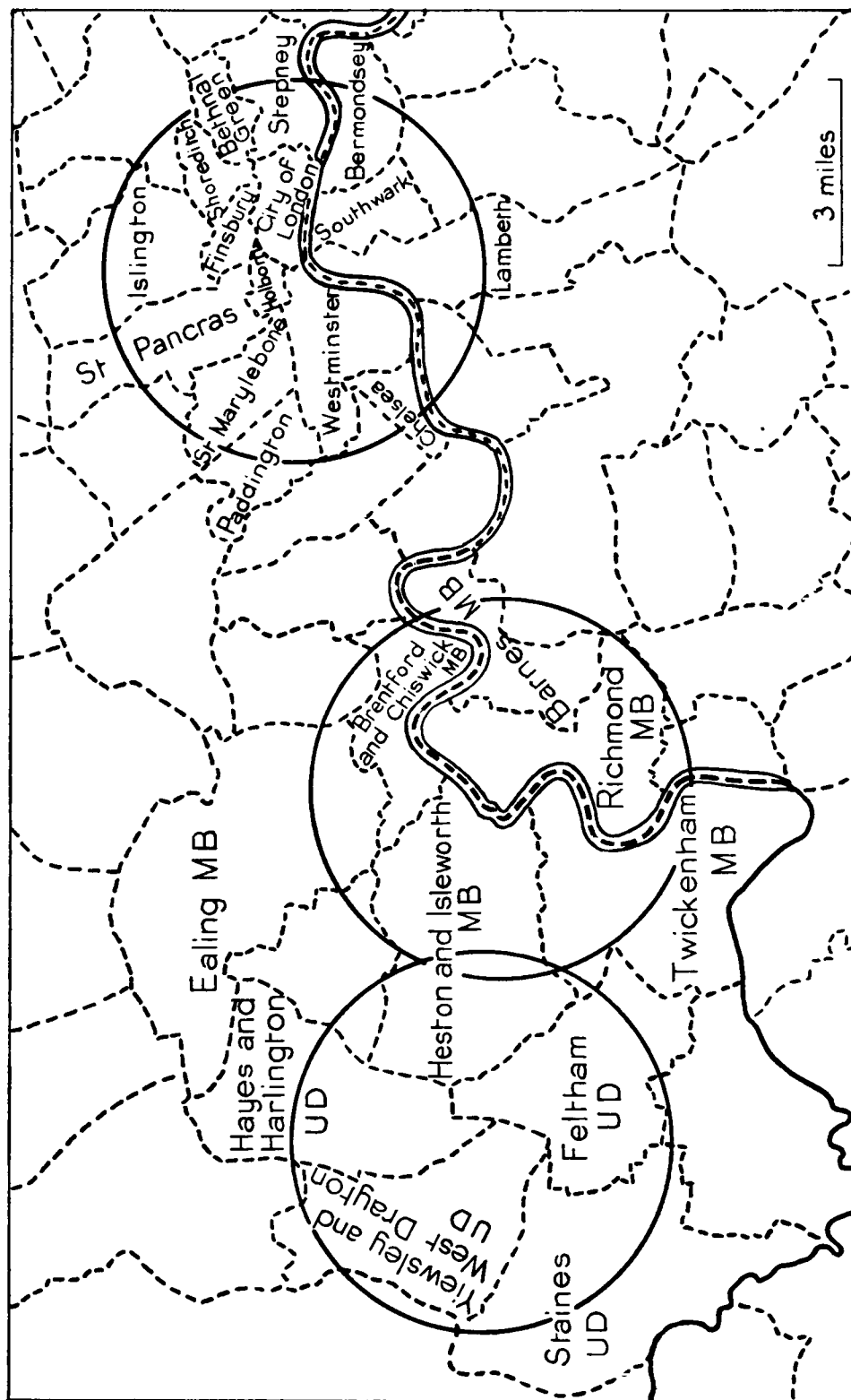


FIGURE 1—LOCATION OF AREAS MENTIONED IN TABLE V  
 Circles show the 3-mile radius areas round (left to right) Heathrow, Kew and Kingsway

14 per cent of Heston and Isleworth, and 6 per cent of Twickenham were covered by smoke control. Heathrow is in Yiewsley and West Drayton close to the boundaries with the urban districts of Hayes and Harlington, and Feltham; smoke control commenced in December 1960 in Yiewsley and West Drayton, in June 1958 in Hayes and Harlington, and in November 1961 in Feltham. By the end of 1962, smoke control applied to 37 per cent of Yiewsley and West Drayton, 51 per cent of Hayes and Harlington and 20 per cent of Feltham. It is clear that progress in smoke abatement has been substantially greater in the Kingsway area than it has been in the regions around Kew and Heathrow, and this may have been a contributory factor to the marked decrease in the frequency of dense fog at Kingsway for the period 1955-62. Figure 1 shows the location of areas mentioned in Table V.

However, dense persistent fog still occurs in central as well as in outer London. The last persistent fog was in December 1962, and it is interesting to compare the frequency of dense and thick fog at Kingsway and Heathrow during December 1962 with similar frequencies for December 1952 when there was an outstandingly persistent fog. Table VI gives the number of hours of dense and thick fog at Kingsway and Heathrow in the Decembers of 1952 and 1962. Comparison of the two Decembers shows that at Heathrow there is a decrease of about 11 per cent in the frequency of thick fog, but an increase of about 20 per cent in the frequency of dense fog, while at Kingsway there is a decrease of about 22 per cent in the frequency of thick fog and a marked decrease of about 57 per cent in the frequency of dense fog.

TABLE VI—NUMBER OF HOURS OF DENSE AND THICK FOG AT KINGSWAY AND HEATHROW IN DECEMBER 1952 AND DECEMBER 1962

	Kingsway		Heathrow	
	Dense fog <i>number of hours</i>	Thick fog	Dense fog <i>number of hours</i>	Thick fog
December 1952	69	81	61	113
December 1962	30	63	73	101

**Conclusions.**—During the period 1947-62, dense and thick fog occurred more frequently in the suburbs than in central London, except that there was a marked tendency for Kingsway to have more dense fog than Croydon during the first 6 years of the period. The frequency of both dense and thick fog tended to decrease during the 12 years 1947-58, but there was a gradual increase in the frequency at Croydon during this period. Smoke control may have contributed to the marked decrease in the frequency of dense fog at Kingsway for the period 1955-62.

**Acknowledgements.**—The author wishes to thank the various Local Authorities in the Greater London area who provided details of their Smoke Control programmes. He is also indebted to the Chief Meteorological Officer, London (Heathrow) Airport for the provision of fog statistics for Heathrow, and to the staff of the London Weather Centre for assistance in extracting and checking data.

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# MARKOV CHAIN MODEL OF COLD SPELLS AT LONDON

By J. E. CASKEY, Jr.

U.S. Weather Bureau, Washington D.C.

**Introduction.**—Because of the growing body of evidence that persistence found in many time series of meteorological data is well represented by a Markov chain, it is of interest to apply the model to some of the data in the interesting article by Lowndes<sup>1</sup> on cold spells at London. The model has previously provided useful representations of daily rainfall distributions for a wide variety of geographical and climatic situations (see Gabriel and Neumann,<sup>2</sup> Caskey,<sup>3</sup> and Weiss<sup>4</sup>). Persistence in a time series of wind directions also has been found by Barton, David, and Fix<sup>5</sup> to have characteristics of a multiple-state Markov chain.

**The probability of a cold spell continuing.**—In the Markov chain model, the probability of any day being a 'cold day' (defined by Lowndes' criteria) depends on whether or not the preceding day was a cold day. The probability is independent of earlier days. Thus, the probability of a cold spell of length  $n$  days continuing  $k$  further days is  $p^k$ , where  $p$  is the conditional probability that a day will be cold if the previous day was cold. Note that  $p$  is independent of  $n$ ; that is,  $p$  is a constant.

To be in agreement with this Markov chain probability relation, the probabilities for 'further day,' 'further 2 days,' 'further 3 days,' and 'further 4 days' in Lowndes' Table I should be equal to  $p$ ,  $p^2$ ,  $p^3$ , and  $p^4$  respectively, where  $p$  is a constant. Most of the values in his Table II(b), for the summer months, are indeed in excellent agreement with the relation  $p^k$ ; to good approximation, the probability for cold spells of various lengths continuing for a further day is constant,  $p = 0.80$ ; moreover, the probabilities for 2, 3, and 4 further days are well approximated by  $(0.80)^2 = 0.64$ ,  $(0.80)^3 = 0.51$ , and  $(0.80)^4 = 0.41$  respectively.

The agreement of the probabilities in Lowndes' Table II(a), for the winter months, with the relation  $p^k$  is less satisfactory. However, for cold spells of length 6 days or more, the probability of continuing a further day is approximately constant,  $p = 0.85$ ; with this value of  $p$ , the values of  $p^k$  for  $k = 2, 3, 4$  are 0.72, 0.62, and 0.52, again in good agreement with Lowndes' values for 'further 2 days,' 'further 3 days,' and 'further 4 days' respectively. Although the Markov chain property does not hold as well for data in Table II (a) as for data in Table II (b), frequency distributions for the winter months may nevertheless be reasonably well represented by a Markov chain model by using an average value of  $p$ , approximately 0.84.

The values of  $p$  used in the following section are, in agreement with the above discussion, 0.84 for winter months, 0.80 for summer months, and 0.82 for the whole year.

**Frequency of cold spells of four days or more.**—In the Markov chain model, the frequency  $f_n$  of cold spells of length  $n$  days ( $n \geq 4$ ) is given by the following formula which is obtained by simple algebraic manipulation of equations in earlier papers:<sup>2,3</sup>

$$f_n = N(1 - p)p^{n-4}, n \geq 4,$$

where  $N$  is the total number of cold spells of length 4 days or more, and  $p$  is the conditional probability discussed in the preceding section. From Lowndes' Figure 2<sup>1</sup> the values of  $N$  are 162 for winter, 194 for summer, and 356 for the whole year. The respective values of  $p$  are 0.84, 0.80, and 0.82, as selected in the preceding section.

With these values of  $N$  and  $p$ , the above formula was used to compute values of  $f_n$  which may be compared with those given by Lowndes' Figure 2. The comparison is made in our Table I. The agreement of Lowndes' frequencies with the computed frequencies appears to be sufficiently close, especially for cold spells 5 days or more in length, to justify using the Markov chain model as a simple representation of the frequency distribution of cold spells at London. The departure of the model frequency from the observed frequency of spells of 4 days in winter (also reflected in the whole year comparison) is not surprising in view of the correspondingly large departure of the first entry in Lowndes' Table II (a) from the average value of all entries on the first row.

TABLE I—COMPARISON OF OBSERVED FREQUENCY (LOWNDES' FIGURE 2) WITH COMPUTED MARKOV CHAIN FREQUENCY OF EACH LENGTH OF COLD SPELL

Length of cold spell in days	Winter months		Summer months		Whole year	
	Observed	Computed	Observed	Computed	Observed	Computed
4	38	26	39	39	77	64
5	24	22	26	31	50	53
6	15	18	27	25	42	43
7	14	15	23	20	37	35
8	10	13	17	16	27	29
9	8	11	11	13	19	24
10	9	9	11	10	20	19
11	5	8	6	8	11	16
12	4	6	6	7	10	13
13	6	5	7	5	13	11
14	2	5	5	4	7	9
15	5	4	1	3	6	7
16	1	3	4	3	5	6
17	3	3	0	2	3	5
18	5	2	0	2	5	4
19	1	2	3	1	4	3
20	3	2	1	1	4	3
21	2	1	3	1	5	2
22	0	1	1	1	1	2
23	0	1	2	1	2	1
24	0	1	0	0	0	1
≥25	7	4	1	1	8	6
Total	162	162	194	194	356	356

**Conclusion.**—The data on cold spells at London, given in Figure 2 and Table II of Lowndes' paper, may be approximated by a Markov chain model. The data for the summer months are particularly well fitted by a Markov chain in which the conditional probability  $p$  of a day being cold, if the preceding day was cold, is 0.80. The data for the winter months and for the whole year, excluding cold spells of length 4 days, are also well represented by a Markov chain in which  $p$  is 0.84 and 0.82, respectively.

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## SUBSIDENCE IN THE MIDDLE AND LOWER TROPOSPHERE— PART I

By C. J. BOYDEN

**Summary.**—A criterion for subsided air is adopted in terms of the dew-point depression at the 700 mb or 500 mb level. The existence and slope of a column of subsided air are related to sea-level pressure, the speed and vertical shear of wind, and the vertical gradient of potential wet-bulb temperature. The results are consistent with subsided air originating mainly in descent down the transition zone of a frontal surface, the dryness subsequently extending in depth by further subsidence.

[Part II of the paper examines more closely the history of subsided air from the time it descends a frontal transition zone until it settles in an area of high pressure. From a comparison between computed downward velocity and dryness it is seen that subsided air quickly moves away from its source. The lower boundary of the frontal mixing zone in air joining an anticyclonic circulation is identified with the anticyclonic inversion. Dry air over an anticyclone is found to exist primarily through advection, though subsidence within the circulation makes the greater contribution if the anticyclone becomes highly developed.]

**Introduction.**—Subsidence at any level is determined by the divergence in the underlying layers of atmosphere. It therefore takes place in regions which tend to retain their position relative to features of the flow pattern. However, since at most levels the wind speed is greater than the speed of the isobaric features, any subsided air is likely to be carried away from the part of the upper pattern where the subsidence took place. Only in a closed, slow-moving circulation, such as a persistent anticyclone, is subsided air able to remain subjected to subsidence.

This paper is concerned with the manner in which regions of subsidence and areas of subsided air (particularly at the 700 mb level) are related to the pattern of upper winds and more especially to the sea-level analysis. Subsidence is prominently associated with the frontal surface, where ascending air often has its counterpart in an underlying layer of descending air (see, for example, Sawyer<sup>1</sup>). There is also broad-scale subsidence over the anticyclone, particularly during the period of growth. These are two manifestations of subsidence which differ in character. Frontal subsidence takes place in a layer of air of much the same depth as a frontal transition zone, but it is accompanied by horizontal motion greatly exceeding the vertical descent, at least in the lower half of the troposphere; frontal subsidence at the 700 mb level extends over an area comparable in size with that covered by the frontal rain. Subsidence over an anticyclone, on the other hand, is more gradual than frontal subsidence and takes place more nearly in the vertical.

It will be shown that a substantial part of the subsided air in the lower troposphere originates at a frontal surface. In due course much of this air settles over developing anticyclones because these are systems over which the



wind speed decreases. Further subsidence takes place over the growing anticyclone because of broad-scale divergence, including frictional outflow, but only over the strong and persistent anticyclone is this component of the subsidence as large as the frontal subsidence to which the air was subjected before it joined the anticyclonic circulation. Accordingly, the term 'anticyclonic subsidence' will be applied only to the subsidence undergone by anticyclonic air after its surface circulation becomes closed.

In more detail the ideas which will be developed are as follows. Subsidence takes place down the transition zone of most warm fronts in the middle troposphere and mainly at this type of front. The subsided air normally found behind a cold front mostly arrives in that state from the upwind ridge and warm front. Subsided air over a ridge or cold anticyclone is located just below its bounding frontal surface, some further subsidence taking place through a great depth during and after the growth of the anticyclone. The transition from subsided air in a frontal zone to subsided air in a cold anticyclone is claimed to be one in which the lower boundary of the frontal transition zone becomes the inversion of the anticyclone. During this process there is a sinking towards the horizontal of the frontal and isothermal surfaces, and eventually turbulence in the lowest layers of the atmosphere exerts a controlling influence on the structure of the inversion.

This sequence of events was studied in relation to fronts and anticyclones existing in the winter months. The anticyclones were of cold origin and were not systems of great maturity. No attempt was made to follow the evolution of well established or semi-permanent anticyclones since it would have been difficult to determine the source of the air and moreover adiabatic assumptions would not have applied.

**The measurement of subsidence.**—Direct measurements of subsidence usually depend on the assumption that the air has a property which can be regarded as conservative for as long as the subsidence is taking place. It will be shown that subsidence can normally be regarded as a fairly rapid process up to the time the air becomes stagnant over a persistent high. Until this stage is reached it therefore seems justifiable to regard upper air temperature changes as adiabatic. There are then three main methods by which the air can be followed during subsidence. Each has certain advantages and disadvantages.

The conservation of potential dry-bulb temperature ( $\theta$ ) is commonly used because this element is measurable at high levels where a humidity measurement is no longer reliable enough to be used as a tracer. A drawback to  $\theta$  is that it takes no account of the latent heat of cloud and therefore assumes the atmosphere to be cloudless. When subsidence is being measured this may not be important. There is, however, a further limitation. All that can be measured by a local change of  $\theta$  is the component of motion perpendicular to isentropic surfaces. When subsidence takes place nearly along these surfaces, as frontal subsidence does, there is little indication in the change of the isentropic field.

The potential wet-bulb temperature ( $\theta_w$ ) is a refinement of  $\theta$  in that it takes into account the latent heat of evaporation and condensation. This advantage is one which counts for more when ascent of air is being studied than when the problem is concerned with descent. The important feature of  $\theta_w$ , unlike  $\theta$ , is that it persists during vertical motion as an identification of an air mass. But

there are two drawbacks to the use of  $\theta_w$  which are not possessed by  $\theta$ . Firstly, it is less sensitive than  $\theta$  in measuring vertical movement because in the average atmosphere its vertical gradient is smaller. Secondly,  $\theta_w$  requires a knowledge of humidity, an element difficult to measure accurately and one which cannot at present be estimated satisfactorily from radiosonde observations above mid-troposphere.

In the present investigation considerable use has been made of a quantity not far removed from relative humidity, namely the depression ( $\Delta$ ) of the dew-point below the dry-bulb temperature. Its great advantage over  $\theta$  and  $\theta_w$  is that it provides a measure of descent in the vertical, since isobaric surfaces are practically horizontal, and it is proportional to the height through which the air has descended from a state of saturation, regardless of the height or temperature at which the subsidence takes place. Since in cloudless air  $\Delta$  increases by nearly  $1^\circ\text{C}$  for each 100 m descent, it is a very sensitive measure of subsidence. As with  $\theta_w$ , its use is confined to the middle and lower troposphere and its precision is limited by the accuracy of humidity measurements. It is therefore desirable to consider how effectively  $\Delta$  can be used in the present investigation.

**The use of humidity measurements up to the 500 mb level.**—In the British radiosonde the humidity element is a strip of goldbeater's skin, which measures the relative humidity. It suffers from the disadvantages of hysteresis and lag. The magnitude of both effects has been studied by Glückauf.<sup>2</sup>

Glückauf concluded that hysteresis was small at relative humidities exceeding 70 per cent. As an example of the effect in air drier than this he found that, if the instrument read correctly a relative humidity of 10 per cent, its reading was about 8 per cent too low when the humidity was increased to 40–50 per cent. Hysteresis appeared to be independent of temperature in the range that is found below mid-troposphere over southern England in winter.

It is not easy to relate Glückauf's figures for lag to the readings obtained from a radiosonde. At medium humidities the time for half the magnitude of a sudden change of relative humidity to be recorded varied from 6 sec at  $0^\circ\text{C}$  to 18 sec at  $-11^\circ\text{C}$  (corresponding to a height rather above the 700 mb level in winter) and 42 sec at  $-27^\circ\text{C}$  (roughly the temperature at the 500 mb level). A somewhat greater lag was found when the relative humidity was very low. In terms of ascent by a British radiosonde, 10 sec corresponds to a rise of about 60 m.

As a partial safeguard against the use of unreliable humidities, the British practice is not to report a dew-point in certain circumstances. It is omitted on all occasions when the dry-bulb temperature is below  $-40^\circ\text{C}$ . At temperatures between  $-21^\circ\text{C}$  and  $-40^\circ\text{C}$  the dew-point is not reported for relative humidities lower than 10 to 35 per cent (depending on the temperature). At temperatures of  $-20^\circ\text{C}$  or higher the dew-point corresponding to 5 per cent is reported whenever the relative humidity is observed as 5 per cent or less. As a result of this procedure it was found that in the layer from 700 mb to 500 mb about 3 per cent of the dew-points in three winter months were indeterminate, though of course an upper limit for the dew-point was known on every occasion.

On the upper air ascents it was usually found that extremely dry air was concentrated in a shallow layer. On the majority of occasions it was therefore considered that over-estimation of the lowest dew-points, either because of the lag or because the dew-points were indeterminate under the reporting procedure, applied over too small a depth to have any material effect on the conclusions reached.

To a large extent the analysis has avoided the complications described above by regarding air as subsided when the dew-point depression was 20°C or more, without normally attempting to discriminate further. It should also be mentioned that in an analysis based largely on humidities at the two standard levels of 700 mb and 500 mb it is not profitable to seek great precision. The driest air is to be found at a variety of heights, and at the 700 mb level in particular the humidity may vary considerably with time simply because of small vertical movements of a layer in which the vertical gradient of humidity is large. In spite of this reservation it was found that when there was subsided air at 700 mb this was on the average the level of the driest air in the lower half of the troposphere. Thus if a single level is used for detecting subsidence in the lower troposphere, 700 mb is probably the best.

**Comparative subsidence at the levels of 700 mb and 500 mb.**—An analysis was made of radiosonde observations taken twice daily over the British Isles during January, November and December 1962. These months were chosen because there was a variety of weather over the British Isles and an absence of prolonged anticyclonic periods.

Table I shows the frequency of dew-point depressions ( $\Delta$ ) observed at all radiosonde stations in the British Isles. Figures in brackets give the number of indeterminate values included in the adjoining total. Almost all of these occurred when the dew-point depression at 500 mb exceeded 21°C and at 700 mb exceeded 30°C, and it was largely for this reason that  $\Delta \geq 20^\circ\text{C}$  was chosen as the criterion for subsided air.

TABLE I—FREQUENCIES OF DEW-POINT DEPRESSION IN RANGES OF 5°C OVER THE BRITISH ISLES IN JANUARY, NOVEMBER AND DECEMBER 1962

Level	Dew-point depression (°C)							
	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39
				<i>number of occasions</i>				
500 mb	332	579	347(1)	187(4)	144(40)	21	30(21)	0
700 mb	456	462	285	177	133	61	57(35)	6

Note: When the depression was 20°C or more the air was regarded as subsided. Figures in brackets give the number of indeterminate values included in the adjoining total.

Bearing in mind that indeterminate dew-points usually relate to a very narrow tongue within the subsided air, it is reasonable to regard them as of little significance in assessing the depth through which the air has subsided. (This was confirmed by a separate analysis of the Crawley figures, in which there were few indeterminate values.) It is then found that, on the average, subsided air (as defined) descended from a state of saturation through about 2½ km to both the 500 and 700 mb levels. This is equivalent to a little more than 150 mb down to the 500 mb level and about 200 mb to the 700 mb level.

Subsidence from 300 mb down to the 500 mb level, or from 400 mb to 700 mb, appears to be very rare. Moreover, all these figures should be regarded as over-estimating the average subsidence during a single development, since it is unlikely there would have been complete saturation when the subsidence began. Subsidence involving cloudy air would not of course be allowed for in Table I since the dew-point depression does not respond to the vertical motion of cloudy air.

**The association between subsided air at the 700 mb and 500 mb levels.**—Table I shows that for the British Isles as a whole, subsided air at 700 mb was shown on one report in six, and subsided air at 500 mb on one report in eight. These proportions apply only to the period examined and not to a single station. The question that next arises is whether subsidence is to be expected at both levels at the same time and if so whether one mass of subsided air is likely to lie vertically above the other.

To ascertain this an analysis was made of the reports from Aughton (Liverpool), this station being chosen because it is near the middle of the upper air network. In the three months there were 34 reports of subsided air at 700 mb over Aughton, and on 18 of these occasions it was also subsided there at the 500 mb level. Of the remaining 16 occasions there was subsided air at 500 mb over some part of the British Isles on all but 2.

Subsided air at 500 mb existed over Aughton on 30 occasions, 18 being those when the air at 700 mb also was subsided. Of the remaining 12 occasions there was subsided air at 700 mb over some other stations on all but 3.

Thus on 92 per cent of the occasions when there was subsided air over Aughton at either level there was subsided air over some part of the British Isles at the other level. (The 92 per cent may be contrasted with the chance probability of 51 per cent.) This 92 per cent comprises 52 per cent when there was subsided air at both levels over Aughton (and probably elsewhere) and 40 per cent when subsidence at the second level occurred elsewhere than over Aughton. The figure would certainly have been higher than 92 per cent but for the occasions when subsided air at one level escaped the observational network.

These results lead to the expected conclusion that subsidence takes place at much the same time at both levels, and since, as shown earlier, the descent is through the same average depth to both the 700 mb and 500 mb levels, it is reasonable to regard subsidence in the middle and lower troposphere as a single mechanism.

The figures also show that on nearly half the occasions of subsided air at 700 mb there was a slope to the tongue of subsided air. There are two causes of the slope and they are of equal importance. The first is that most subsidence takes place down the transition zone of a frontal surface. The second is that within the transition zone, between the 700 mb and 500 mb levels, there is a shear of wind in the direction of the surface front. Thus a tongue of air which subsides down a frontal surface subsequently tends to become aligned along the direction of the front. A cross-section perpendicular to a front therefore cuts through the tongue of subsided air, and if dry air is found at, say, the 700 mb level, the isopleths of dew-point depression are likely to be closed around it rather than to include the air at 500 mb (see, for example, Figure 2).

When such a tongue of subsided air enters an anticyclonic circulation it moves differently at different heights and the relationship between subsided air at the two levels becomes obscured. Nevertheless when subsided air at the 500 mb level over a well developed anticyclone is found vertically above subsided air at 700 mb its existence is usually due to anticyclonic subsidence acting both on the subsided air in the frontal transition zone and on the air above it.

**Potential wet-bulb temperature as evidence that subsidence is essentially a frontal development.**—A frontal boundary is defined in terms of a temperature gradient. The concentration of isothermal surfaces in the region of a front may be changed in position or strength by differential subsidence and there is then some doubt as to precisely where the frontal surface lies. The potential wet-bulb temperature ( $\theta_w$ ) is not altered by subsidence and is therefore an excellent parameter for maintaining historical consistency.

Figure 1 shows the distribution of  $\delta\theta_w$ , the difference in potential wet-bulb temperature between 500 mb and 700 mb, taken from the Crawley radiosonde ascents during the 6 months January 1961 and 1962, November 1961 and 1962 and December 1960 and 1962. The histogram shows frequencies for all occasions and separately for those when the air at 700 mb was subsided. All occasions taken together gave a mean  $\delta\theta_w$  of 3.1°C (median 2.5°C). This mean was based on frontal as well as non-frontal situations and for this reason alone is much higher than the 1–1.5°C which Belasco<sup>3</sup> found for various air masses in winter.

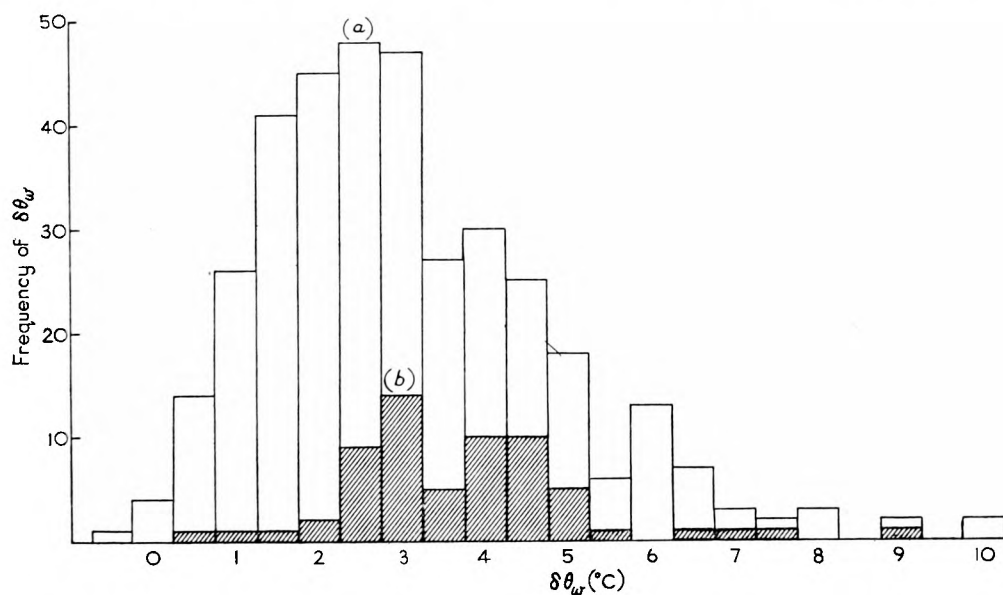


FIGURE 1—FREQUENCY DISTRIBUTION OF POTENTIAL WET-BULB TEMPERATURE DIFFERENCE ( $\delta\theta_w$ ) BETWEEN THE 500 MB AND 700 MB LEVELS DURING SIX WINTER MONTHS

(a) On all occasions and (b) on occasions when the air at 700 mb was subsided.

Taking only those occasions when the air was subsided at 700 mb (and perhaps also at 500 mb) the mean  $\delta\theta_w$  was found to be 3.7°C (median 3.4°C). Being

significantly higher than average this figure supports the thesis that when the air at 700 mb was subsided the air between 700 mb and 500 mb originated in a frontal zone. A feature of particular interest is that 84 per cent of the values of  $\delta\theta_w$  for subsided air lay between 2.5°C and 5.0°C, between which values there were 54 per cent of all observations. Within this range there was a 27 per cent probability that the air was subsided, as against 6 per cent outside it. Similar analyses on occasions when air was subsided at both levels gave much the same results.

A downward gradient of potential wet-bulb temperature somewhat greater than average is therefore likely to be found in subsided air, and it is almost a requirement that  $\delta\theta_w$  should reach at least 2.5°C.

In reaching this conclusion it is necessary to confirm that the larger values of  $\delta\theta_w$  did not occur because the selection of subsided air at 700 mb involved the selection of air with low  $\theta_w$  at that level. This proved not to be so since the mean  $\theta_w$  in subsided air at 700 mb was 7.4°C, as against 6.9°C for all occasions, whether subsided or not.

Another possibility to be considered is whether the high mean  $\delta\theta_w$  in subsided air could have been a consequence of the subsidence rather than a prerequisite. It is thought that this was not so because the same mean  $\delta\theta_w$  was found whether the air was subsided only at 700 mb or at both levels, and because  $\delta\theta_w$  depended little on the degree of subsidence of the air.

**Subsidence at a warm-front surface.**—Figure 2 depicts a cross-section ahead of a fairly typical warm front, based on the soundings from Camborne, Crawley and Hemsby at 0000 GMT on 20 December 1962. The frontal transition zone is shown by the concentration of isopleths of potential wet-bulb temperature and, as usual, the most highly subsided air is centrally placed in this band; the lower edge of the dry air zone is marked as a surface of subsidence. It will be observed that the isopleths of dew-point depression are closed below the 500 mb level, the subsided air aloft having been carried forward of the subsided air at 700 mb by the wind shear along the direction of the front.

This paper makes no attempt to discuss the causes of subsidence but it might be doubted whether the average pattern of divergence is such as to require the same amount of subsidence to both the 700 mb and 500 mb levels and yet be such as to halt the descent abruptly only a small way below the 700 mb level. However, it is not easy to establish whether the descent ceases where  $\Delta$  becomes small or whether  $\Delta$  is small, in spite of adiabatic warming, because frontal rain evaporates into the air subsiding down the transition zone. Whether the subsidence ceases or not the rain can be regarded as introducing a boundary to the dry air, and the average width of a warm-front rainband is such as to prevent dry air from appearing below the level of about 800 mb. Dry air might exist at lower levels in the transition zone if the rain belt were narrow or of negligible intensity, but then it is likely that the front would be thermally weak and the high-level wind shear required for subsidence would be absent. Since most dry inversions above the ground, whether directly associated with fronts or occurring in non-permanent anticyclones, are regarded as being of frontal origin, the comparative uniformity of the level at which they first appear is considered to be due to the uniform width of the band of frontal rain and the uniformity of frontal slope.

*Crown copyright*

PLATE I—THE TRANSMITTER OF THE CLOUD BASE RECORDER

The main chassis is shown out on tracks into the servicing position (see page 154).



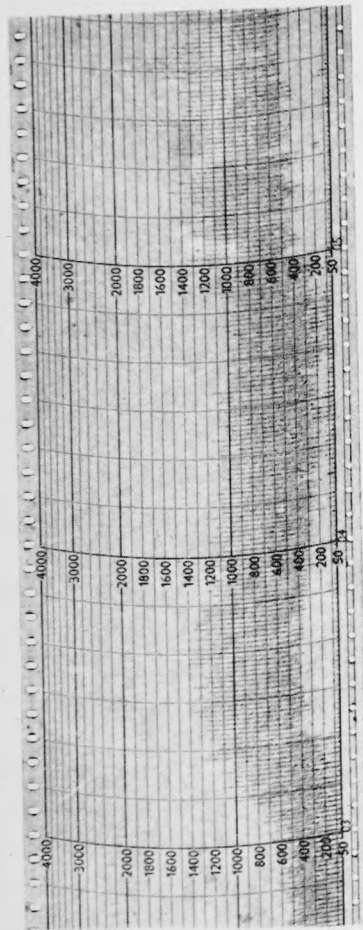


*Crown copyright*

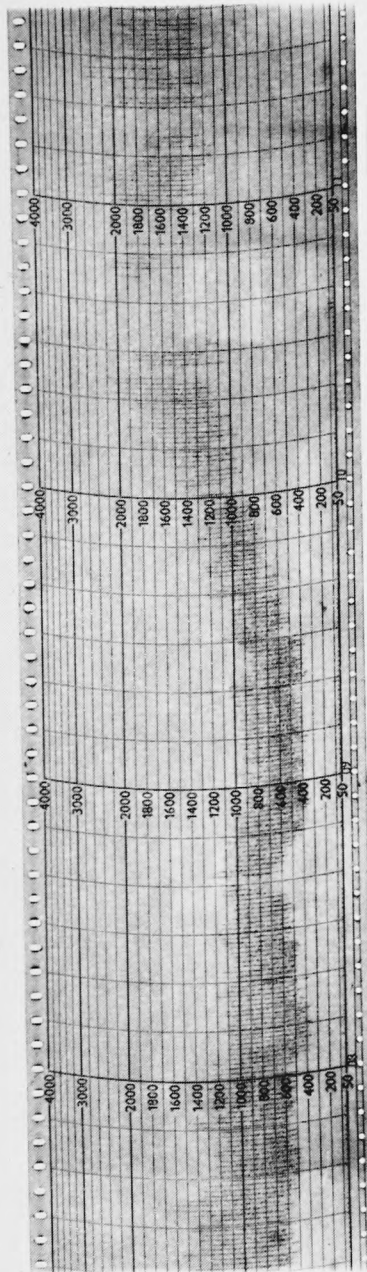
PLATE II—THE RECORDING UNIT OF THE CLOUD BASE RECORDER

See page 154.



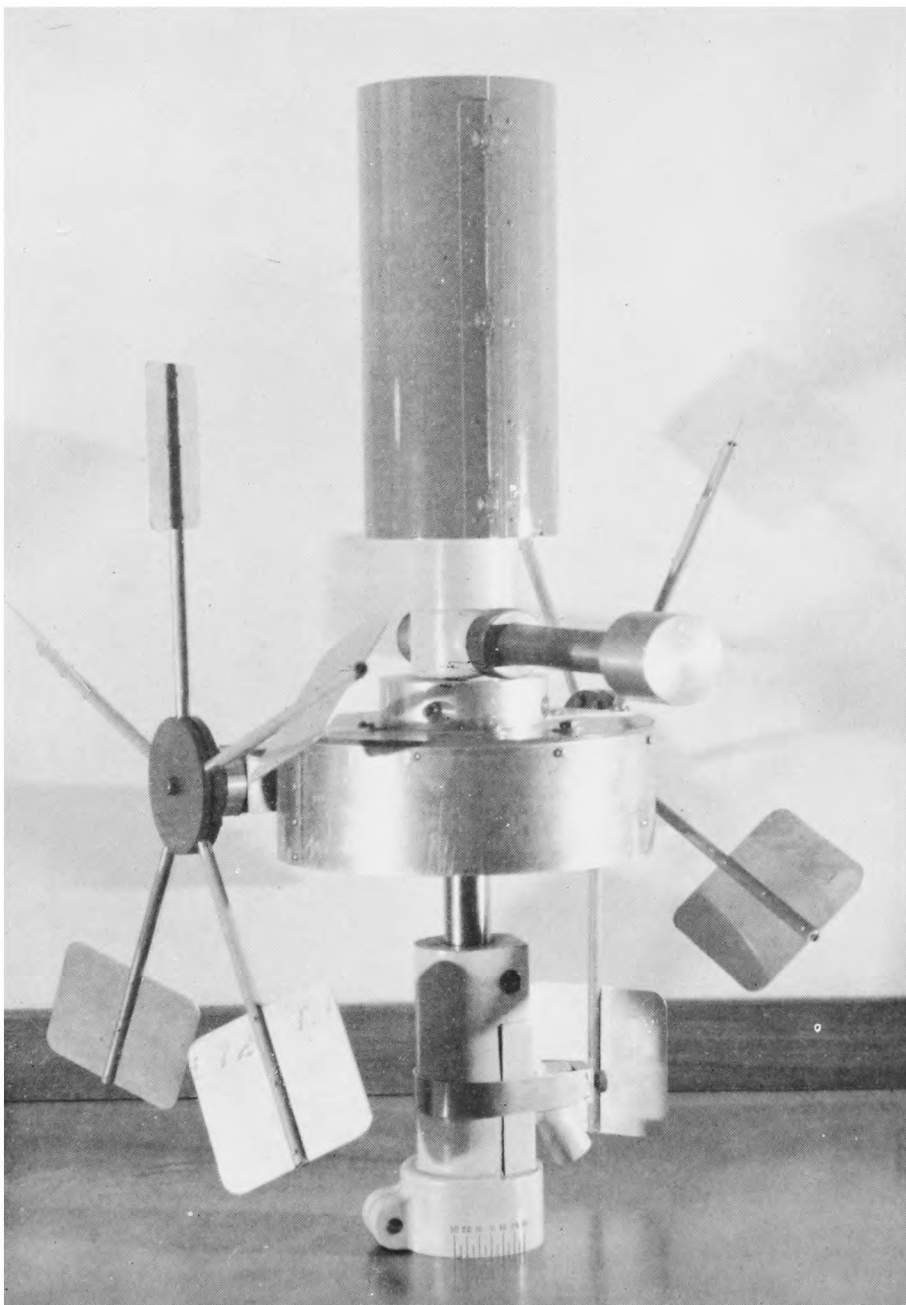


Fog lifting into low stratus.



Stratus lifting and dispersing.

To face p.145



*Crown copyright*

PLATE IV—WIND DIRECTION HEAD FOR THE AUTOMATIC WEATHER STATION  
This contains 18 switches to select voltages equivalent to 20 steps (see page 155).

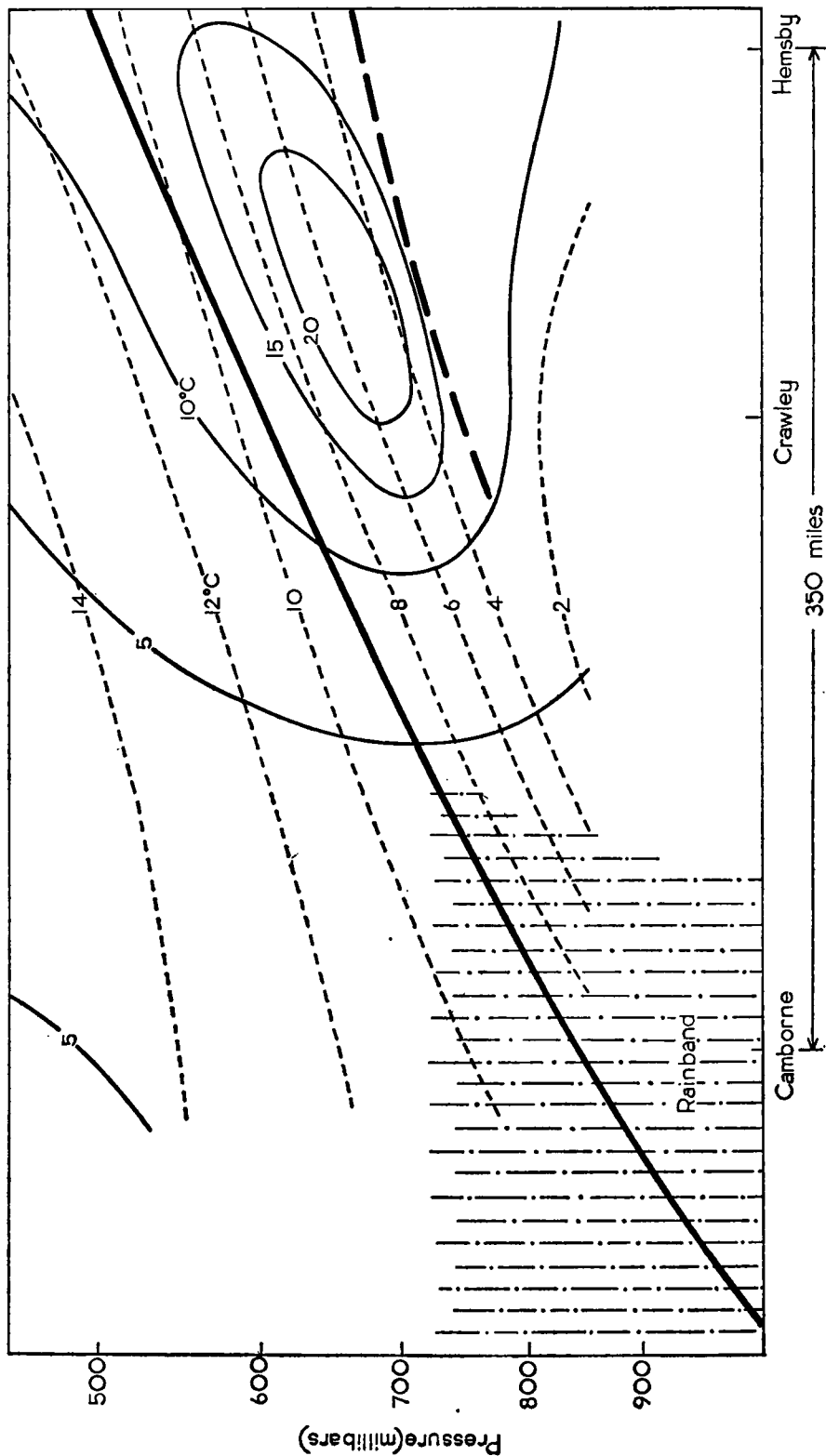


FIGURE 2—CROSS-SECTION THROUGH A WARM-FRONT SURFACE AT 0000 GMT ON 20 DECEMBER 1962

— Isopleths of dew-point depression ( $\Delta$ ),  
 - - - Isopleths of potential wet-bulb temperature ( $\theta_w$ ).  
 — Frontal surface, - - - surface of subsidence.

**Subsidence at a cold-front surface.**—Essentially a section through a cold-front surface is similar to one through a warm-front surface. A difference which is often found is the extension of the dry air near the 700 mb level to a point ahead of the surface cold front, in which case the front tends to be a fairly weak one. If, as is believed, the dry air originates far away from the cold front, this overhang beyond the front would result from the low-level thermal wind being appreciably veered relative to the cold front.

Whereas some subsidence takes place because of divergence behind a cold front, the history of the post-frontal air strongly supports the view that in the main the subsidence takes place when the air is at a considerable distance from the cold front. Trajectories were drawn of subsided air behind a number of cold fronts, assuming that the air moved at all times with the wind at 700 mb. The task was difficult because of the inevitable uncertainties over the Atlantic but satisfactory trajectories were considered to have been obtained for the air at 700 mb behind 10 cold fronts. Of these, one showed that the air travelled with the fast-moving surface low for the  $1\frac{1}{2}$  days during which the system was within the boundaries of the 700 mb chart. The air behind two other cold fronts, on occasions when the trajectories were more than usually uncertain, appeared to originate ahead of the depression to which the cold front belonged and eventually arrived in the north-westerly flow behind the cold front. The remaining seven centres of subsided air could be tracked back on the charts available at least as far as the upwind ridge or anticyclone. This journey took an average time of  $2-2\frac{1}{2}$  days, so if the subsided air originated ahead of a warm front still further west the complete travelling time was probably nearly a week, depending mainly on the wind speed across the ridge. It is significant that when the trajectories passed close to upper air stations there were reports of dry air on sufficient occasions to suggest that the air was usually subsided at some level the whole time.

### **Some observed relationships between subsidence and other features.—**

(i) *The slope of the isothermal surfaces.*—The thermal wind speed through a layer is proportional to the vertical gradient of temperature and the slope of the isothermal surfaces. Of these two components the latter usually shows the greater variability, so the thermal wind speed can be taken as a rough measure of the isothermal slope.

The frequency of occasions of subsided air over Crawley at either the 700 mb or the 500 mb level, but not at both, showed little relationship with the 700–500 mb thermal wind speed, though the driest air tended to be associated with the lowest speeds. On the other hand, subsided air occurring simultaneously at both levels over Crawley existed twice as often with thermal wind speeds below the median as when they exceeded it.

These results are consistent with subsidence occurring initially where isothermal surfaces have a fairly large slope; with continued subsidence being accompanied by a flattening of these surfaces towards the horizontal; and with later subsidence taking place more nearly in the vertical and therefore affecting a deeper column of air.

(ii) *Wind speed at 700 mb.*—The median speed at 700 mb over Crawley in the 6 months was 23 knots, yet 10 of the 63 observations of subsided air coincided with winds of 40 knots or more, the highest being 79 knots. With speeds above the median, subsided air was only 32 per cent less likely than with speeds below it. Similar figures were found for subsided air at the 500 mb level. These results are consistent with subsidence occurring mainly in stronger winds, the air remaining subsided when it enters a region of lighter winds.

(iii) *Sea-level pressure.*—Subsided air was found on a few occasions with sea-level pressures even below 1000 mb. With surface pressures of 1030 mb or more the air was subsided on 46 per cent of occasions at 700 mb and 26 per cent at 500 mb. Subsidence at only one level occurred about twice as often when pressure was above the median as when it was below it, but nearly 90 per cent of the observations of subsided air extending to both levels occurred with surface pressures in the anticyclonic half. Thus, whereas subsided air in a shallow layer is associated more with high than with low surface pressure, the major characteristic of high-pressure systems is that the subsided air extends through a considerable depth.

**Note.**—Part II will be published in June 1964.

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551.509.314:551.509.323

## THE FORECASTING OF HIGH TEMPERATURES AT REDCAR

By D. C. HENDERSON

**Introduction.**—This short note has been prepared to indicate that a successful method of forecasting high temperatures at a specific location can be devised using simple techniques. It is suggested that a similar technique, perhaps using different parameters, could be employed for this type of problem at other locations.

**The problem.**—In hot weather bacteria tend to multiply and it is possible for them to affect imitation cream. A firm of bakers near Middlesbrough wished to receive warnings of high temperatures from Manchester Weather Centre so that they could cease manufacture and distribution of cakes containing this cream and so obviate any possible risk to public health. The client agreed that it was preferable for warnings to be issued which subsequently prove false rather than have high temperatures without receiving a warning. It was decided that the forecasting technique should as far as practicable use prebaratics and pre-thickness charts of the Central Forecasting Office.

**Techniques used to devise a forecasting method.**—Observations for 1200 GMT in the *Daily Weather Report*\* and for 0001 GMT in the *Daily Aerological Record*\* were examined for each occasion from 1956 to 1962 when the temperature at Redcar (the nearest reporting station) reached 75°F. Brief details of the surface and upper air situations were extracted for each occasion.

\*Meteorological Office. *Daily Weather Report: Daily Aerological Record*. London, HMSO 1956–1962.

(i) It was found that in the 40 cases examined:

- (a) An anticyclone existed in the area 55N 01E-55N 19E-49N 19E-49N 01E-55N 01E on 29 occasions.
- (b) The geostrophic wind was from between 200° and 250° on 27 occasions.
- (c) The pressure at mean sea level was above 1015 mb on 33 occasions.
- (d) There was a warm ridge on the 1000-500 mb thickness chart between 10°W and 10°E on 35 occasions.
- (e) In the months of July, August and September (28 occasions) the 1000-500 mb thickness was 5600 metres or more on 22 occasions. In June and October (11 occasions) it was 5560 metres or more on 8 occasions.

(ii) On 37 occasions there were 3 or more of the above parameters present when the temperature reached 75°F.

(iii) The presence or absence of these parameters was examined on all days (June to September) for the years 1960-61. On 12 days three or more parameters were present with the temperature reaching 75°F. On 18 days three or more were present with the temperature below 75°F. On no occasion did the temperature reach 75°F with less than three present.

(iv) In an attempt to reduce the number of wrong forecasts the following additional parameters were examined:

- (a) *Geostrophic wind speed*.—It was thought strong winds would keep the temperature down but this was found to be incorrect. It was also found that with light winds a sea breeze often developed and the temperature remained below 75°F.
- (b) *Direction of wind*.—It was found that between 1956 and 1962 the temperature never reached 75°F when the geostrophic wind was from between 340 and 160 degrees, that is, from a seaward direction at Redcar.
- (c) *Sunshine*.—It was found that in the same years there had to be at least 3 hours sunshine for the temperature to reach 75°F. The possibility of using other values of sunshine hours as an additional parameter was examined but was found to be unsuitable.

**Conclusion.**—Warnings are now issued on the following basis:

The 1200 GMT prebaratic and 0001 GMT pre-thickness charts are examined to see if at least 3 of the parameters mentioned in (i) above will be present. If so, a warning is issued unless (a) the geostrophic wind direction is from between 340° and 160° through 090° or (b) little or no sunshine is expected the next day.

Temperatures from Redcar are not received at the Manchester Weather Centre daily but a check has been made using data supplied by Headquarters. On this basis, of the 40 days with high temperatures which occurred between 1956 and 1962, 37 would have been forecast. In 1960 and 1961 22 warnings would have been issued, 12 correctly, 10 incorrectly and on no occasion would a warning have been missed. In 1963 3 parameters (with the restrictions absent) occurred on 6 occasions. The temperature reached at least 75°F on 3 of these occasions. There was 1 occasion when the temperature reached 77°F with only 2 parameters being present.

**Acknowledgement.**—The author would like to acknowledge the assistance given by the Climatological Services Branch of the Meteorological Office in supplying the maximum temperatures for Redcar, and the helpful advice given by the Techniques and Training Branch.

551.521.11:551.589.5:519.272

**RELATION BETWEEN MEAN DAILY MAXIMUM TEMPERATURE AND MEAN DAILY SUNSHINE DURATION: VARIATIONS ACCORDING TO TIME OF YEAR AND WIND DIRECTION, DURHAM OBSERVATORY, JULY 1937 TO JUNE 1962**

By A. J. W. CATCHPOLE, B.Sc.,  
(Birkbeck College, London)

**Summary.**—Daily observations of maximum temperature and sunshine duration were reduced to means calculated according to time of year and wind direction. A high degree of positive correlation was observed between the temperature and sunshine means. Clearly this arose from the similarity between the seasonal régimes of both groups of data. When these seasonal changes were eliminated the positive correlations were of smaller magnitude and were often insignificant. This reduction in the degree of correlation was partly due to the small total variations in mean maximum temperature and mean sunshine duration according to wind direction in some months. In winter, when the relatively large contrast between continental and maritime influences emphasized these variations, the positive correlations were again of higher magnitude. Diagrams are given showing the variations of temperature and of sunshine with wind direction.

**Introduction.**—The results contained in this analysis emerged during a study of the general variations of maximum temperature and sunshine duration according to wind direction and the procedures adopted for the extraction and examination of the data were those best suited for this general purpose. Sunshine and temperature observations at Durham Observatory are made according to the requirements of a normal climatological station and the data for this study were extracted directly from the record.

The use of wind data is complex and this is especially true in an analysis concerned with mean or total daily conditions rather than spot observations at 0900 hours or 2100 hours. In this case the wind data were extracted from the record of the pressure-tube anemograph since this provides the best estimate of mean daily wind direction. Each anemogram was inspected and classified into one of 17 groups. These groups included 16 wind directions and an additional group for those days which could not be allotted a mean direction either because of calm conditions, frontal wind change, failure of the instrument etc. Eventually it was found that the classification was too detailed and a more coherent pattern was obtained by reducing the direction groups to 8. As a result 'north' includes 'north-north-east,' 'north-east' includes 'east-north-east' etc. in this paper.

This is a subjective technique but it has the advantages of providing a better estimate of total daily conditions than means of observations at particular hours and being much simpler than a graphical or arithmetical analysis of each chart. An average of between 12 per cent and 20 per cent of the total number of days in each month could not be allotted a mean wind direction by this method and were omitted from the analysis. This percentage was higher in summer, and between the two extremes there was a fairly smooth curve. This summer maximum is probably caused by the relatively high frequencies of low wind speeds at that time.

For each day during the 25 years under consideration, a maximum temperature, a sunshine duration and a mean wind direction were extracted from the record. Initially the temperature and sunshine data were classified into two sets of 96 frequency distributions, each distribution referring to a particular month and wind direction. Means were calculated for each of the frequency distributions. The variations of these means according to wind direction have been emphasized in Figure 1 by plotting individual differences from the appropriate monthly means. In this way seasonal changes are ignored and it is seen that the monthly curves of anomaly of mean maximum temperature and mean sunshine duration are occasionally similar in form. This is mainly true in the winter months when wind direction has a particularly marked effect on the magnitude of the various means. In this paper there will be a discussion of the precise nature of the relationships between the monthly curves in Figure 1.

**Seasonal variations.**—An objective view of the relationships between the two groups of means cannot be obtained until the effects of seasonal régime are eliminated. Any two sets of data which assume higher magnitudes in summer will appear to be correlated although they may be unrelated. In the present case expected degrees of positive correlation are observed when the corresponding means are plotted in climogram form.

**Variations according to wind direction.**—

(i) *Each month.*—Seasonal changes have been eliminated in Figure 1 and in subsequent calculations by the use of relative, rather than absolute, values. For example in January the mean duration of sunshine is 1.6 hours while the equivalent value calculated for north winds alone is 0.9 hours. Therefore the ‘anomaly’ with north winds in January is  $-0.7$  hours.

Figure 1 indicates that in particular months, mean maximum temperatures and mean sunshine durations vary considerably according to wind direction. This is especially true in winter when the greatest contrasts between air masses are expected. For example in February the mean maximum temperature with east winds is six standard deviations below the equivalent mean with south-west winds. Differences between the means of this magnitude are observed from December to March with both the temperature and sunshine data. By contrast, differences are low in summer and often they are insignificant. This is relevant because a positive correlation between the two groups of means is more likely to occur in those months with relatively large differences (see Table I).

TABLE I—MONTHLY CORRELATION COEFFICIENTS BETWEEN THE VARIATIONS ACCORDING TO WIND DIRECTION OF MEAN DAILY MAXIMUM TEMPERATURE AND MEAN DAILY SUNSHINE DURATION (8 PAIRS OF MEANS PER MONTH), DURHAM OBSERVATORY, JULY 1937 TO JUNE 1962

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
$r$	0.95	0.82	0.53	0.11	0.38	0.34	0.54	0.57	0.26	0.38	0.32	0.40
$Pe$	0.02	0.08	0.17				0.17	0.16				

$r$ =correlation coefficient (all values are positive),

$Pe$ =probable error of correlation coefficient (only calculated where required for significance testing).

Probable error testing indicates that these correlation coefficients are highly significant in January and February, and only moderately significant in March, July and August.



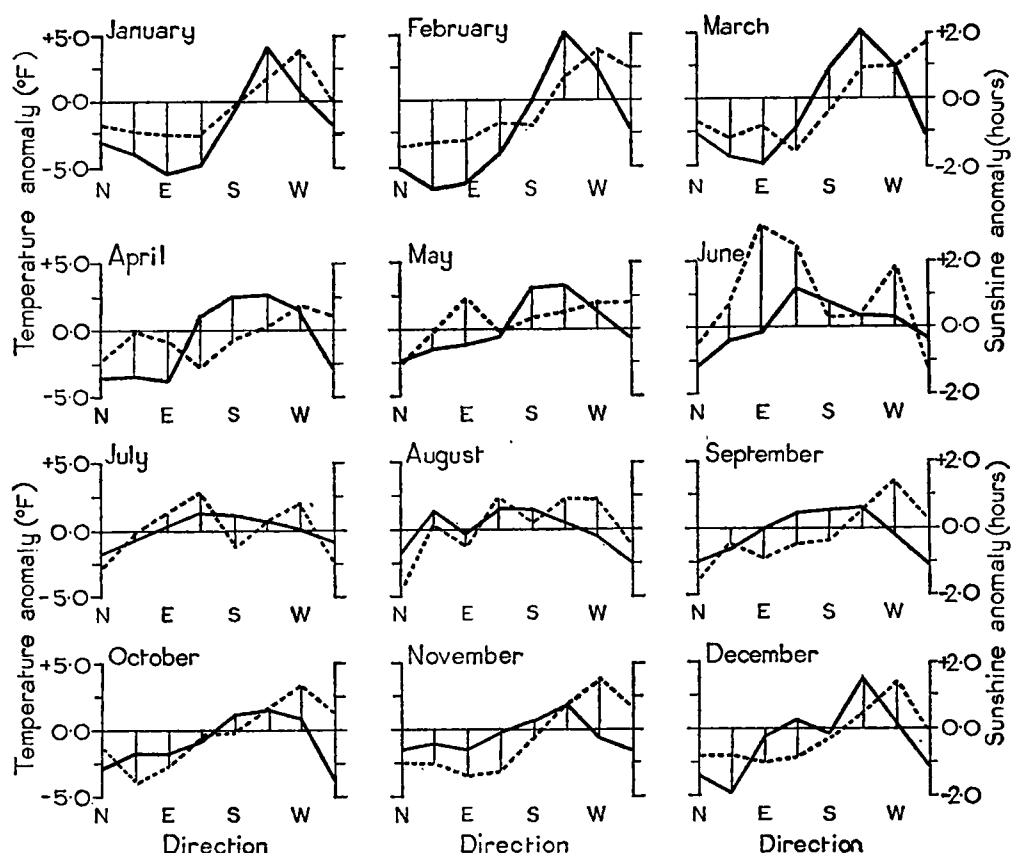


FIGURE 1—VARIATIONS OF THE TEMPERATURE AND SUNSHINE ANOMALIES ACCORDING TO WIND DIRECTION IN EACH MONTH; DURHAM OBSERVATORY, JULY 1937 TO JUNE 1962

———— Temperature anomaly, - - - sunshine anomaly.

(ii) *Seasonal*.—It will be noted that there are smooth seasonal changes in the forms of the curves in Figure 1. In winter the highest means are observed with south-west and west winds. Between April and August these maxima occur progressively with south and south-east winds and there is a return to the original form in the latter half of the year. Consequently there is a larger total range of means with the eastern group of winds, including those from the north, north-east, east and south-east, than with the corresponding western group. Again it is fair to expect higher positive correlations between those pairs of means observed with winds responsible for the greatest total variations (see Table II).

TABLE II—CORRELATION COEFFICIENTS BETWEEN MONTHLY MEAN DAILY MAXIMUM TEMPERATURE AND MONTHLY MEAN DAILY SUNSHINE DURATION (48 PAIRS OF MEANS PER WIND GROUP): CALCULATED ACCORDING TO WIND DIRECTION; DURHAM OBSERVATORY, JULY 1937 TO JUNE 1962

	Eastern group		Western group	Total
$r$	+0.53		+0.10	+0.45
$Pe$	0.07			0.05

Eastern group=north, north-east, east and south-east.

Western group=south, south-west, west and north-west.

$r$ =correlation coefficient.

$Pe$ =probable error.

There is a striking contrast here between the significant correlation coefficient observed with the eastern group of winds and the negligible value with the western group. This is a measure of the importance of the seasonal contrasts in the nature of the continental influences on the climate of Britain.

(iii) *Air-mass effects*.—However the individual curves in Figure 1 are often irregular in form and the corresponding temperature and sunshine curves are occasionally markedly divergent. This is likely to result from accidental causes arising from deficiencies in sample size rather than specific climatological processes. It would appear that these irregularities are sufficiently large to obscure any smooth variations in the relationships between the two groups of means when these are studied for individual wind directions (see Figure 2). In these climograms the data are generally massed together into clusters. Only those clusters observed with south-east, east and north-east winds adopt limited tendencies towards linearity. There are regular variations in the locations of the clusters in Figure 2 and these afford valuable summaries of the nature of air-mass effects.

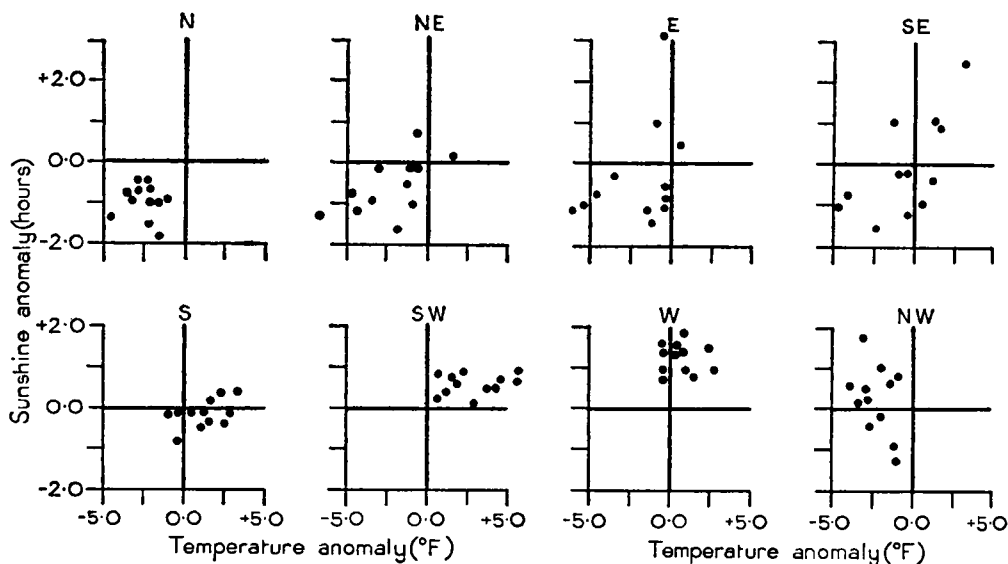


FIGURE 2—RELATIONSHIP OF THE TEMPERATURE AND SUNSHINE ANOMALIES FOR THE EIGHT WIND DIRECTIONS, DURHAM OBSERVATORY, JULY 1937 TO JUNE 1962

551.524.32(414)“324”:551.583.14

## MEAN WINTER TEMPERATURE IN EDINBURGH 1764/65–1962/63

By A. B. THOMSON, M.A.

Records of temperature made in Edinburgh were used in a statistical examination of mean temperature in the three winter months December, January and February and the winter period (December–February) as a whole. The investigation covered the 199 winters 1764/65–1962/63. The records consisted of the R.C. Mossman series published in *World Weather Records* 1921–30,<sup>1</sup> combined with data in the Meteorological Office, Edinburgh.

The mean temperature and standard deviation were calculated for each winter month and for the winter as a whole. Each series was then subdivided

at its (mean  $\pm \frac{1}{2} \times$  standard deviation) and at (mean  $\pm 1\frac{2}{3} \times$  standard deviation) providing five classifications viz. very mild, mild, moderate, cold and very cold.

The main conclusions were:

(i) The winter months showed a general pattern of coldness in the first 100 years and mildness thereafter, but the mild trend was reversed about 1939. There were noteworthy runs when the general pattern of coldness or mildness was the same for consecutive months of the same name, in particular Decembers from 1796 to 1820 (none mild or very mild), Januarys from 1898 to 1939 (none cold or very cold) and Februarys from 1905 to 1928 (only two cold).

(ii) The odds were in favour of persistence of type e.g. cold Januarys were more likely than mild ones after cold Decembers but the character (cold or mild) of a particular month seems to have no connexion with the character of its predecessor of 12 months earlier.

(iii) An examination of the intervals between the 20 coldest months of the same name showed that they were seldom shorter than 3 years, as was also the case with the 20 mildest months. The chances were therefore against a quick recurrence of a January as cold as January 1963 or of a February as mild as February 1961.

(iv) Six winters had mean values below 36°F in the last 100 years against 23 in the first 100 years of the series; the corresponding numbers of winter means of 41°F or above were 13 and 6.

(v) The chances of a cold or of a mild winter following a cold one of the previous year were both about one in four but the figures suggest that a mild winter is more likely to have a mild than a cold successor the next year.

(vi) Of the 20 coldest winters of the series, only two of them (1947 and 1963) occurred in the present century, and these, judged on their mean temperatures, were less severe than some of the earlier ones. The odds were against a quick recurrence (interval less than 3 years) of a winter as severe as any amongst these 20 coldest winters; similarly the odds were against a quick recurrence of a very mild winter.

(vii) The periods 1774–85 and 1809–23 had the greatest concentration (i.e. shortest recurrence intervals) of the 20 coldest winters, and both these periods had also a large concentration of the coldest Januarys.

(viii) There seems no means of judging the future trend but it would be unrealistic to discount the possibility of a recurrence of the low temperature levels of the last half of the 18th and first half of the 19th centuries and, in particular, the striking sequence of low winter means between 1799 and 1820. In 20 of these 22 winters mean temperature was below average, and in 10 of them the deficit exceeded 2°F.

Fuller details are given in *Climatological Memorandum* No. 41.<sup>2</sup>

#### REFERENCES

1. Washington, Smithsonian Institution. World Weather Records. *Smithson. misc. Coll., Washington D.C.*, 90, 1934, p. 23 and p. 511.
2. THOMSON, A. B.; Mean winter temperature in Edinburgh: 1764/65–1962/63. *Met. Off. clim. Memor., London*, No. 41, 1964, (unpublished, available from the Meteorological Office).

## METEOROLOGICAL OFFICE DISCUSSION

### Developments in meteorological instrumentation

The Monday Discussion held on 16 December 1963 at the Royal Society of Arts was concerned with developments in meteorological instrumentation and the opening speaker was Mr. C. E. Goodison. He described two groups of instruments which were either in production or being developed.

The first production instrument he dealt with was the cloud base recorder five of which have been in operation for  $2\frac{1}{2}$  years. This instrument is a modulated light ceilometer which has been developed by the Meteorological Office and is designed to give cloud height from 50 to 4000 feet. There are two airfield units; these are a transmitting searchlight, and a photo-electric cell receiver which has a 900 c/sec tuned amplifier associated with it and combined in the same case. In the office a recording unit with strip-chart mechanism maintains a record of the cloud base. (See Plates I-III.)

A brief description of a manufactured photo-electric visibility meter, was then given, accompanied by some slides showing the installation at the Meteorological Experimental Site near Bracknell.

The new radar equipments—wind-finders and weather surveillance types—which are shortly to be introduced into meteorological service, were then discussed. The wind-finding set is a 10-cm 800-kw equipment which will replace the war-time G.L. radars in use on radiosonde stations. It is capable of automatically following a Met.O Mk.3 target to 200 km and because of extensive use of transistors in the design should prove to have good electronic reliability.

There are two types of weather radar about to be installed at various sites around the world. The Public Weather Centres at home will be supplied with 3-cm sets which should enable the forecaster to watch the progress of precipitation through his area of immediate responsibility. These 3-cm sets are of relatively simple construction and they should be easily operated and serviced and give the minimum of trouble.

The 10-cm weather radar sets will be installed in tropical areas where they should prove a boon to the research branches as well as a good aid to the local forecaster.

There are 15 data loggers of quite advanced design in the Office at present and these will present records of various radiation parameters in two ways, viz. a multi-trace pen recording chart and a punched paper tape. These data loggers will be sited at home and overseas and trial installations of the equipment are also at present being carried out on Ocean Weather Ships.

The last production piece of equipment demonstrated was an electro-mechanical device for sending meteorological messages automatically. There are 69 switches in front of the instrument and after setting these up to the required message all that is then necessary to send the message at full teleprinter speed is to push a button. In the demonstration a teleprinter connected to the automatic message sender printed the message when the 'transmit' button was operated.

A few instruments in the course of development were then described and the automatic weather station (AWS) was the first subject to be discussed. At

an early stage of development the project was divided into two parts. It was decided that the telemetry equipment would be the subject of a specification and contract so that it would 'marry up' well with the transducers which were to be developed by the Office.

The telemetering equipment has now been delivered by the makers. Various slides showing different aspects of it were then shown and a brief description of its characteristics given. Its ability to be interrogated over an ordinary subscriber's line is a most important point since a private wire connexion would be most uneconomical in the role which is foreseen for AWS in the British Isles.

The transducers, which produce an electrical signal in the form of voltages, were the responsibility of the Office and models of them have been built capable of measuring barometric pressure, mean wind speed, wind direction, dry-bulb temperature, wet-bulb depression, total rainfall, rate of rainfall, presence of bright sunshine, and visibility. The details of these nine transducer models were then given with accompanying slides. (See Plate IV.)

Another instrument which was on display but not completely demonstrated was the receiving cabinet of a digital display AWS. This type of station was designed with large airfields in mind where it is difficult to obtain good instrument exposure near the forecast office. By using this version of the AWS which only uses one pair of GPO wires, instruments at a distance of up to 10 miles may be interrogated individually and their readings displayed in a digital form complete with units, e.g. 1015 mb, 15.1°C etc. This instrument was designed and built completely by the Office and also uses the same transducers as the AWS.

The last instrument system Mr. Goodison described was a new type of satellite cloud-cover picture transmission. The previous TIROS satellites had various limitations on their performance, one of the principal barriers being that of communication between the satellite and the forecaster. This link at present is a long and tortuous one involving tape recorders in the satellite, specially equipped ground stations in North America, rectification procedures, and the ordinary meteorological communication channels. Because of this delay, pictures useful to the forecaster may be delayed by up to 24 hours. The 'automatic picture transmission' (APT) equipment, which will be carried by future meteorological satellites, broadcasts each picture by radio immediately after it has been taken. This means that any meteorological organization equipped with a fairly elementary ground receiving station will be able to have satellite cloud-cover pictures almost as soon as they are taken. The Meteorological Office is at present investigating the possibility of producing a Met.O. designed ground station to receive these APT signals from satellites.

One of the principal speakers in the discussion was Mr. V. R. Coles (Assistant Director Met.O. (Central Forecasting)) who described an automatic chart plotter which was being produced for Met.O.2. This illustration brought a comment on its international acceptability. Various points on the instruments shown were discussed and whilst it was agreed that electronics had advanced automatic observing techniques some basic problems still remained, such as the maintenance of a clean wick on the wet-bulb thermometer.

The Director-General wound up the discussion by emphasizing that the instrument revolution was only of comparatively recent origin and that Robert Hooke who set up the first meteorological observing station in the 17th century would have had no difficulty in recognizing all instruments in use in the thirties whereas the equipment with which a modern meteorological office was furnished would be quite foreign to him.

## REVIEWS

*An introduction to the hydrodynamical methods of short period weather forecasting*, by I. A. Kibel', (translated from the Russian). Edited by R. Baker. 9½ in × 6 in, pp. xiii + 383, *illus.*, Pergamon Press Ltd., Headington Hill Hall, Oxford, 1963. Price £5.

Dr. Kibel' wrote a well known paper in 1940 in which he derived formulae for predicting the motion of pressure centres and so may be regarded as having given fresh impetus in Russia to the study of what is now called numerical weather prediction. Since then he has been the inspirer of the many Russian meteorologists who have carried out research work on numerical weather prediction and has himself contributed significantly. A text book written by such a great expert in this field can only be welcome.

The basis of the book is a series of University lectures given by the author in 1956 and the text was first published in Moscow in 1957. Dr. Kibel' may thus be regarded as the author of the first text book dealing adequately with the recent advances in applying hydrodynamics and computing methods to predicting the behaviour of the atmosphere. It is a pity that the English translation has had to be so long delayed for there have been considerable advances since Dr. Kibel' wrote his book; however in a field in which progress is rapid any text is likely to appear out-dated within a few years and since there is no other book which covers the ground in the same detailed way, Dr. Kibel's book remains the most authoritative, in English as well as in Russian.

Somewhat naturally there is a distinctly Russian flavour about the contents and indeed the author indicates that the foreign work is described mainly by its computed results while the theoretical Russian work is described in detail; at the same time it is clear that he has a wide and up-to-date knowledge of the parallel research work which was being carried out elsewhere in Europe and America. It is surprising that the research during these formative years should have been so similar and that the same ideas were being investigated in both the East and West. There are notable differences, especially in technique, but these should not mask the similarity of the physical ideas lying behind the mathematical equations that form the basis of the arithmetical computations. The difficulty of making a comprehensive survey was thus reduced and Dr. Kibel' has been able to deal with both aspects in a coherent whole. The Russian research work in particular was aimed at a systematic examination of the quasi-geostrophic vorticity approach to the problem of using the hydrodynamical equations for prediction and that is the essence of this book.

Throughout the book there is a note of formality which we associate with a university text in mathematical physics and which ensures a logical development; this may seem rather painstaking at times but it is pedagogically desirable.

The first two chapters are concerned with laying the foundations—the thermal physics of the boundary layer expressed in mathematical terms and the equations of motion in the free atmosphere in hydrostatic equilibrium. All of this is very carefully set out and the calculations, such as that of the change from cartesian to pressure co-ordinates, carried out in detail. The third chapter is the important one which gives the orders of magnitude of the various terms which arise in the equations when synoptic-scale motions are considered; this of course is vital for the subsequent development and is carefully written. Dr. Kibel' might now not be so decided in his view that the tendency equation cannot be used to estimate pressure changes with time in view of more recent work using the primitive equations.

Having laid the foundations in these early chapters, the main interest lies in Chapters 4, 7, 8 and 9 which present the non-linear problem and its solution for both a single-layered fluid and a multi-layered one. The Russian approach to the problem is to formulate a single differential equation giving the height tendency in terms of the horizontal and pressure derivatives of the contour heights and to solve this equation under suitable boundary conditions. The solution is generally given in terms of an integration which involves as a weighting factor the Green's function for the problem and its boundary conditions. The crux of the problem is to find an expression for the Green's function. In principle when this is done the problem is solved; in practice the integrations have to be carried out in the simple manner of replacing them by sums. The approach more familiar to us is to concentrate on simple models right from the start, obtain sets of simultaneous differential equations which are simpler to manipulate and use finite difference techniques which do not require the construction of a Green's function. Both methods are given but the details are confined to the Green's function method; both require a great deal of computation on an electronic computer and it is not clear which is the more economic. Dr. Kibel' gives examples of forecasts computed by different methods but since the different computations do not refer to the same dates it is not possible to assert that any method is superior to another.

There are other chapters concerned with linearized models, frontal zones and the introduction of the physical boundary effects into the computations and they maintain the same high standard. This standard has not been maintained editorially in the English translation for there are many minor errors and infelicities of expression. There are irritating mis-spellings of names, such as Gilbert for Hilbert, which should have been checked, the residual at a point is never called the discrepancy and the mathematics in the original Russian had less errors than has the translation. One point in favour of the translation is that an index has been added.

This is an excellent and valuable text which dynamical meteorologists will welcome as an exposition of the basic physical ideas behind numerical prediction and the research carried out, as seen in 1956; perhaps a rather different book would be written in 1964.

E. KNIGHTING

*Die Faxfibel*, by Dr. Martin Rodewald. 9½ in × 8½ in, pp. 71, illus., Dr. -Ing. Rudolf Hell, 23 Kiel, Grenzstrasse 1-5, 1963.

“What the seaman must know about weather charts” is the title of a primer on the use of weather charts such as are broadcast by many countries nowadays as facsimile reproductions of the charts drawn in a meteorological office.

The book is simply written by an experienced meteorologist, Dr. Rodewald, belonging to the German marine weather service at Hamburg. After introducing the international weather symbols used on weather charts, the author shows how wind can be estimated from the pressure field, and gives a nomogram which includes allowance for curvature of isobars. Another chapter deals with the main frontal systems, illustrating among other things ‘wave’ development on a front, and the weather and wind associated with fronts.

One of the features of the book is the high standard of the reproduction of the numerous charts and diagrams, and the care shown in the author’s choice of material to illustrate various parts of the text. Typical tracks of depressions and anticyclones are shown as well as tracks of tropical storms. The use of certain special charts is explained, with examples of forecast charts, upper wind charts, sea and swell charts and ice charts.

Some of the more general rule of thumb methods of forecasting are given, as well as rules applicable to special weather situations and for forecasting developments—all well chosen examples, though mainly in the German forecasting tradition.

Finally some types of persistent weather patterns are illustrated for the North Atlantic and, as is reasonable in a book for seamen, a few types are also given for the Mediterranean, Gulf of Mexico, Arabian Sea and the Far East.

The booklet deserves a wide public though apparently issued primarily as advertising material to encourage shipowners to install a particular make of Facsimile apparatus whose development and operation are described in an appendix.

W. S. G.

## HONOUR

We note with pleasure the election of Professor P. A. Sheppard, C.B.E. as Fellow of the Royal Society on 19 March 1964.

## OFFICIAL PUBLICATION

The following publication has recently been issued:

*Meteorological Glossary*, 4th Edition. London, HMSO, 1963. Price 32s. 6d.

This, the 4th Edition of the *Meteorological Glossary* has been almost completely rewritten and the opportunity has been taken to include many more items than were contained in the previous editions.

The items include most of the terms and concepts which are in common use in the various branches of meteorology and some others which are less familiar. In addition, relevant information from mathematics, statistics, physics and other branches of geophysics is included.



While emphasis is placed, in certain items, on British terminology, methods and data, much the greater part of the book contains information which is applicable to all parts of the world.

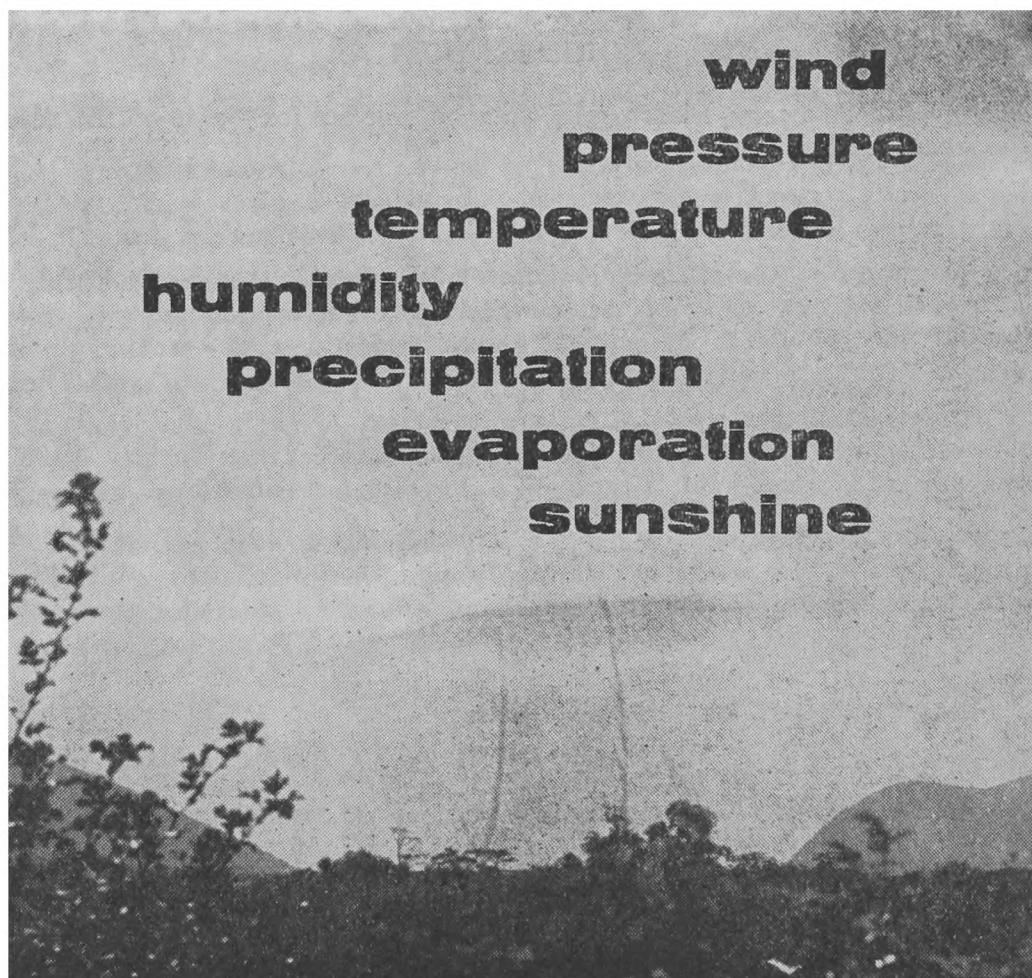
Many of the Figures are new and the 28 Plates now include 8 coloured ones for the first time.

### **CORRIGENDUM**

*Meteorological Magazine*, March 1964, page 76, line 29: for “30 to 40 °E” read “30 to 40° further east”.

# **METEOROLOGICAL INSTRUMENTS**

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# THE METEOROLOGICAL MAGAZINE

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## NOCTILUCENT CLOUDS

By J. PATON

Department of Natural Philosophy, Edinburgh University

Noctilucent, or luminous night clouds, usually described as 'rare,' occur more frequently than is generally realized. They are seen in Scotland much more often than the only other type of cloud that is situated above the tropopause, the mother of pearl or nacreous clouds. These latter clouds, which occur at heights between 22 and 30 km, reveal their nature by their iridescence; there can be little doubt that they are water clouds, formed orographically. It was at first considered surprising that water in concentration sufficient to form visible clouds should exist at these heights in the stratosphere. It was judged impossible that noctilucent clouds, which are situated at the much greater height of 82 km, could also be water (ice) clouds, and they were generally assumed to consist of volcanic or meteoric dust. During the summer of 1962, sounding rockets fired in northern Sweden successfully collected noctilucent cloud particles and provided strong indications that the particles, in fact, consisted of ice. This discovery has so stimulated interest in the clouds that an international conference was held in May 1964 to prepare plans for further studies.

It is the purpose of this paper to review the present state of our knowledge of noctilucent clouds and, in particular, to present an analysis of observations made between 1949 and 1963 in the British Isles, mainly in central Scotland.

**Geometry.**—The clouds are extremely tenuous and are always situated at a height of about 82 km. They are visible therefore only at night in that part of the sky where they are directly illuminated by sunlight and where the sky background is sufficiently dark to permit their weak luminescence to be perceptible. Absence of ordinary clouds and excellent visibility are necessary conditions for observing the clouds.

Assume that the clouds cover the whole sky and that they extend along the line EGFN' in Figure 1. If observing conditions are suitable, an observer at O will expect to see the clouds after sunset in azimuths near to that of the sun in the portion of the sky between his horizon at E and the point F where the boundary AA' of the earth's shadow is at a height of 82 km. For some time after sunset however, there remains near the horizon above the sun strong sky illumination—the twilight glow—arising from scattering in the illuminated atmosphere above K (the intersection of OE and AA'). The brightness of the

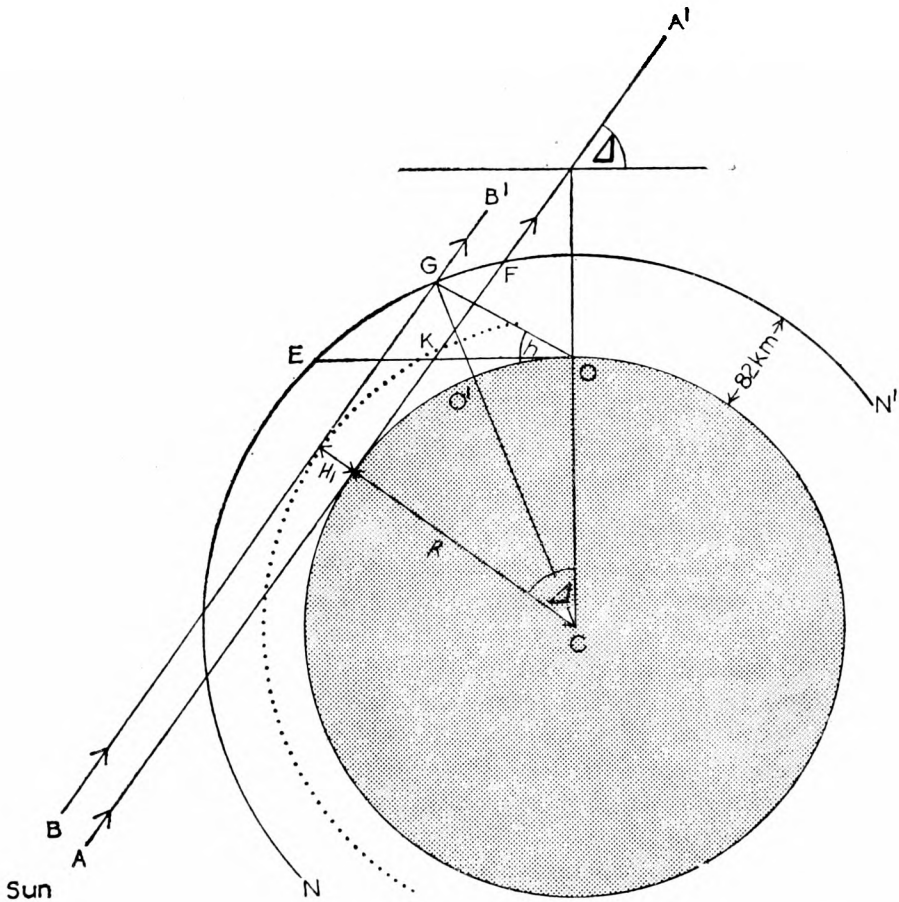


FIGURE 1—GEOMETRY OF NOCTILUCENT CLOUD OBSERVATIONS

twilight glow diminishes steadily as the sun descends further below the horizon and K moves to higher levels. It is only when the sun is about  $6^\circ$  below the horizon that the difference between the brightness of the clouds and the sky background becomes sufficiently great for the clouds to be perceptible. This difference reaches its maximum when the sun is about  $10^\circ$  below the horizon and it is then that the clouds are at their brightest. As the sun continues to descend below the horizon, the area within which the clouds are observed and the brightness of the clouds both decrease as the point F moves towards E, until, when the depression of the sun ( $\Delta$ ) is greater than about  $16^\circ$ , the clouds are no longer illuminated and disappear. When the sun ascends again before dawn, these events are repeated in reverse order as the depression of the sun decreases from about  $16^\circ$  to  $6^\circ$ . At places and the times of the year when the sun never descends more than  $16^\circ$  below the horizon, the clouds may be seen continuously without a break during the night.

Even in ideal conditions, visibility is seldom good enough to permit a land-based observer to see the clouds right down to the horizon; they may be seen however to within 1 or  $2^\circ$  above the horizon. Observers in aircraft frequently report seeing the clouds right down to the horizon.

At their upper limit, the clouds are never seen right to the boundary F of the earth's shadow. Extinction is caused by losses, mainly by scattering in passage through the troposphere and lower stratosphere but also by the presence of

normal tropospheric clouds, so that only those rays from the sun above a height  $H_1$  over the shadow boundary are of sufficient intensity to render noctilucent clouds visible. If the limiting effective ray is  $BB'$ , then the point at greatest elevation ( $h$ ) at which the clouds will be visible from  $O$  is  $G$ , refraction being neglected. Corresponding values of  $\Delta$  and  $h$  (Figure 1) for various assumed values of  $H_1$  may be calculated. A series of six curves (Figure 2) has been drawn showing the relation between  $\Delta$  and  $h$  corresponding to limiting rays that pass at minimum distances of 0, 10, 20, 30, 40 and 50 km ( $H_1$ ) from the earth's surface. Measurements of  $H_1$  are given in Appendix I.

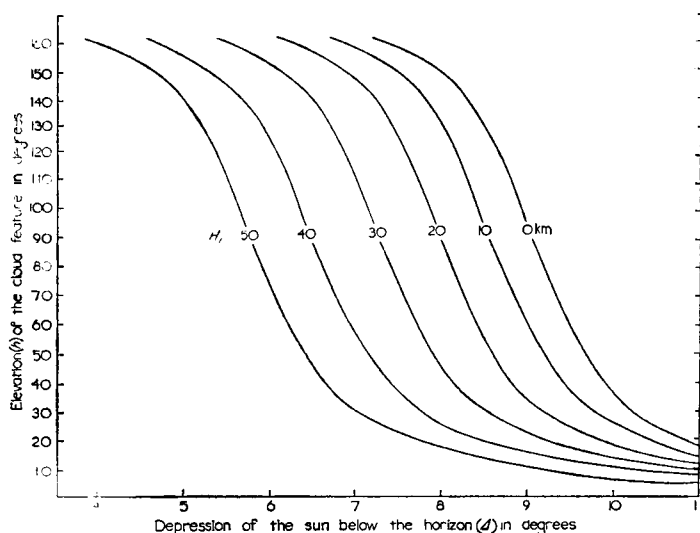


FIGURE 2—CURVES SHOWING THE RELATION BETWEEN  $\Delta$  AND  $h$  FOR VARIOUS VALUES OF  $H_1$

**The general character of displays observed in Scotland.**—Since 1949, regular watch for the clouds has been kept at Abernethy ( $56^{\circ}20'N$   $3^{\circ}19'W$ ). In 1954, members of the Aurora Survey, which had recently been established, began to report also displays of noctilucent clouds from various places in the British Isles, and later, during the International Geophysical Year (IGY), some observers in western Europe began to co-operate. In 1960, night-flying aircrews from the RAF Station at Leuchars, Fife, commenced regular observations. Observers record on each night if the clouds are present or absent or if observing conditions are too bad to make possible a decision about the presence or absence of the clouds. When the clouds are present the horizontal and vertical extent of the cloud field is recorded at intervals during the display. This organization of observers continues in operation each summer during the period when the clouds occur.

None of the 70 displays observed at Abernethy became visible until the sun was at least  $6^{\circ}45'$  below the horizon. At the season in late June and early July when the clouds most frequently occur, the sun reaches this position about 75 minutes after it sets. On almost every occasion, the first elements of cloud emerge from the clear sky close to the north horizon in the sector between north-north-west and north-north-east and thereafter are usually seen to extend laterally eastwards. Contrary to what one would expect, the area of the sky within which the clouds are seen does not always contract to reach a minimum at local midnight when the sun reaches its lowest point below the horizon.

Sometimes the elevation above the northern horizon of the upper limit of the cloud field increases slowly as midnight approaches, but only occasionally exceeds an elevation of  $10^\circ$  during the whole night. It is reasonable to conclude that on these occasions, the upper limit of the visible cloud marks the southern boundary of the cloud mass and that the whole mass either is drifting slowly southwards or is extending southwards by the continuous formation of fresh cloud.

The clouds usually appear in the form of thin, cirrus-like streaks, sometimes only one or two isolated filaments being visible, while at other times the cloud elements are closely compacted in an almost continuous mass resembling cirrocumulus or altocumulus undulatus (Plates I–V). Weaker and more tenuous displays have the form of decayed cirrus and there is often a structureless background (nebula) rather like cirrostratus. It is not surprising therefore that the clouds are usually reported as cirrus. The noctilucent clouds can usually be distinguished from ordinary clouds by the fact that they remain brighter than the sky background and glow with a ‘pearly, silvery light,’ generally showing some tinges of blue coloration. Tropospheric clouds, in the absence of bright moonlight, appear dark against the night sky and generally show easily perceptible movement.

Turbulent eddies with apparent vertical extension sometimes develop, most frequently in the eastern portion of the display after midnight. The most vigorous turbulence was observed on the night of 24–25 July 1950, when a brilliant display of noctilucent clouds occurred simultaneously with an active aurora.<sup>1</sup>

The lower portion of noctilucent clouds near the horizon may be reddish in colour. The total light scattered by the clouds may be great; it has been possible on several occasions to write notes by it without the need of artificial light. A great display of the clouds is quite magnificent and is an unforgettable sight.

Though successive photographs reveal continuous change in the fine structure of the clouds, the changes proceed sufficiently slowly and at such a great distance from the observer that they are imperceptible to the naked eye. The cloud mass appears to be quite stationary though patches of cloud may appear and disappear here and there within a few minutes. The progress of changes may however be observed by using binoculars.

Time-lapse photography of extensive displays shows complicated wave motion across the cloud mass. The passage of a system of waves over the cloud field is revealed by what is apparently an increase in brightness at the crests and a decrease at the troughs. The wave systems are sometimes quite complex, producing what have been called ‘knots’ (Grišin<sup>2</sup>) of increased brightness at the intersections between waves of separate systems, and an apparent motion of the cloud. For this reason, measurements of drift determined by parallactic photography may be seriously in error. Observed drift of individual and isolated elements of the clouds is almost invariably towards the south-west; on a few occasions, however, it was in the opposite direction and the clouds disappeared over the northern horizon leaving an empty sky in ideal observing conditions and at a time of night when any cloud present could have been readily identified.

On most nights, the elevation above the northern horizon of clouds observed in central Scotland does not exceed  $10^\circ$ . On four nights, however, (24–25 July

1950; 5-6 July 1953; 18-19 June 1959 and 29-30 June 1960) the behaviour of the cloud mass was what would be expected if it covered the whole sky to the southern horizon. The observed upper limit of the cloud mass was initially at an elevation well above  $10^\circ$  but then retreated slowly towards the horizon until local midnight. Thereafter the area of the sky containing visible cloud increased steadily and when the depression of the sun decreased to just below  $8^\circ$ , the cloud, already visible in most of the northern half of the sky between north-west and east, extended steadily through the zenith into the south-south-east. These events are explained by the form of the curves in Figure 2. The fact that the clouds quickly become visible at increasing elevations and are soon seen in the southern sky when  $\Delta$  is around  $8^\circ$  indicates that  $H_1$ , the nearest approach to the earth of the illuminating sunlight, lies between 20 and 30 km. In the 1953 display, for example, at 0202 Universal Time (UT) (depression of the sun  $7^\circ 40'$ ) the whole sky north of a line from the south-south-east horizon to the north-west horizon, through an elevation of  $75^\circ$  above the northern horizon on the meridian, was filled with parallel bands of cloud that appeared to converge by perspective. Thereafter the clouds soon were seen in the zenith, and when the depression of the sun became less than about  $6^\circ 40'$  the increasing brightness of the eastern sky extinguished the cloud in the east, but clusters of parallel bands now appeared in the western sky and the last cloud elements were just discernible in the south-west when the sun reached a point  $6^\circ$  below the horizon about one hour before sunrise. A similar pattern of events was observed on each of the four nights mentioned, during which ordinary cloud was absent and visibility excellent—conditions that are essential for the identification of the extremely tenuous structure of the last vestige of cloud as it vanishes in the brightening sky before dawn. On these nights then, the cloud mass clearly extended well south of the observing station at sunrise and if this were also the situation at the preceding sunset, then one would expect to observe the same sequence of events in reverse order, the clouds appearing first in the south-eastern sky as the sun reaches a depression of  $6^\circ$  below the horizon about one hour after sunset. An especially careful watch of the whole sky was kept at this time on the night of the last of the four displays but the clouds were not observed until 15 minutes later, when they first appeared above the north-north-east horizon. The cause of this may be partly subjective (the eye being more sensitive and better adapted to discern the weak and tenuous clouds in the increasing intensity of light before dawn) and partly due to the greater average clarity of the atmosphere at sunrise. Of course, it may be that the clouds did not extend into the southern part of the sky until later in the night.

The least and greatest values of the depression of the sun below the horizon when the clouds have been visible are  $5^\circ 55'$  (0309 UT, 25 July 1950 and 0220 UT, 19 June 1959) and  $15^\circ 50'$  (0019 UT, 2 August 1957). On this last occasion the clouds were situated very close to the northern horizon so it appears that the clouds are clearly identifiable only when the depression of the sun below the horizon is between about  $6^\circ$  and  $16^\circ$ . Included in the list of observations in the U.S.S.R. during 1957-58<sup>3</sup> are some occasions, small in number compared with the total, where the clouds were reported when the depression  $\Delta$  of the sun lay outside the range  $6^\circ$  to  $16^\circ$ . In one case  $\Delta$  was as small as  $1.7^\circ$ , in another as great as  $21.5^\circ$ .

At Abernethy therefore, the clouds, when present, should be seen continuously without a break during the night between 10 May and 3 August, for during that period the sun never descends more than  $16^\circ$  below the horizon. Outside this period, the cloud would be unilluminated and therefore invisible for a period around midnight when the depression of the sun is greater than  $16^\circ$ . In fact this is outside the season during which the clouds are visible in central Scotland (Table I).

**The height and geographical position of noctilucent clouds.**—Measurements of the height ( $H$ ) of the clouds by parallactic photography have been made using the base lines Abernethy–Blairgowrie ( $56^\circ 35'N$   $3^\circ 21'W$ ) and Abernethy–Newton Stewart ( $54^\circ 58'N$   $4^\circ 29'W$ ). Using auroral cameras,  $f/1.25$  and high-speed plates, exposure times are of the order 5 to 10 seconds, and simultaneity of exposures is achieved by linking the stations by telephone. The first of these base lines is rather short, 27.6 km, and unfavourably orientated for these measurements; the second, of length 169.8 km, is more satisfactory. Measurements range from 79 to 85 km. The mean value of 82 km is the same as that obtained by Størmer<sup>4</sup> in Norway and by various observers in the U.S.S.R.<sup>5</sup>

This remarkable constancy in height permits the geographical situation of the clouds to be accurately determined from observations of elevation  $h$  and azimuth  $A$  of cloud features. The relation between the geodetic distance  $D$  of a cloud feature  $X$  from an observing station  $O$  and the observed elevation  $h$  of the feature is shown in Figure 3. During each display a continuous record of the changing pattern of the clouds was kept both photographically and by visual

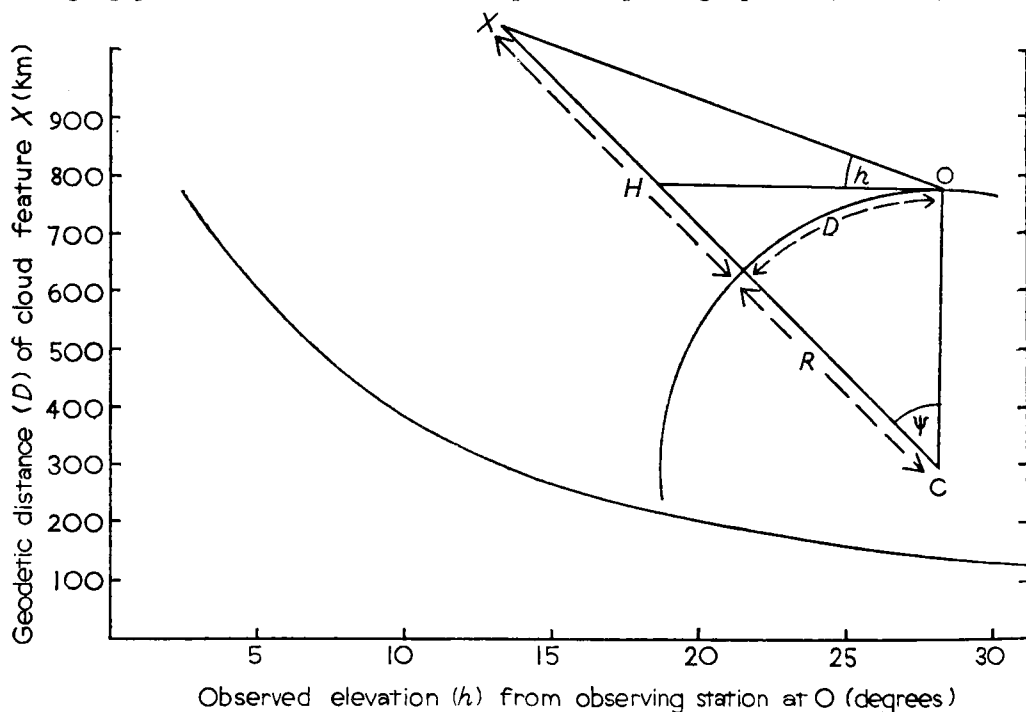


FIGURE 3—THE RELATION BETWEEN THE GEODETIC DISTANCE OF A CLOUD FEATURE FROM AN OBSERVING STATION AND THE OBSERVED ELEVATION AT THE STATION

Inset figure shows the geometrical relationships.  $D$  can be found from the following equations:  $\tan h = \cot \psi - R/[(R + H)\sin \psi]$ ,  $D = (\pi/180)R \psi$  ( $\psi$  in degrees), assuming  $H$  (height of cloud) = 82 km and  $R$  (radius of earth) = 6370 km.



TABLE I—DATES OF OBSERVATIONS OF NOCTILUCENT CLOUDS AT BEN NEVIS  
OBSERVATORY (1883-1904) AND IN EAST-CENTRAL SCOTLAND, MAINLY AT  
ABERNETHY, PERTHSHIRE (1949-1963)

Night	May		June		July		August Abernethy
	Ben Nevis	Abernethy	Ben Nevis	Abernethy	Ben Nevis	Abernethy	
1-2					1885	1957(59.5°) 1959(59°) 1961	1957(>62°)
2-3						1954 1961	1960(62°)
3-4					1889	1959(56°)	
4-5			1888		1889	1961	
5-6				1959		1953(<56°) 1959(59.5°) 1961	
6-7			1888		1887	1955 (58.5°)	
7-8			1889		1888	1955(60°)	
8-9				1955 1962		1959	
9-10			1889		1891	1959(58.5°) 1960(60.5°)	
10-11			1889			1949(59.5°) 1959	
11-12						1960(59.5°) 1963	
12-13				1961		1960(59.5°) 1962(60°)	
13-14					1891 1892	1959(59.5°)	
14-15					1891	1959(60°) 1962	
15-16			1888		1890	1959(56°) 1962 1963	
16-17			1895		1890	1963	
17-18			1886 1888 1889		1887	1961(62°) 1963(60°)	
18-19				1959(<56°) 1960(60°)	1902	1960(61°)	
19-20				1951(57.5°) 1960			
20-21			1888	1960(58°)	1887	1960(60°) 1961(60°) 1963(58°)	
21-22			1888 1889			1960(59°)	
22-23			1888				
23-24			1888	1959	1892	1963	
24-25			1887 1888		1892	1950(<56°) 1959	
25-26			1888	1960(<56°)		1960(60°) 1963	
26-27	1889 1890	1960	1887 1888	1959		1956	
27-28				1960(59°)			
28-29		1959	1887 1890	1963		1960(62°)	
29-30			1887	1960(59°) 1961(57°)			
30-1 or 30-31			1888	1950(58°) 1960(58.5°) 1961			
31-1						1961(62°)	

Figures in brackets give the approximate latitude of the southern boundary of noctilucent clouds on nights when this was measurable.

observation using high-power binoculars (magnification 25) with a trunnion and turn-table mounting on a tripod, the purpose being to map the projection of the cloud mass on the earth's surface. A chart on which this projection may be accurately plotted was constructed in the following manner.

The plane of the chart is tangential, touching the earth at the observing station. The position of a point on the chart corresponding to any point on the earth's surface is found by imagining a vertical plane through the station and the point on the earth's surface, intersecting the tangential plane in a straight line through the station. The position of the point on the chart lies on this line at a distance  $D$  from the station equal to the true distance of the corresponding point on the earth's surface, measured along a great circle between the station and the point. Projections on this chart will then fulfil the condition of conformity, i.e. azimuths measured from the station are unaltered by the projection. The chart is constructed by calculating  $D$  and  $A$ , measured from the observing station, for points of intersection of meridians and parallels. When meridians and parallels have been thus drawn, outlines of coasts may then be sketched in. The scale used was 1 cm to 10 km.

The foot points of cloud features are readily mapped on the chart from observations of  $A$  and  $h$  (giving  $D$ ), using a steel measuring tape pivoted at the station.

It is only occasionally that the clouds are observed in central Scotland at elevations greater than  $10^\circ$  above the northern horizon. The cloud mass is therefore usually situated to the north of Scotland at distances greater than about 400 km (Figure 3) from Abernethy, and so is illuminated at some time during the night to its southern boundary, whose position can be determined. On two occasions, however, (3–4 and 15–16 July 1959) the clouds appeared as far south as the zenith and on four nights (see last paragraph on page 164) they were observed almost to the south horizon; they are visible in this latter position only at the end of the display, just before sunrise. The latitude of the southern boundary of the clouds to the nearest  $\frac{1}{2}^\circ$  on nights when it was measurable (i.e. sky clear of low cloud and excellent visibility during the whole night) are entered in brackets in Table I.

On most nights the clouds extended to the north horizon so that the northern boundary of the clouds lay somewhere to the north of latitude  $65^\circ$ . On several nights however during the early part of the observing season, the clouds were never observed to extend down to the horizon and a well marked northern boundary existed at an elevation of around  $10^\circ$ . The positions of the northern boundary on these nights were  $60.5^\circ\text{N}$  on 18–19 June 1959,  $60.5^\circ\text{N}$  on 19–20 June 1951 and  $60^\circ\text{N}$  on 20–21 June 1960. On the first and third of these occasions, the absence of cloud below an elevation of  $10^\circ$  was confirmed by observations from aircraft at heights above 40,000 feet. Unless an entirely separate cloud mass existed far to the north, it appears then that the *extension of the clouds in latitude* during the early part of the season may sometimes be no greater than  $1$  or  $2^\circ$ ; during the six occasions when the cloud was observed overhead or to the south of the observing station, the meridional extension was at least  $10^\circ$  and probably considerably greater.

Towards the end of the observing season at Abernethy ( $56^\circ 20'\text{N}$ ) in late July and early August, the clouds recede northwards and have never been observed later than 3 August. They have been observed in Shetland ( $60^\circ\text{N}$ ) until 7 August and at Torsta, Sweden, ( $63^\circ 15'\text{N}$ ) until 16 August.<sup>6</sup> The southern

boundary of clouds observed in western Europe clearly retreats northwards in late summer and autumn reaching about 70°N by mid-August. That a similar movement occurs north of Alaska is suggested by the observations at College (64°53'N) on 17 August,<sup>7</sup> and on an ice island (76°18'N 170°W) on 13 September;<sup>8</sup> the latter is the highest latitude from which observation of the clouds has been reported.

A comprehensive synoptic study has been organized by Šaronov<sup>9</sup> in the U.S.S.R. and statistical analyses have been published by Gromova<sup>10</sup> and Bessonova<sup>11</sup> for the periods 1885–1956 and 1957–59 respectively. The most northerly and southerly latitudes in which the clouds have been seen are 71.5°N and 45.5°N; they are seen most frequently in latitude 55°N and in the first 10 days in July; and the earliest and latest dates on which the clouds have been seen are 5 March and 24 October. There appears to be no indication of the seasonal movement of the clouds observed to occur in western Europe; in fact, observations of the clouds have been reported from U.S.S.R. stations in latitudes 46° to 66° in March, and 56° to 61° in October. There is ample evidence that the clouds are never seen in places south of latitude 40°. No single occurrence was recorded during the course of careful observations by trained observers during 700 cloudless summer nights at Ashkhabad<sup>12</sup> (37.5°N 58.5°E). It may be taken as established that the latitude of the southern boundary of the clouds is never lower than about 45°N. The northern limit is uncertain because of prevailing cloudiness and the sparse population in high latitudes, but it is at least 80°N.

The *extension in longitude* is more difficult to determine, for not much synoptic data are available. The greatest recorded extensions occurred on the night of 3–4 July 1959 when the clouds were visible along the northern horizon in the south of England, and were seen up to the same elevation of 5° from a ship, S.S. *Lismoria*, in about the same latitude in the St. Lawrence Estuary (50°N 63°W) as well as in the U.S.S.R. at a station at 52°N 118°E. On many occasions, the clouds have been seen in Scotland during nights when their occurrence has been reported in the U.S.S.R. in longitudes 22° to 143°E (Table II).

TABLE II—NIGHTS DURING WHICH CLOUDS WERE OBSERVED BOTH IN SCOTLAND (56.3°N 3.3°W) AND THE U.S.S.R.

Date	Position of station in U.S.S.R.	
	°N	°E
24–25 July 1950	55.9	37.4
5–6 July 1953	58.1	38.8
8–9 June 1955	56.8	60.6
6–7 July 1955	56.3	44
26–27 July 1956	58.1	38.8
5–6 June 1959	56	31
1–2 July 1959	57	61
3–4 July 1959	52	118
5–6 July 1959	53	50
9–10 July 1959	55	113
10–11 July 1959	54	36
13–14 July 1959	49	143
14–15 July 1959	59	25
15–16 July 1959	58.2	22.3
19–20 June 1960	56.2	44
25–26 June 1960	56.2	44
27–28 June 1960	56.2	44
17–18 July 1961	59.2	25

So the zonal extension of the cloud system may sometimes be at least  $180^\circ$  of longitude, and the southern boundary appears to be fairly closely aligned along a circle of geographical latitude.

On at least one occasion, the western boundary of the clouds over Europe must have been sharply defined. On the night of 1–2 July 1962, a fine display was visible in Sweden and Denmark, yet no cloud was observed at any time during the night in Scotland where skies were clear except for a continuous bank of cloud extending up to about  $15^\circ$  above the eastern horizon.

There appears to be no published record of observations in the southern hemisphere although observations were made and photographs taken by W. Holman in a U.S. ship in high southern latitudes in 1962 of what were almost certainly noctilucent clouds; unfortunately the photographs were unsuccessful (personal communication from B. Fogle).

**The dates and frequencies of displays observed in Scotland in latitude  $56^\circ$  to  $57^\circ\text{N}$ .**—The dates on which noctilucent clouds have been observed at Abernethy between 1949 and 1963 are recorded in Table I. The list includes some displays obscured by cloud at Abernethy but reported by observers in aircraft based at Leuchars, 20 miles distant from Abernethy, and flying at high levels above east-central Scotland. Occasions when there was any doubt of identification, usually because of low cloud, poor visibility or the extremely tenuous nature of the observed clouds, have been omitted. The remarkable frequencies of occurrence during the summers of 1959 (15 nights) and 1960 (17 nights) will be noted.

It was known that the observers at Ben Nevis Meteorological Observatory ( $56^\circ48'\text{N } 5^\circ00'\text{W}$ ) had recorded in their log, notes on what they called “pearly-white cirrus” which they had seen frequently between 1887 and 1891, just at the time when Jesse<sup>13</sup> in Germany and Ceraskij<sup>14</sup> in Russia had first recognized these clouds as being different from ordinary clouds. A photograph found among the Observatory records\* leaves no doubt that these were in fact noctilucent clouds (Plate VII). The dates on which they were seen have been extracted from the Ben Nevis Observatory log-books<sup>15,16</sup> and are entered also in Table I. (This Observatory was in operation between the years 1883 and 1904.) The latitudes of Abernethy and Ben Nevis differ by less than  $\frac{1}{2}^\circ$ ; the similarity in the distributions of nights of noctilucent clouds will be apparent. Since the geographical situation of the clouds has been shown to vary seasonally, the data used in comparing frequencies should strictly refer to a particular latitude. It is clear that in latitude  $56^\circ$  to  $57^\circ$ , the normal period of appearance of the clouds is between about 15 June and 3 August, the frequency being greatest in the first half of July. It will be observed that this accords with the observations made in the U.S.S.R.,<sup>10,11</sup> which also showed that the clouds are most frequently seen around latitude  $55^\circ$ . The clouds are occasionally observed in Scotland earlier than 15 June, sometimes as early as 26 May, but usually only during the years of maximum frequency of occurrence. The Ben Nevis frequencies are 1887, 7; 1888, 13; 1889, 8; 1890, 4; and 1891, 3. It is significant that though the optical requirements are satisfied symmetrically on either side of Midsummer Day (at Abernethy and Ben Nevis the

\*BUCHAN, A.; The Ben Nevis Observatories and the work done there. And OMOND, R. T.; Life and observing at the Ben Nevis Observatory. *Proc. phil. Soc. Glasg., Glasgow*, **27**, 1895–96, Plate III, No. 9.

clouds would be illuminated during the whole night between 10 May and 3 August) and though observing conditions at these two stations are on the average better before than after midsummer, the clouds have never been observed between 10 May and 26 May, and only occasionally between 26 May and 15 June. Further, though the period of time during which the clouds may be visible after sunset and before sunrise (depression of the sun between  $6^{\circ}$  and  $16^{\circ}$ ) is less at other times of the year, it would still be sufficient even in winter to permit recognition of the presence of noctilucent clouds in suitably clear conditions. Careful watch has been kept, yet they have never been observed in central Scotland outside the period 26 May–3 August. Though the great majority of occurrences recorded in the U.S.S.R. are between mid-June and early August, the clouds have been reported in latitude  $55^{\circ}$  as early as March and as late as October.<sup>10,11</sup>

The observations at Ben Nevis and at Abernethy show pronounced maxima of frequency of occurrence in 1888 and 1960. Vestine<sup>17</sup> has made a thorough search of the literature for noctilucent cloud observations made in all latitudes in the northern hemisphere and has found that there was a pronounced maximum frequency in 1887 and smaller maxima in 1911 and 1932. The observations of Størmer between 1932 and 1939 and those in Scotland since 1939 make it reasonably certain that no maximum frequency of the order of the frequencies of 1959–60 occurred between 1932 and 1959. Comparison of the frequencies recorded at Ben Nevis in 1887–90 with those at Abernethy in 1959–60 suggests that the frequencies of these recent years have been at least of the same order as those of 1887–88; observing conditions on the summit of Ben Nevis would be much affected by cloud and less favourable than at Abernethy. It may be significant, but it is probably fortuitous, that the noctilucent cloud maxima in 1887, 1911, 1932 and 1960 each occurred during the phase of declining solar activity, three to four years after sunspot maximum.

Combining the observations in Scotland with those recorded in the U.S.S.R. reveals that noctilucent clouds were present almost continuously over some part of northern Europe for long periods during 1959 (26 June–17 July), 1960 (18 June–1 July) and 1961 (29 June–9 July).

**Associations of noctilucent clouds with meteorological conditions in the lower stratosphere.**—Using the weather maps of the Central Forecasting Institute of the U.S.S.R., Grišin<sup>2</sup> has investigated the relations of over 100 displays of noctilucent clouds between 1922 and 1959 with meteorological events at mean sea level and claims that “each appearance of noctilucent clouds is accompanied by an absolutely definite pattern of values of the meteorological elements in the lower troposphere.” His conclusions may be summed up thus:

(i) For a quite lengthy period before each display, there is a rapid increase in M.S.L pressure over the region underlying the display; the speed of displacement of the isobars is of the order of 800 to 1800 km per day, the higher pressure occurring in the direction of the noctilucent clouds, “independently of the general direction of anticyclonic movement during the period.”

The intensity and the geographical extent of the region of this pressure change are directly proportional to the brightness and the area of the subsequent noctilucent clouds and, in the case of bright and well defined displays, the cloud striations are in general orientated approximately in the same direction as the underlying M.S.L isobars.

(ii) A period of unusually frequent occurrence of noctilucent clouds is always associated with abnormally high seasonal temperatures over a wide area of the earth's surface, especially during the month preceding the displays.

A statistical analysis of the data contained in Table I showed no significant relations with surface pressure and temperature of the kind found by Grišin using the observations made in the U.S.S.R. The method of superposed epochs was applied to examine the variations in M.S.L. pressures and temperatures at Lerwick during the five days preceding each display. Lerwick is situated near the southern border of most of the displays.

### **The nature of the particles comprising noctilucent clouds.—**

(i) *SIZE*.—The first continuous spectra of noctilucent clouds were obtained by Grišin.<sup>18</sup> The interpretation of these spectra is difficult since they contain the effects of atmospheric extinction in the primary and scattered light and of twilight, each of which can be only roughly estimated. Deirmendjian and Vestine<sup>19</sup> showed how corrections for the contribution of twilight may be applied by using spectra of the clear sky obtained in conditions as close as possible to those existing during the photography of the cloud spectra. The spectra of Grišin were then interpreted as being due to single scattering by spherical dielectric particles whose radii do not exceed  $4.0 \times 10^{-5}$  cm.

Since the state of polarization of the scattered light is not significantly changed by the selective extinction of the atmosphere and its intensity is sensitive to the presence of large particles and is easily measurable, Witt<sup>20</sup> was led to devise a photographic method of measuring the polarization of light from noctilucent clouds in two spectral regions. By comparing his measurements with curves computed theoretically using Mie theory, he finds that the radius of the particles is  $1.0 \times 10^{-5}$  cm if the assumed refractive index is 1.55, and  $1.3 \times 10^{-5}$  cm if the refractive index is 1.33. The polarization observed at large scattering angles indicates that there can be no significant number of particles with radius greater than  $2.4 \times 10^{-5}$  cm. The method can give no information concerning the existence or number of very small particles. Since no significant variation in the behaviour of the polarization was noticed, it was concluded that no change in the size of the particles took place during the observations.

(ii) *ORIGIN*.—(a) *Volcanic*.—It was presumably the fact that spectacular atmospheric optical phenomena following the Krakatoa eruption in August 1883 were widespread and continuing just at the time when Jesse<sup>13</sup> and others were making the first studies of the characteristics of noctilucent clouds, that led to the belief that the clouds were of volcanic origin. There can be no doubt that dust and gases, among them water vapour, are projected up to heights of at least 30 km during eruptions. Vestine<sup>17</sup> however has pointed out that the period 1880–87 was one of quite outstanding meteoric and comet activity and that no unusual noctilucent cloud occurrences followed the great eruptions of Katmai, Alaska, in 1912, while brilliant displays of the clouds were reported after the descent of the meteorite at Tunguska, Siberia, on 30 June 1908;\* he therefore favoured a cosmic origin of the particles. While allowing that volcanic material might diffuse upwards in sufficient quantity to form noctilucent

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\*Gromova<sup>21</sup> questions whether the intensely luminous sky phenomena reported after the Tunguska meteorite were actually noctilucent clouds.

clouds, Ludlam<sup>6</sup> also concluded that there is no evidence that a close relationship exists between volcanic activity and the occurrence of the clouds.

(b) *Cosmic*.—Comparing the dates of maximum frequency of occurrence of noctilucent clouds given by Vestine and those of *meteor showers* provided by Lovell and Clegg, Bowen<sup>22</sup> claimed that “noctilucent clouds tend to appear at precisely the same date or within a few days of the meteor streams.” The occurrences recorded in Table I show no close relationship of the kind claimed by Bowen. In fact, during the major meteor showers, the number of visually observed meteors is not much more than twice that of *sporadic meteors* so that the latter provide the main source of meteoric material in the upper atmosphere.

Ludlam<sup>6</sup> concluded that noctilucent clouds are simply a visible haze top formed by the concentration of dust particles in a layer below the inversion at the mesopause (see Figure 4). Solar heating of the ozone layer, which at the time of occurrence and in the geographical situation of the clouds remains sunlit almost continuously day and night, would produce a steep lapse rate in the region between the 55 and 80 km levels. Dust deposited in this convective region would become concentrated in a layer below the inversion at the mesopause. If irregularities or wave motions occur at the top of the layer then the variations in optical thickness would produce structure, especially when observations are made at low elevations, as is usual with noctilucent clouds.

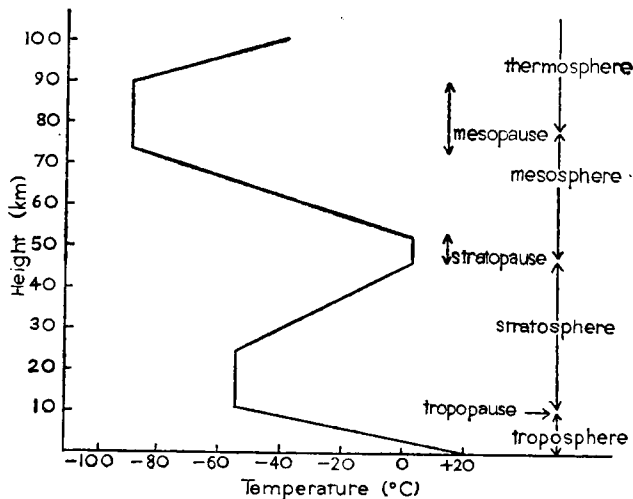


FIGURE 4—MAIN FEATURES OF THE TEMPERATURE STRUCTURE OF THE ATMOSPHERE

There is difficulty in explaining why the clouds, if they consist of dust, appear only in high latitudes. Ludlam suggests that if the particles are charged or consist of iron, they would tend to precipitate into the upper mesosphere in high latitudes. A more plausible explanation is provided by the calculations of Murgatroyd and Singleton<sup>23</sup> of the meridional circulation sufficient to transport heat between radiational sources and sinks in the stratosphere and mesosphere. This reveals a continuous region of ascending air throughout the summer hemisphere extending from a height of about 50 km to above 80 km. The calculated speeds of ascent increase towards the summer pole and, in the latitudes where noctilucent clouds appear, are of the order of 1 cm per second, sufficient to support and to concentrate near the 80-km level at least the smallest dust particles.

Hoffmeister<sup>24</sup> attributes a similar origin—the impact of clouds of micro-meteorites—to the clouds, but suggests that the dust concentration is formed mainly in low latitudes and at heights above 150 km. While the dust slowly sinks it is carried to higher latitudes by “very persistent south-westerlies in the ionosphere and eventually collects at the surface of the discontinuity which separates the mesospheric wind system from the currents in the lower ionosphere.” It is argued that the formation of well defined cloud layers is possible only when large-scale turbulence is absent. In this way are explained the sudden appearance and disappearance of cloud features and the rarity of occurrence of the clouds.

(c) *Condensation on nuclei*.—During a brilliant display observed in Scotland on 24–25 July 1950 two observers, McKellican and Paton,<sup>25</sup> independently noticed a change in colour from vivid blue to white in portions of the cloud. Visually observed changes in colour at the luminance of noctilucent clouds may well be subjective but there can be little doubt that blue coloration varies from display to display and during particular displays, and that in some displays particles with radii in the Rayleigh region are present in sufficient numbers to strongly colour the clouds. While Witt<sup>20</sup> observed no significant variations in the behaviour of the polarization during his observations, it is worth noting that if condensation occurs on a meteoric nucleus, the effect on the polarization of the increasing radius would be offset by the effect of the decrease in refractive index; polarization measurements may then fail to reveal small changes in radius of the particles.

The general appearance and behaviour of the clouds and the continuous changes observed in the fine structure strongly suggest that they are identical with cirrus. The observed behaviour of the clouds during displays observed in Scotland on the same night, 18–19 June, in two successive years, 1959 and 1960, is significant. The nights were both continuously clear with excellent visibility, so that the displays were observed in ideal and identical conditions. Each display became visible at the same (and normal) time, 2310 UT. The display in 1959 persisted until 0220 UT when the last elements of visible cloud vanished in the south-western sky as the sun reached a position about 6° below the horizon. In 1960 however, the clouds, which initially covered a wide area of the northern sky, began to dissipate even before midnight and had vanished by 0055 UT. There was no indication of drift northwards over the horizon; the cloud filaments appeared to slowly disintegrate *in situ* like evaporating cirrus clouds.

The appearance and persistence of the cloud mass near to a height of 80 km is most readily accounted for by assuming that it is formed by condensation at the temperature minimum existing at this level (Figure 4). The work of Murgatroyd<sup>26</sup> indicates that the lowest temperatures at 80 km occur in high latitudes in summer and that winter temperatures at this level are considerably higher. While providing a plausible explanation for the occurrence of the clouds only in high latitudes and only in summer, this also suggests that the observed seasonal changes in the meridional extension of the clouds may provide a visible indication of the variations in the meridional extent of the region of low temperature at 80 km. The conclusion of Murgatroyd and Singleton<sup>23</sup> that there exists throughout the summer mesosphere a general ascent of air with greatest speeds in higher latitudes supports also a condensation hypothesis.



The difficulty of this hypothesis is the explanation of the manner in which water vapour may penetrate in sufficient quantity to the mesopause. From the measurements of Brasefield<sup>27</sup> of water content in the stratosphere between heights of 22 and 35 km, Hvostikov<sup>28</sup> deduced that on certain days the values of the temperature and humidity at the mesopause may be such as to cause the formation of clouds consisting of ice crystals. He claimed, in fact, that saturation may occur at temperatures as high as 181°K to 187°K and quotes actual measurements of temperature by rockets over middle latitudes in the U.S.S.R. of  $154 \pm 30^\circ\text{K}$  at 85 km. At the 80-km level, the total pressure is approximately  $10^{-2}\text{mb}$  and the density is  $10^{-8}\text{gm per cm}^3$ , while if the temperature is 150°K, the saturation vapour pressure over ice is  $6 \times 10^{-8}\text{mb}$ , the saturation mixing ratio over ice is  $6 \times 10^{-3}\text{gm per kg}$ , and the saturation vapour density over ice is  $10^{-13}\text{gm per cm}^3$ . These data lend support to the possibility that physical conditions leading to the formation of ice crystals may sometimes exist at the mesopause. Hesstvedt<sup>29</sup> has computed a model of an ice cloud assuming a temperature profile and wave motion in agreement with observations, and concludes that the possibility of ice-cloud formation exists.

Finally, direct evidence indicating the presence of ice crystals in noctilucent clouds has been obtained by rocket soundings<sup>30</sup> in northern Sweden during the summer of 1962. Sampling surfaces were mounted in cylindrical containers and exposed between altitudes of 75 and 95 km during ascent only. Two successful ascents were made, one on 7 August when no noctilucent clouds were visually observed, and the other on 11 August when observations at an observing site 150 km south of the rocket range showed that the clouds extended overhead at the range. On each occasion, the containers were recovered sealed and in excellent condition within an hour after the launching. Examination of the collecting surfaces showed significant differences on the two flights. Those from the flight through the cloud gave a count for particles of diameter greater than 0.05 micron of 4 to 30 times  $10^{10}$  per square metre, which was greater by two to three orders of magnitude than the count found on the flight made when cloud was absent. The number of particles per unit area and the size distributions were found to accord with the observed light-scattering properties of the clouds. Studies of the composition using electron beam microprobes showed evidence of particles containing both iron and nickel. Electron micrographs of the surfaces showed a circular pattern surrounding the larger particles (Plate VI), which is likely to have been caused by an ice coating which surrounded the particles at the time of deposition and subsequently evaporated.

It is reasonable therefore to conclude that noctilucent clouds consist of ice crystals that have formed on a nucleus of cosmic origin and that the formation of the clouds is largely controlled by the temperature existing at the mesopause.

## Appendices

### **I. The attenuation of sunlight during its passage through the troposphere and lower stratosphere before reaching noctilucent clouds.—**

(i) By plotting the maximum elevation  $h$  of the features situated in the direction of the sun against the calculated depression  $\Delta$  of the sun below the horizon, the nearest approach to the earth of the illuminating beam of sunlight may be found by interpolation from the family of curves (Figure 2). The method is valid only when the clouds are known to extend high in the sky, as was the case on the nights given in Table III.

Date	Time (UT)	TABLE III $h$	$\Delta$ at O'	$H_1$ (km)	Type of cloud
18-19 June 1959	0014	15.0°	10°18'	23	} well defined streak
1-2 July 1957	0017	12.4°	10°35'	24	
5-6 June 1959	0018	10.3°	10°55'	28	
25-26 June 1960	0005	~20°	10°17'	14	nebula

The first three cases agree with the general deduction made in the first paragraph on page 165; the last, for the case of the nebular form, is probably unreliable since it is impossible to measure the height of clouds of this form for the reason that it lacks the well defined edges that are necessary for parallactic measurements. The height of this form may be very different from 82 km.

(ii) The height, measured vertically, of the clouds above the earth shadow may be determined by observing the time at which the clouds *first appear directly overhead*. The depression  $\Delta$  of the sun at this time can be determined from

$$\sin \Delta = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \theta,$$

where  $\varphi$  is the latitude of the observing station and  $\delta$  and  $\theta$  are the declination and hour angle of the sun respectively. The hour angle  $\theta$  is found from the time (UT) using

$$\theta = \text{ET} + \text{UT} - \lambda \pm (12 \text{ hours}),$$

where ET is the equation of time and  $\lambda$  the longitude west of Greenwich expressed as a time. ET and  $\delta$  are obtained from the *Astronomical Ephemeris*.<sup>31</sup>

The relation between height  $H_2$  of the earth shadow (overhead) and the depression of the sun below the horizon is shown in Figure 5. The precise time at which the clouds first appeared overhead was recorded on the following two occasions:

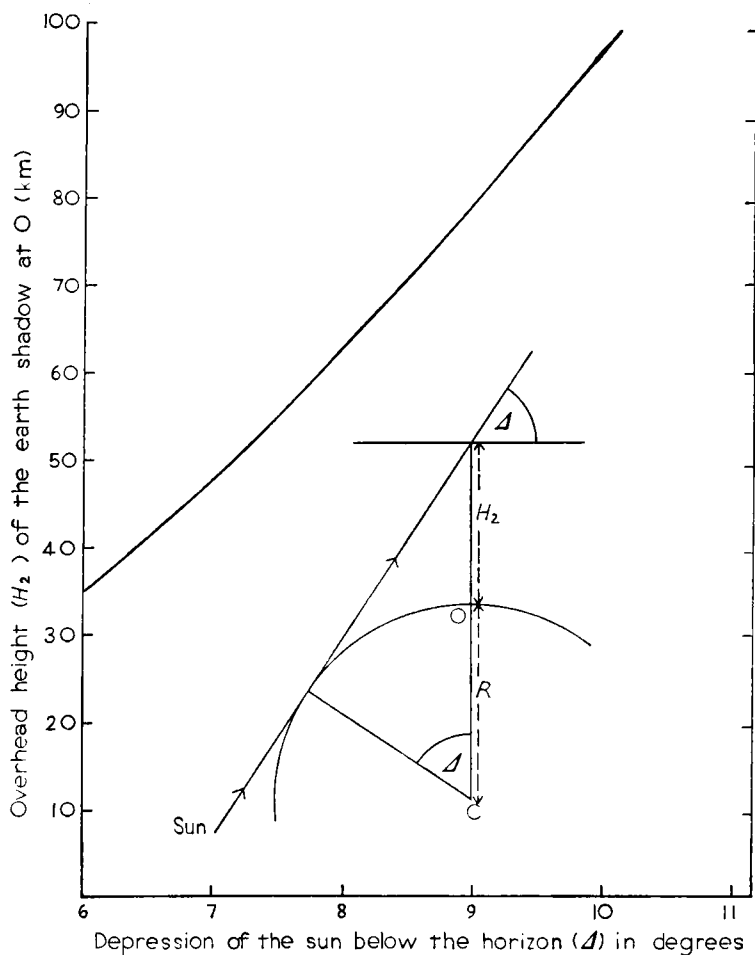


FIGURE 5—THE RELATION BETWEEN THE OVERHEAD HEIGHT OF THE EARTH SHADOW AT AN OBSERVING STATION AND THE DEPRESSION OF THE SUN BELOW THE HORIZON AT THE STATION

Inset figure shows the geometrical relationships.  $H_2$  can be found from the following equation:

$$H_2 = R[(1/\cos \Delta) - 1]$$



*Photograph by J. Paton*

PLATE I—AUROREAL ARC WITH NOCTILUCENT CLOUD BELOW ALONG THE HORIZON:

A RARE COINCIDENCE

(see p. 164)



*Photograph by C. Wilson*

PLATE II—NOCTILUCENT CLOUD OBSERVED AT NEWTON STEWART, WIGTOWNSHIRE,  
25-26 JUNE 1960



*Photograph by J. Paton*

PLATE III—NOCTILUCENT CLOUD OBSERVED AT ABERNETHY, PERTHSHIRE  
(see p. 164)



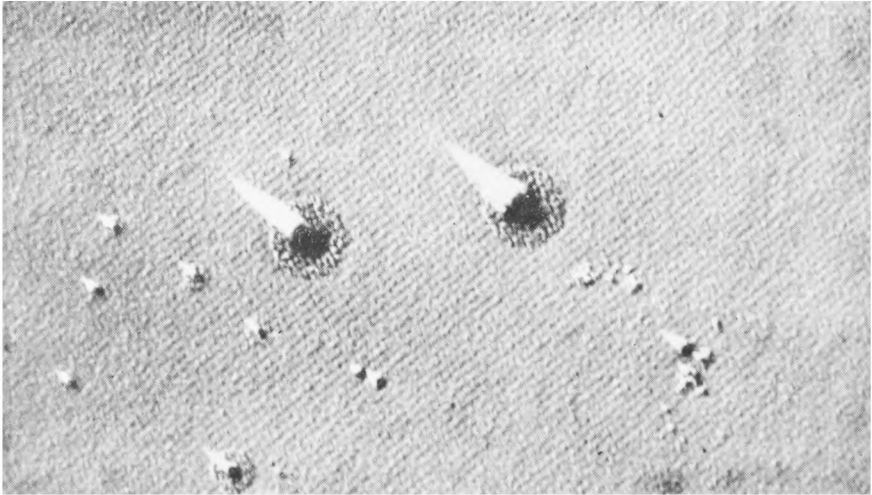
*Photograph by J. Paton*

PLATE IV—NOCTILUCENT CLOUD OBSERVED AT ABERNETHY, PERTHSHIRE



*Photograph by J. Paton*

PLATE V—NOCTILUCENT CLOUD OBSERVED AT ABERNETHY, PERTHSHIRE  
(see p. 164)



1 micron

Reproduced by permission of G. Witt

PLATE VI—ELECTRON MICROGRAPH OF CLOUD-COLLECTING SURFACE  
(see p. 175)



Reproduced from *Proc. phil. Soc., Glasgow, 1895-96*

PLATE VII—AN EARLY PHOTOGRAPH OF NOCTILUCENT CLOUD

“The interest in this picture lies in the fact that the photograph was taken at midnight and represents a cloud near the northern horizon lit up by the sun. This phenomenon is only seen near the summer solstice, when the sun, though invisible, is so little below the horizon at midnight that its rays reach and illuminate high clouds midway between Ben Nevis and the Arctic Circle.”

This caption accompanied articles by Alexander Buchan and R. T. Omond on the Ben Nevis observatories, published in the Proceedings of the Philosophical Society of Glasgow, 1895-96, (see page 170).

Date	Time (UT)	$\Delta$ at O	Height overhead of earth shadow $H_2$	Vertical height of clouds above shadow	$H_1$
5-6 July 1953	0203	$7^{\circ}43'$	58 km	24 km	24 km
25-26 June 1960	0154	$7^{\circ}39'$	57 km	25 km	25 km

$H_1$  may also be determined using Figure 2.

(iii) The same measurement may be determined for any well defined cloud feature by first finding, by the method described in the third paragraph on page 166, the geographical co-ordinates of the point O', above which the feature is overhead. The depression of the sun at this point is then calculated and the overhead height of the earth shadow determined as in (ii). The forms selected in Table IV are those at maximum elevation in each azimuth; all are well defined streaks and are at elevations of  $9^{\circ}$  or greater.

TABLE IV

Date	Time UT	$h$ degrees	$A$	$D$ km	$\phi$ at O'	$\lambda$ at O'	$\Delta$ at O'	Height of earth shadow at O' kilometres	Vertical height of cloud above earth shadow
18-19 June 1959	0014	15.0	0	280	$58^{\circ}50'$	$3^{\circ}19'W$	$7^{\circ}45'$	59	23
1-2 July 1957	0017	12.4	0	330	$59^{\circ}20'$	$3^{\circ}19'W$	$7^{\circ}35'$	56	26
5-6 July 1959	0018	10.3	0	380	$59^{\circ}45'$	$3^{\circ}19'W$	$7^{\circ}29'$	55	27
18-19 June 1959	0037	10	345	390	$59^{\circ}40'$	$5^{\circ}00'W$	$6^{\circ}51'$	46	36
	0037	14	012	300	$59^{\circ}00'$	$2^{\circ}20'W$	$7^{\circ}24'$	54	28
	0137	15	080	280	$56^{\circ}40'$	$1^{\circ}10'E$	$7^{\circ}10'$	50	32
18-19 June 1960	2357	10	020	390	$59^{\circ}40'$	$1^{\circ}00'W$	$6^{\circ}55'$	47	35
19-20 June 1951	2310	15	030	280	$58^{\circ}30'$	$1^{\circ}00'W$	$7^{\circ}16'$	52	30
	0117	27	320	160	$57^{\circ}20'$	$5^{\circ}00'W$	$8^{\circ}22'$	68	14
20-21 June 1960	2330	15	050	280	$58^{\circ}00'$	$0^{\circ}10'E$	$8^{\circ}17'$	67	15
25-26 June 1960	2315	19	355	225	$58^{\circ}20'$	$3^{\circ}30'W$	$7^{\circ}17'$	51	31
1-2 July 1957	2302	10	030	390	$59^{\circ}20'$	$0^{\circ}00'$	$7^{\circ}14'$	50	32
1-2 July 1959	2235	10	050	390	$58^{\circ}30'$	$1^{\circ}45'W$	$6^{\circ}43'$	44	38
5-6 July 1959	2330	9	030	420	$59^{\circ}30'$	$0^{\circ}20'E$	$7^{\circ}22'$	53	29
9-10 July 1959	0130	17	010	250	$58^{\circ}25'$	$1^{\circ}50'W$	$7^{\circ}30'$	55	27
24-25 July 1950	0210	12	0	335	$59^{\circ}20'$	$3^{\circ}20'W$	$7^{\circ}40'$	57	25

It will be noted that the first three cases in this table are the same as those in (i). On the nights of 19-20 June 1951 and 20-21 June 1960, the clouds were visible in a position much nearer the earth shadow than on all other occasions.

**II. Visual observation of noctilucent clouds.**—The synoptic studies described in the paper will continue and the following notes are provided for use by observers who may wish to join in contributing to these studies.

Observers should record (i) the night of occurrence specified by two dates, e.g. 20-21 June 1963, and the latitude and longitude of the observing station: (ii) the period(s) of time, GMT, during which the clouds were observed: (iii) the horizontal and vertical extent, expressed in degrees of azimuth and elevation, at specified times, say every quarter hour, half hour or hour. This information is best conveyed by drawing a rough sketch showing the configuration of the cloud elements and the co-ordinates, elevation and azimuth of the visible boundaries of the cloud, i.e. the maximum elevations in different azimuths and the limiting azimuths, east and west of north. The angular measurements are easily made when a theodolite or alidade is available. If no instrument is available, less exact methods may be used. A foot-rule held at arm's length subtends an angle of about  $25^{\circ}$  at the eye, so each inch corresponds to about  $2^{\circ}$ : (iv) general notes on the nature and behaviour of the clouds. Photographs are, of course, of great value. The time at which photographs are taken should be recorded to the nearest minute. With fast monochrome film, exposure times are of the order of 5-10 seconds at  $f/3.5$ ; with colour film of rating ASA 25, exposure times are 40-60 seconds at  $f/3.5$ . It is advisable to take several photographs at different exposures.

Observations and photographs sent to the Balfour Stewart Auroral Laboratory, The University, Drummond Street, Edinburgh 8, will be gratefully acknowledged. Photographs will be returned after copying.

**Acknowledgements.**—The author is greatly indebted to the late Mr. J. B. McKellican and Mr. Charles Wilson who operated the cameras at Blairgowrie and Newton Stewart respectively, and to Mr. G. V. Black for invaluable assistance in photographic matters.

The synoptic studies were made possible by the co-operation of members of the staff at meteorological stations and of the Aurora Survey. Mr. L. L. Alexander of the Meteorological Office at RAF Leuchars, initiated and organized the regular nightly observations in night-flying aircraft at his station, and Lt. Cdr. L. B. Philpott of the Marine Branch of the Meteorological Office arranged for observations in selected ships. Mr. J. Østergaarde Olesen has



provided for many years valuable and detailed accounts and photographs of displays observed from Rönne, Bornholm; his reports have been transmitted to us by the Danish Meteorological Institute. The meteorological services of other west European countries have provided copies of records reported to them. The assistance of all who have taken part in this work either by organizing or making the observations is gratefully acknowledged.

Thanks are also due to Miss Slow of the Royal Society and Mrs. Hallissey of the Balfour Stewart Laboratory for assistance in the translation of papers in Russian.

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## METEOROLOGICAL OFFICE DISCUSSION

### Problems of rainfall forecasting

The last Monday discussion of the 1963/64 session was opened by Mr. D. E. Jones. He suggested that the lack of methods for making quantitative rainfall forecasts is related to the complexity of short-period rainfall patterns. This complexity is due partly to convection, partly to orographic processes, and partly to meso-scale phenomena, 50–150 miles across, which move through general rain areas. For short-period forecasts the meso-scale needs to be considered explicitly and an adequate reporting rain-gauge network is required and composite radar pictures of rainfall would be useful. For longer-period forecasts the effects of the small scales can be reduced by taking a large enough space average, but they cannot be removed. Mr. Jones then discussed the uses of numerical forecasts, graphical methods and statistical methods for forecasting rainfall, and some of the limitations of these methods.

Mr. R. Dixon described a statistical investigation which showed that an important factor in forecasting rainfall at warm fronts, cold fronts and in warm sectors was geostrophic vorticity advection at the 300 mb level. Other factors were the precipitable water in the 1000–500 mb column and the departure from average of the 500 mb temperature. The presence of convective overturning was found to be important but difficult to include in a forecast scheme. The statistics also showed that the above meteorological variables were not relevant to the rainfall at occlusions.

During the general discussion Mr. F. H. Bushby suggested that the neglect of the local rate of change of vorticity might be important and Mr. Dixon agreed. Mr. P. Graystone showed some 24-hour rainfall forecasts computed from the dynamical equations by numerical forecasting methods, and Mr. A. E. Parker advocated the use of the hodograph for detecting the whereabouts of frontal waves.

Mr. V. R. Coles said that the Central Forecasting Office was interested in short-period forecasts in the categories light, medium, or heavy rain 18 hours ahead, but he thought Mr. Dixon would have difficulty in forecasting the 300 mb vorticity advection. Mr. Dixon thought that vorticity advection or some similar dynamical parameter would need to be forecast if rainfall forecasting was to be done quantitatively.

## SUBSIDENCE IN THE MIDDLE AND LOWER TROPOSPHERE— PART II

By C. J. BOYDEN

**Summary.**—A closer examination is made of the history of subsided air from the time it descends a frontal transition zone until it settles in an area of high pressure. From a comparison between computed downward velocity and dryness it is seen that subsided air quickly moves away from its source. The lower boundary of the frontal mixing zone in air joining an anticyclonic circulation is identified with the anticyclonic inversion. Dry air over an anticyclone is found to exist primarily through advection, though subsidence within that circulation makes the greater contribution if the anticyclone becomes highly developed. Part I of this paper was published in the May issue.<sup>1</sup>

**Frontal descent as the primary source of subsided air.**—No systematic investigation was made of the association between the frontal pattern and the field of computed vertical velocity, but the study of a number of charts showed subsidence was occurring in areas where it would be expected on theoretical grounds. General reasoning can conveniently be based on a formula due to Penner,<sup>2</sup> in which the vertical velocity at 600 mb,  $\omega_6$ , is expressed in the form

— $\omega_6 = K_1 \times (\text{vorticity advection at 500 mb}) + K_2 \times (\text{advection of 1000–500 mb thickness}),$

where  $K_1$  and  $K_2$  are constants. This formula shows that subsidence ( $\omega_6$  positive) is favoured by the advection of negative vorticity and of cooler air.

Figure 1 shows a typical 500 mb contour field above two depressions and the intervening weak ridge. Penner's formula suggests the existence of three subsidence areas  $S_1$ ,  $S_2$  and  $S_3$ . At  $S_1$  there is negative vorticity advection, both through curvature and shear, and any advection of warm air is at a fairly slow

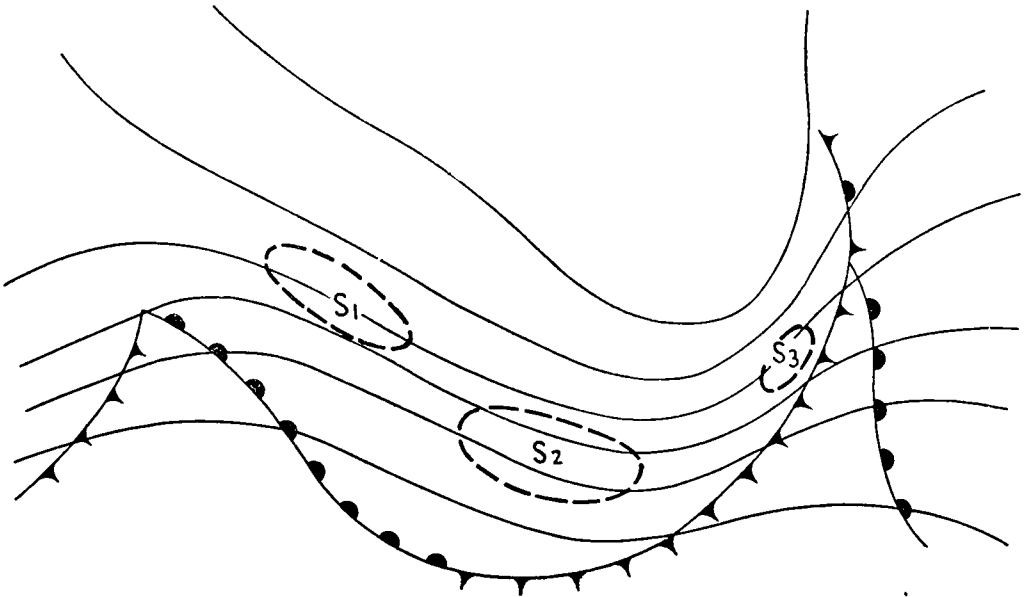


FIGURE 1—CHARACTERISTIC PATTERN OF SUBSIDENCE BETWEEN TWO DEPRESSIONS  
IN RELATION TO THE 500 MB CONTOUR FIELD

————— 500 mb contours, areas of subsidence outlined in bold broken lines.

rate. Area  $S_2$ , in and to the west of the upper trough, is one of negative vorticity advection and the thickness advection is usually small. Area  $S_3$  is one in which there is strong negative thickness advection.

Computed subsidence areas obtained from numerical prediction tend to conform to this pattern, though with considerable variation in detail. Area  $S_2$  is usually the most pronounced of the three and area  $S_1$  may be linked with it. Area  $S_3$  is usually the smallest and does not appear regularly although, as was mentioned in Part I<sup>1</sup> of the paper, subsided air produced upstream is nearly always found behind a cold front.

These three subsidence areas are associated with the upper flow pattern, which in turn is dominated by the temperature field with which the surface fronts are associated. It is therefore logical to regard areas  $S_1$  and  $S_2$ , under the western limb of the upper trough, as being associated with the upper part of the warm-front surface, and the weaker area  $S_3$  as a feature of the cold front. If the ridge intensifies there may be a corresponding growth of  $S_2$  but this anticyclonic subsidence is a secondary feature in time and usually in magnitude, as will be shown later.

The subsided air from  $S_1$  and  $S_2$  drifts downstream to give a broad channel of unevenly subsided air lying roughly parallel to the fronts and within their transition zone. What happens to subsided air near  $S_3$  (which originated mainly in  $S_1$  and  $S_2$ ) depends on the upper flow over the downwind depression. If this system is in a mature stage of development there is often little movement of air at the 700 mb level relative to the surface depression. At other times the dry air at 700 mb may invade the central area of the depression.

The effect of the ridge developing into an anticyclone may be visualized by superimposing a growing clockwise circulation between the depressions. Subsided air in the region of  $S_1$  is usually the first to join the circulation, next the subsided air near  $S_2$  is captured and finally, if the circulation becomes extensive enough, the subsided air existing in the region  $S_3$ . It should be added that, assuming the depression upstream of  $S_1$  becomes occluded during this development, the 700 mb flow through the air subsided at  $S_1$  becomes diffluent. In consequence the area of subsided air becomes elongated across the flow and may split into two parts, one moving north-east and the other south-east. An example of this is included in the sequence described in a later section (see Figure 6(b)).

**The association between subsidence and dry air at 700 mb.**—The idea that most subsidence is primarily frontal is tenable only if it can be shown that the air can retain its subsided state when it drifts away from the regions where the descent took place. This can be established by investigating how close is the association between dry air and descending motion. A comparison was therefore made between charts of numerically computed 1000–600 mb vertical velocity and charts of the 700 mb dew-point depression. The occasions were selected at random, though with some preference for days when the situation over the north-east Atlantic was fairly mobile.

The comparison was made in two ways. The first was to select over Europe all centres of maximum vertical velocity (provided it was not less than 3 mb/h) and compare their magnitude with the dew-point depression at the same

place. The result from 86 comparisons is shown in Figure 2. The median curve shows a clear tendency for downward motion ( $\omega$  positive) to be accompanied by dryness but it will be noted that the slope is due entirely to there being a number of occasions of high relative humidity in ascending air. When the dew-point depression was moderate or large there was no association with the sign of the vertical motion.

In the second method, the centres of subsided air were identified and a histogram was plotted of the computed vertical velocities at these points (Figure 3). As in Part I, air is regarded as subsided if the dew-point depression at the 700 mb level is at least  $20^{\circ}\text{C}$ . The symmetry of the histogram confirms that the existence of subsided air at 700 mb is unrelated to the simultaneous vertical motion, and therefore that subsided air can maintain its identity long after it leaves its source.

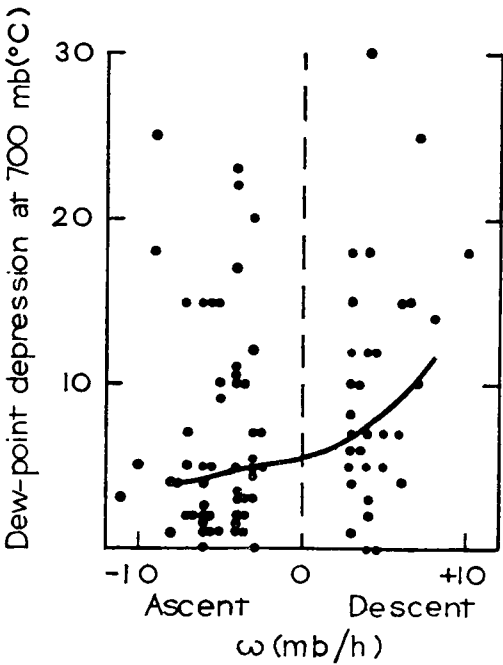


FIGURE 2—700 MB DEW-POINT DEPRESSION AT CENTRES OF MAXIMUM VERTICAL VELOCITY ( $\omega$ ), WITH MEDIAN CURVE  
 — Median curve.

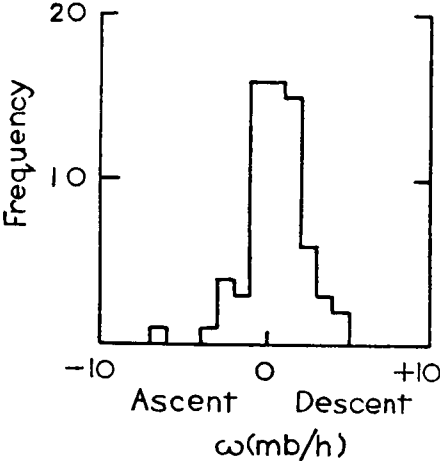


FIGURE 3—FREQUENCY DISTRIBUTION OF VERTICAL VELOCITY (1000–600 MB) AT CENTRES OF SUBSIDED AIR AT THE 700 MB LEVEL  
 The zero vertical velocity is noted on the left of its frequency column.

It is not difficult to account for this dissociation. The divergence requiring descent is associated with the pattern of flow, whereas the subsided air is carried through the pattern in the 700 mb wind. Thus a region of descent is likely to be a region of dry air, but downwind from it there will also be dry air which has blown away from the source, and it is a matter of chance whether this air finds itself in a region of ascent or descent.

In comparing dryness with descent velocities, the magnitude of the velocity should be treated with reserve. The computed velocity is a mean through a layer 400 mb deep, and a parabolic profile is assumed. Subsidence down a frontal surface is concentrated in a shallower layer, and the rapidity with which the dry air appears suggests it often subsides at a rate faster than the computed velocity. When frontal subsidence to 700 mb takes place through a

depth of 150 mb or more, as commonly occurs, the computed downward velocity is unlikely to exceed 5 mb/h for any length of time. Nevertheless the subsidence appears to take place in less than the 1–2 days which this velocity would require, and indeed the air is unlikely to remain in the same part of the vertical velocity field for so long. For the same reason the magnitude of a downward velocity cannot be taken as a measure of the dryness of the air since the time it spends in the subsidence area is equally important.

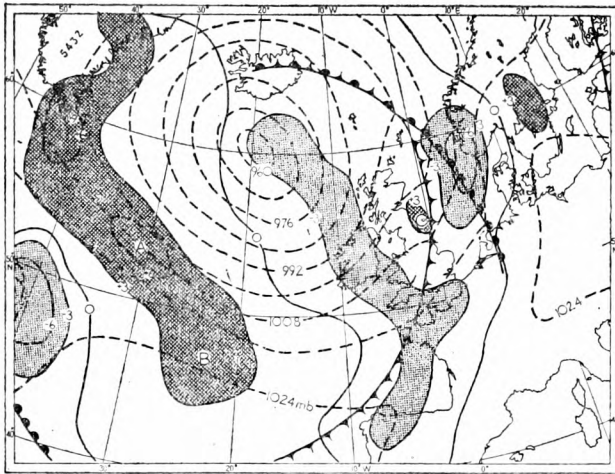
**The evolution of a pattern of subsided air at 700 mb.**—Some relationships between subsidence and the existence of dry air are illustrated in a typical sequence shown in Figures 4 to 8. The 5 pairs of diagrams cover a period of 4 days from 0000 GMT on 13 May to 0000 GMT on 17 May 1963. Of each pair of charts Figure (a) shows the surface analysis and the isopleths of mean vertical velocity in the 1000–600 mb layer and Figure (b) shows the same surface fronts, the isopleths of dew-point depression at the 700 mb level and the 700 mb contours to indicate the movement of the dry areas. Certain subsidence areas (S-areas) on the vertical velocity charts are identified by letters and the same letters (primed) are used on the other charts for centres of maximum dew-point depression (dry areas) which can be associated with them.

The pattern of dew-point depression at 700 mb is by no means a precise pattern of humidity in the lower troposphere. Subsided air is often characterized by a large vertical gradient of dew-point depression, so small air movements through the 700 mb surface may substantially alter the shape and size of an isopleth round dry air at this level. Nevertheless, the main features of the charts of dew-point depression can usually be followed without difficulty for at least a day or two, as will be seen from the following series.

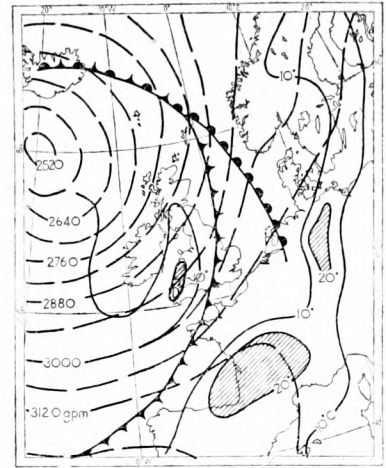
(i) *Figures 4(a) and (b)*—0000 GMT, 13 May 1963.—The S-area near Greenland is of no relevance and may be due to orography. Areas A, B and C in Figure 4(a) lie respectively at the left entrance to the warm-front jet stream, just upwind of the upper trough west of Ireland and behind the cold front (cf. S<sub>1</sub>, S<sub>2</sub> and S<sub>3</sub> of Figure 1). On Figure 4(b) no attempt has been made to draw isopleths over the Atlantic, but the characteristic dry-area D' near Wales will be noted. This lies in a region of ascent behind the cold front and doubtless originated in S-area A–B.

(ii) *Figures 5(a) and (b)*—0000 GMT, 14 May 1963.—The warm front moved quickly across the Atlantic and is now west of Ireland. There are now two S-areas E and F, which the upper air charts suggest may be the A and B of 24-hours ago, though E is best regarded as occurring ahead of an approaching warm front. The dry-areas A' and B' are undoubtedly associated with S-areas A and B of Figure 4(a), as is the post-cold-front dry-area G'. The dry air A' has been overrun by an isopleth of ascent, as commonly happens ahead of a warm front.

(iii) *Figures 6(a) and (b)*—0000 GMT, 15 May 1963.—Ahead of the warm front approaching the British Isles there are the two characteristic S-areas H and J, with corresponding dry-areas on Figure 6(b). Dry-areas A' and B' have now gone their separate ways in the diffluent 700 mb flow, and G', like D', has disappeared from the 700 mb level, at least temporarily. There is dry air from south-west of England to the Azores, but most of this lies within the warm sector and need not be discussed.

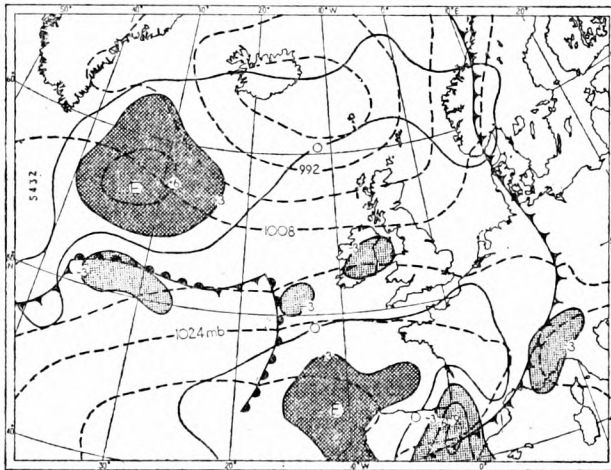


(a) Mean vertical velocity chart

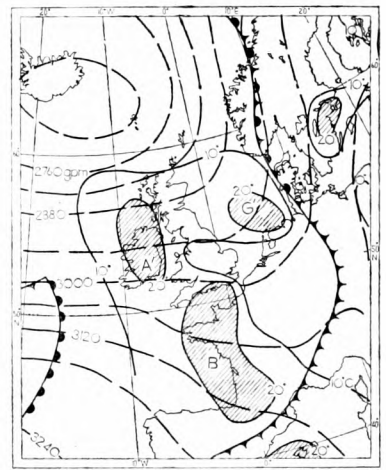


(b) Dew-point depression chart

FIGURE 4—0000 GMT, 13 MAY 1963

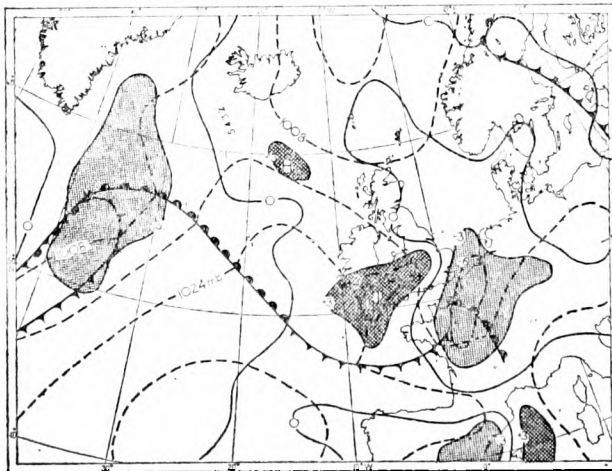


(a) Mean vertical velocity chart

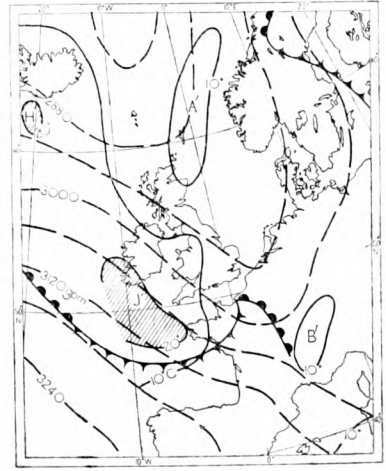


(b) Dew-point depression chart

FIGURE 5—0000 GMT, 14 MAY 1963

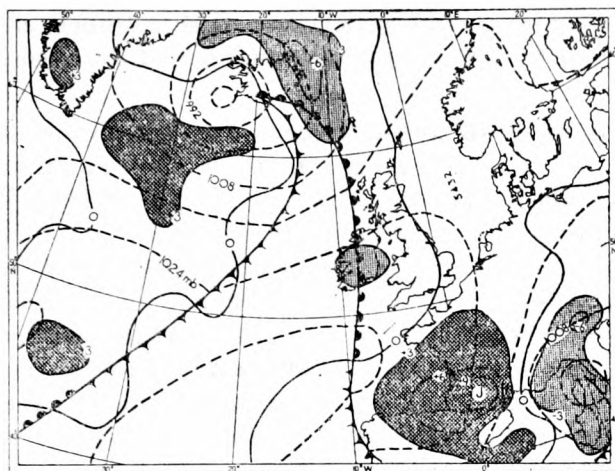


(a) Mean vertical velocity chart

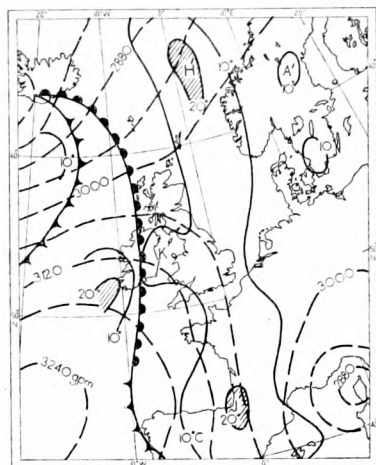


(b) Dew-point depression chart

FIGURE 6—0000 GMT, 15 MAY 1963

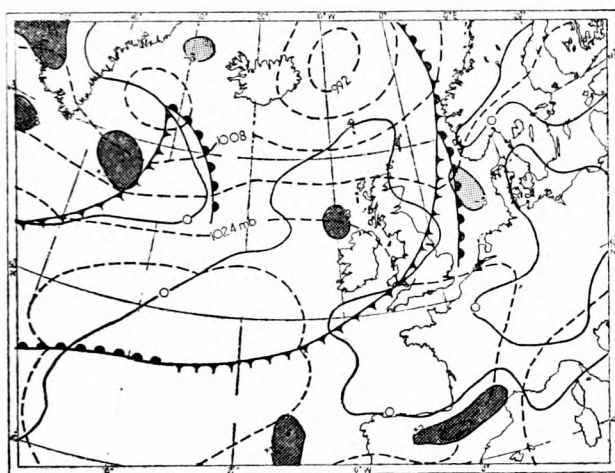


(a) Mean vertical velocity chart

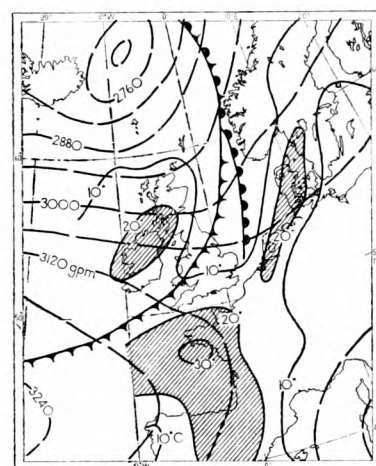


(b) Dew-point depression chart

FIGURE 7—0000 GMT, 16 MAY 1963



(a) Mean vertical velocity chart



(b) Dew-point depression chart

FIGURE 8—0000 GMT, 17 MAY 1963

(a) ——— Isopleths of vertical velocity ( $\omega$ ) in mb/h,  
 - - - isobars. Vertical motion ( $> 3$  mb/h) upwards  
 shown by light shading, downwards by dark shading.

(b) ——— Isopleths of dew-point  
 depression ( $^{\circ}\text{C}$ ), - - - 700 mb  
 contours (gpm). Areas of subsided  
 air are shaded.

(iv) *Figures 7(a) and (b)*—0000 GMT, 16 May 1963.—S-area J is now a major one centred over southern France and coinciding with generally dry air. Vertical velocities are small over the North Sea, the Norwegian Sea and Scandinavia but Figure 7(b) shows dry-area H', as well as other dry areas over Sweden which can reasonably be related to A' and G'.

Dry-area K' over the Irish Sea is of interest. Like H', it must have formed ahead of the warm front but now lies in a region of moderate ascent.

(v) *Figures 8(a) and (b)*—0000 GMT, 17 May 1963.—The several dry-areas which formed ahead of one or other of the warm fronts now constitute a dry area extending from Sweden to France. This position is close to the axis of a pronounced surface ridge in which only a small change of pressure would have

been necessary to turn the system into a cold anticyclone. The subsided air would then have spread throughout the circulation independently of the effects of anticyclonic subsidence.

**Some aspects of current theories of subsidence.**—The association of dry air with anticyclones may well have given rise to the impression that subsidence within anticyclones is the main way in which dry, subsided air masses are produced. The main purpose of the present paper is to draw attention to the importance of the substantial descending motions which occur even in strong winds at some distance from anticyclones. Subsidence should not be conceived as a mechanism which occurs solely or even primarily within almost stationary air masses associated with anticyclones, but rather as occurring within strongly baroclinic regions of moderate or strong winds, much of the dried air ultimately finding its way to the relatively stagnant areas associated with anticyclones. Thus the degree of subsidence in air above an anticyclone cannot be taken as a measure of the subsidence that has taken place actually over the anticyclone, and the evolution of the subsided air cannot be deduced solely from its final state.

It may be sound, for example, to associate rising pressure with subsidence, but there is no basis for associating rising pressure with dry air aloft unless the subsiding air is in a circulation from which it cannot escape. This was confirmed (for the 6 winter months used in Figure 1 of Part I<sup>1</sup>) by tabulating the 12-hour pressure tendencies on all occasions (i) when there was subsided air at 700 mb over Crawley and (ii) when subsided air at 700 mb first appeared over Crawley. In neither case was there any association with the sign of the pressure tendency, so the dryness must have developed at an earlier stage and probably elsewhere. The infrequency with which subsidence takes place mainly *in situ* is illustrated further by Figure 9 which shows the Crawley

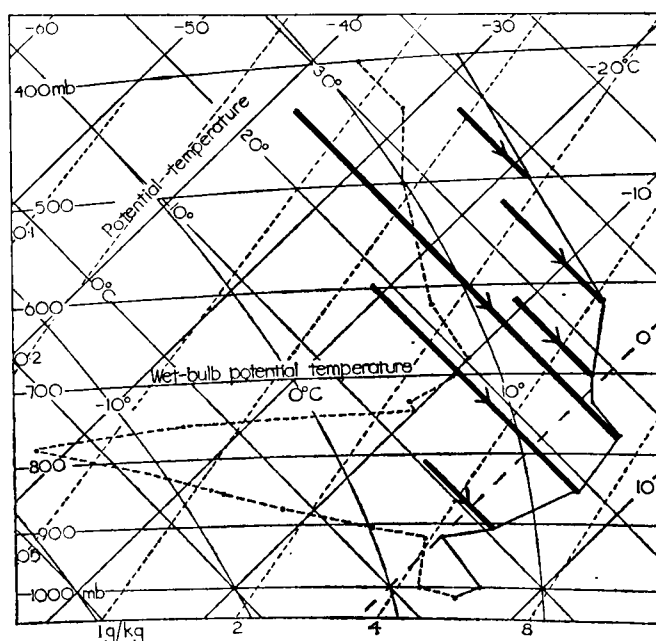


FIGURE 9—TEPHIGRAM FOR CRAWLEY, 0000 GMT, 27 NOVEMBER 1962  
Arrows show the descent necessary from a state of saturation to give the observed dry-bulb temperatures and dew-points.

———— Dry-bulb temperature, - - - dew-point temperature.



tephigram at 0000 GMT on 27 November 1962, when an anticyclone lay over England. Like many other such ascents it depicts a temperature and humidity distribution which could not have evolved by subsidence of a vertical column of air without varying advection at different levels. Arrows at various points show the subsidence necessary to transform a saturated atmosphere into that observed on 27 November. Because of the rapid increase of humidity with height above the 700 mb level no reasonable initial curve can be constructed on the assumption that the humidity was fairly uniform before subsidence began.

These two examples are additional to the evidence given earlier in the paper that advection is a most important factor in the evolution of subsided air. Any mechanism proposed to account for the structure of subsided air is therefore questionable if it is based solely on vertical movement. This criticism may be made of the hypothesis that an anticyclonic inversion originates at a moisture discontinuity—probably a cloud layer—and that the temperature discontinuity is due largely to differential dynamical warming in the clear and cloudy air during subsidence. Such an explanation does not seem a very likely one because a discontinuity of temperature gradient may well be a requirement for a uniform cloud top to develop. The hypothesis is unnecessary if the inversion is regarded as originating at the lower surface of a frontal transition zone, the discontinuity being due largely to advected subsidence. Acceptance of a frontal origin does not explain why the inversion is so sharply marked, but the question is left as a problem in the mechanics of the front, not of the anticyclone.

What is being questioned is the origin of the dry inversion or isothermal layer which first appears at a height of perhaps 2–4 km, well above what is regarded as the surface turbulent layer. It is not disputed that continuing subsidence is of the first importance in accentuating the inversion, particularly through differential warming. In the present investigation it was found from mean values that as the inversion sank (and probably became cloudy at its base) the rise of temperature at its top was about double the rise at its base, the difference doubtless being due to the heat used in evaporating cloud, as well as to radiational cooling. Below about 2 km, as Namias<sup>3</sup> found, the structure of the lower part of the inversion layer was dominated by the characteristics of the turbulent surface layer of the atmosphere. The amalgamation of the frontal inversion with these turbulent layers was accompanied by a marked increase in the mean depth of the inversion layer.

**Anticyclonic subsidence.**—This term is used throughout in relation to the sinking that takes place within an anticyclone and is not to be confused with the total subsidence of air now within the anticyclone, which will be shown to have occurred mainly outside the boundaries of that circulation.

It is impossible to draw a reliable trajectory of air ending in the central part of an anticyclone, both because of vertical shear and because the winds become light, so it is necessary to use mean values to estimate the magnitude of anticyclonic subsidence by relating the sinking to the rise of surface pressure.

A rough estimate was made by comparing the median dew-point depression in subsided air at 700 mb for sea-level pressures below 1020 mb and for 1030 mb and above. Corresponding to a mean pressure difference of about 25 mb there

was a dew-point depression increase of 5°C. This indicates a mean descent through 50 mb near the 700 mb level, assuming there was no initial systematic variation of dew-point depression within the layer from 700 mb to 600 mb.

A sounder estimate was made by measuring the change, relative to sea-level pressure, of the mean height of tops of inversions below air that was subsided at the 700 mb level. For this purpose the 6-months' observations at Crawley were supplemented by observations from Long Kesh (N. Ireland) and Shanwell (Fife). The results are given in Table I.

TABLE I—VARIATION OF THE LEVEL OF THE INVERSION TOP WITH SEA-LEVEL PRESSURE WHEN THE AIR AT THE 700 MB LEVEL WAS SUBSIDED, FOR 6 WINTER MONTHS AT CRAWLEY, LONG KESH AND SHANWELL

Range of sea-level pressure (mb)	< 1020	1020–1029	≥ 1030
Mean sea-level pressure (mb)	1011	1025	1035
Number of inversions or isothermal layers	37	52	30
Mean pressure at inversion top (mb)	784	815	841

There is little doubt that the base of an inversion sinks at a different rate from the air at its level, but on the other hand the cloudless air near the inversion top is unlikely to move through it appreciably because the vertical gradient of potential temperature is large and discontinuous. Differential subsidence can cause the inversion top to move relative to the air on occasions when the change from a positive to a negative lapse rate is gradual, but this is not common enough to invalidate deductions from mean values. The lowering of the inversion top is therefore regarded as a good measure of the descent of the air immediately above it. The mean descent through nearly 60 mb as the pressure rose through 24 mb is in close agreement with the estimated descent at the 700 mb level. This may be a slight underestimate because inversions above the 700 mb level were not included, but the 3 sets of figures in Table I are sufficiently consistent, when taken in pairs, to be regarded as representative.

Descent through 60 mb at the 800 mb level is small in terms of height since there was an accompanying rise of 24 mb in the sea-level pressure. The mean descent was therefore only through 300–400 metres, which may be compared with estimates<sup>3</sup> of about 100 m/day due to frictional outflow from anticyclones.

In discussing Table I it has been assumed that the change of sea-level pressure from 1011 mb to 1035 mb represents the development of an anticyclone. On this basis the anticyclonic subsidence in the lower troposphere, when the system is of no great maturity, is well below half the total subsidence (which was found<sup>1</sup> to average 200 mb to the 700 mb level for all modes of subsidence), the remainder being frontal subsidence. On the other hand, in a strong and persistent anticyclone the inversion top can sink practically to ground level. This means that some of the air above it subsides through a depth of perhaps 200 mb below the inversion levels given in Table I. On such an occasion the anticyclonic subsidence would exceed the frontal subsidence.

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**JOINT MEETING OF THE WORLD METEOROLOGICAL ORGANIZATION COMMISSION FOR AERONAUTICAL METEOROLOGY AND THE INTERNATIONAL CIVIL AVIATION ORGANIZATION METEOROLOGY AND OPERATIONS DIVISIONS, PARIS 1964**

By A. A. WORTHINGTON, B.Sc.

The Third Session of the Commission for Aeronautical Meteorology of the World Meteorological Organization (WMO) was held jointly with the Meteorology and Operations Divisional Meeting of the International Civil Aviation Organization (ICAO) in the Centre de Conférences Internationales, Paris, from 20 January to 15 February 1964.

It was attended by some 135 representatives of Members of WMO and/or Contracting States of ICAO and some 35 representatives of other international organizations. Mr. A. Viaut, delegate of France was elected Chairman of the simultaneous sessions.

The United Kingdom delegation was led by Mr. P. J. Meade, Deputy Director of the Meteorological Office. It included Mr. J. W. Blanchard, Mr. J. T. Ormston, Mr. G. P. Peacock and Mr. E. A. Rockliffe from the Ministry of Aviation, and Mr. D. G. Harley and Mr. A. A. Worthington from the Meteorological Office.

The Meeting was the first of its kind inasmuch that it included an ICAO Operations Division element whereas past joint sessions have only involved the Commission for Aeronautical Meteorology of WMO and the Meteorology Division of ICAO. On the whole, the departure from previous practice was worthwhile. It is most important that aeronautical meteorology keeps pace with developments in aviation. There is a need for fairly frequent reviews of the meteorological services for aviation both from the operational side in evolving and stating operational requirements and from the meteorological side in determining how best to meet the requirements.

The Meeting gave particular attention to the requirements for take-off and for approach and landing, requirements which are becoming more exacting, particularly with the move towards all-weather operations and automatic landing. The operational importance of information on vertical shear of the horizontal wind in the first 300 feet above the runway was recognized. A requirement for more precise information on surface wind over the runway was also expressed. It was evident that there is a need for greater accuracy than at present in the observing of light winds and a need for more detailed information on 'variations from the mean wind' in strong wind conditions. Information on runway visual range was established as a world-wide requirement at aerodromes equipped with precision approach runways or with runways for take-off having high-intensity edge lighting and/or centre-line lighting. The continuing operational requirement for information on slant visual range was accepted although it was appreciated that a further investigation was still to be done before the requirement could be met.

In discussing observations of temperature, cloud height, runway visual range, etc., the Meeting listed the operationally desired accuracies and the currently obtainable accuracies. The question was how best to promote the narrowing of the gap between the desired and attainable accuracy, allowing of course for the

inherent variability of the element concerned. In this regard, the good siting of observing stations and of instrumental equipment was stressed and the need for remote-indicating instruments and careful installation and maintenance of instruments was emphasized. It was also agreed that account should be taken of the operationally desired accuracies in specifications for meteorological instruments and in the development of observing practices.

There was lengthy discussion of the procedures for meteorological reports from aircraft. The aim in the discussion was to strike a reasonable balance between the information required by meteorologists and the reporting workload on aircrew in relation to other cockpit duties. The traffic load on air-ground telecommunications also had to be borne in mind. The outcome was the development of simplified procedures operative on a world-wide basis. Regional option was limited to exemption or designation of aircraft in areas of high air traffic density. It was considered that wind and temperature data should always be included in reports made on a routine basis; the reporting of other elements should be largely left to the pilot's discretion. The wind derived from precision navigational aids was stated to be the preferred wind for reporting purposes and to distinguish it from 'mean' wind it is to be given the indicator "SPOT."

The accuracy of forecasts was briefly discussed. The need for a statistical approach in expressing required accuracies was recognized as was the need for verification of forecasts.

On the subject of pre-flight meteorological service, the work was largely a question of reviewing existing procedures to promote uniformity in practice whilst retaining any necessary flexibility.

The main point in the consideration of in-flight meteorological service was the question of the criteria for significant changes in respect of forecasting visibility and cloud height in trend-type landing forecasts. The criteria adopted for the lower ranges were changes to, or passing one of, the values 200, 400, 600 or 800 metres for visibility, and 100, 200 or 300 feet for cloud height.

There was a useful exchange of views on the question of centralization, on an international basis, of forecasting services. Though the principles of an area forecast system were agreed, development in detail was largely left for future action.

The main discussion on the subject of aeronautical climatological data centred round the need to cater for the introduction of supersonic transport in the early 1970's. It was agreed to take steps to promote the availability of data which may be required for the design of supersonic aircraft and for the advance planning of supersonic operations. In this it was recognized that not only was there a necessity for the collection of data but also a necessity for the making of reliable observations up to the supersonic operating levels.

In the consideration of meteorological message forms it was agreed that there was no operational requirement for a linkage to be maintained between the AERO and the SYNOP figure forms. Also in the interest of catering for the needs of the user of operational meteorological data a 'direct-reading' message form was developed.

The Commission for Aeronautical Meteorology held a few separate meetings to deal with domestic matters. Mr. W. A. Dwyer, Australia; was elected President of the Commission and Mr. P. K. Rohan, Republic of Ireland, was elected Vice-President.

## REVIEW

*International auroral atlas*, published for the International Union of Geodesy and Geophysics. 11½ in × 8 in, pp. 71, *illus.*, University Press, Edinburgh, 1963. Price: 45s.

The *International auroral atlas* which has been published for the International Union of Geodesy and Geophysics (IUGG) replaced, at the beginning of the International Quiet Sun Year, the *Photographic atlas of auroral forms*, published also by IUGG before the 2nd International Polar Year, and which has been the standard work of reference for over 30 years.

The difference between the two atlases is a measure of the increase in our knowledge and techniques and in international collaboration which has taken place in the interval. The photographs in the former atlas were all taken in Norway—and some of the excellent photographs were taken 50 years ago: those in the new atlas have been taken by scientists in many parts of the world. There are 4 colour plates, 32 black and white plates, 19 all-sky photographs and the Ellsworth all-sky camera strip which shows by photographs at minute intervals the auroral changes which took place in a period of 24 minutes.

If the atlas were intended to be no more than a collection of fine photographs it would get full marks, but it is, of course, an illustrated guide, on the same lines as the *International cloud atlas*, to the various forms and to the method of reporting them. The notation and the recording code has been little changed, and the reasons for change have been explained; this is praiseworthy as is also the introduction of additional coding which can be used by the more experienced observer. An auroral display is considered as made up of one or more components, and each component is described by a code group of 5 figures or letters which describe the 'condition' and 'qualifying symbols' (quiet, active, pulsing, multiple, fragmentary, coronal), the 'structure' (homogeneous, striated, rayed), the 'form' (arc, band, patch, veil, rays, non identifiable), the 'brightness index' (0 to 4) and the 'colour class' (*a* to *f*). The code is simple and even observers who rarely see the aurora should have no difficulty in remembering it or looking it up quickly when a display occurs.

Finally there are maps of the northern and southern polar areas on which are printed the isolines of the parameter  $\theta$ . This means nothing to the general reader of the atlas who will not be interested in parameters of the geomagnetic field: it would have been clearer if on each map had been drawn the line of maximum zenithal auroral frequency as determined during the International Geophysical Year, and on either side the lines defining the limits of the auroral frequency.

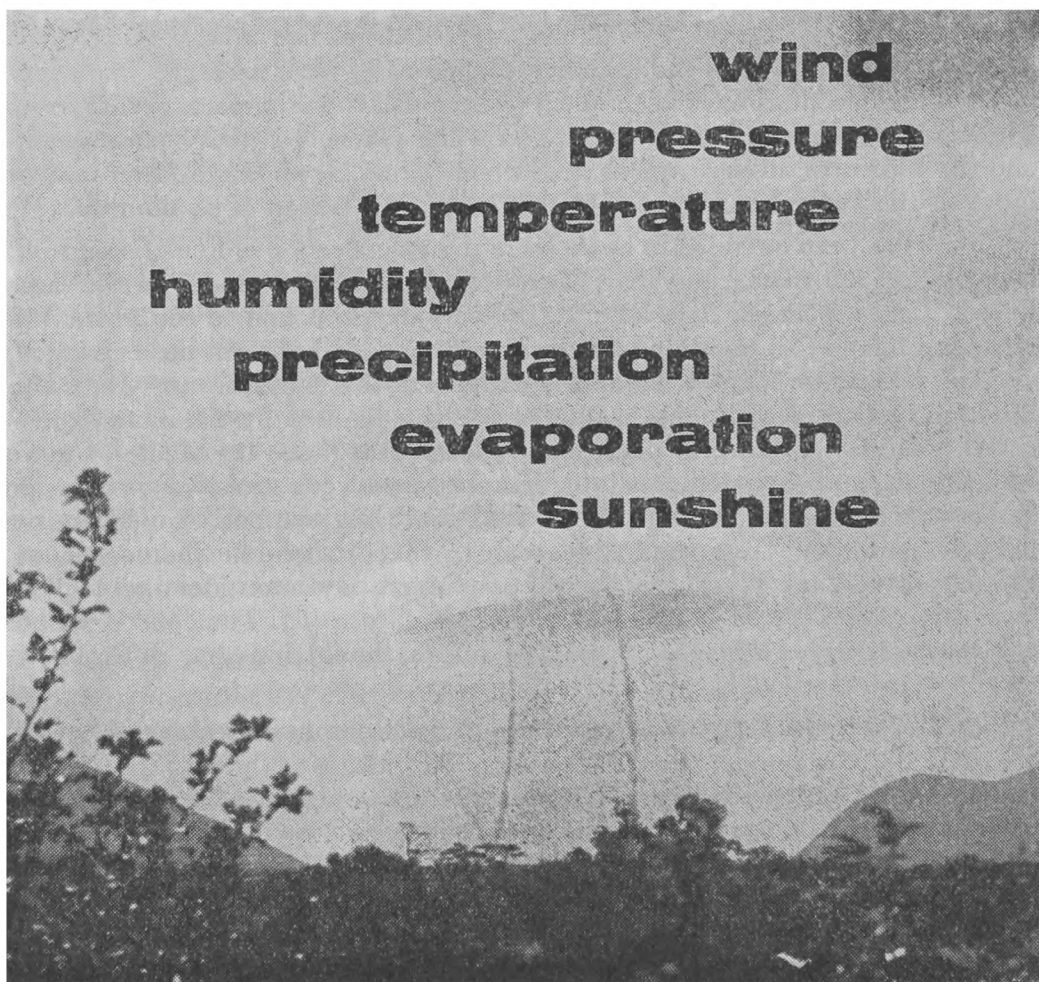
Anyone who has witnessed the beauty and splendour of a display of the 'merry dancers' will expect the International Auroral Atlas to be a publication of the highest quality: he will not be disappointed—it is a thing of beauty and will be a joy for many years to come.

R. A. HAMILTON

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# THE METEOROLOGICAL MAGAZINE

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## FLUORESCENT PARTICLES AND THEIR USE IN STUDYING AIR MOTION

By N. THOMPSON

**Summary.**—Experiments are described in which fluorescent particles of zinc cadmium sulphide were released from an aircraft and used as a 'tracer' to measure vertical diffusion. An apparent loss of these particles with increasing time of travel was noted and further studies showed that the main cause of this loss was a decrease in the fluorescent efficiency of the particles after exposure to daylight.

**Introduction.**—Many meteorological investigations entail tracking parcels of air, often with the aid of balloons or by means of air-mass characteristics and synoptic charts. But a more direct method of tracking is to label an air parcel by injecting into it a suitable tracer material. One such material is zinc cadmium sulphide<sup>1,2</sup> in the form of fluorescent particles and it is usually referred to as F.P. The material is finely ground, with particles mainly in the size range between 1 and  $5\mu$  ( $1\mu = 10^{-4}$  cm); it fluoresces brightly with a characteristic yellow colour when illuminated with ultra-violet light, and is also manufactured in forms that fluoresce red or green. The material is usually released into the atmosphere after being fed into a strong air blast which breaks up aggregates of the particles, and is sampled either by drawing the air containing it through very fine filters, or by impacting it onto treated surfaces. Under ultra-violet light, the particles can be counted through a relatively low-powered microscope magnifying 80 to 100 times. Concentrations lower than 10 particles per cubic metre can be measured by these techniques. Each gram of F.P. contains about  $10^{10}$  particles, and with suitable source strengths the material is satisfactory for diffusion experiments over distances ranging from a few metres to 100 km or more. This article discusses a few of the meteorological experiments carried out with F.P. in this country. Initially, these were to study vertical diffusion, but some of the later investigations were concerned with aspects of the tracer technique.

**Some measurement of vertical diffusion.**—In experiments carried out to study vertical diffusion over distances of travel up to 130 km, the particles were released as a line source from an aircraft flying across wind, and were collected by sampling instruments mounted at heights of up to 6000 ft on the cable of a single captive balloon (see Plate I). These instruments were drum impactors, mounted on units containing pumps operated by light-weight batteries. The units were controlled from the ground, with provision for switching the pumps on and off, and also for rotating the drums through small angles to expose a succession of fresh sampling surfaces. Some of the results

are shown diagrammatically in Figures 1(a) and 1(b), where the numbers of particles collected have been plotted against sampling height for 8 experiments. Three of the experiments (numbers 4, 5 and 6) were over relatively short distances (mean travel 16 km), but the remainder involved travel of about 130 km. The diagrams reveal a combination of comparatively rapid diffusion at lower levels (e.g. experiments 4 and 5), with much slower, or negligible, diffusion in the vicinity of temperature inversions. For example, in experiment 1 where conditions were unstable, particles had failed to diffuse to 5000 ft even after travelling about 130 km although the inversion base lay less than 1000 ft below this level. In experiment 2 a very strong subsidence inversion (8°C) was present between 6000 and 6500 ft and the F.P., released several hours before in convective conditions, reached 6000 ft in only small numbers.

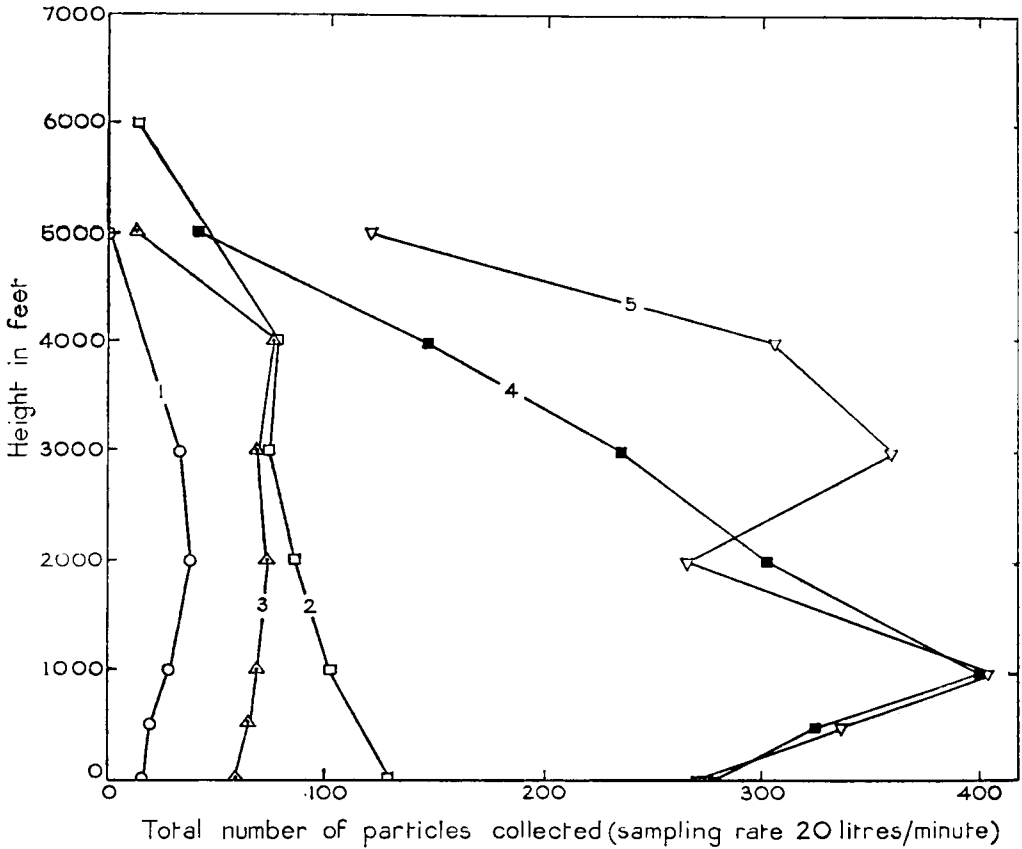


FIGURE 1(a)—PARTICLE COLLECTION PROFILES, 1959

Experiment number	Release height <i>feet</i>	Distance of travel <i>kilometres</i>	Approximate inversion height <i>feet</i>	Amount	Cloud Type	Base <i>feet</i>
1	1000	126	4500	1/8	Ac	15,000
2	1000	135	6500	1-3/8	CuSc	3500-4500
				7/8	Sc	5000-6500
3	1000	129	5500	1-6/8	Sc	3800-4000
4	1000	16	5500	1/8	Cu	4500
				5-7/8	Sc	5000
5	1000	16	5500	3-6/8	Ac	9000-12,000

The layer below the inversion was unstable in experiment 1 and slightly unstable in experiments 2-5.



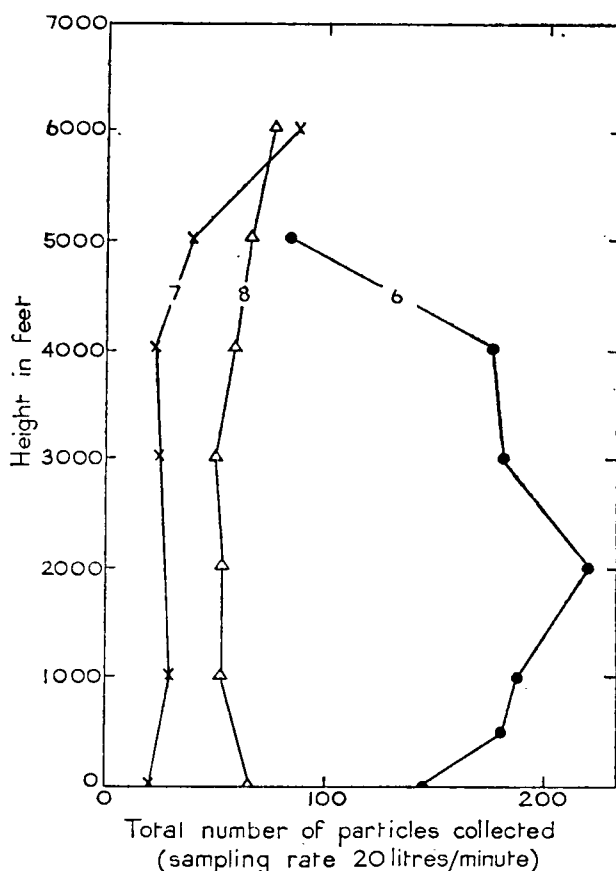


FIGURE 1(b)—PARTICLE COLLECTION PROFILES, 1960

Experiment number	Release height feet	Distance of travel kilometres	Approximate inversion height feet	Amount	Cloud Type	Base feet
6	2000	15	7000	2-4/8	CuSc	6000
				1-4/8	Ac	10,000
7	5500	129	7500	1-4/8	Cu	3500 bec. 4000
				6-7/8	Sc	5000 bec. 7000
8	3750	118	7500	1-5/8	Cu	3500-5000
				4-7/8	Sc	7000

The layer below the inversion was slightly unstable in experiments 6-8.

Similar results were found from experiment 3. All demonstrated that upward transfer was slow in the vicinity of inversions, and experiment 7, with its higher-level release (5500 ft) also showed this slow transfer, since a marked peak persisted at about the release level after several hours' travel. Generally, F.P. released several thousand feet below the marked temperature inversion became more or less uniformly distributed in the convectively turbulent layer below the inversion after a very few tens of kilometres travel.

Vertical turbulence (i.e. the standard deviation of the wind inclination to the horizontal) was measured in all experiments by vanes attached to the balloon cable<sup>3</sup> and records obtained from vanes within the inversions always showed low values of turbulence. The assumption often made that these subsidence inversions act as barriers to vertical diffusion therefore seems justified for periods of travel of at least a few hours.

**An apparent loss of F.P.**—One of the factors determining the total number of particles collected is the source strength or rate of emission of F.P. This did not vary much between the experiments, but Figures 1(a) and 1(b) show that larger numbers of particles were collected at short ranges. This was somewhat unexpected, because the depth of the layer through which the particles were mixed was similar in nearly all the experiments, and the source lines were sufficiently long for cross-wind diffusion to produce no dilution.

The sampling data, together with simultaneous observations of wind speed from airmeters attached to the vanes measuring turbulence enabled the quantity called the 'recovery' to be deduced. This is the number of airborne particles carried past the samplers per gram of F.P. originally emitted and is given by

$$\Omega = \frac{D}{m} \int_0^H \frac{Un}{s} dz,$$

- where  $\Omega$  = recovery,
- $D$  = length of emission line,
- $m$  = mass of powder released,
- $H$  = depth of layer over which particles were distributed,
- $s$  = sampling rate,
- $U$  = wind speed at height  $z$ ,
- $n$  = number of particles collected at height  $z$ .

Values of  $Un/s$  were plotted against height and the integration carried out graphically. In some cases, the particles had diffused above the highest sampler, and it was necessary to extrapolate before performing the integration. For this reason the recoveries obtained from experiments 7 and 8, with about 125 km of travel, were more uncertain than the others. Occasionally the effective source strength was increased or decreased by confluent or diffuent airflow and a correction was applied for this. The results appear in Table I.

TABLE I—PARTICLE RECOVERIES

Experiment number	Distance of travel kilometres	Mean times of travel hours	Recovery particles per gram $\times 10^{10}$
1	126	6.0	0.32
2	135	5.6	0.91
3	129	4.2	0.97
7	129	3.5	1.12
8	118	5.3	0.84
Means for experiments 1,2,3,7,8	127	4.9	0.83
4	16	1.5	1.97
5	16	1.5	2.64
6	15	0.8	1.40
Means for experiments 4,5,6	16	1.3	2.00

A *t*-test showed the differences of mean long-range and short-range recoveries to be highly significant ( $> 0.1$  per cent level).

The plausible reasons for this apparent loss of F.P. with increasing travel were considered to be:

- (i) A redistribution of particles in the atmosphere, e.g. by penetration of the temperature inversion or by cross-wind diffusion, or diffuence.
- (ii) Deposition of the particles on the ground.
- (iii) A decrease in the efficiency of the tracer with increasing time of exposure to the atmosphere, for example by chemical decomposition or by loss of fluorescent brightness.
- (iv) Deficiencies of the tracer technique, for example in sampling or assessment of samples.

A more detailed study showed item (i) to be relatively unimportant; the effect of diffuence was allowed for as far as possible in computing the recoveries, and penetration of inversions was soon rejected since experimental results, including some not mentioned here, have never shown this to occur to any significant degree. Experiments to test the validity of the remaining items are described below.

**Deposition of small particles on the ground.**—The mean settling velocity of F.P. is about 0.1. cm/s, but near the ground this is effectively increased because the inertia of the particles will allow them to impact on vertical as well as horizontal surfaces. The particles are therefore deposited onto surfaces and objects such as grass, trees and buildings. The particles are normally uniformly distributed through a layer much deeper than the height of these roughnesses, and continual turbulent mixing will maintain this approximate uniformity provided that the rate of deposition is small. Under these conditions, there is an approximately exponential decrease in the number of airborne particles with increasing distances of travel. The rate of deposition is conveniently expressed in terms of the 'deposition velocity,' which is the downward velocity that the particles very near the ground must have to produce the observed deposition. This rate of deposition per unit area is given by the deposition velocity multiplied by the particle concentration. The mean recoveries at the two distances (Table I) imply a deposition velocity of about 10 cm/s, provided that this is the only way in which the F.P. is being lost. This is much greater than a value (0.25 cm/s) found from experiments on the deposition of radio-actively tagged F.P. onto grass in a wind tunnel.<sup>4</sup> This latter estimate may not be a good one for field deposition because of the different wind profile near the ground, and deposition on trees and buildings and other large surface roughnesses might be larger.

**An attempt to estimate deposition of F.P. on trees.**—It is not practicable to use a microscope to make quantitative estimates of the deposition of F.P. on foliage. There is a simple alternative which proved to be sufficiently accurate for the present purpose. Suppose the wind direction is perpendicular to a long belt of trees of similar height. Slightly in front of the trees the mean airflow is horizontal, but nearer the belt, a proportion of the airflow is deflected upwards. Of the air actually entering the trees, a proportion passes upward through the tree tops during the passage through the belt and the remainder passes out on the downward side. An experiment was carried out to measure these proportions for an airflow past a belt of trees about 60 m deep and 12 m high. About 15 per cent of the air was deflected over the trees on the upwind side and another 50 per cent passed upwards through the tree tops instead of flowing through the trees. While these observations were obtained, a number of cross-wind line releases of F.P. were made about 1 km upwind of the trees

and were sampled by arrays of drum impactors, upwind and downwind of the belt. The numbers of particles passing through vertical sections upwind and downwind of the belt were found, and compared with the corresponding airflows. The observations showed a rather wide scatter but suggested that total deposition was very small. A tentative upper limit for this, used in conjunction with an estimate of tree cover over the area involved in the large-scale vertical diffusion measurements, was only sufficient to explain less than 10 per cent of the loss in these experiments.

**The size distribution of F.P.**—Some studies of the size distributions of collected particles confirmed that deposition was not the major cause of the F.P. loss. Large particles are more likely to be deposited on obstacles than small particles. Suppose, for example, particles of two sizes,  $1\mu$  and  $4\mu$ , are carried by a 5 m/s airflow past a cylinder of 0.1 cm diameter mounted with the axis perpendicular to the flow. The cylinder would collect about 50 per cent of the  $4\mu$  particles but scarcely any of the smaller ones. Deposition would therefore result in a gradual decrease in the relative numbers of the large particles. There was an indication in earlier work that the reverse was occurring. A series of specially designed experiments, involving the sampling of cross-wind line releases of F.P. by cascade impactors at distances up to 80 km, was carried out to confirm this. This kind of impactor splits up the sample into four slightly overlapping size ranges and is, therefore, a very convenient apparatus for measuring particle size. The sizing characteristics differ slightly between impactors, and to reduce uncertainties of interpretation, six or eight were used at each of three positions, at about 15, 40 and 80 km downwind of the line source. The glass slides on which the particles are impacted, were changed at the same time interval at all stations (quarter-hourly or half-hourly). The amounts of atmospheric pollution impacted on the slides were therefore kept reasonably small. Assessment was by techniques similar to those used for the drum-impactor samples. Table II gives the results from two experiments carried out during daylight hours.

Experiment Number	Distance of travel <i>kilometres</i>	Period of travel <i>hours</i>	Mean percentage of particles collected by impactor stages			
			Stage 1	Stage 2	Stage 3	Stage 4
1	14	0.6	1.4	24.5	62.0	12.1
	39	1.3	3.5	35.7	58.9	1.8
	73	2.2	8.0	42.0	49.4	0.6
2	13	0.5	1.7	27.0	66.1	5.1
	39	0.9	3.2	29.8	63.7	3.4
	76	1.6	8.6	46.5	44.6	0.3

Diameters of particles collected are  $>8\mu$  in stage 1;  $3-8\mu$  in stage 2;  $1-3\mu$  in stage 3; and  $<1\mu$  in stage 4.

The percentage of particles collected by the fourth stages of the impactors decreased quickly with time of travel to insignificant values after about 2 hours, implying an almost complete disappearance of particles of less than about  $1\mu$  diameter. There was also a systematic decrease in the proportion of particles collected by the third stages (roughly between  $1\mu$  and  $3\mu$  diameter). Assuming that none of the particles normally collected by the second stages of the impactors were lost by deposition, each experiment suggested about a 40 per cent decrease in recovery between the extreme sampling positions. An unexplained feature was that the systematic increase in the proportion of particles collected by stage one was too large to be accounted for by loss of particles normally collected by stages three and four.

The results from one experiment carried out at night appear in Table III.

TABLE III—NIGHT-TIME SIZE-DISTRIBUTION EXPERIMENT

Distance of travel kilometres	Period of travel hours	Mean percentage of particles collected by impactor stages			
		Stage 1	Stage 2	Stage 3	Stage 4
16	1.8	0.6	21.2	60.9	17.2
40	2.8	0.2	27.3	63.0	9.5
80	3.9	1.8	31.5	58.4	8.3

Diameters of particles collected are  $> 8\mu$  in stage 1;  $3-8\mu$  in stage 2;  $1-3\mu$  in stage 3; and  $< 1\mu$  in stage 4.

It is seen that the decrease in the proportion of small particles was much less pronounced than in the day-time experiments, in spite of the longer periods of travel involved. This suggests that the apparent loss of particles might in part be due to some sort of chemical decomposition in daylight, or to progressive loss of ability to fluoresce under ultra-violet light.

**Measurement of fluorescent brightness.**—Another investigation has now shown that the fluorescent brightness of the small particles of the particular types of F.P. used, does in fact decrease with time of travel in day-time experiments, the decrease being rapid at first. This appears to account for at least part of the 'loss' of F.P. found in the experiments. The decrease in brightness is much less during night-time experiments. The rate of decrease in brightness was found to be greater for a British than an American material, presumably because of the different activators used in their manufacture.

**The comparison of F.P. with an 'absolute' tracer.**—A fairly precise estimate for the apparent loss of material was obtained by comparing the F.P. with a radio-active tracer. The rate of decay of the radio-active material was known, and corrections for it were easily made.

Simultaneous releases of F.P. and radio-xenon ( $^{133}\text{Xe}$ , an inert radio-active tracer in gaseous form, with a half-life of 5.3 days) were made at the same position, at constant rates over periods of about two hours, and were sampled simultaneously at two positions about 15 and 60 km downwind. The  $^{133}\text{Xe}$  source was limited in size, so the two sampling stations were arranged as far as possible to lie continuously in the tracer's plume, by moving them from time to time. Since the half width of the plume was  $5$  or  $10^\circ$ , considerable care was needed in planning the experiments and siting the mobile observation points. Synoptic charts at hourly intervals are of little use in trajectory forecasting with this degree of accuracy. The technique used was to estimate the direction of travel of the tracers from the vector mean winds up to about 2000 feet, obtained from pilot-balloon ascents made quarter-hourly at the release point, and then to supplement these data with measurements of the position of the plume with a mobile F.P. sampler, each sample being examined immediately in a portable dark room. About six pairs of plume fixes were obtained in each of the three experiments in this way, each pair being transmitted to a control centre about 15 minutes after being made. The technique, used in conjunction with frequent communication with the sampling stations, was precise enough to secure success in the experiments. The xenon samples were corrected for decay and compared with the corresponding F.P. samples and showed that a mean apparent loss of about 50 per cent of the F.P. occurred during travel between the two sampling stations, or during the period from 1 to 3 hours after release.

An improved method of assessment of F.P. samples was introduced for the last of these experiments. This involved an increase of several times in the intensity of the ultra-violet illumination, together with vertical instead of oblique illumination of the sampler drums under the microscope. The same samples were also assessed by the original method and the numbers of particles found by both means were compared. The new assessment increased particle counts by between 20 and 30 per cent for samples from both the stations, but the overall percentage loss occurring during travel between stations was almost unchanged.

**General experimental precautions.**—The results of experiments using F.P. as a tracer are all too easily vitiated by contamination of sampling surfaces with F.P. This contamination can easily arise if the supplies of F.P. and the dispensing equipment are stored in buildings close to the sampling apparatus and the assessment laboratory. All experiments should as far as possible be planned to ensure that large enough samples are collected so that purely statistical variations are small. This implies suitably large sources of F.P., but on the other hand any experiment involving the use of this tracer should always be carried out with the smallest practicable source in order to reduce the inevitable contamination of such things as trees and buildings. The conflict of requirements often results in the source strength finally adopted being a compromise. If restrictions in the source are necessary, then the experiment requires more careful planning to be successful.

**Conclusion.**—Zinc cadmium sulphide is a useful tracer for meteorological studies of diffusion over a wide range of distances because of its comparatively easy detection and the great sensitivity of the technique. However, decay of the tracer does occur, chiefly when it is used during the day-time. In experiments designed to measure diffusive spread, such as the cross-wind or vertical spread of plumes or the along-wind growth of instantaneous cross-wind line sources, tracer decay is unimportant because in these cases one is only concerned with relative concentrations of the particles through a cross-section of the plume or line. However, difficulty is introduced in the assessment of absolute concentrations, although for night-time travel of 2 or 3 hours the tracer deficiencies can probably be ignored. Correction factors as large as 2 have to be applied to day-time results for similar times of travel in order to estimate absolute concentrations.

**Acknowledgements.**—The author wishes to thank the many people who contributed to this work, in particular Mr. G. F. Collins of the Chemical Defence Experimental Establishment (CDEE), Porton Down, who was responsible for many details of the tracer technique used in these experiments and who made the measurements of fluorescent brightness of F.P. Others involved were Dr. A. E. J. Eggleton and his colleagues at the Atomic Energy Research Establishment at Harwell, the Balloon Development Establishment at Cardington, Messrs. R. A. Titt, J. I. P. Jones and H. E. Butler of CDEE, and Dr. F. Pasquill who gave much advice.

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## OBSERVATIONS OF NOCTILUCENT CLOUD NEAR MIDWINTER

By R. A. HAMILTON

Until recently noctilucent cloud has been regarded as a phenomenon seen only in the summer (Ludlam<sup>1</sup>) but during the International Geophysical Year noctilucent cloud was observed from late March to early November by observers in the U.S.S.R. (Pavlova<sup>2</sup>). It seems almost certain that some form of noctilucent cloud was seen by four observers at Lerwick Observatory (60.1°N, 1.2°W) on 5 January 1964, from 1630–1655 Universal Time (UT) (sunset was at 1515 and civil twilight at 1611 UT).

The noctilucent cloud was first observed to the north-west at about 1630 UT as a band of white cirrus-like cloud at an elevation of about 60°, clearly contrasting with the weak red tinge of small patches of cirrus still visible. By 1640 the red-tinted cirrus had disappeared and the band of noctilucent cloud was clearly visible moving eastwards and by 1650 was almost vertically overhead; it was white against the sky which was now dark, though not sufficiently dark for the Milky Way to be seen. It was seen by three meteorological observers who without hesitation described it as having the appearance of cirrus cloud: it was in the form of filaments, very similar to that illustrated in Plate 42 of the abridged *International Cloud Atlas*.<sup>3</sup> The band was about 4° in width and about 10° in length and appeared to be moving or developing along the axis of the band at a rate of about 1½° per minute. It disappeared very soon after 1655 when an attempt was being made to telephone observers in other parts of Scotland. The sudden disappearance is consistent with the view that the cloud was sunlit.

It is very unlikely that it was part of an auroral arc that was seen—it was oriented at about 45° to the geomagnetic meridian, and differed in appearance from any aurora any of the observers had ever seen. The Lerwick magnetograms showed that magnetic conditions were very quiet at the time—the *K*-index was 1.

At 1655 UT the depression of the sun was 10° 45'. If it is assumed that the cloud was overhead and just illuminated at 1655 and that the refraction was twice 34' (see *Meteorological Glossary*<sup>4</sup>), then the calculated height was 91 km—somewhat higher than the mean height of 82 km in summer—and the cloud velocity was roughly 40 metres/second towards the south-east. This is in reasonable agreement with the observation of Greenhow and Neufeld<sup>5</sup> who give the mean January wind at a height of 85 to 100 km as 17 m/s towards east and south-east. However the height must have been considerably in excess of this height as the light from the sun which passes through the lower layers of the atmosphere would be too weak to illuminate the cloud.

As it has been thought that cosmic dust plays an important part in the formation of noctilucent clouds, it may be significant that this noctilucent cloud was observed at the time of the Quadrantid meteor shower 3–4 January: it was on a rather smaller scale than the usual summer observations, and somewhat higher, and may have been produced by dust from this meteor shower.

It is interesting to note too that its appearance was preceded by a steady rise of pressure of 20 mb during the preceding days, and that the lower half of the atmosphere was abnormally warm in the area to the north of Scotland during December 1963 and January 1964: Grišin<sup>6</sup> reported that the occurrence of noctilucent cloud in the U.S.S.R. was always preceded by a more or less long and rapid increase of surface pressure, and was always associated with abnormally high temperatures over a wide area, especially during the preceding month. Paton<sup>7</sup>, however, found that these conditions do not occur in the case of noctilucent cloud in north-west Europe.

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## DELAYED CLEARANCE OF LOW CLOUD BEHIND COLD FRONTS AT MANCHESTER AIRPORT

By L. DENT

**Summary.**—Delayed clearances of cloud behind cold fronts at Manchester have been examined for 32 cases occurring during 1959–62. The phenomenon is thought to be caused by the lifting of moist frontal air and is most marked with geostrophic wind directions between 310° and 330°. In most cases cloud lifts to above 1000 feet within 3 hours. Diagrams are given which can be used for forecasting (from the wind in the cold air and the mean dew-point depression in the frontal zone) (a) the length of delay in clearance and (b) the lowest cloud base behind the cold front. Seasonal and diurnal effects are noted and also the effect of curvature of the isobars. Two examples are quoted with synoptic charts.

**Introduction.**—The passing of a cold front is usually marked by lifting of the cloud base and a dispersal of low stratus, often followed by broken cloud. Occasionally however, this improvement is delayed for several hours after the passage of the front. At Manchester Airport cold fronts approaching from the north-west are frequently marked by a sudden lowering of the cloud base often to 200 ft above airfield level, causing temporary disruption to aircraft operations. The clearance of this low cloud varies from one front to another and on occasions has been delayed for over 6 hours. On the other hand, cold fronts followed by south-westerly winds are usually free from low stratus in the cold air. These differences may in part be explained by topography in terms of shelter and exposure as shown in Figure 1. Air reaching Manchester from a direction between 270° and 330° must cross the Irish Sea and, after reaching Manchester, is subsequently lifted over or is deflected by the Pennines. From other wind directions the air reaching the Airport is modified by high ground or by a long land track.

**Previous work.**—Previous work on the study of cold fronts has dealt mainly with the structure of the frontal boundary. In 1951 Sansom<sup>1</sup> introduced the classification of anafront or katafront by using two simultaneous soundings of wind and temperature. More recently Miles<sup>2</sup> has discussed the presence of



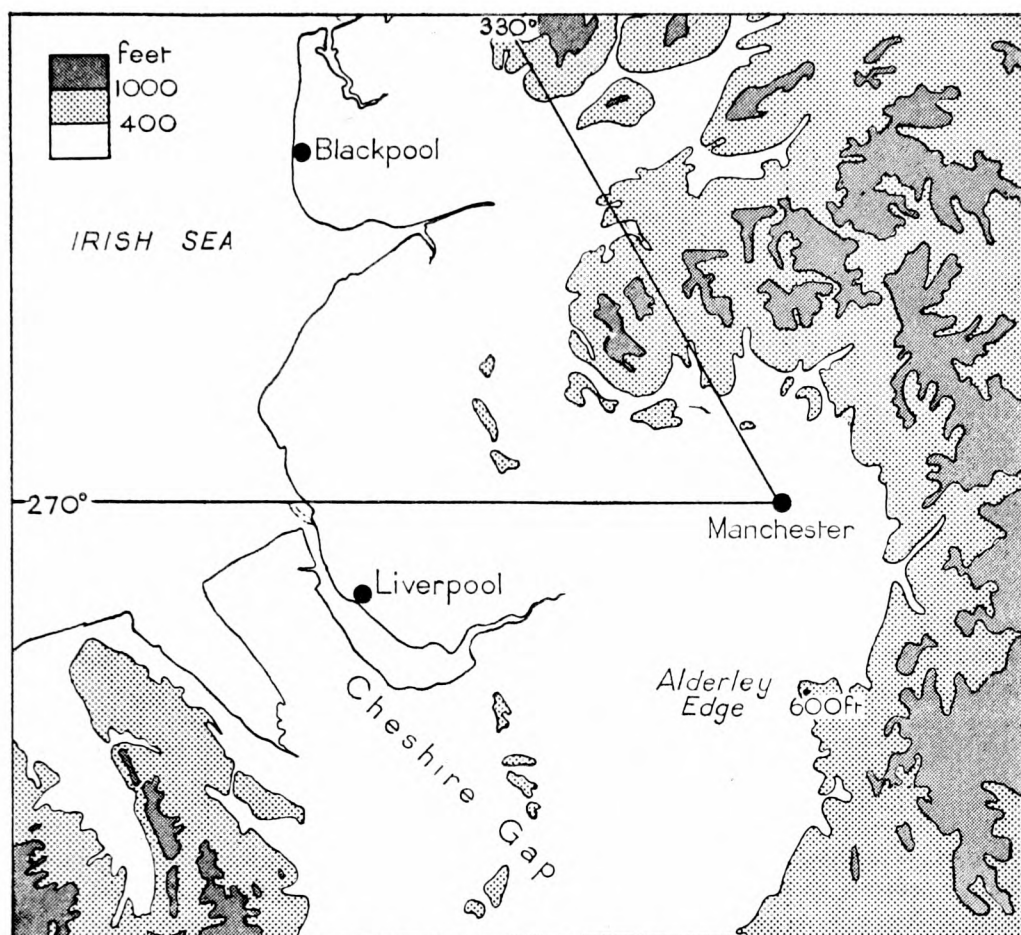


FIGURE 1—MAP OF THE MANCHESTER AREA

The bounding lines 270-330° have been drawn from Manchester City. Similar lines drawn from the Airport (near to Alderley Edge) include very little high ground.

sharp humidity boundaries ahead of some cold fronts at levels about 700 mb. Morris<sup>3</sup> has studied delayed clearances behind cold fronts at selected stations in the United Kingdom. He suggests that delays in the cessation of rainfall are associated with relaxing upper troughs on a synoptic scale, whilst delays in the clearance of low cloud are thought to occur on a meso-scale and follow different patterns at different stations.

Following the investigation by Morris, 30 cold fronts and 2 non-frontal troughs have been examined at Manchester Airport for the 3 years September 1959 to September 1962. These fronts and troughs all reached Manchester from the north-west and were included in the analyses of the *Daily Weather Report*.<sup>\*</sup> The sample does not include any quasi-stationary fronts nor those with noticeable wave development.

As a measure of the delay in cloud clearance, the time taken from the passage of the surface front to the lifting of the low stratus to over 1000 ft above airfield level was chosen as the most suitable parameter, and is referred to as *D* in the notes which follow. Figure 2 shows the frequency of such delays amongst the 32 cases studied. The delays are grouped in time steps of one hour. When *D* was a whole hour it has been grouped with the time range below that value, for

<sup>\*</sup>Meteorological Office. *Daily Weather Report*. London, HMSO.

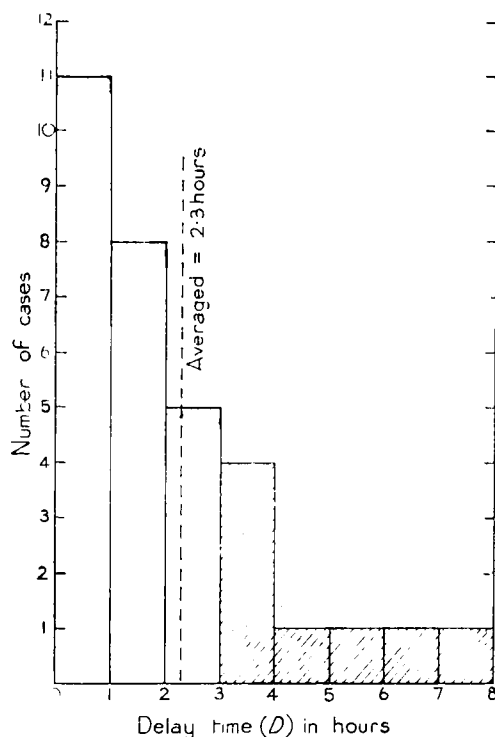


FIGURE 2—FREQUENCY OF THE DELAY TIME IN THE LIFTING OF LOW STRATUS, IN RANGES OF 1 HOUR

$D$  = delay in the lifting of low stratus to above 1000 ft above airfield level.

instance  $D = 3.0$  hours is included in the frequency diagram for 2–3 hours. From Figure 2 it can be shown that 75 per cent of the 32 fronts cleared Manchester Airport as specified within 3 hours, whilst the average delay was 2.3 hours. The remaining 8 cases (25 per cent) had delayed clearances ranging from 3.5 to 7.5 hours and these are considered in detail.

**Classification of fronts.**—By examining the winds and temperature soundings at a conveniently placed ascent through the cold air, the 32 cases were classified as shown in Table I.

TABLE I—CLASSIFICATION OF CASES OF DELAYED CLEARANCE

Analysis type	Number	Mean delay hours	Number with delay over 3 hours
Katafront	22	1.9	3
Anafront	6	3.3	3
Troughs	2	5.7	2
Doubtful	2	1.0	0

The eight cases with  $D$  greater than 3 hours are listed in Table II.

Table I shows that anafronts, although uncommon as a class (6 cases out of 32), produced delayed clearances of over 3 hours quite often (3 cases out of 6). The non-frontal troughs cleared slowly and so did a few katafronts (3 cases out of 22).

The lowest cloud bases ranged from 100 to 900 ft above airfield level and 11 out of 32 cases had cloud at 200 ft or below. The lowest cloud usually occurred at the passage of the surface front and thereafter a steady but often slow improvement followed. These cloud features were common to the three analysis types, and it seems therefore that this classification is probably less

TABLE II—DETAILS OF CASES OF DELAY IN CLEARANCE GREATER THAN 3 HOURS

Analysis type	Date of delay	Delay	Mean cloud amount	Lowest cloud during delay		Rainfall with front		Curvature of isobars in the cold air*
				Base above airfield	Mean cloud amount	Amount	Duration	
		<i>hours</i>		<i>feet</i>		<i>mm</i>	<i>hours</i>	
Anafront	19.1.60	3.5	5/8	400	2/8	3.0	3.0	<i>C</i>
Anafront	13.1.61	7.0	6/8	100	5/8	8.5	8.9	<i>A</i>
Anafront	24.8.61	4.5	5/8	200	3/8	8.6	3.0	<i>A</i>
Katafront	22.6.61	4.0	6/8	100	2/8	0.5	1.4	<i>A</i>
Katafront	29.3.62	3.5	8/8	200	5/8	0.1	0.2	<i>C</i>
Katafront	16.6.62	5.5	5/8	200	2/8	2.2	1.5	<i>A</i>
Trough	1.1.60	7.5	7/8	400	4/8	1.5	1.2	<i>C</i>
Trough	22.7.62	4.0	5/8	200	2/8	3.0	2.4	<i>C</i>

\**C* = cyclonic curvature, *A* = anticyclonic curvature

important in detecting a likely delayed clearance than the combined arrangement of low-level winds, temperatures and topography.

It is probably possible to distinguish further between cold fronts from the north-west which have north-westerly winds in the warm sector from those with south-westerlies in the warm sector. In the former case, which is uncommon, the low stratus forms ahead of the cold front and clears quickly behind it. Only one of this type of cold front was included in the 30 examined, but one more conforming to the pattern described has occurred since September 1962. The remainder had south-westerly winds in the warm sector and it is amongst these that a delayed clearance is likely. With this type of front the surface wind at Manchester is often held well back to south by the flow through the Cheshire Gap. This sharpens the frontal trough and accentuates the wind veer on the front. In addition the lowering in cloud base is sudden as the wind swings from a sheltered to an exposed direction.

**The factors controlling a delayed clearance.**—After the passage of the front the presence of low stratus is probably controlled by the wind direction and speed in the cold air, and by temperature and dew-point separation. Frontal development may also be significant, but its effect would be more noticeable at levels above the low-stratus layers.

The delay in clearance of low cloud, and probably the level to which the cloud lowers, will vary in the first instance with the post-frontal wind direction which is influenced by topography. It seems reasonable also, to suppose that higher wind speeds and larger dew-point depressions will each contribute to a quicker clearance of low cloud and to higher cloud bases.

Denoting the geostrophic wind in the cold air as from direction  $F$  (degrees) at speed  $S$  (knots) and the mean dew-point depression in the frontal zone as  $\theta$  (degrees Celsius), both the delay  $D$  and the cloud base may be expected to vary with  $F$  and the product  $S \times \theta$ . A representative value of  $\theta$  is obtained by taking the mean of six stations, three on each side of the cold front.

On Figure 3 the product  $S\theta$  is plotted against  $F$  and beside each point is noted the delay  $D$ . Isopleths of  $D$  are drawn and these confirm that for a given wind direction the delay  $D$  decreases for increasing values of the product  $S\theta$ . The most significant feature is the region of maximum values of  $D$  associated with the geostrophic winds between  $310^\circ$  and  $330^\circ$ . These directions correspond

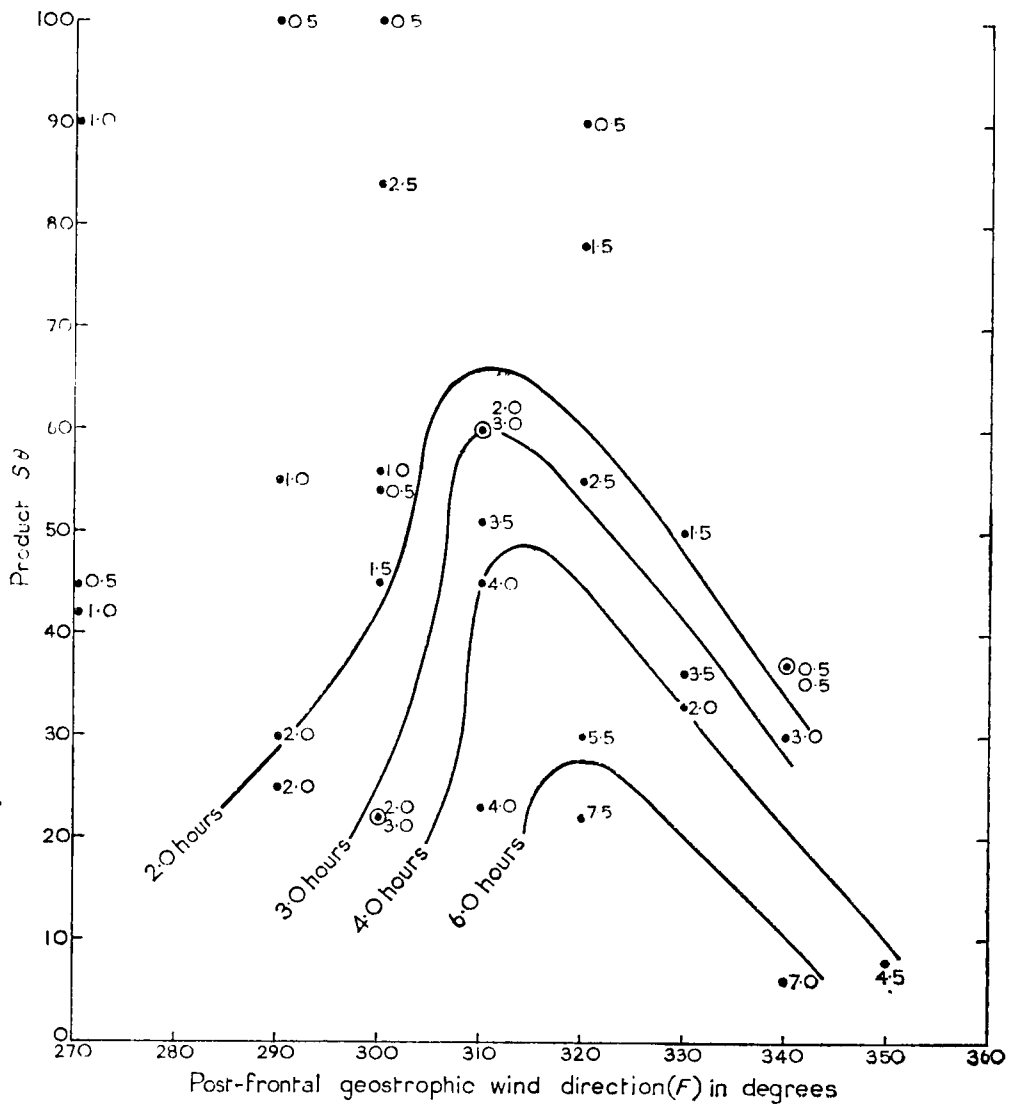


FIGURE 3—ISOPLETHS OF DELAY TIME RELATED TO WIND DIRECTION AND PRODUCT  $S\theta$

$S$  = geostrophic wind speed in the cold air, in knots.

$\theta$  = mean dew-point depression of the frontal zone, in  $^{\circ}\text{C}$ .

to the longest sea track over the Irish Sea to which air can be exposed before reaching Manchester Airport, and also along these directions air is lifted over Alderley Edge, 4 miles away (see Figure 1). Only short delays occur when  $F$  lies between  $270^{\circ}$  and  $300^{\circ}$ , and because of sheltering effects a sharp transition takes place around  $340^{\circ}$ .

On Figure 4 the product  $S\theta$  is again plotted against  $F$  and beside each point is noted the lowest cloud base. Smooth lines have been drawn to embrace the points with cloud base at 200 ft and also, though with some uncertainty, at 600 ft. The shape of the 600-ft line is difficult to explain, but it is of secondary importance compared with the 200-ft line which is well supported by the observations, and shows a peak between  $310$  and  $330^{\circ}$  similar to that in Figure 3. Altogether 27 out of 32 cases fit the lines of Figure 4 as drawn, and 29 out of 32 fit the lines of Figure 3.

**Seasonal and diurnal effects.**—Table III gives the seasonal distribution of the fronts.

TABLE III—SEASONAL DISTRIBUTION OF THE FRONTS

Season	All cases		Cases with cloud base 200 ft or below	Cases with delay over 3 hours
	Number	Mean delay hours		
Mar.-May	7	1.4	2	1
June-Aug.	11	2.6	5	4
Sept.-Nov.	7	1.8	2	0
Dec.-Feb.	7	3.7	2	3
Total	32		11	8

Whilst the incidence of cold fronts from the north-west was spread fairly evenly through the seasons, delayed clearances of over 3 hours were more common during winter and summer than in the transitional months.

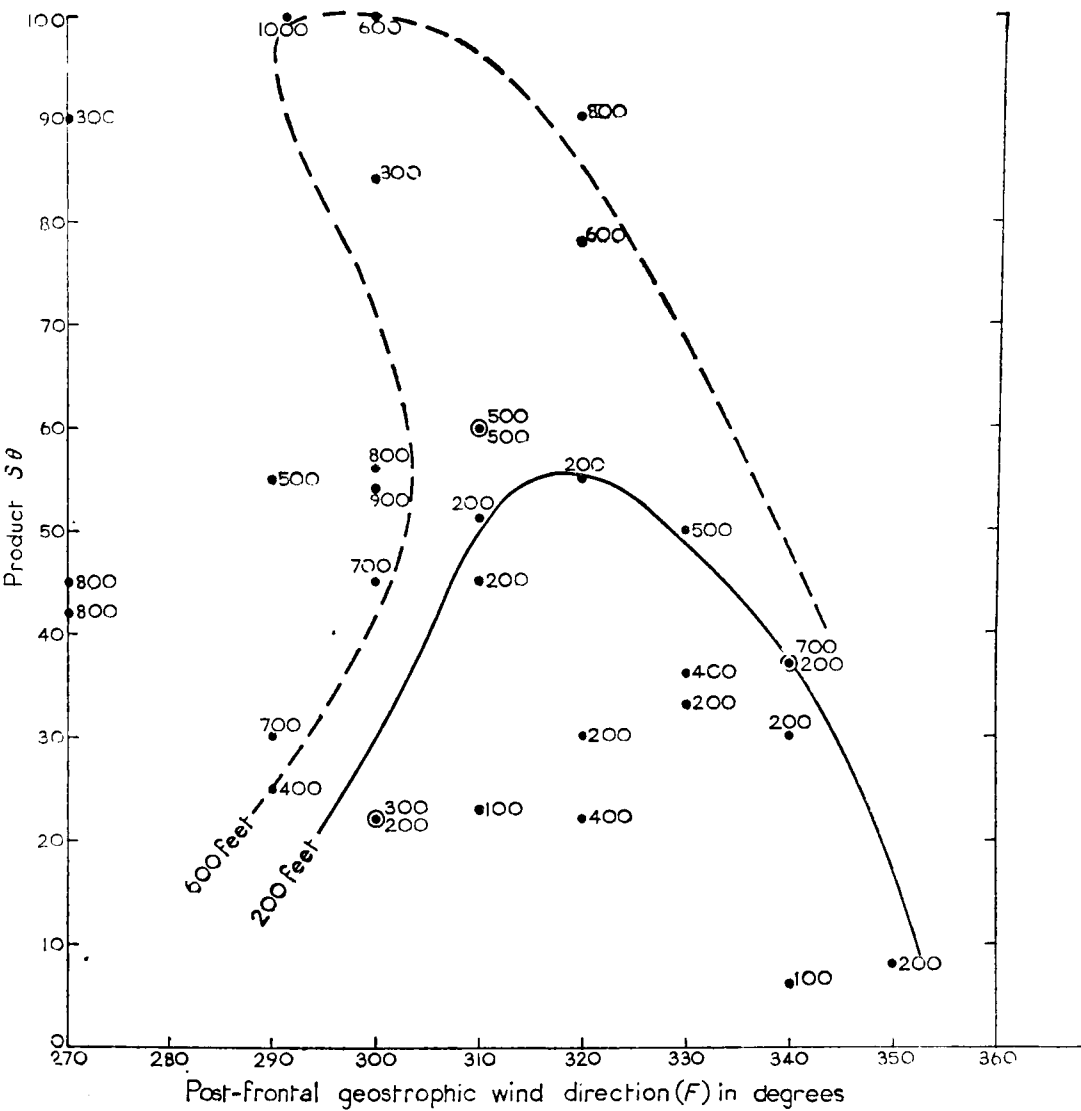


FIGURE 4--ISOPLETHS OF LOWEST CLOUD BEHIND THE COLD FRONT RELATED TO WIND DIRECTION AND THE PRODUCT  $S\theta$

$S$  = geostrophic wind speed in the cold air, in knots.  
 $\theta$  = mean dew-point depression of the frontal zone, in °C.  
*Errata*—the cloud base at  $F290^\circ$ ,  $S\theta = 100$  should be 600ft.

An examination of times of frontal passage reveals that 7 out of 8 cases with  $D$  over 3 hours occurred between 2200 and 0900 GMT, the one day-time cold front passing Manchester at 1530 GMT in January.

**Curvature effects.**—Anticyclonic curvature of the isobars in the cold air was most common amongst the whole sample of fronts (19 cases out of 30) and also amongst the fronts with delayed clearances of over 3 hours as shown in Table II. The two trough lines excepted, the four longest delays in clearance were all accompanied by anticyclonic curvature.

**Examples.**—Details are given of 2 occasions of delayed clearance at Manchester.

(i) *Anafront: 13 January 1961.*—This front passed through Manchester Airport at 0850 GMT and moved south-east at 12 kt. The anafront classification is confirmed from Figure 5(a) showing the post-frontal rain belt, and by Figure 5(b) showing the absence of any subsidence inversion at Aughton at 1100 GMT and the decrease with height of the component of wind normal to the front.

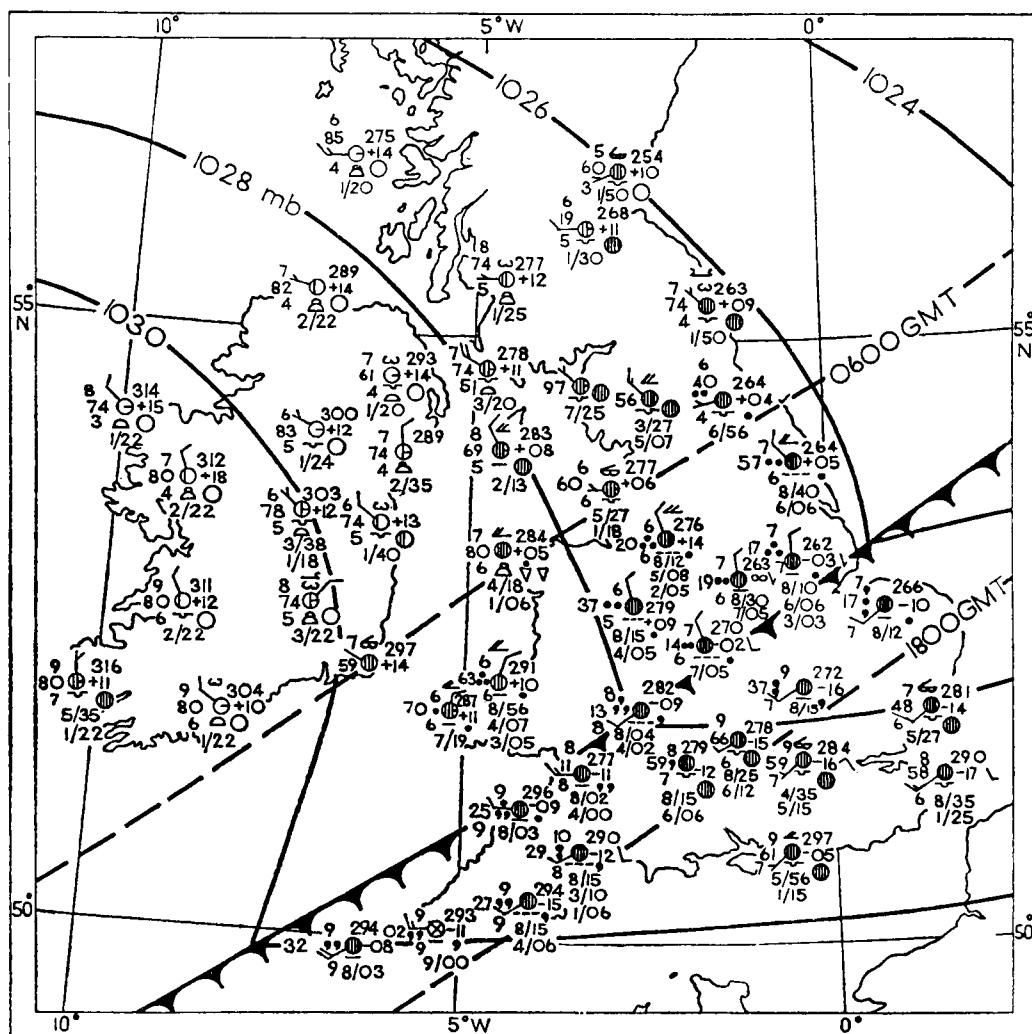
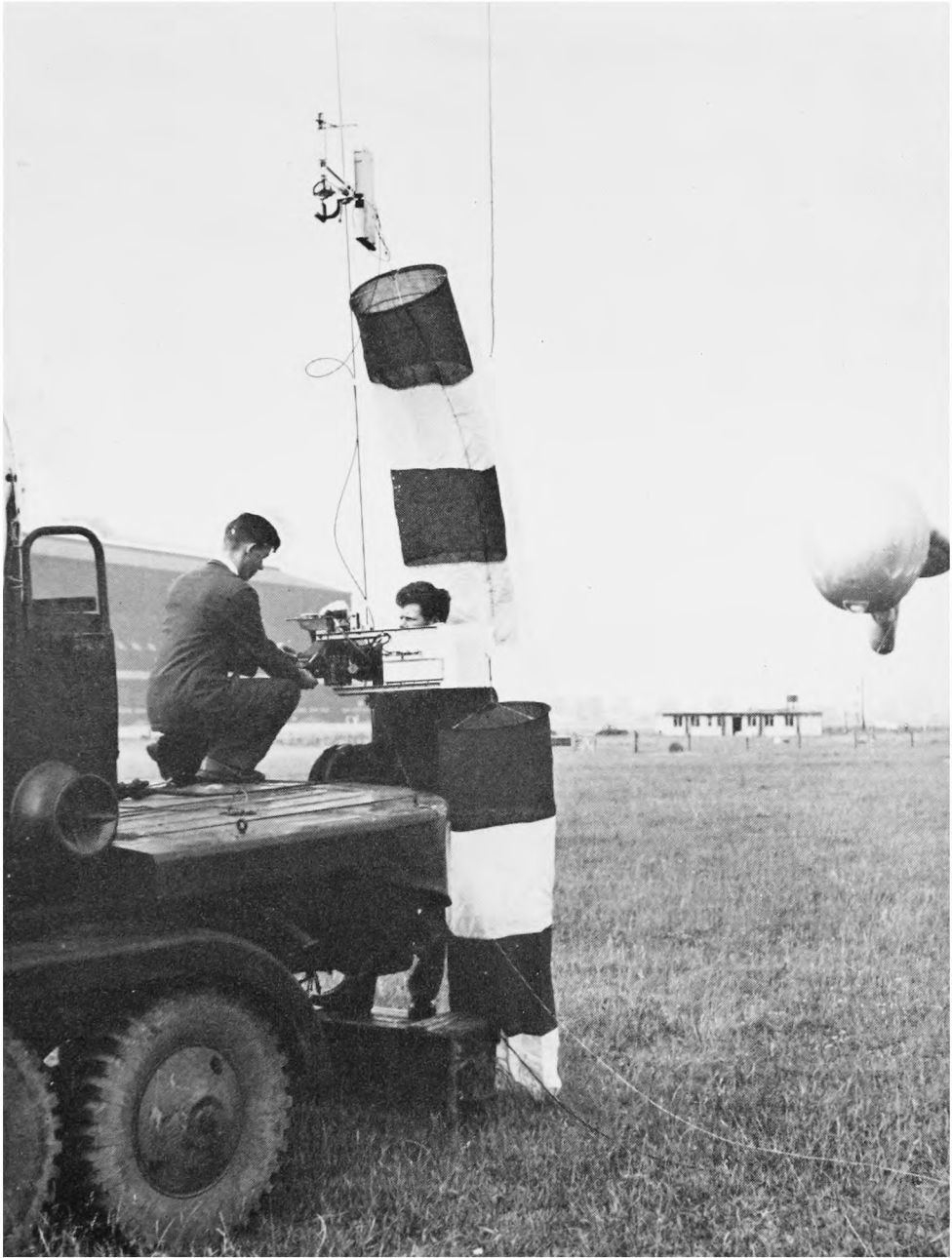


FIGURE 5(a)—ANALYSIS FOR 1400 GMT, 13 JANUARY 1961

The position of the cold front at 0600 and 1800 GMT is shown by a pecked line

Ahead of the front, 2.1 mm of rain was recorded at Manchester Airport whilst 6.4 mm fell between 0900 and 1430 GMT. Figure 5(c) shows the variation



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PLATE I—APPARATUS USED IN VERTICAL DIFFUSION EXPERIMENTS

One of the sampling units has been attached to the cable of the captive balloon and is being tested before being hauled aloft. Above it is an instrument for measuring the inclination of the wind to the horizontal and the wind speed (see page 193).



PLATE II—POSITIONS OF RAIN-GAUGES AND TROUGH (RIGHT) LOOKING NORTH,  
BAGLEY WOOD, OXFORD

See also Figure 1 on page 214.





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PLATE III—SUNSHINE RECORDER SITED ON THE ROOF AT THE TOP STATION OF  
THE CAIRNGORM CHAIRLIFT IN COIRE CAS

Instruments, including rain-gauge and thermometers, were installed at this high-level station in the Cairngorms in June 1963. The sunshine recorder is 3615 feet above mean sea level.

*To face p. 209*



*Photograph by J. P. Hudson*

PLATE IV—APPARATUS WITH MOUNTED EVAPORIMETERS USED IN THE GEZIRA  
EXPERIMENTS

See page 218.

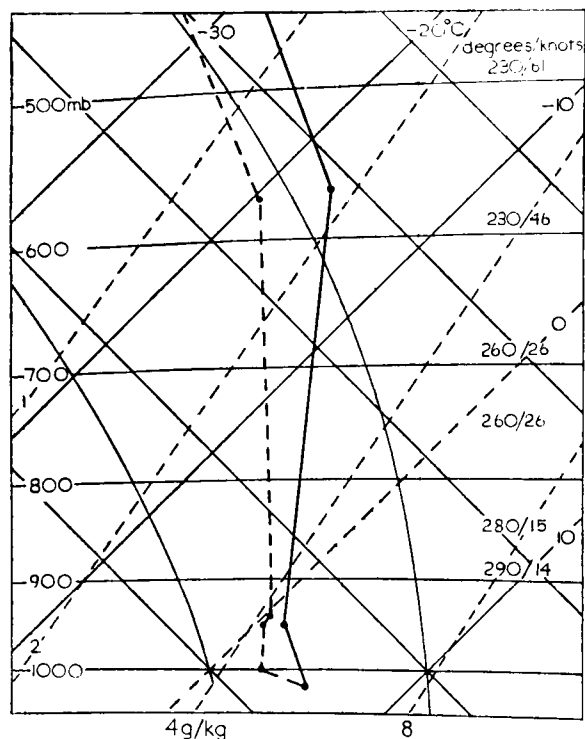


FIGURE 5(b)—TEPHIGRAM FOR AUGHTON, 1100 GMT, 13 JANUARY 1961  
 · — · — · Dry-bulb temperatures; · - - · dew-point temperatures.  
 Winds are shown at standard levels.

of cloud base from 0600 to 1800 GMT and also a copy of the pressure-tube anemogram. In common with most cold fronts from the north-west at Manchester, the cloud base fell suddenly, in this case from 600 ft to 100 ft, as the wind veered. After about one hour the cloud began to lift slowly and by 1600 GMT was above 1000 ft. At 1800 GMT low stratus returned with base varying between 500 ft and 1000 ft before lowering into fog and reducing visibility to 30 yards by 0000 GMT on 14 January 1961. The fog persisted until the morning of 15 January but its formation, preceded by a return of low stratus, was due to cooling assisted by the clearance of the frontal cloud which was judged to occur soon after 1600 GMT on 13 January.

After the frontal passage at 0850 GMT the geostrophic wind veered to  $340^{\circ}$  12 kt and the dew-point depression of the air in the frontal zone was  $0.5^{\circ}\text{C}$ , so that the front was noted on Figure 3 by  $F = 340^{\circ}$  and  $S\theta = 6$  with 7.0 hours delay.

Table IV compares the duration of post-frontal cloud below 1000 ft and also the duration of rainfall (post-frontal) for four stations, Blackpool, Manchester, Shawbury and Birmingham. This information was deduced from hourly charts.

TABLE IV—POST-FRONTAL CLOUD AND RAINFALL FOR ANAFRONT EXAMPLE

Station	Delay	Lowest cloud base	Duration of
	hours	above airfield	rainfall
		feet	hours
Blackpool	4	500	6
Manchester	7	100	6
Shawbury	4	300	4
Birmingham	3	400	3

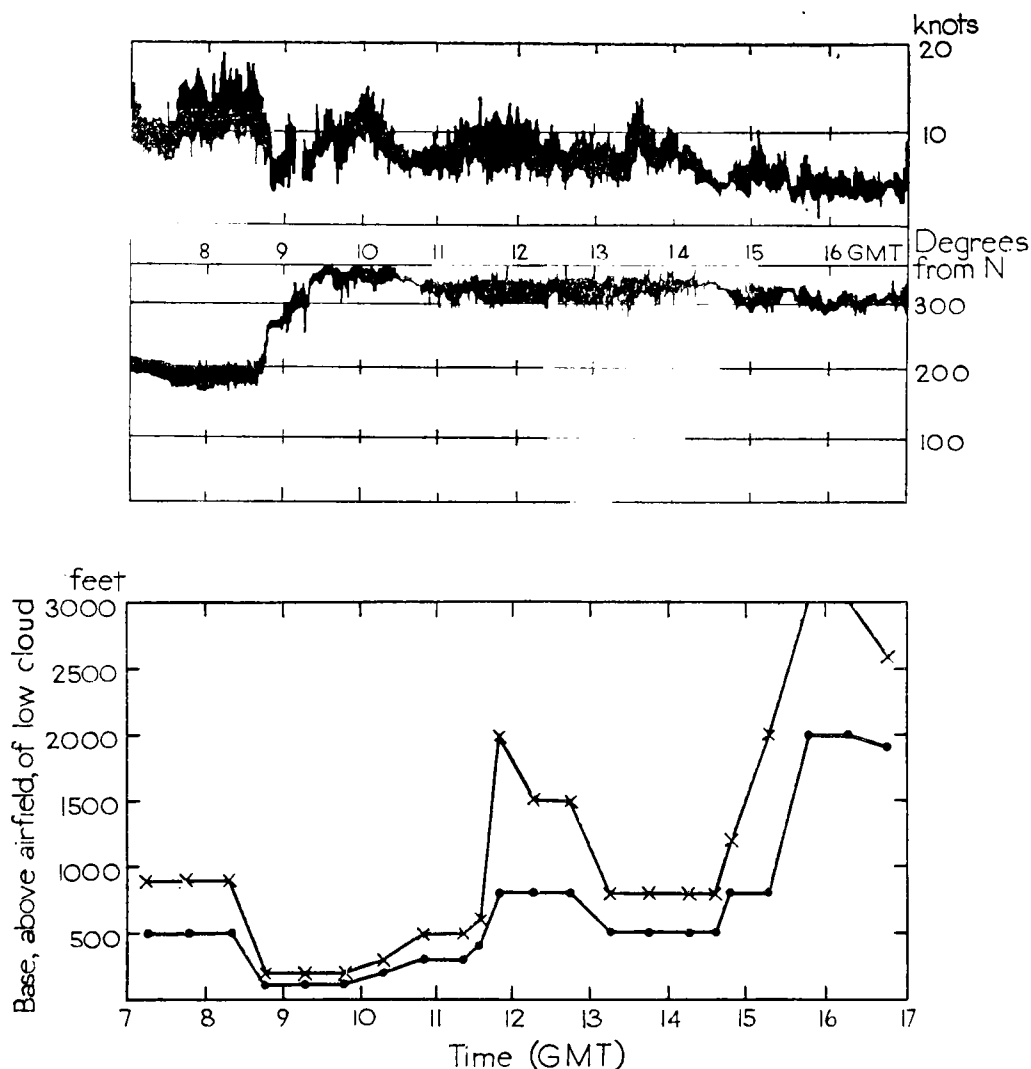


FIGURE 5(c)—ANEMOGRAM FOR MANCHESTER AIRPORT AND CHANGES IN THE BASES OF LOW CLOUD ON 13 JANUARY 1961

The top diagram shows the anemogram (pressure-tube anemograph) and the bottom diagram the changes in the low cloud.

— Base above airfield of the lowest layer of stratus; x-x-x-x base above airfield of second layer.

*Errata*—the first three points of the lowest cloud layer should be at 600 ft.

From Table IV it might be considered that the duration of low stratus is linked to the duration of rainfall. This may be so with anafronts but a second example is described which will show that low stratus is also a feature of katafronts with little rain.

(ii) *Katafront*: 22 June 1961.—On this occasion the cold front passed Manchester Airport around 0800 GMT with the surface wind veering gently from 220 to 290° between 0700 and 0800 GMT. The temperature rose 2°C by 0900 GMT because diurnal heating more than compensated for any air-mass changes. Only 0.5 mm of rain fell between 0600 and 0800 GMT and a trace between 0800 and 1200 whilst successive hourly charts showed the front to be weak with respect to rain and frontal contrasts. Figures 6(a) and 6(c) confirm that it was a weak katafront. Nevertheless the cloud base at Manchester Airport fell from 800 ft at 0600 GMT to 100 ft by 0730 and Figure 6(b) indicates how this

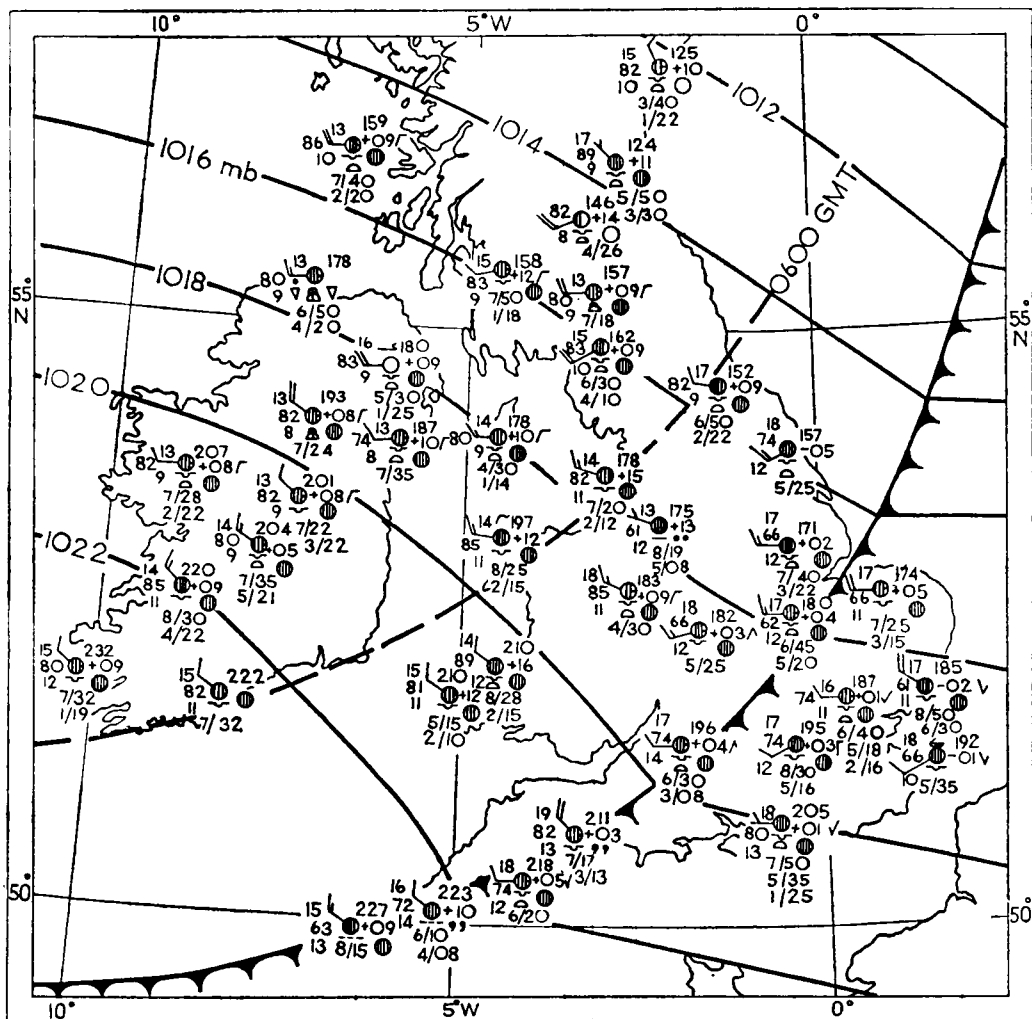


FIGURE 6(a)—ANALYSIS FOR 1100 GMT, 22 JUNE 1961

The position of the cold front at 0600 GMT is shown by a pecked line

low cloud lifted slowly to 1000 ft by 1200, a delay of 4 hours. The geostrophic wind in the cold air at 0800 GMT was  $310^{\circ} 23$  kt and the mean dew-point depression in the frontal zone was  $1.0^{\circ}\text{C}$ , so on Figure 3 the front was noted as  $F = 310^{\circ}$  and  $S\theta = 23$ , with 4.0 hours delay. No other station in England appears to have experienced the same duration of cloud and low cloud base that occurred at Manchester Airport. Table V compares cloud bases at four stations.

TABLE V—POST-FRONTAL CLOUD FOR KATAFRONT EXAMPLE

Station	Delay	Lowest cloud base
	hours	feet
Blackpool	4.0	500
Manchester	4.0	100
Shawbury	2.0	800 (cloud amount 1/8 only)
Birmingham	nil	above 1000

It is worth noting that the difference in cloud base between Blackpool and Manchester Airport was 400 ft in both examples although the two stations differ by only 200 ft in height above mean sea level.

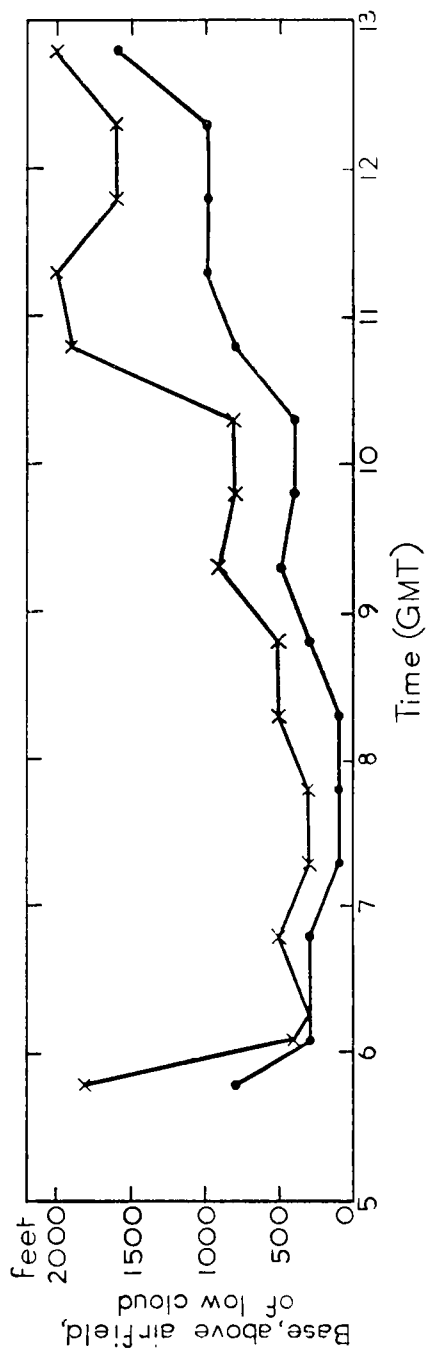
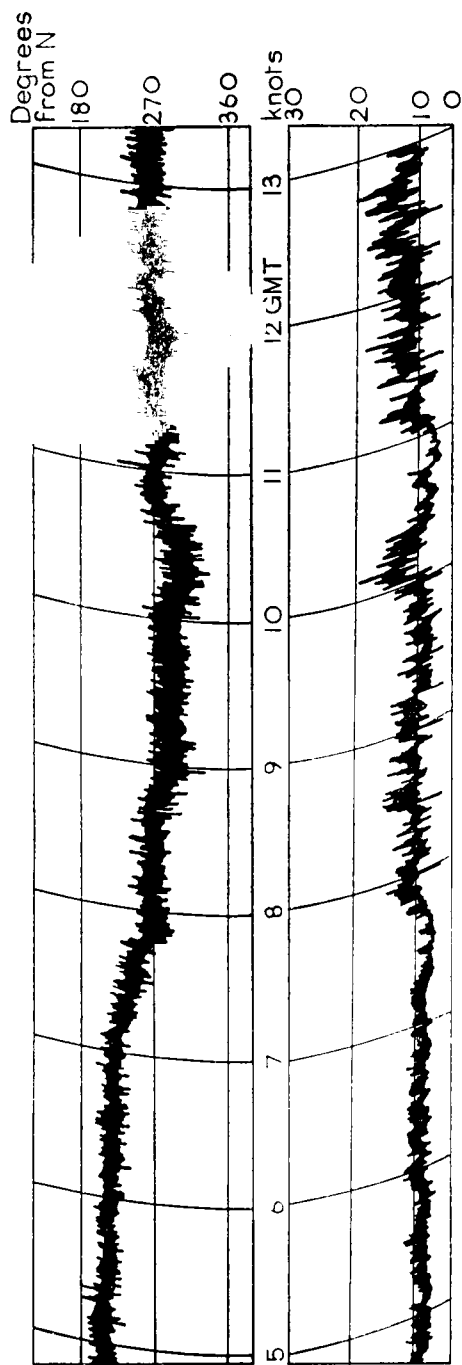


FIGURE 6(b)—ANEMOGRAM FOR MANCHESTER AIRPORT AND CHANGES IN THE BASES OF THE LOW CLOUD ON 22 JUNE 1961

The top diagram shows the anemogram (electrical anemograph) and the bottom diagram the changes in the low cloud. — Base above airfield of the lowest layer of stratus; x-x-x base above airfield of second layer.

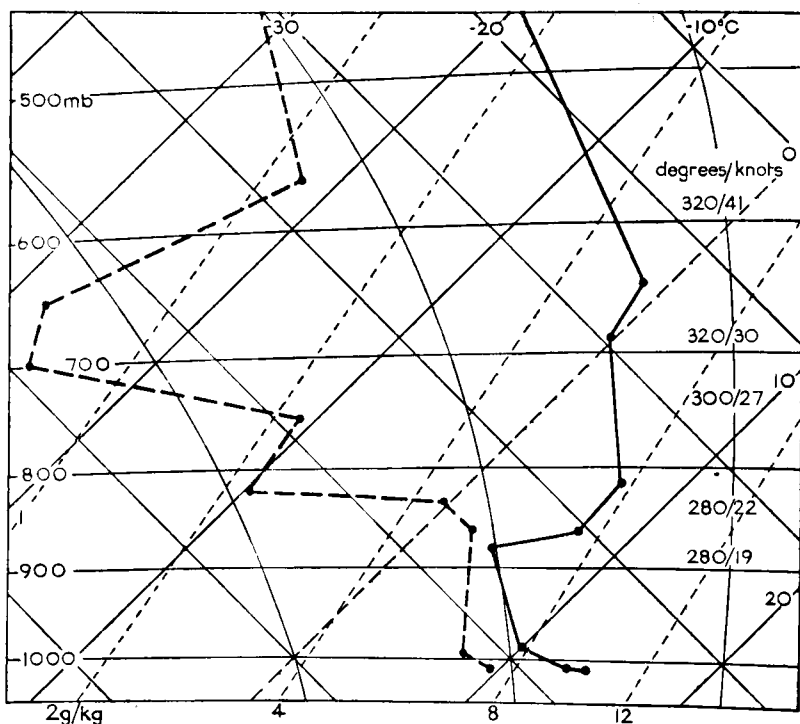


FIGURE 6(c)—TEPHIGRAM FOR AUGHTON, 1100 GMT, 22 JUNE 1961

———— Dry-bulb temperatures; - - - - dew-point temperatures.  
Winds are shown at standard levels.

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### DEW IN RAIN-GAUGES

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**Introduction.**—The condensation in rain-gauges of water from a moist atmosphere depends upon the heat relations of the collecting funnel. The surface temperature of the funnel may fall below air temperature by heat losses through conduction and radiation: condensation occurs when the temperature of the surface reaches the dew-point. The amount of dew collected depends on the transport of water vapour to the surface and the dissipation of latent heat. Since the latter differs from one design or rain-gauge to another, it may account for some of the differences in behaviour between gauges.

**Reports of differences in gauge performance attributed to dew.**—Poncelet<sup>1</sup> compared various standard national gauges at Brussels, and discovered that the British Meteorological Office 8-inch gauge registered a relatively greater catch in the months of January to March. This was particularly the case when gauge catches within two or three days after periods of frost were compared. For 10 such periods (28 rain days) the total amounts caught by duplicate 8-inch gauges were 2.42 and 2.44 inches, whereas a

gauge not in direct contact with the ground and usually catching a similar amount of rain, caught 2.20 inches. This excess Poncelet attributed to the fact that the British gauges, being in close contact with soil which was colder than the ambient air temperature, acted as condensers. He also noted that the German rain-gauges collected noticeably more in frosty foggy weather, because of the large internal surface area of the funnel available for the deposition of frost. Even when examining data from the Congo, Poncelet discovered that a gauge with a collecting area of 1 square metre, sunk into the ground so that its lip was level with the ground surface, caught on the average 7.3 per cent more rain at night, but 14.9 per cent less by day, than the national gauge which was raised above the ground. The differences he again explained by reference to the heat inertia of the ground-level gauge; its contact with the soil favoured evaporation at times, but also favoured the deposition of morning dew.

Evidently, there is considerable possibility that the design and installation of rain-gauges affect their relations to dew, and further, that the differences may be significant. The problem has been examined in a simple comparison of rain-gauges in a sheltered site near Oxford.

**Installations and results.**—A copper trough with the characteristics shown in Table I, was supported on four legs of  $\frac{3}{4}$ -inch angle iron (see Plate II) and sited 4.6 metres east of a Meteorological Office 5-inch gauge set up in the standard manner (see Plate II and Figure 1). A second 5-inch gauge was installed 2.7 metres north of the first. The base of the Meteorological Office rain-gauge is buried 19 cm below ground level.

TABLE I—CHARACTERISTICS OF THE RAIN-GAUGES

Gauge	Height of lip	Weight of copper and brass	Shape	Details of funnel Collecting area	Internal surface area
	<i>cm</i>	<i>kg</i>		<i>square metres</i>	
Trough	77.5	7.7	rectangular	0.566	1.022
5-inch gauges	30.5	1.8	circular	0.0127	0.061

As examples of the difference between the gauges in their efficiency to catch dew, Table II shows three records unaffected by rainfall. In these cases the greater collection of dew by the trough gauge is very evident, and the effect over a year might be appreciable. The difference amounts to between 0.002 and 0.003 inches of water on average condensed each night.

TABLE II—CONDENSATION IN GAUGES IN THE ABSENCE OF RAINFALL

Date	Days since previous reading	Met.O. 5-inch gauges 'north' 'south'		Trough gauge
		<i>inches</i>		<i>inches</i>
11.10.62	8	0.006	0.006	0.027
18.10.62	7	0.003	0.003	0.016
8.12.62	12	0.005	0.009	0.047

Table III shows the relationship between the precipitation measurements from the gauges for each 3-monthly period over 2 years. From these it is evident that the trough is consistently less efficient at catching rainfall, perhaps because of its greater height, more evaporation, or less in-splash. However, the trough consistently collected more dew, if this is the correct explanation of the constant term. Possibly as a result of these opposing effects, the annual total for 1961 showed an excess collection of 0.24 inches by the trough, whereas 1962 showed a slight excess by the 5-inch gauges, perhaps reflecting a difference in the distribution of the sizes of storms between the two years. The difference



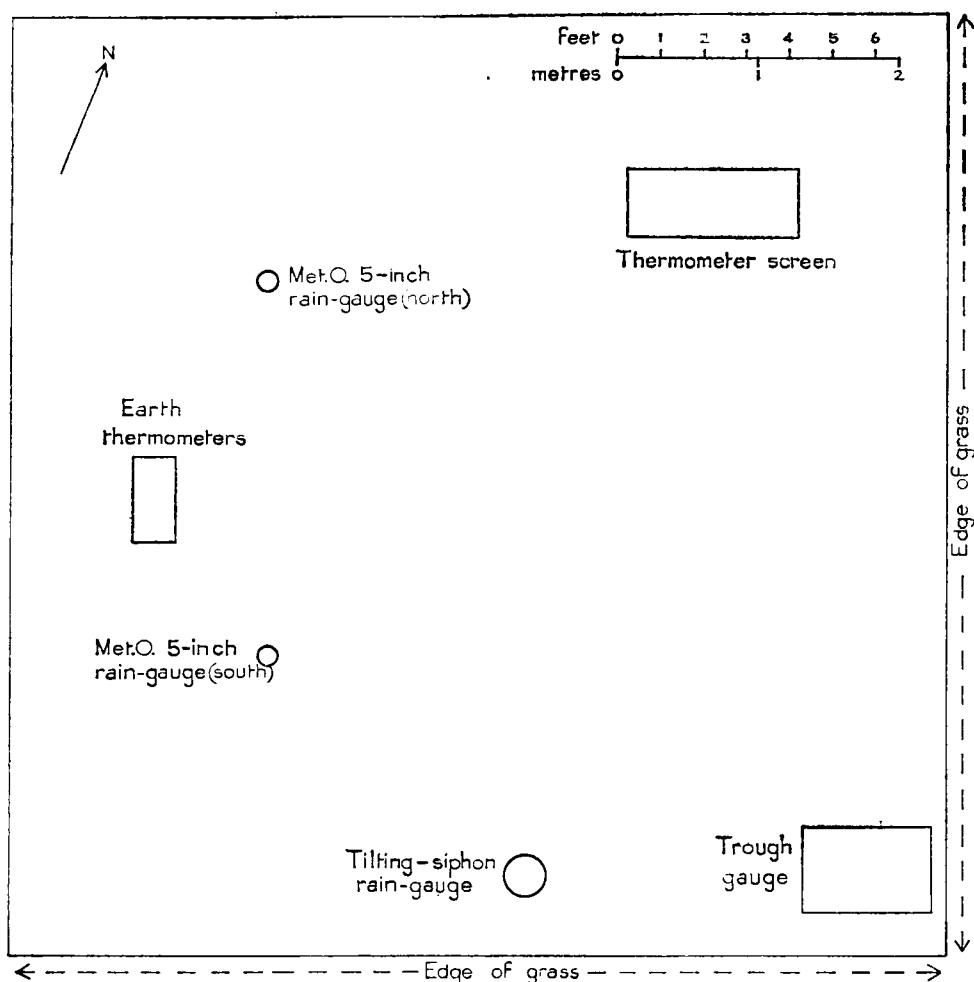


FIGURE 1—PLAN OF THE SITE USED IN THE COMPARISON BETWEEN RAIN-GAUGES AND TROUGH, BAGLEY WOOD, OXFORD

Trees to the south-south-west of the site give an angle of elevation of  $27^\circ$ , otherwise there is no obstruction within the conventional distance-height 2:1 rule. See also Plate 1.

TABLE III—SIMPLE LINEAR REGRESSIONS OF TROUGH CATCH( $\bar{Y}$ ) ON MEAN 5-INCH GAUGE CATCH( $x$ ) (INCHES OF PRECIPITATION)

Period	1961	1962	Ratio of regression constant to mean number of nights per record	
			1961	1962
'Winter' (Jan.-Mar.)	$\bar{Y} = 0.0043 + 0.989x$	$\bar{Y} = 0.0032 + 0.981x$	0.0013	0.0009
'Spring' (Apr.-June)	$\bar{Y} = 0.0037 + 0.999x$	$\bar{Y} = 0.0052 + 0.981x$	0.0013	0.0013
'Summer' (July-Sept.)	$\bar{Y} = 0.0049 + 0.975x$	$\bar{Y} = 0.0031 + 0.978x$	0.0017	0.0012
'Autumn' (Oct.-Dec.)	$\bar{Y} = 0.0061 + 0.976x$	$\bar{Y} = 0.0106 + 0.951x$	0.0029	0.0037

between the constants of the seasonal regressions in Table III is not significant, neither is the difference between slopes. However, it may be noted that the highest constant occurred in autumn in both years. If the constants are rightly attributable to dew formation, it would be logical to adjust them according to the mean number of nights to which the rainfall collections refer in each season, since this varies from 2.1 to 4.1 nights per record. The adjusted figures are shown in the last two columns of Table III, where it is seen that the difference

in the efficiency of dew collection is about a thousandth of an inch a day, but that in autumn the excess in the trough may rise to three times this figure. The differences between the gauges in the absence of rainfall (Table II) agree with this estimate of the daily excess in the trough for the months of October and December. Monteith<sup>2</sup> notes that maximum nocturnal relative humidities occur in autumn, and also that from mid-September to mid-October cloudless nights are most frequent. These are two conditions which favour dew-fall. Since the trough is virtually insulated from the soil, its collection of dew is likely to contrast (especially in autumn) with that of the Meteorological Office gauges in contact with warm soil (cf. Monteith<sup>3</sup>).

Further analysis of the data failed to show that mean nightly difference in the catch of dew (computed from the regressions) was significantly correlated with the difference between the 12-inch soil temperature and the air temperature. However, this was probably due in part to the exclusion of measures of cloud cover and wind speed which are important in dew formation.<sup>2</sup> Even when the dew deposition from a recorder (Hirst<sup>4</sup>) was included as an 'independent variable' in a multiple regression, the differences between the trough and 5-inch gauges were not closely correlated with the temperature differences. The temperature and dew-fall figures used in these analyses, since they were measured on instruments at a considerable distance from the gauges, were perhaps too approximate for the purpose.

### Discussion.—

(i) *Dew and the accuracy of rain-gauges.*—Since the efficiency of the collection of dew by rain-gauges appears to vary according to the design or installation of the gauge, it complicates the relationship between the gauges used in various national networks. This difference in relative accuracy may be sufficiently important to affect the international comparisons of rain-gauges.

Certain types of rain-gauges which have been suggested as an approach to the absolute measurement of rainfall by eliminating splash and wind effects, have been partially buried in the soil. Such designs will be particularly influenced by the thermal lag of the soil, and thus their collection of dew will be distinct from other types of gauge. This must be considered to detract from their value as absolute gauges.

(ii) *Inclusion of dew-fall in precipitation measurements for hydrological purposes.*—In connexion with water-balance studies, the suggestion has been made<sup>5</sup> that the condensation and absorption of water on the vegetation and in the soil is of considerable importance and ought to be added to the rainfall (although the magnitude of dew-fall was over-estimated in early experiments<sup>6</sup>). An instrument which measures rainfall, but also records dew-fall, might be considered more suitable for hydrological purposes. However, the measurement of dew-fall on the artificial collecting surface of a rain-gauge is probably very different from the amount of dew-fall on soil and vegetation;<sup>2</sup> and is considerably affected by the design and installation of the gauge.

A weighed lysimeter in Ohio has been employed for recording dew and rainfall,<sup>5</sup> since it provides a more or less natural vegetated surface. However, it is probable that dew-fall and transpiration were sometimes simultaneous, when neither was detected by this instrument. It appears<sup>2</sup> that an important proportion of the dew is merely the distillation of water from one surface to

another, and this is not detected by a weighed lysimeter. The distillation is extremely local and thus has no significance in the water balance of large areas. The results presented by Long<sup>7</sup> suggest that the importance of distillation relative to deposition from the air above, diminishes as the height of the crop is greater. The amount of dew recorded by a weighed lysimeter would thus be dependent on the vegetation involved. It is probable that dew does not add water to a site in a hydrologically effective manner, since the water condensed on vegetation usually passes into the atmosphere very quickly.

**Conclusions.**—Since condensation is so subject to rain-gauge design, and because of the lack of relevance of dew-fall to many purposes for which precipitation measurements are used, it is suggested that Poncelet's conclusions should be adopted; that the measurement of dew-fall is the subject of completely different techniques, and dew collection in rain-gauges ought to be regarded as an error. It might be instructive to devise a gauge whose funnel is maintained at ambient air temperature to minimize this source of error, and thus discover the magnitude of the error in conventional designs.

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## NOTES AND NEWS

### Agronomic implications of advection

A very interesting lecture was given in the lecture theatre at the Headquarters of the Meteorological Office, Bracknell, on 26 February 1964, by Professor J. P. Hudson of the Department of Horticulture, Nottingham University. It was accompanied by many striking slides showing experimental work in progress.

The subject of the lecture concerned agronomic research in the Gezira area in the Sudan at the junction of the White and Blue Niles, with main emphasis on evaporation and irrigation problems of such crops as lucerne and cotton. The uncontrollable variability in yield of the latter crop was a worrying aspect, as shown, for example, in consecutive recent years when cotton crops were respectively 155 per cent and 35 per cent of the long-term average. Although disease and pests can play an important part, weather must also be an essential factor in causing such variability.

An outline was given of the problem. The Gezira authority dictated absolutely what crops had to be grown on their scheme for two million acres, and where, in some 20,000 fields (or strips) which had been laid down with almost geometrical accuracy, each 300 yards  $\times$  1 mile in size—the experimenter's dream in many ways. Strips planted with irrigated crops such as cotton were irregularly alternated with fallow strips, so the ground presented a patchwork appearance.

Several main factors influenced the progress of the crop, such as the day-to-day weather, the pattern in which fields were arranged, and edge and zone effects. Edge effects related to the boundary between a transpiring crop and dry fallow land, and zone effects referred to the position of the crop within the whole cultivated area (roughly half the size of Wales).

The point was briefly made that contrary to popular belief weather variation did occur in the Sudan, and temperatures, humidities and wind strengths did not remain near average values, even if the sun was nearly always unobscured by cloud. Dry winds blew from the north fairly persistently however for much of the period of experimentation, and this gave rise to the clearly defined pattern of edge and zone effects already mentioned.

Instruments used to investigate the weather factor included thermometers in screens, evaporimeters and lysimeters. A hundred simple evaporimeters were specially made for this work and consisted of small aluminium dishes held in insulators, or moulded plastic containers of about the same size, and preliminary experiments confirmed that reproduceable results could be achieved from these provided certain simple precautions were taken. Plate IV shows a typical piece of equipment as used in the field with the plastic-type evaporimeters mounted at five different heights up to 2 metres above ground, so that readings both above and in the crop could be taken.

Profiles of evaporation change were taken across stripped areas, and the results for two random dates are shown diagrammatically in Figure 1 which brings out the initial fall in the evaporation rate as soon as a crop was entered and the subsequent steadying to near a constant value after a penetration of about 100 yards. As soon as the crop was left, and dry fallow was entered, a sharp increase in evaporation occurred, almost to the pre-cotton level.

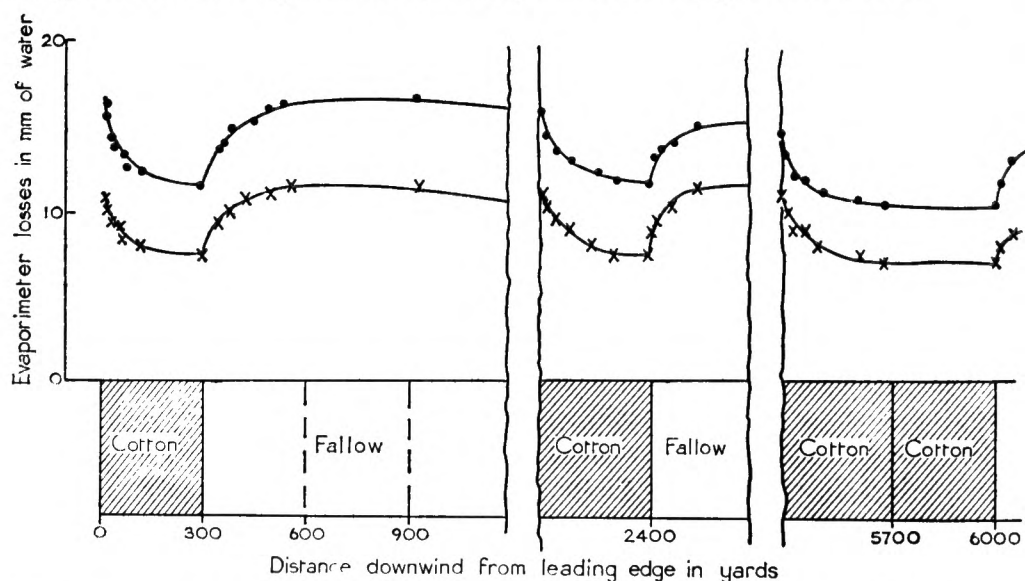


FIGURE 1—PROFILES OF EVAPORATION CHANGE TAKEN ACROSS A STRIPPED AREA ON TWO RANDOM DATES

—•—•— 31 December

—x—x— 19 December

Variation at different heights was brought out on another slide (Figure 2). This showed the rapid increase in evaporation rate above the surface in a

field of lucerne, with a point of inflexion at approximately the level of the crop top. The evaporation rate above open desert is also shown for comparison purposes.

Professor Hudson concluded by saying there were perhaps three main approaches to the assessment of water need: first-principle method such as Penman's, empirical methods of trial and error, and those based on simple instruments such as the evaporimeter used in the Gezira experiments.

An interesting discussion ensued. The Director-General thought temperature readings would be necessary to support evaporation measurements. Professor Hudson replied that these had been taken in some experiments though inevitably not in all. Subsequent discussion covered points such as the variability of crop yields being importantly due to disease as well as to frequency of irrigation need and arrangements of fields. Day-to-day evaporation varied by up to 30 per cent and weekly evaporation by 11 per cent in one period of 28 days. The zone effect was 1 per cent per mile downwind and the variation due to arrangement of fields could be 10 per cent, with half the reduction of evaporation taking place in the first 50 yards of crop across the leading edge of exposed fields. The

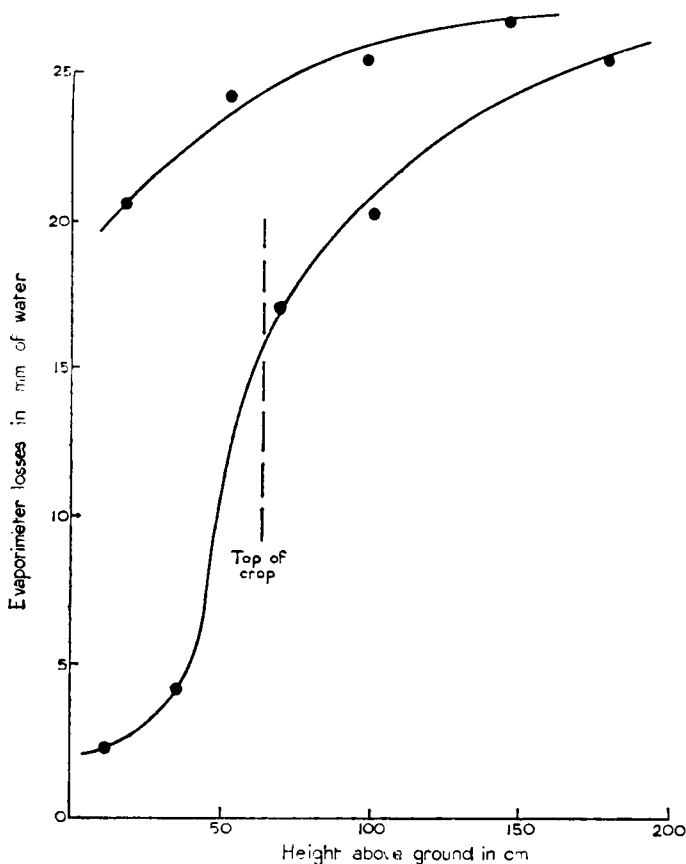


FIGURE 2—VARIATION OF EVAPORATION WITH HEIGHT ABOVE THE DESERT AND ABOVE A CROP OF LUCERNE

Upper curve—evaporation curve above desert; lower curve—evaporation curve 40 metres within a strip of lucerne.

point was made by Mr. L. P. Smith that the timing of irrigation might therefore be at least as important as edge effect and there would be advantage in irrigation on a need rather than a routine basis. In reply to a question, Professor Hudson

agreed that there would probably be real advantage in having all fields orientated north-south but that fairly definite proof would have to be given to the Gezira Board before the extensive replanning that would be involved could be contemplated.

The Director of Research brought the meeting to a close by thanking Professor Hudson very sincerely for the excellent and interesting account which he had just given—this was real practical applied meteorology, and it had been a pleasure to hear of such work in progress.

G. W. HURST

### **Meteorological Service of Canada**

#### **Resignation of Dr. P. D. McTaggart-Cowan, M.B.E.**

On 31 December 1963, Dr. P. D. McTaggart-Cowan resigned his position as Director of the Meteorological Service of Canada to become the first President of the Simon Fraser University in British Columbia.

Dr. McTaggart-Cowan is well known to many members of the Office staff, especially in relation to his work on transatlantic aviation meteorology. He was a Rhodes Scholar and studied physics at Oxford, where he also rowed in his college eight. In recent years he has been active in the sphere of international meteorology, first as an acting member of the Executive Committee in place of Dr. Andrew Thomson, whom he succeeded as Director of the Meteorological Service of Canada in 1959, and later as President of Regional Association IV. During the World Meteorological Organization Congress of 1963 he acted as Chairman of the Committee set up to consider administrative and financial matters.

There is no doubt that Pat McTaggart-Cowan will be greatly missed in the world of meteorology. His crisp incisive speech and unfailing courtesy made him a natural leader, both in technical and administrative problems. The new university is fortunate in having for its first head a man who is not only deeply interested in education but also has the intellectual gifts and physical stamina to make his ideas felt. Although, like many others, I regret the disappearance from international meteorological meetings of a wise and friendly companion, I recognize that in his new field he is fulfilling a life-time's ambition, and we may confidently expect that with his guidance the Simon Fraser University will become a notable element in the life of his country. We wish him all success.

O. G. SUTTON

#### **Appointment of Dr. T. G. How as Director**

We have been informed that Dr. T. G. How has been selected to succeed Dr. P. D. McTaggart-Cowan as Director of the Meteorological Service of Canada. We wish Dr. How every success in his appointment.

### **United States Weather Bureau**

#### **Retirement of Dr. F. W. Reichelderfer**

On 1 October 1963, Dr. Francis W. Reichelderfer retired from the post of Chief of the United States Weather Bureau, after holding office since 1939. In this period he not only guided the Bureau during years of spectacular change but also took a large part in international work. He was one of the 'founding fathers' of the World Meteorological Organization and as its President in the

critical initial period he, more than anyone else, gave it stability and a sense of purpose.

His record of achievement from the early days of naval aviation onwards is recorded in glowing terms in the journals of his country. Here I wish to add simply a personal word of admiration for a man whom I have known since 1948, both in America and elsewhere. The impression that remains is not only of wisdom and unruffled judgement but above all of unfailing kindness and courtesy. No one ever appealed to 'Reich' for help in vain, and he has never spared himself in his devotion to both the science and the profession of meteorology. His many friends in this country, both inside and outside the Office, will join with me in wishing him and Mrs. Reichelderfer many years of serene happiness in their well earned retirement.

O. G. SUTTON

### **New Chief of the United States Weather Bureau**

Dr. Robert M. White, who succeeded Dr. Reichelderfer as Chief of the United States Weather Bureau on 1 October 1963, was previously President of the Travelers Research Center, Hartford, Connecticut. He was born in Boston in 1923 and studied meteorology at the Massachusetts Institute of Technology, gaining the master's degree in 1949 and the doctorate in 1950. He also has been Chief of the Cambridge Research Center's Meteorological Development Laboratory.

We wish Dr. White all success in his new and onerous position.

### **REVIEWS**

*Weather and man*, World Meteorological Organization (WMO), Tech. Pap. No. 67. 9 in  $\times$  6 $\frac{1}{4}$  in, pp. 80, *illus.*, Geneva, WMO, 1964. Price: Sw.F. 2. (Also available from HMSO. Price: 3s. 6d.)

As acknowledged in an authoritative foreword by the Secretary-General of WMO the major part of the booklet—an exciting reply to the challenge of the United Nations Development Decade—has been written by Mr. L. P. Smith of the Meteorological Office. Mr. Smith has followed up his earlier "Weather and food" (which has already received world-wide praise from agriculturists) by a thought-provoking contribution to the problem of economic planning of the world's natural resources in the weather environments in which they perforce must be developed.

It was to be expected that the author would place agriculture at the forefront of the various subjects tackled. He has now, however, enlarged his field of interest by going on to discuss such topics as industry and trade, insurance and legal matters, transport (sea, land and air), the tourist industry, health, recreation, sports etc. in their relations to weather and climate.

Mr. Smith, writing in his usual lucid yet simple style (the booklet is one which tempts the reader to read it at one sitting), develops the idea that although aviators have for many years seriously considered the function of weather in their operations (from the viewpoint of safety of life as well as commercially) and have been meticulous in laying down their meteorological requirements which they have expected to be met, operators in other forms of activity have been slow to realize the effect of weather, have neglected to

formulate their needs and for the most part have failed even to discuss their problems with professional meteorologists able to help them. In his introduction the author indicates that weathermen have an essential part to play in natural development. "... the correct application of the science of meteorology is an investment in both personal and national fortunes ..."

Out-of-door activities obviously cannot escape the effect of weather and therefore the efficient manager should plan with both possibilities and probabilities in mind. For greatest economic gain, however, a complete pooling of ideas, operational and meteorological, is necessary.

In the chapter on Health, Mr. Smith hints at various effects of weather (including the psychological) and quotes a most interesting example of a chain reaction where ill health in South Australia was caused by early favourable monsoon rains in far off Queensland, the link being a rare migration of birds arising from an increase of breeding due to generous food supply.

Elsewhere the subject of meteorological disasters is discussed. Gales, floods and forest fires all receive attention, Encouraging figures are given of the reduction in hurrican disaster deaths in the U.S.A. where adequate warning services have been installed, However, we are warned that crying wolf may sometimes be expensive since it is estimated that a false hurricane warning may cost the city of Miami three-quarters of a million dollars a time.

Although Mr. Smith, as has already been mentioned, is largely responsible for the publication, a chapter on Water Resources has been contributed by Mr. Max Kohler of the U.S. Weather Bureau while suggestions made by the Director of the Israel Meteorological Service have also been incorporated.

It is a pity that the otherwise admirable selection of photographs in the booklet should be marred by the inclusion of an illustration of an operation rapidly becoming out of date—a pilot-balloon ascent—on the cover.

All meteorologists, especially those in the Public Service sector, should study this booklet and thus be stimulated to turn their thoughts to customers' needs. Perhaps more desirable, however, is that those in charge of industrial concerns of building and civil engineering projects, those planning future townships, health campaigns etc. should learn from its contents. "Weather and man" deserves the widest circulation in this field.

N. B. MARSHALL

*Grosswetterkunde und langfristige Witterungsvorhersage*, by Franz Baur. 10 $\frac{3}{4}$  in  $\times$  7 $\frac{3}{4}$  in, pp. 91, *illus.*, Akademische Verlagsgesellschaft, Frankfurt am Main, 1963. Price: 35 DM.

This book represents the proceedings of a seminar, held in Bad Homburg, Germany in October 1961, on large-scale meteorology and long-range weather forecasting. The occasion provided Franz Baur, unrivalled in his experience of the problems of long-range weather forecasting, with a platform from which to expound the results of his own and his close associates' researches.

Professor Baur's conclusions may be briefly summarized as follows. Methods of long-range forecasting which involve linear regression, periodicity, or symmetry points are doomed to failure. Real singularities of weather exist but are too unreliable to be useful. Large-scale weather patterns ("Grosswetterlagen"), involving the averaging of weather elements in space and time, must be recognized and the pattern of their occurrences, their relation to more local weather characteristics, their transitions and interrelations, etc. must be



studied. Changes in large-scale weather are, in no sense, the result of the coincidence of 'chance' events and they are therefore predictable. Complex but important relationships exist between solar activity and meteorological elements: solar faculae are a particularly valuable index in this respect.

The importance attached by Professor Baur to solar activity is made clear in the exposition of his method as applied to the then-approaching winter of 1961-62. It is of interest that at an earlier point he had dismissed as quite inadequate a forecasting technique capable of predicting three times out of four, the correct sign of the deviation from the mean. If, as is implied and as appears to be the case, Professor Baur's method achieves a degree of success substantially higher than this then those meteorologists—they include the reviewer—who have been sceptical about the existence of any proved connexion between solar activity and surface meteorology may have to revise their opinions. The difficulty here lies in applying an adequate significance test since the various relationships employed have been selected, from a large but indeterminate number of possibilities, because of their high proportionate success in past data. Fresh data with which to test the relationships accumulate only slowly.

In connexion with the controversial solar influence two further possibilities cannot be eliminated at present. First, the forecasts up to 1961 (not very numerous) may have enjoyed a large measure of good luck. Second, the success achieved may be a dependable measure of what is to be expected in the future but this success may result entirely from considered factors other than the solar connexions, despite the apparent emphasis placed on the latter.

The book contains an article, by another contributor, on connexions between tropospheric and stratospheric circulations. Some 10 pages of the volume are devoted to a discussion which took place during the final session. English abstracts of the (German) lectures and reports are given throughout.

D. H. MCINTOSH

## HONOUR

The following award was announced in the Birthday Honours List on 8 June 1964:

M.B.E.

Mr. W. McKay, Senior Experimental Officer, Meteorological Office, Seychelles.

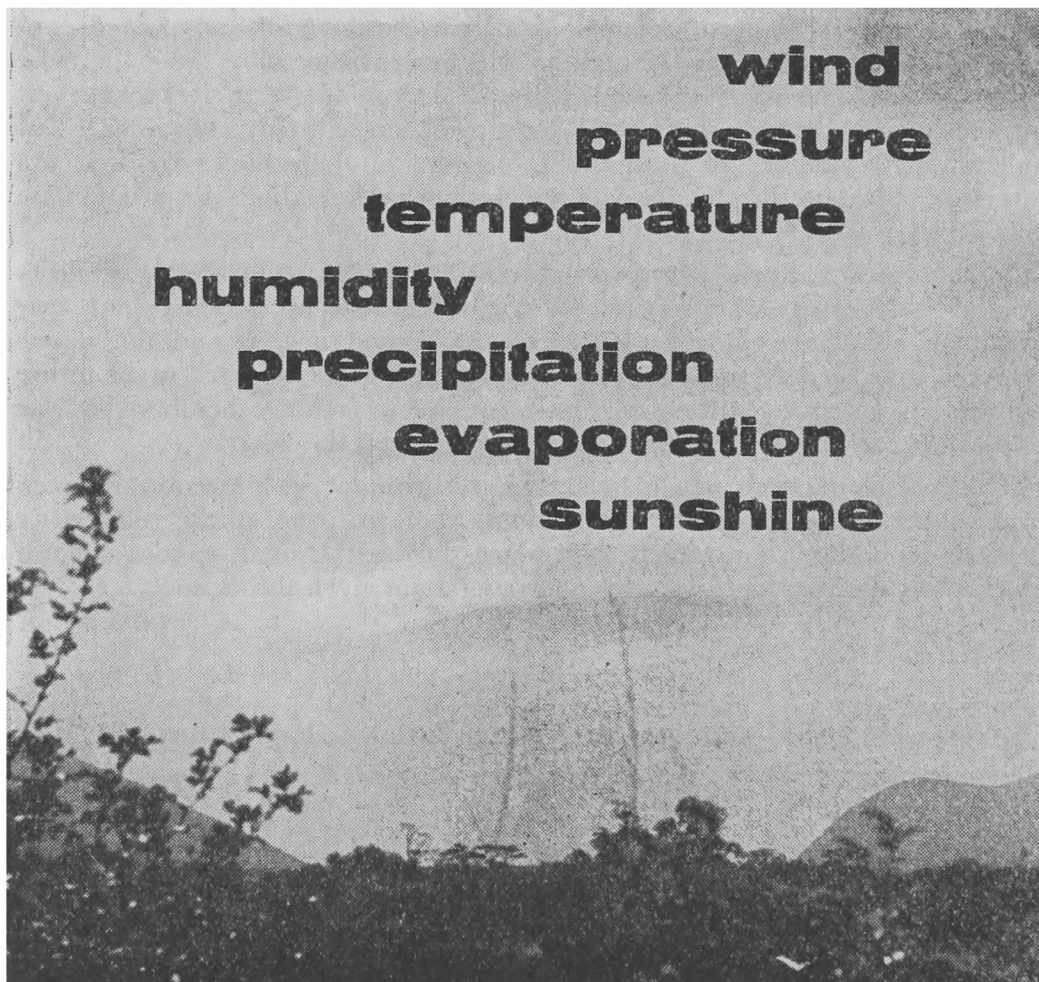
## OBITUARY

It is with deep regret that we record that on 31 May 1964, two firemen, Mr. R. Bain of Greenock and Mr. J. Kelly of Glasgow, lost their lives in a serious fire in the boiler room of the ocean weather ship *Weather Adviser*. Our sympathy is extended to the widows and their families.

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# THE METEOROLOGICAL MAGAZINE

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## **VERY LOW HUMIDITY IN THE EAST OF SCOTLAND IN DECEMBER 1962**

By F. H. W. GREEN, A. WATSON and N. PICCOZI  
The Nature Conservancy

One glance at the thermograph and hygrograph charts for early December 1962 at the Climatological Station maintained by the Nature Conservancy at Moss-side, Strachan (400 ft above mean sea level), Kincardineshire, indicated that air humidity must have been phenomenally low on 3 December and again on 5 December. Closer examination of the records at this, and various neighbouring stations, showed that relative humidities must have fallen at least down to 7 per cent, slightly below those reported for Moor House,<sup>1</sup> Westmorland, Achnagoichan,<sup>2</sup> Strathspey, and others.<sup>3,4</sup> Since the low humidities in December 1962 coincided with some low temperatures, phenomenally low dew-points must have occurred. The occurrences were discussed with Mr. R. Cranna, Superintendent of the Meteorological Office, Edinburgh, and the following account has been compiled with his help.

At Moss-side, the hygrograph trace shows that relative humidity (measured as a percentage) began to fall from about 80 at 0800 GMT on 3 December to about 10 at 1000 GMT and to 7 or below at 1400 GMT, remaining below 20 until 1800 GMT. It rose to about 60 by midnight, remained high (85 to 100) all next day, but fell rapidly after 0800 GMT on 5 December, and then fluctuated violently between 18 and 70 up to 2200 GMT. It tended downwards after this, to about 22 by midnight, and became about 16 between 0200 and 0500 GMT on 6 December, after which it rose to about 70 by 1000 GMT. The sky was largely clear on 3 and 5 December, but was cloudy during the intervening day (see Figure 1).

That the hygrograph was reasonably accurate was checked as carefully as possible from all the wet-bulb and dry-bulb thermometer readings available. Sources of error in the hygrograph are discussed in the *Handbook of meteorological instruments, Part I*<sup>5</sup> but the general shape of the graphs would not be in doubt. Roughly five hours after the observation time at 0900 GMT on 3 December the dew-point must have fallen to about  $-15^{\circ}\text{F}$  since the thermogram indicated  $47^{\circ}\text{F}$  and the humidity reading was about 7 per cent. There is the possibility of error in the exact timing of the clocks on the thermograph and hygrograph, but it is clear enough that very low humidities and dew-points were attained, and this is borne out by the records at other stations, notably at Whitehillocks (845 ft),

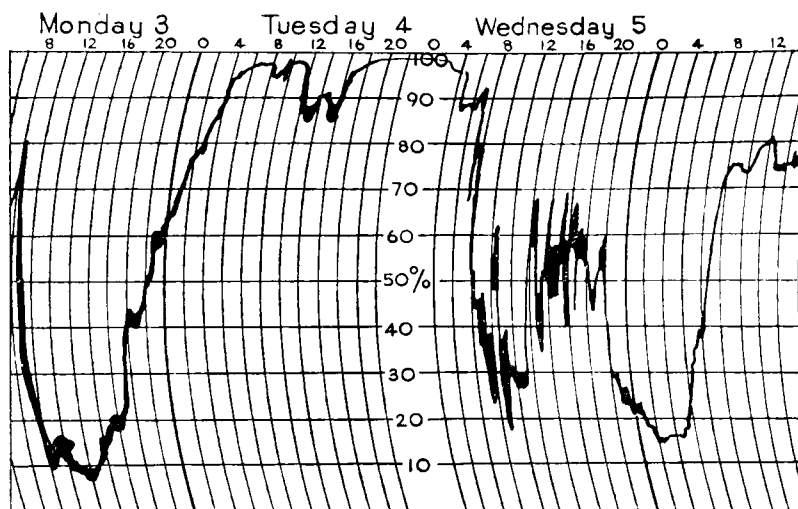


FIGURE 1—HYGROGRAM FOR MOSS-SIDE, STRACHAN, FOR 3-5 DECEMBER 1962

Tarfside (Angus), which lies in Glen Esk about 18 miles across the hills, as the crow flies, from Moss-side. Here there are no autographic instruments, but at 0900 GMT the dry-bulb thermometer reading was 46.5°F and the wet bulb 33.5°F, giving a relative humidity of 7 per cent and a dew-point of -16°F, one degree lower than at Moss-side; it may well have fallen even lower after 0900.

Some low humidities, and consequently low dew-points, also occurred during this period at the following stations (all heights above M.S.L.): Dinnet (580 ft), Dyce (190 ft), Craibstone (300 ft), Aberdeen (Mannofield) (171 ft) and Balmoral (927 ft) all in Aberdeenshire; Fettercairn (Glensaugh) (560 ft) in Kincardineshire; Achnagoichan (1000 ft) and Glenmore Lodge (1120 ft) in Inverness-shire. Although there were no records of relative humidities below 40 per cent or dew-points below 20°F at any of these stations at 0900 GMT, such low figures were surpassed, at other times, at Dyce, as shown by the following data from the Dyce instrumental records:

3 December at 1800 GMT—temperature 45.3°F, dew-point 17.6°F, giving a relative humidity of about 32 per cent.

6 December at 0600 GMT—temperature 41.5°F, dew-point 8.6°F, giving a relative humidity of about 27 per cent.

Autographic records corrected as carefully as possible by reference to fixed-time instrumental observations, give approximate periods with relative humidity below 40 per cent as shown in Table I.

TABLE I—PERIODS OF RELATIVE HUMIDITY BELOW 40 PER CENT IN EARLY DECEMBER 1962

Station	Periods of relative humidity below 40 per cent			
	3 December GMT	5 December GMT	5-6 December GMT	6 December GMT
Moss-side	0900-2000	0900-1300 1500-1600	2200-0800	
Glenmore Lodge	1200-1300 1600-1700	0900-2100	2300-0600	
Achnagoichan	0800-1700	1300-2100		
Dyce	1100-1600 1700-1800			0600-0700

The chief feature of the synoptic situation on 3 December was an anticyclone over central Europe, and the cold air coming over eastern Scotland had had a trajectory mainly over land. It had warmed slightly over the southern part of Britain, and subsidence may have occurred further north. It appears that the low humidities were not entirely confined to north-east Scotland, for, although no very low humidities were noted elsewhere in Scotland, they occurred sporadically in England and in Wales. It was noticed that the 0900 GMT observations at the Nature Conservancy's Moor House Field Station (1830 ft) in Westmorland were:

3 December—temperature 43°F, dew-point -5°F, relative humidity 9 per cent.

5 December—temperature 40.5°F, dew-point 3°F, relative humidity 21 per cent.

A mercury-in-steel thermograph (dry-bulb and wet-bulb) was in operation at Moor House at this time. Readings, corrected from the autographic traces between 1100 and 1130 GMT on 3 December according to careful comparison checks, were: dry-bulb 48°F, wet-bulb 35°F so that the dew-point was -3°F and the relative humidity was 10 per cent.

Strangely, also, another Conservancy Station, Swyddffynnon (540 ft) in Cardiganshire had at 0900 GMT on 5 December, a temperature of 44°F, a dew-point of 13°F and relative humidity of 26 per cent. Mr. E. H. I. Rogers of the Meteorological Office Headquarters, Bracknell, looked up the records for 0900 GMT from other high-level stations south of the Border. Among Spadeadam (900 ft), Malham Tarn (1297 ft), Onecote (1350 ft), Alwen (1100 ft), Bwlchgwyn (1267 ft) and Tredegar (1028 ft), only two stations recorded relative humidities below 40 per cent and these were Spadeadam on the 3rd and 5th and Malham Tarn on the 5th. From the observations published in the *Daily Weather Reports* it was noticed that some fairly low humidities occurred at a number of widespread places, but only the following showed relative humidities of less than 40 per cent, and only at the times stated: Aberporth at 0000 and 1800 GMT on 5 December and Manchester at 1200 GMT on the 5th.

On 4 December the influence of a front, parallel to the isobars, lying to the west, was felt at all the stations investigated, and it became cloudy. On 5 December conditions reverted to a situation similar to two days before; the return of the dry air at Strachan would seem to have been very unsteady, for the thermograph and hygrograph traces on 5 December show remarkable fluctuations; it was indeed blowing hot and cold. Later that day air seems to have been arriving from further west, as it became milder and more humid, and the remarkably dry air did not return again.

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# WEATHER NOTE: A NOVEMBER RAIN ON THE GREENLAND INLAND ICE

By J. M. HAVENS, M.Sc.

U.S. Army Natick Laboratories

In the course of a field investigation undertaken by the U.S. Army Natick Laboratories, Massachusetts, U.S.A., for the purpose of relating meteorological parameters to snow surface conditions at DYE 2 (66°29'N, 46°22'W), a DEW-line station, an unusual occurrence of rain was experienced on 1 November 1963 at an elevation of 2330 metres (7650 feet) above M.S.L. on the the southern part of the Greenland inland ice.

**Weather observations.**—The surface weather observations at the station are taken on a routine synoptic schedule by Federal Electric Corporation employees on the station's 'weather deck', about 22 metres (71 feet) above the snow surface. During the period of special three-hourly observations by the U.S. Army an instrument screen was set up at standard height over the surface. The temperatures recorded at these two heights showed marked differences, sometimes as great as 10°–15°C, during inversion conditions that developed

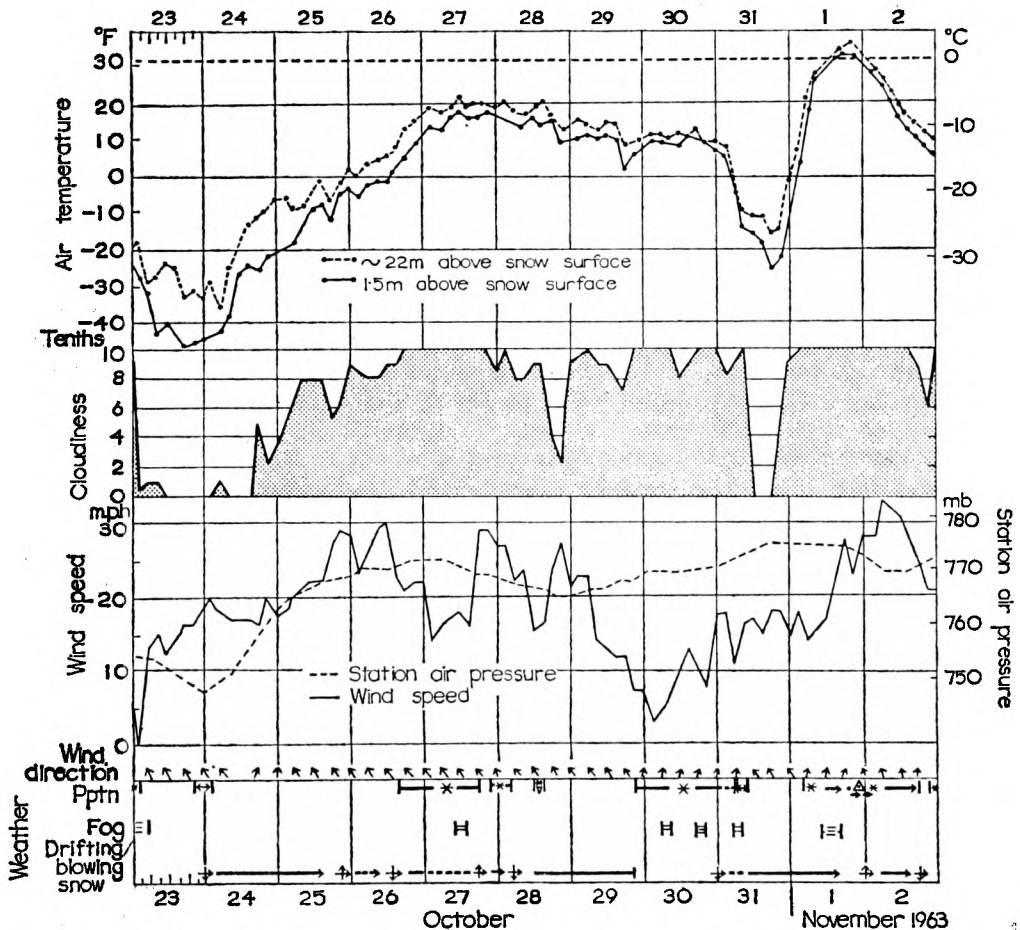


FIGURE 1—COURSE OF THE WEATHER AT DYE 2, GREENLAND, FROM 23 OCTOBER TO 2 NOVEMBER 1963

under clear skies and light or gentle winds. A Bendix-Friez aerovane, sited about 6 metres (20 feet) above the surface, indicated wind speed and direction on dials located in the station building.

Figure 1 describes the three-hourly weather observations at DYE 2 for the period 23 October through 2 November 1963. As cloudiness and windspeeds increased and snowfall began on 1 November the temperature in the surface screen rose by  $32.8^{\circ}\text{C}$  ( $59^{\circ}\text{F}$ ) in a 24-hour period to a maximum of  $+0.6^{\circ}\text{C}$  ( $33^{\circ}\text{F}$ ). This cyclonic activity was associated with an occluded low near Frobisher Bay, Baffin Island, (Figure 2(a)) and strong warm air advection aloft. Twenty-four-hourly positions of the low show its approximate trajectory from 29 October when an advancing cold front became incorporated into hurricane GINNY then located off the east coast of the United States, changing the hurricane into an extratropical disturbance. The synoptic situations in Figure 2 have been copied from operational fascimile charts prepared by the National Meteorological Analysis Center, Washington, D.C., with the exception that the  $0^{\circ}\text{C}$  isotherm on the 700 mb chart has been redrawn, in view of the surface observations at DYE 2, to include a larger area of southern Greenland, Figure 2(b).

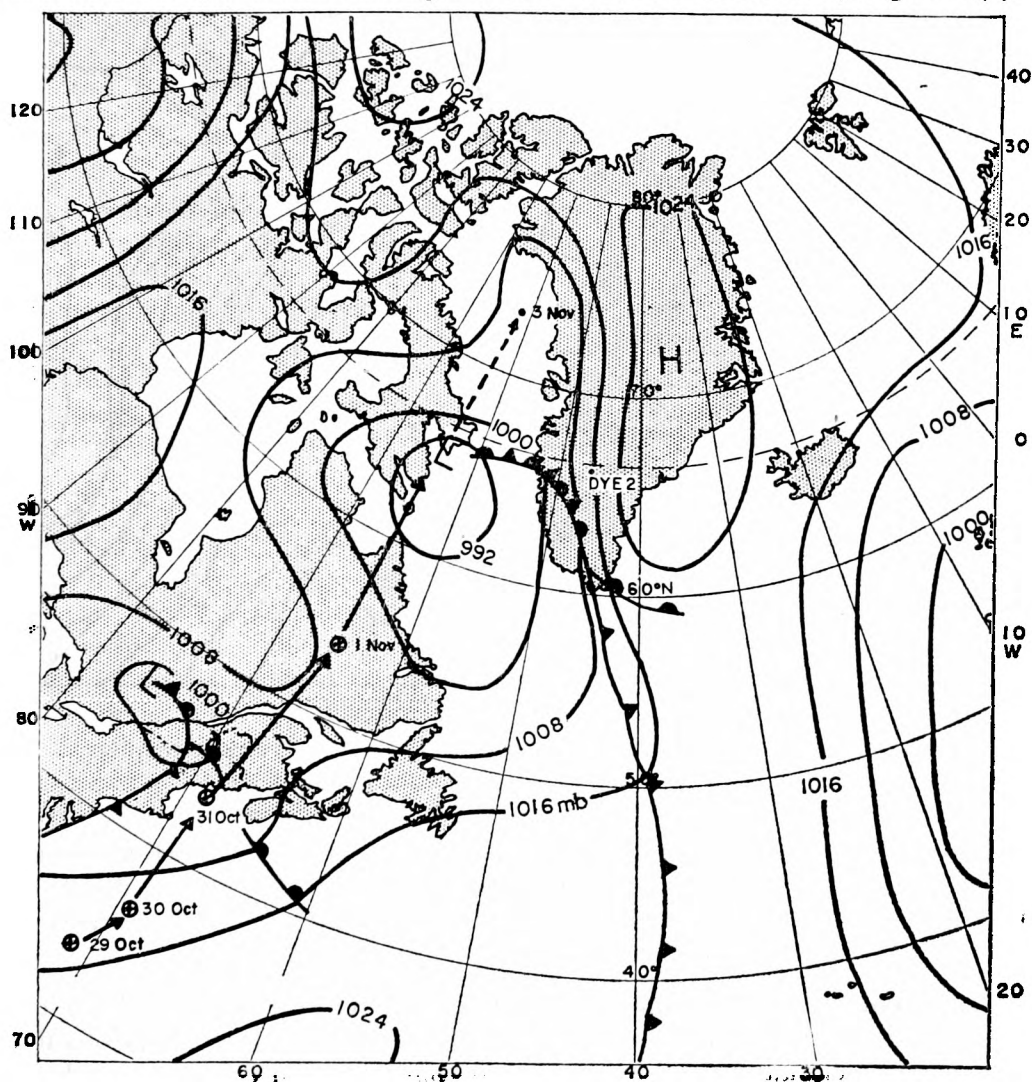


FIGURE 2(a)—SURFACE CHART FOR 0000 GMT, 2 NOVEMBER 1963  
Arrows show the track of the depression and crosses the 24-hour positions.



Figure 1 also includes the precipitation sequence during the evening hours of 1 November: snow to rain to sleet, and then back to snow. Although the rain, which was light in intensity, did not freeze onto the station building, it may have frozen onto the snow surface, at least for a time. The rain, and associated melting, resulted in an ice crust about 1 cm thick that probably can be identified in snow pits in future years.

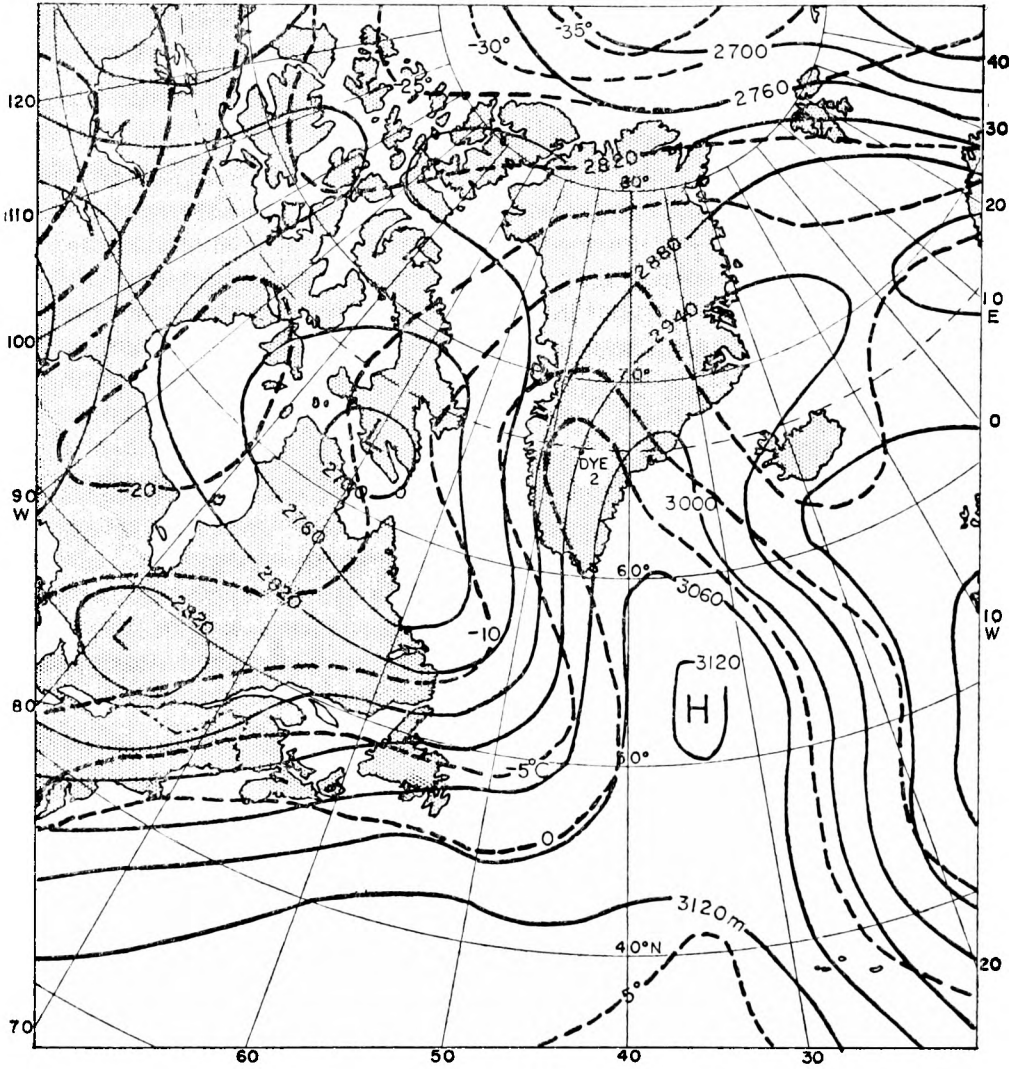


FIGURE 2(b)—700 MB CHART FOR 0000 GMT, 2 NOVEMBER 1963  
—— Contours                      - - - Isotherms

**Sub-surface snow temperatures.**—The warm weather at DYE 2 strongly affected the temperature régime in the first metre of snow. Figure 3 illustrates the sub-surface temperature changes that occurred during two 5-day periods that include the period of marked air temperature variations.

**Comment.**—This November rainfall on the Greenland inland ice undoubtedly represents an extreme meteorological condition. It would be of value to learn of its climatological expectancy, perhaps through the correspondence column of this magazine.



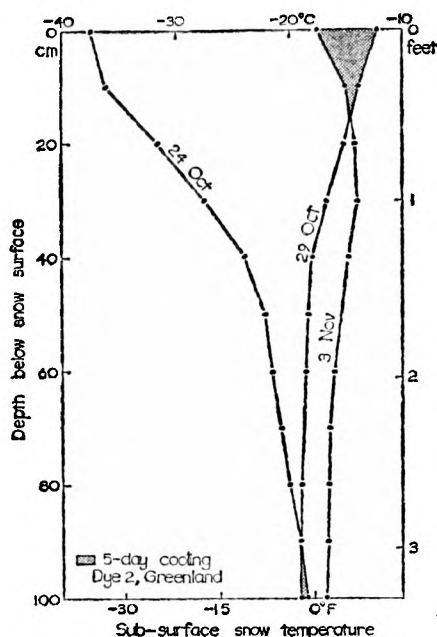


FIGURE 3—SUB-SURFACE SNOW TEMPERATURES AT DYE 2, GREENLAND, ON 23 AND 24 OCTOBER AND 3 NOVEMBER 1963  
Shaded areas show the 5-day cooling at Dye 2.

**Acknowledgements.**—I greatly appreciate the helpfulness and hospitality extended to me by the American and Danish personnel at DYE 2. Sgt. L. E. Holden, U.S. Army, assisted with the weather observations at the station. Suggestions and comments for this note were made by Mr. Donald W. Hogue who also spent several weeks at DYE 2 during 1963. The figures were prepared by Miss Gertrude B. Barry.

**Editor's note.**—It is of some interest that at 0000 GMT on 2 November 1963, the total thickness (1000–500 mb) in this Greenland area reached the maximum recorded in the 1949–53 period.

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## DRY SPELLS OF THREE DAYS OR MORE AT LONDON FROM NOVEMBER TO APRIL

By C. A. S. LOWNDES

**Introduction.**—This work provides a statistical background to the problem of forecasting dry spells at London in the winter months. A dry spell was defined as a period of three or more consecutive days at Kew with no precipitation other than a trace of dew. Tabulations of the total daily rainfall from midnight to midnight GMT at Kew Observatory were used to extract the dates of the beginning and end of periods when not more than a trace was recorded. The weather records for Kew in the *Daily Weather Report*\* were then examined and any day during these periods with precipitation other than dew recorded in the Beaufort letters was discarded and the dry-spell periods amended accordingly. The spells were extracted for the periods 1931 to 1939 and 1943 to 1958, a total of 25 years. The spells for each month were listed separately. Where a spell extended from one month to another, it was included in the month which contained the greater part of it.

\*London, Meteorological Office. *Daily Weather Report*.

A similar report on dry spells at London during the summer half of the year has been published earlier,<sup>1</sup> the same definition of a dry spell being used. Where possible, the statistics relating to the summer months are included in this paper for comparison.

**The frequency of dry spells of three days or more.**—There were 190 spells during the whole period, giving an average of 1.3 spells per month. For the 6 summer months the average was 1.6 spells per month.

Table I shows the average number of spells for each individual month, ranging from 1.0 in December, January and February to 1.9 in March.

TABLE I—AVERAGE NUMBER OF SPELLS FOR EACH MONTH

Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
1.1	1.0	1.0	1.0	1.9	1.6	1.9	1.6	1.8	1.8	1.3	1.4

Each of the 6 months, however, was without dry spells in a number of years. Table II shows the number of months with no dry spells ranging from 2 for March and April to 11 for December. Roughly one in two Decembers, one in three Februarys and one in four Januarys and Novembers had no dry spell of 3 days or more.

TABLE II—NUMBER OF MONTHS WITH NO DRY SPELLS (IN 25 YEARS)

Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
7	11	7	8	2	2	3	3	3	2	7	5

Considering all months of the year, the number of months with no dry spell in individual years ranged from 1 in 1933, 1943, 1947, 1948 and 1955 to 5 in 1946. There were 3 consecutive months with no dry spell on only two occasions, November, December, January 1938 to 1939 and October, November, December, 1939. About half of the 25 years had 2 consecutive months with no dry spell. Only one year had two such periods, February–March and September–October 1954. Most of the periods occurred in the winter half of the year and none were associated with the months March–April, July–August and August–September. Apart from this, the periods were distributed in a random manner throughout the years. However, there were no such periods in the four consecutive years 1947 to 1950.

If we consider the number of months with no dry spell of 4 days or more we obtain Table III. About half the Novembers, Decembers and Januarys had no dry spell of 4 days or more.

TABLE III—NUMBER OF MONTHS WITH NO DRY SPELLS OF 4 DAYS OR MORE (IN 25 YEARS)

Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
14	15	13	10	5	4	3	3	5	5	10	10

The frequency of each length of spell is shown in Figure 1. Of the spells 33 per cent were of 3 days and 17 per cent of 4 days, so that half the spells were of 3 or 4 days duration. Spells of 3 to 7 days made up 83 per cent of the total. Of the remainder 14 per cent were of 8 to 11 days and 3 per cent were 12 days or more in length; the longest spell lasted 18 days. In the summer months there were 5 per cent less spells of 3 days and 5 per cent more of 4 days. Otherwise the percentages were almost the same. The longest spell in the summer months lasted 19 days.

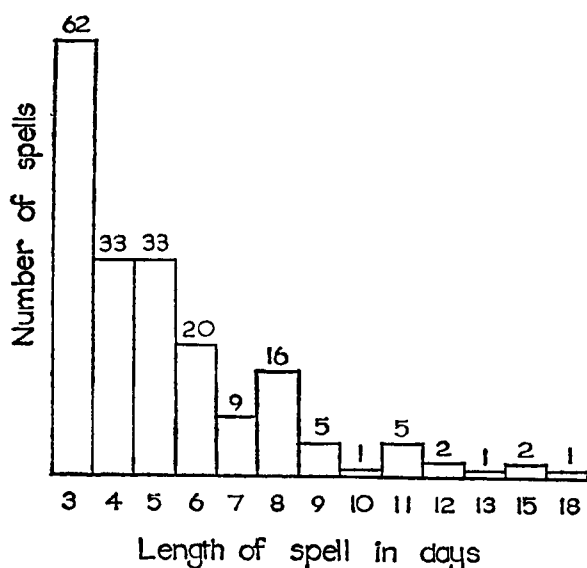


FIGURE 1—FREQUENCY OF EACH LENGTH OF SPELL, NOVEMBER TO APRIL  
Total number of spells = 190.

**The probability of a dry spell continuing.**—The frequency of each length of spell was plotted against the length of spell, a best fitting curve drawn through the points and the frequency corresponding to each length of spell read off from the curve. Table IV shows the probability values calculated from the frequencies obtained in this way. The probability of a dry day after spells of from 3 to 12 days is roughly constant at about 0.7 for both the winter and the summer months, although the values are mainly slightly lower for the winter period.

TABLE IV—THE PROBABILITY OF A DRY DAY AFTER DIFFERENT NUMBERS OF SUCCESSIVE DRY DAYS

	Length of dry spell in days									
	3	4	5	6	7	8	9	10	11	12
November to April	0.67	0.69	0.69	0.67	0.66	0.65	0.65	0.65	0.68	0.70
May to October	0.72	0.69	0.68	0.69	0.72	0.73	0.73	0.73	0.75	0.75

**The synoptic types associated with dry spells at London.**—A short description of the synoptic type in the region of the British Isles was written for each spell. On nearly all occasions this involved a description of the position, movement or formation of the anticyclone or ridge with which the dry spell was associated. The types were then classified according to the region from which the high or ridge moved towards the British Isles or in which the high was situated, often with a ridge extending to the British Isles. The regions are shown in Figure 2. For example, highs moving from the south-west or ridges extending from highs situated to the south-west were classed as Type V; highs as Type VH and ridges as Type VR. A type which began with a ridge extending from the south-west from which a high then developed or broke away was classed as Type VRH. There were only two occasions when a dry spell was not associated with a high-pressure system and these were classed as Type

IX. On these occasions a shallow depression extended over the Continent and the British Isles. Both were very localized dry spells and rain occurred in parts of south-east England.

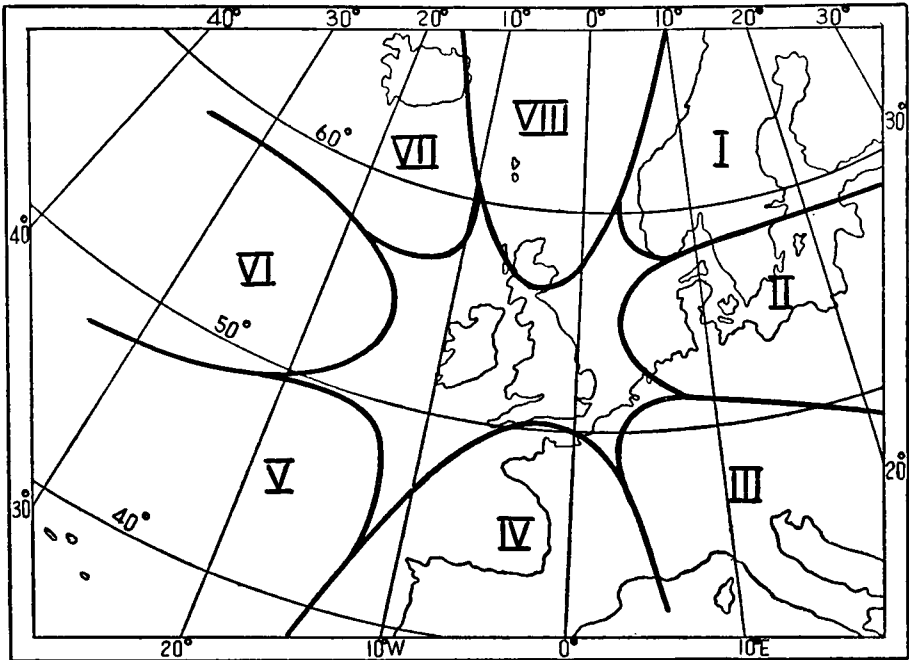


FIGURE 2—THE REGIONS USED IN THE CLASSIFICATION OF SYNOPTIC TYPES

The types were sub-classified by a suffix figure according to the track taken by the high or the orientation of the ridge with respect to the British Isles. Exactly the same classification was used as for the summer months, with additions as necessary. The complete classification is shown in Table V together with the number of spells associated with each type. For the purpose of this Table, if a spell was made up of more than one type, it was grouped under the type which predominated.

TABLE V—CLASSIFICATION OF SYNOPTIC TYPES (NOVEMBER TO APRIL)

Total number of spells = 190			
Synoptic type	Class	Number of spells	
Ridge from Scandinavia extended over British Isles . . . . .	IR <sub>1</sub>	2	
High over Scandinavia . . . . .	IH	8	16
High moved from Scandinavia—over British Isles to Continent . . . . .	IH <sub>1</sub>	2	
—east of British Isles to Continent . . . . .	IH <sub>2</sub>	6	
Ridge from east extended—over British Isles . . . . .	IIR <sub>1</sub>	5	8
—over southern British Isles . . . . .	IIR <sub>2</sub>	2	
—to south of British Isles . . . . .	IIR <sub>3</sub>	1	
Ridge from east extended over British Isles, then high formed over British Isles and persisted . . . . .	IIRH <sub>1</sub>	2	3
Ridge from east extended to south of British Isles, then high formed to south of British Isles and persisted . . . . .	IIRH <sub>2</sub>	1	
High to east of British Isles . . . . .	IIH	10	11
High moved from east to British Isles . . . . .	IIH <sub>1</sub>	1	
High over Continent . . . . .	IIIH	13	

TABLE V—CLASSIFICATION OF SYNOPTIC TYPES (NOVEMBER TO APRIL) *contd*

High to south of British Isles .. .. .	IVH	6	18
High moved from south to Norwegian Sea—across British Isles .. .. .	IVH <sub>1</sub>	—	
—east of British Isles .. .. .	IVH <sub>2</sub>	1	
High moved from region of Spain, south of British Isles, to eastern Europe .. .. .	IVH <sub>3</sub>	9	
High moved from south across British Isles to Continent .. .. .	IVH <sub>4</sub>	2	
Ridge from SW extended—to west of British Isles .. .. .	VR <sub>1</sub>	—	7
—over British Isles .. .. .	VR <sub>2</sub>	2	
—over southern British Isles .. .. .	VR <sub>3</sub>	2	
—to south of British Isles .. .. .	VR <sub>4</sub>	3	
Ridge from SW extended over British Isles, then high formed over British Isles and moved to—Norwegian Sea .. .. .	VRH <sub>1</sub>	—	9
—Scandinavia .. .. .	VRH <sub>2</sub>	2	
—North Sea .. .. .	VRH <sub>3</sub>	—	
—Continent .. .. .	VRH <sub>4</sub>	3	
—west .. .. .	VRH <sub>5</sub>	—	
Ridge from SW extended to south of British Isles, then high formed to south or SE of British Isles and persisted or moved east .. .. .	VRH <sub>6</sub>	4	
High to SW .. .. .	VH	3	39
High moved from SW—to a position west or NW of British Isles .. .. .	VH <sub>1</sub>	1	
—west of British Isles to Norwegian Sea .. .. .	VH <sub>2</sub>	—	
High moved from SW over British Isles—to Norwegian Sea .. .. .	VH <sub>3</sub>	—	
—to Scandinavia .. .. .	VH <sub>4</sub>	1	
—to North Sea .. .. .	VH <sub>5</sub>	3	
—to Continent .. .. .	VH <sub>6</sub>	13	
—then to west .. .. .	VH <sub>7</sub>	3	
High moved from SW, south of British Isles, to Continent .. .. .	VH <sub>8</sub>	15	
Mobile ridge moved from west across British Isles .. .. .	VIR <sub>1</sub>	—	7
Blocking ridge, or col, associated with high to south, moved from west across British Isles .. .. .	VIR <sub>2</sub>	3	
Ridge from west extended over British Isles .. .. .	VIR <sub>3</sub>	4	
High to west of British Isles .. .. .	VIH	3	21
High moved from west, north of British Isles or over N. Scotland —to Norwegian Sea .. .. .	VIH <sub>1</sub>	—	
—to Scandinavia .. .. .	VIH <sub>2</sub>	—	
High moved from west over British Isles—to Scandinavia .. .. .	VIH <sub>3</sub>	—	
—to North Sea .. .. .	VIH <sub>4</sub>	—	
—to Continent .. .. .	VIH <sub>5</sub>	10	
—to SW approaches .. .. .	VIH <sub>6</sub>	2	
—then to west .. .. .	VIH <sub>7</sub>	3	
High moved from west, south of British Isles, to Continent .. .. .	VIH <sub>8</sub>	3	
Ridge from NW extended over British Isles .. .. .	VIIR	—	2
High to NW .. .. .	VIIH	2	17
High moved from NW—west of British Isles to SW approaches .. .. .	VIIH <sub>1</sub>	1	
—west of British Isles to Continent .. .. .	VIIH <sub>2</sub>	—	
—to British Isles .. .. .	VIIH <sub>3</sub>	4	
—across British Isles to Continent .. .. .	VIIH <sub>4</sub>	6	
—across British Isles to SW .. .. .	VIIH <sub>5</sub>	1	
—east of British Isles to Continent .. .. .	VIIH <sub>6</sub>	3	
Ridge from north extended—over British Isles .. .. .	VIIIR <sub>1</sub>	1	2
—east of British Isles .. .. .	VIIIR <sub>2</sub>	1	
High to north of British Isles or over Scotland (low to south of British Isles) .. .. .	VIIHH	3	13
High moved from Norwegian Sea—east of British Isles to Continent .. .. .	VIIHH <sub>1</sub>	5	
—to east of British Isles .. .. .	VIIHH <sub>2</sub>	2	
—across British Isles to Continent .. .. .	VIIHH <sub>3</sub>	1	
—to west of British Isles .. .. .	VIIHH <sub>4</sub>	2	
Shallow depression over Continent and British Isles .. .. .	IX	—	2

The highest proportion of spells (29 per cent) was associated with high pressure to the south-west of the British Isles (Type V). Of these, about half were associated with highs which moved from the south-west across the British Isles to the Continent or south of the British Isles to the Continent. Some 15 per cent of the spells were associated with high pressure to the west of the British Isles (Type VI). Of these, nearly half were associated with highs which moved from the west across the British Isles to the Continent or south of the British Isles to the Continent. Of the remaining spells, about 10 per cent were associated with high pressure to the north-east (Type I), to the east (Type II), to the south-east (Type III), to the south (Type IV), to the north-west (Type VII) and to the north (Type VIII).

Table VI shows the percentage of spells which were associated with each class of synoptic type together with the corresponding percentages for the summer months. The proportion of spells associated with Type V was only about half that for the summer months. For all the remaining types (excluding Type IX) the proportion was above that for the summer months and for all except Types VI and VIII about two to three times higher.

TABLE VI—THE PERCENTAGE OF SPELLS ASSOCIATED WITH EACH CLASS OF SYNOPTIC TYPE

	I(NE)	II(E)	III(SE)	IV(S)	V(SW)	VI(W)	VII(NW)	VIII(N)	IX
	<i>percentage number of spells</i>								
November to April	9	12	7	9	29	15	10	8	1
May to October	5	5	2	3	62	11	5	6	1

Table VII shows the number of spells in each month which were associated with each class of synoptic type, expressed as a percentage of the total number of spells in each month. The percentage of Type V varies between 16 per cent in February and 50 per cent in April, but there is no evidence of a systematic variation from month to month as is apparent in the period May to October when the percentage rises to a maximum of about 80 per cent in July and August. The only suggestion of systematic variation occurs with Type IV which reaches a maximum of 16 per cent in January and February.

TABLE VII—THE PERCENTAGE OF SPELLS IN EACH MONTH ASSOCIATED WITH EACH CLASS OF SYNOPTIC TYPE

Synoptic type	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
	<i>percentage number of spells</i>											
I(NE)	4	17	8	4	21	0	4	5	2	2	3	14
II(E)	25	8	16	12	10	2	4	0	2	2	9	14
III(SE)	7	13	4	8	6	5	0	8	2	0	0	5
IV(S)	7	8	16	16	8	5	9	0	2	0	3	3
V(SW)	18	25	40	16	21	50	55	64	80	78	50	39
VI(W)	28	8	8	16	15	13	9	10	10	11	16	11
VII(NW)	7	4	0	20	15	10	9	5	0	2	6	11
VIII(N)	4	17	4	8	4	13	10	8	0	5	13	3
IX	0	0	4	0	0	2	0	0	2	0	0	0
	<i>total number of spells</i>											
	28	24	25	25	48	40	47	39	45	45	32	36

**The make-up of the longer spells.**—As in the summer months the highest proportion (26 per cent) of spells of 7 days or more was predominantly associated with Type V but in the summer months the proportion was 66 per cent. However, over half of the spells of 7 days or more which were associated with Type V in the winter months occurred in April. For the other 5 winter

months November to March, the highest proportion of the spells (19 per cent) was associated with Type II and a further 16 per cent with Types I, V and VI.

**Conclusions.**—As in the summer months, the highest proportion of the dry spells of 3 days or more at London was associated with high pressure to the south-west of the British Isles (Type V) but the proportion of 29 per cent was only about half that for the summer months. The second highest proportion of the spells, as in the summer months, was associated with high pressure to the west (Type VI) and the proportion of 15 per cent was similar to that for the summer months. However, for the 5 months November to March, the highest proportion of the spells of 7 days or more was associated with high pressure to the east (Type II) and the second highest proportion with high pressure to the north-east (Type I), to the south-west (Type V) and to the west (Type VI).

For the summer months, rules for forecasting dry spells associated with a spread of high pressure from the south-west or west of the British Isles (Types V and VI) have been obtained.<sup>2</sup> About half the dry spells which actually occur are forecast. In order to forecast a similar proportion of the dry spells which occur in the winter months it will be also necessary to forecast dry spells associated with a spread of high pressure from other directions, for the longer spells in particular from the north-east or east (Types I and II). A further paper will be published shortly giving rules for forecasting dry spells in the winter months.

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1. LOWNDES, C. A. S.; Dry spells of three days or more at London from May to October. *Met. Mag., London*, **89**, 1960, p. 105.
2. LOWNDES, C. A. S.; The forecasting of dry spells of three days or more at London and in south-east England in May to October. *Met. Mag., London*, **89**, 1960, p. 131.

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## RESEARCH IN AIRCRAFT: TWENTY-ONE YEARS OF THE METEOROLOGICAL RESEARCH FLIGHT

By R. F. ZOBEL, O.B.E.

**Introduction.**—The Meteorological Research Flight (MRF) was formed at Farnborough in August 1946. This however was in the nature of a change of name and location, rather than the original creation. The true beginning of the Flight may be regarded as having occurred at Boscombe Down in the second half of 1942. It was then that special facilities were made available for meteorological investigations to be carried out by aircraft of the High Altitude Flight and a meteorologist was posted in to take charge of the investigations. Thus the Meteorological Research Flight had its beginnings a little over 21 years ago. It is therefore 'of age' and this may be an appropriate moment briefly to review its history and achievements, to compare them with earlier work and to take a glimpse into the future.

**Early aerological work using aircraft at Farnborough.**—The early investigators of the atmosphere, naturally enough, used the tools at their disposal, i.e. kites and balloons. This was pioneering work and was done largely by the inspiration, enthusiasm and endeavour of individuals. The days of institutional, organized research had not yet arrived and the rate of progress was slow.

The invention of the aeroplane in the early years of the century had led to the Royal Balloon Factory at Farnborough becoming the Royal Aircraft Establishment (RAE) and this further led, after rather protracted negotiations,

to the opening at Farnborough of the first Branch Office of the Meteorological Office, or outstation as we would now call it, in 1913. It is appropriate therefore to note in passing the jubilee of the first aviation outstation—the office at Farnborough. British aviation has had its home at Farnborough from the days of ballooning in the 1870's, so it was but natural that the meteorological demands of aviation should first arise there. In meeting them it is clear that the Director of the Office (Dr. W. N. Shaw, as he then was) also had well in mind the dividends that might accrue to the science of meteorology by the use of aircraft to carry meteorological instruments aloft.

A memorandum concerning the use of aircraft written by him in 1913 included the following items:

- (a) the relative vertical motion of the air and the machine;
- (b) the absolute vertical motion of the machine;
- (c) the construction of a light vane to show deflections of the relative wind from the horizontal, recording on an open time-scale chart with a gyroscope or other steadying device to show changes of inclination of the aeroplane;
- (d) a method of indicating 'bumps' by vertical accelerometer or other means;
- (e) temperature and other meteorological elements including electrical elements.

These concepts have a distinctly modern note, but progress has been made, as will appear later. However, little immediate headway was made with this programme. The outbreak of World War I may have been the cause of little or no attempt being made, the demands of gas warfare and gunnery receiving higher priority. Prior to 1920, the only aerological work undertaken at Farnborough appears to have been an attempt in 1916 to relate visual range from an aircraft to horizontal visibility. That problem is still unsolved.

Early in 1921 however the meteorologist-in-charge (later to become famous for his discoveries in radar—Sir Robert Watson-Watt) wrote: "Full weight should be given to the fact that the association.....with the Royal Aircraft Establishment would, if fully utilized, provide an invaluable aid to meteorological research." Just prior to this an aeroplane psychrometer had been fitted to a DH9 machine and some observations were obtained up to a height corresponding to 550 mb. The tempo was now beginning to increase, but a great deal of effort was spent on a rather curious attempt during 1922 to release a balloon from an aircraft at 15,000 feet. The aim was to follow it some distance into the stratosphere by theodolites on the ground. It is not until this same year that reports of work indicate any investigations into 'bumps' being carried out. This was directed mainly to problems relating to the control of aircraft in polar air.

Somewhat sporadic measurements of accelerations were made during the mid-1920's, but the main effort was put into developing strut psychrometers of various kinds. Various types were used from time to time—the Marvin, the Jaumotte, the Barothermograph—and these were fitted to a variety of aircraft—DH9, Plover, Siskin, Bristol Fighter.

Plate I is a photograph taken about 1926 and depicts a considerably modified Bristol Fighter. The pipe under the upper mainplane was for the purpose of ducting air, undisturbed by propeller or engine exhaust, into the observer's cockpit where the temperature and humidity were measured. This method was



later tried out operationally by the Duxford 'Met. Flight' and found to be impracticable. Regular vertical ascents by that flight were commenced in 1927.

The establishment of the Duxford flight naturally meant that some at least of the experimental flying was arranged to be done on aircraft of that flight. Nevertheless a certain amount of activity continued at Farnborough. By the outbreak of World War II the main undertaking was the investigation of icing on aircraft.<sup>1</sup> The tempo, which had never been fast, was again very slow. At no time between the wars was there any staff specially assigned to research using aircraft. Perhaps not very surprisingly the results obtained were rather modest for a lapse of time of 20 years. One thing that is very evident is the co-operation and assistance of the RAE, just as it is today. What was lacking were men and resources. The Annual Report of the Director of the Meteorological Office for 1927-28 shows the state of affairs clearly. It states: "Owing to the large amount of routine work, the opportunities for doing original research are very limited, but in all departments of the Office more or less purely scientific work is undertaken. The greater part of this work, however, is done out of office hours by the staff purely from the interest they have in the work..... More original work would be undertaken if the staff of the Office were larger. At present there is no special provision for pure research, every post in the Office carrying with it a definite amount of fixed work."

It was this state of affairs which was brought to an end in 1942. One of the first steps in this direction was the commencement of organized research using aircraft at Boscombe Down.

**The Boscombe Down era.**—It is an ill wind that blows no good and World War II was no exception. Scientific and technological advancement occurred in many fields at a much greater rate than hitherto. War in the air demanded that meteorology should be one of those fields.

The urgency with which the Meteorological Research Committee, itself only formed in November 1941, viewed the necessity for aircraft to be specifically allocated to meteorological research, may be judged by the fact that by the following August the necessary arrangements had been made and Dr. Brewer was in post. At that time the High Altitude Flight had two Spitfire and one Boston aircraft, but additional aircraft were allocated and these later included Fortress, Mosquito and Hudson aircraft.

The original concept was that the Flight should have two main aims, firstly to develop instrumentation and techniques for the several meteorological reconnaissance flights which then existed and secondly, to conduct investigations into the physics of the atmosphere. Early effort was much concerned with the development of instruments to measure temperature and humidity using the faster aircraft then in service. The outcome was two instruments still in regular use; the flat-plate resistance thermometer and the Dobson-Brewer frost-point hygrometer. The latter was the first instrument capable of providing reliable values of humidity in the stratosphere. It was indeed so outstanding at the time that offers to lend hygrometers were made to the U.S.S.R., the U.S.A., Canada and Australia in 1945, but the first successful ascent was actually made in December 1943. The results are reproduced by Frith<sup>2</sup> in his account of the MRF in 1948.

The information in those days was not easily obtained. The Fortress aircraft in which the early stratospheric flights were made had a ceiling of 37,000 feet, but it was unpressurized and the cabin heating was far from adequate. There

was considerable difficulty in finding a crew, all of whom could withstand the physical strain of the climbs. The climb to ceiling took about an hour and observations were made on descent. It was not possible to observe on the ascent because by the time a high altitude was reached the crew became too cold and exhausted to persist in the climb to the ceiling.

**Work at Farnborough.**—The field of activity widened rapidly. By the time the MRF was formed under that title at Farnborough in 1946 the rather out-of-balance combination of two scientific officers and four aircraft (two Mosquito PR 34's and two Halifax Mk. VI's) were tackling a formidable list of problems. The following four were of high priority:

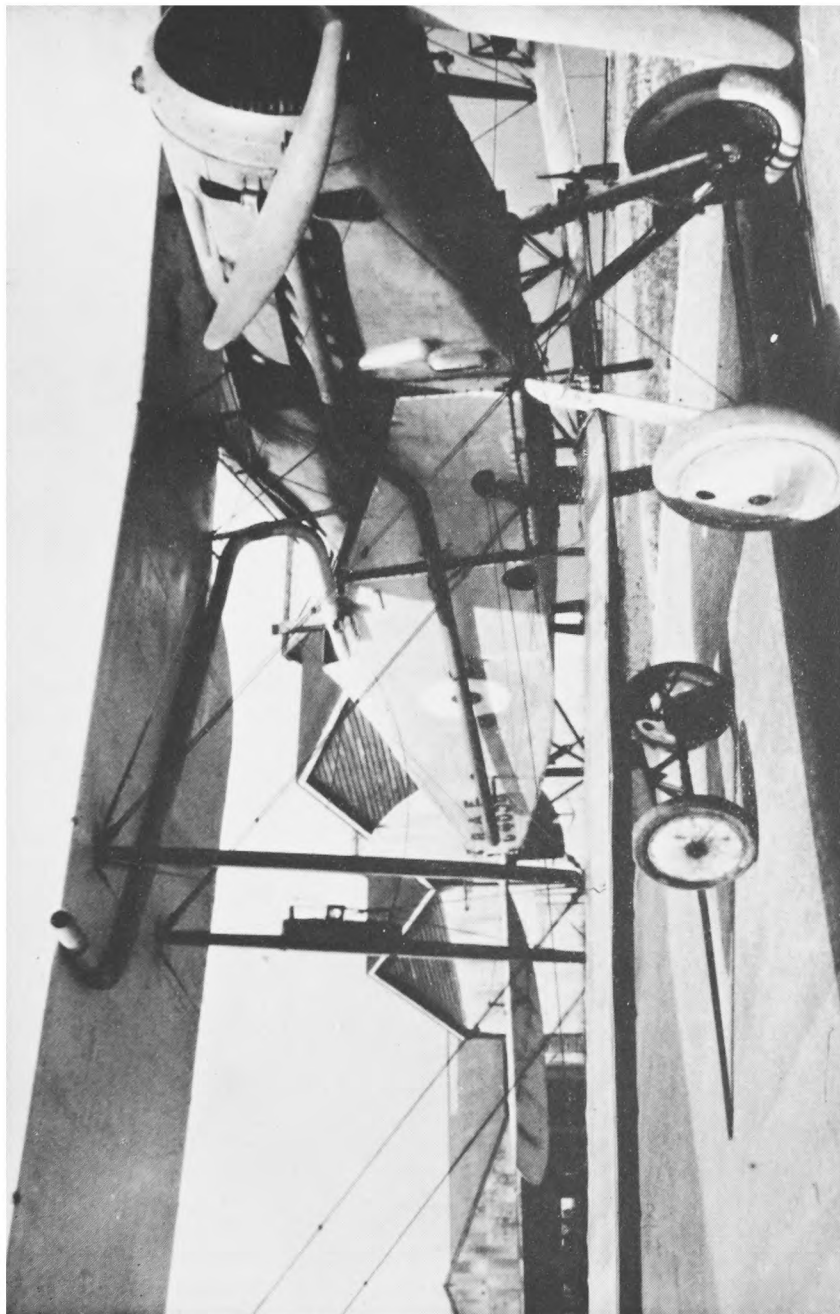
- (a) investigation of water content of the troposphere and lower stratosphere under various conditions;
- (b) observation and investigation of temperature, humidity and wind in the stratosphere in low and high latitudes;
- (c) exploration of rain-producing clouds;
- (d) investigation of size distribution of water particles in clouds.

The first of these problems had come into prominence earlier owing to the tell-tale appearance of condensation trails in the wake of high-flying bombing and reconnaissance aircraft. However it transpired later that atmospheric water vapour content was not the primary factor. MRF observations settled the matter beyond doubt.

As the years went by the list of problems became even longer. New ones were added, but old ones seldom removed. It is true of so many facets of nature that substantial progress to its understanding only serves to reveal further complexities demanding solution. This is perhaps outstandingly true of atomic physics, but it is true too of atmospheric physics. Progress has been made and MRF has made its contribution, often considerable, but some aspects, at least, of the problems enunciated by Sir Napier Shaw in 1913 are still not completely solved.

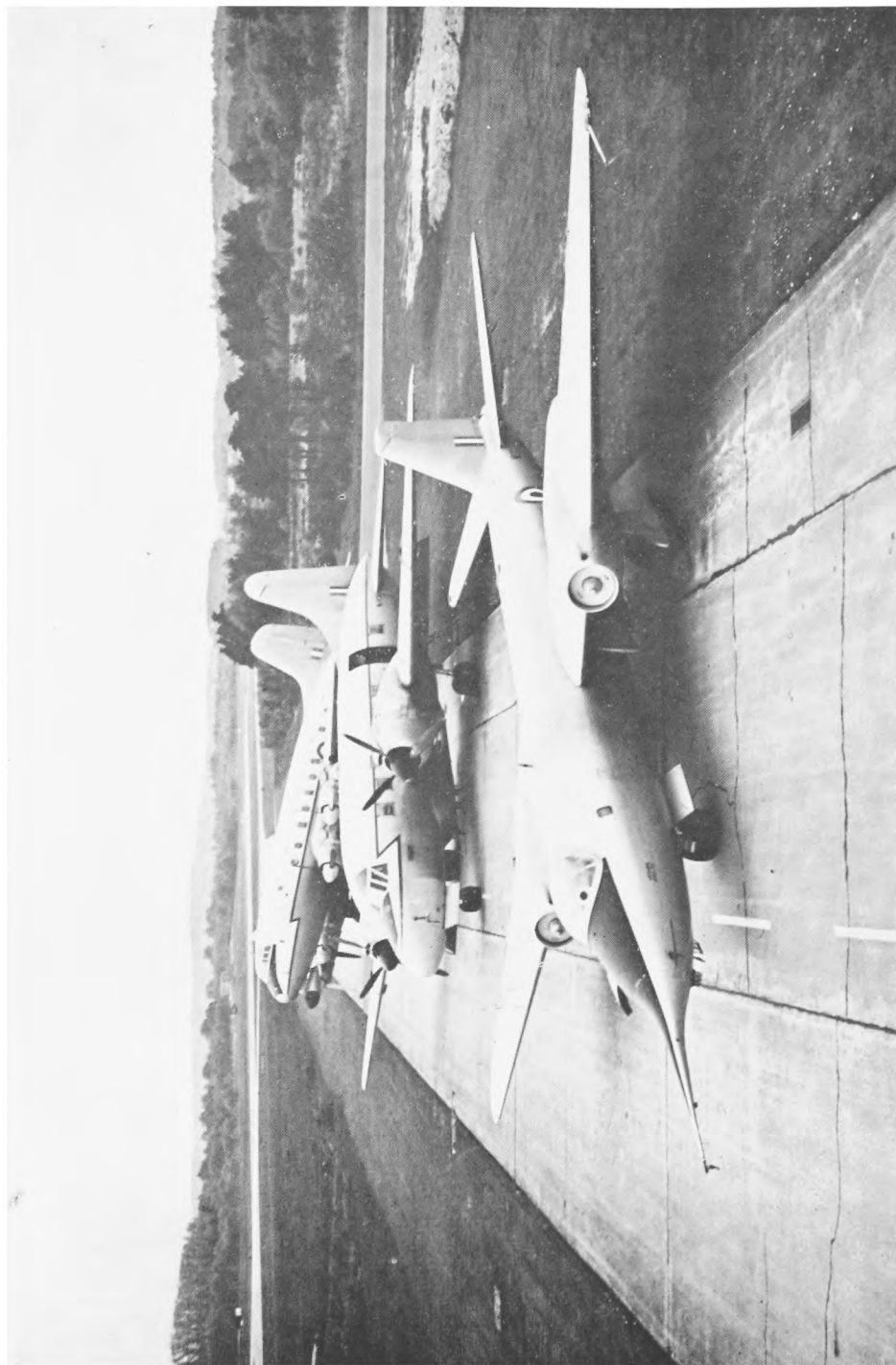
It would be quite impossible in this short article to review or even to quote the long list of scientific papers which has been published by MRF staff, neither is it its purpose. Nevertheless, it would be inappropriate not to mention an example of the work of Murgatroyd,<sup>3</sup> who played a leading part in the exploration of the stratosphere by aircraft and who was Head of the Flight for 12 years. The topics discussed by MRF writers are many: development of instruments, atmospheric temperature and humidity, cloud physics, condensation and sublimation nuclei, water content and drop sizes in cloud and precipitation, the structure of fronts, tracers of atmospheric circulations (ozone, water vapour, radio-activity), radiation and albedo, jet streams, and others. One of the few branches of meteorology in which there has been no participation is atmospheric electricity—strangely enough, the meteorological element singled out by Shaw in 1913, and in spite of the fact that the Varsity aircraft has twice been damaged by lightning.

**The current programme of research.**—So much for the past. What of the present? The Flight is now equipped with one Hastings, one Varsity and one Canberra aircraft. These are shown in Plate II. The Canberra has only just come into service as the replacement for a similar aircraft unfortunately lost in an accident. The loss caused a considerable break in stratospheric investigations. The instrumentation of the Hastings aircraft has recently been described by



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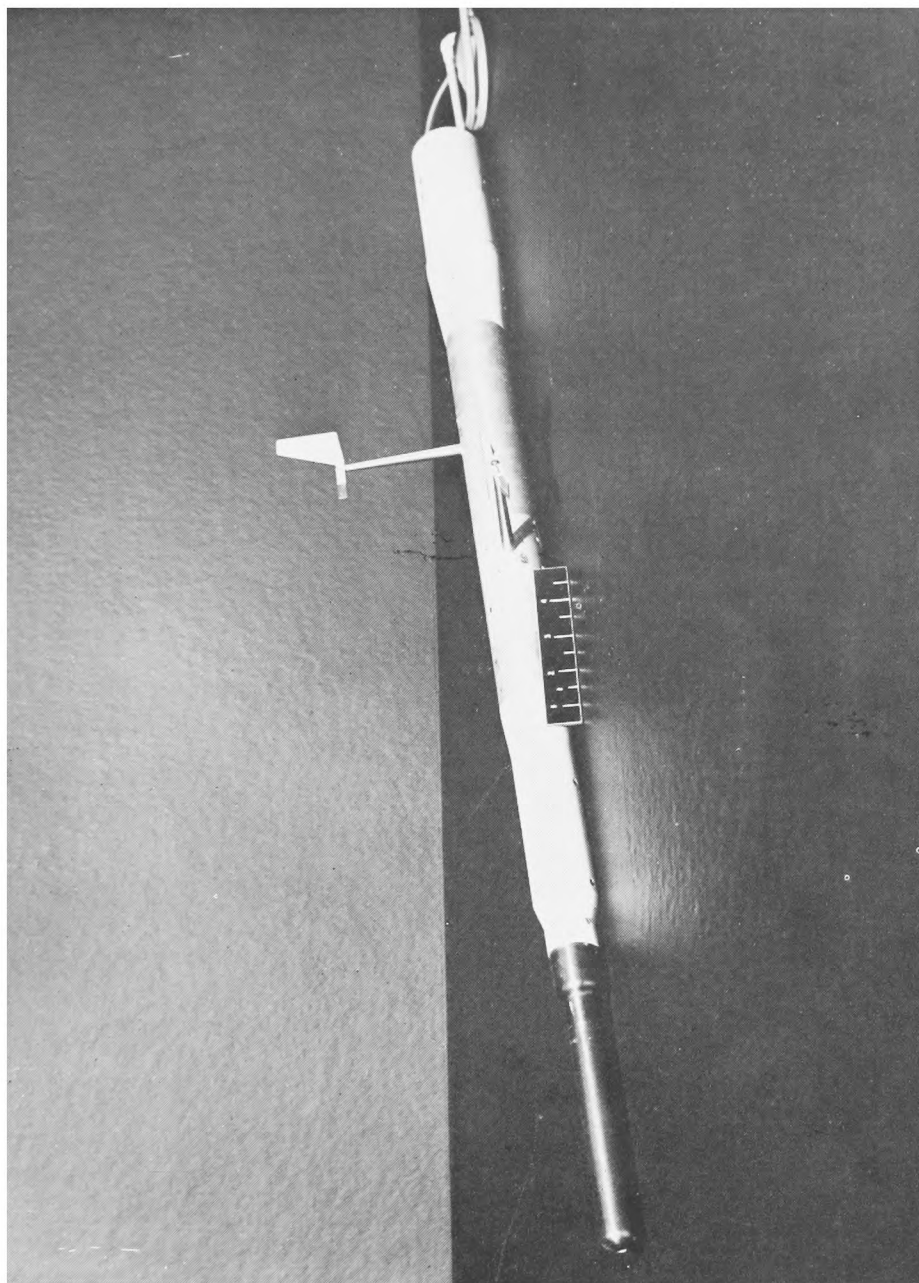
PLATE I—MODIFIED BRISTOL FIGHTER, ABOUT 1926, SHOWING AIR DUCT TO COCKPIT  
AND PSYCHROMETER WITH LENS CONTROL WIRES  
(See p. 238)



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PLATE II—HASTINGS (FARTHEST), VARSITY AND CANBERRA (NEAREST) AIRCRAFT  
OF THE METEOROLOGICAL RESEARCH FLIGHT

(See p. 240)



*Crown copyright*

PLATE III—CANBERRA NOSE PROBE INCORPORATING TWO PERPENDICULARLY  
MOUNTED WIND VANES AND PITOT TUBE. (SCALE SHOWS INCHES)

(See p. 241)



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PLATE IV—HUNT TROPHY  
Awarded to the British Ocean Weather Ships in 1964 (see page 254).

Grant.<sup>4</sup> The Varsity aircraft has rather similar, but less elaborate, instrumentation. It serves as an independent research vehicle for a number of purposes and also as a test-bed for new instruments and techniques.

The opportunity has been taken to equip the new Canberra aircraft with rather sophisticated instrumentation for the measurement of the vertical gust velocity of the air, a parameter of importance in studies, for example, of convection, jet streams and cloud dynamics.

It may be shown that the vertical gust component  $W_g$  acting on an aircraft is given by:

$$W_g = V_a (\alpha \cos r - \beta \sin r - \dot{\theta}) + W_a + l \frac{d\theta}{dt}, \quad \dots (1)$$

where  $\alpha$  and  $\beta$  are the angles of attack about the transverse and vertical axes respectively,  $\theta$  is pitch angle,  $r$  is roll angle,  $V_a$  and  $W_a$  are the forward and vertical speeds of the aircraft and  $l$  is a simple dimension of the installation. The angles of attack,  $\alpha$  and  $\beta$ , are measured by wind vanes mounted on a probe as shown in Plate III. The probe can also be seen mounted on the modified nose of the Canberra in Plate II. The angles  $\theta$  and  $r$  are measured with gyroscopes. Forward speed  $V_a$  is obtained in the usual manner, whilst  $W_a$  is obtained by electronic integration of the vertical accelerations of the aircraft which are given by a sensitive accelerometer mounted on a gyroscopically controlled platform. The derivative  $d\theta/dt$  is obtained directly from a further gyroscope.

At present the records consist of photographic traces produced by the deflections of galvanometers. At an airspeed of 150 metres per second a great deal of information requiring a great deal of processing (e.g. equation (1) above) may be accumulated in a very short time. For this reason it is hoped to develop, in the near future, a digital system for producing a record on magnetic tape compatible with a *Mercury*-type computer. This should very greatly accelerate the output of results, not only for air motion parameters, but for most or all of the 20 or so parameters normally recorded in the air. At the present time these measurements are mainly directed to studies of convection, radiation, cloud physics and dynamics, structure of fronts, clear air turbulence and ozone content.

Recently Cornford<sup>5</sup> has made an interesting, but so far not completely confirmed, discovery of a rainy layer near the main base of nimbostratus cloud in winter warm fronts. He has analysed the results of flights in such fronts. The rate of rainfall was calculated from the indentations by the raindrops on a continuously running foil of aluminium. He finds the somewhat surprising result that on some occasions the rate of rainfall near the cloud base (usually about 2000 feet) is several times that at the ground. A short account of the Monday Discussion of this topic is to be found in an earlier issue of this Magazine.<sup>6</sup>

Enough has been said of present activities to show that the Flight has plenty of interesting work to do.

**The future.**—One of the great difficulties of aerological work lies in finding a suitable observational platform in the free atmosphere. We have already mentioned earlier work in which instruments were raised on kites and free or tethered balloons. Indeed the two latter are still in use. More recently radar has allowed some measurements to be made without the need to raise any instru-



ments. All these however have a common fault in that they lack mobility. The aeroplane has much to commend it from this point of view as it does not have to wait for the weather to come to it. Nevertheless it is far from an ideal platform. Its very mobility means that corrections which are related to airspeed become large, the motion of the aircraft disturbs the properties of the atmosphere which it is desired to measure and the high rate of sampling means that very sensitive, quick-response instruments are required if a knowledge of small-scale, local variations is required.

The aeroplane has other deficiencies. Not only is it a fast-moving platform but it is a very unsteady one too. It pitches, rolls, yaws, sideslips and flexes. As indicated above, the MRF employs gyroscopes to overcome some of these difficulties where they are important, but one cannot eliminate them completely. Costs are also high. For work of the highest accuracy very precise and very expensive gyroscopes are required. The aeroplane also has limited altitude. Whilst new aircraft, ever flying higher and higher, pose new meteorological problems there is a need for a platform at flying height before the production aircraft begins to operate there. But very seldom is a research aircraft of any kind available to provide such a platform. The tropical stratosphere is still largely unexplored by aircraft.

So the aeroplane is not an ideal vehicle from which to conduct meteorological research, but it is a very useful one and one to which meteorologists owe much. As the supply of problems is unlikely to run out and as a slower, steadier, yet highly mobile platform is not yet in sight the aeroplane is likely to remain our research vehicle for some time yet.

The Meteorological Research Flight has come of age with a good record of achievement behind it. Nowadays the Flight has its own scientific staff, its own aircraft, its own RAF aircrew and a new building with laboratories and excellently equipped workshop. It has the tools to enable it to continue its record of achievement. There is still plenty to be done.

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## AN ACCUMULATED TEMPERATURE MAP OF THE LONDON AREA

By T. J. CHANDLER  
University College London

Heating engineers are frequently interested in accumulated temperatures below certain base temperatures. Manley<sup>1</sup> has argued the case for a datum of 14°C (57°F) mean temperature below which some form of artificial heating becomes necessary but for present purposes the more customary 15.6°C (60°F) will be taken. This is 2.7°C (5°F) below what in this country can be regarded



as a desirable comfort temperature, the difference being accounted for by solar radiation through windows and incidental heat gains from lighting, cooking and persons within the building.

Knight and Cornell,<sup>2</sup> amongst others, have shown that for buildings maintained at an indoor temperature of 18.3°C (65°F), there is quite a close relationship between fuel consumption and accumulated temperature below 15.6°C (60°F) over corresponding periods of time. This suggests that the degree-day total below 15.6°C (60°F) measures a large part of the heating requirements of buildings, particularly where the incident wind speeds are low, as in the more densely settled parts of cities.

Sometimes, however, heating engineers have taken their climatological records from a nearby rural station, failing to realize the substantial differences between temperatures inside and outside cities. This is well illustrated in London.

Averages of accumulated temperature may be derived in a number of ways<sup>3</sup> but for present purposes the method described in Meteorological Office Form 3300<sup>4</sup> (designed for use with a 5.6°C (42°F) base) has been used to derive accumulated temperature below 15.6°C (60°F) by using suitably adjusted individual monthly values of mean daily maximum and minimum temperatures. A map was first prepared for 1959–62 using records from more than 50 stations established by the London Climatological Survey<sup>5</sup> as well as synoptic and climatological stations sending monthly returns to the Meteorological Office. This short-period analysis was then used as a guide for a longer-period study from 1951–60 based upon 15 stations. Figure 1 shows the annual pattern and Table I gives the individual monthly values.

Two main factors differentiate accumulated temperatures within Greater London: altitude and urban exposure. Totals of more than 4000 Fahrenheit degree-days occur in the elevated rural areas of south Hertfordshire, north of London, and on the North Downs to the south of the city. Similar values occur on Hampstead Heath and also, no doubt, in comparable areas such as Harrow Hill in north London. The lowest values occur in the inner north-east suburbs of Islington, Finsbury and Shoreditch. The urban influence accounts for a reduction of about 400 degree-days, or about 10 per cent of the values at comparable heights outside London. Elevation controls are more difficult to assess since they cannot be separated from associated changes in the urban morphology. Even so, the fall-off in degree-day totals from Upper Holloway, Tufnell Park and Kentish Town to Hampstead is outstanding. If Regent's Park and Hampstead are compared (both stations with a fairly open exposure and 2.5 miles (4 kilometres) apart in north London), the decrease in the annual total of degree-days amounts to 532 in 321 feet (98 metres), an average of about 1.7 degree-days per foot. This is considerably more than the average of 1.0 degree-days per foot in southern England<sup>3</sup> and emphasizes the position of Hampstead Heath and comparable areas above the majority of London's heat-islands.

Figure 1 makes a fair summary of London's heat-island as it affects regional temperatures. The obvious asymmetry is mainly owing to the character of the urban development, with some of the highest building densities in the City of London and in the compactly developed areas of inner north-east London. The character of the immediate urban environment is, in fact, highly

TABLE 1—ACCUMULATED TEMPERATURE BELOW 60°F, LONDON, 1951-60,  
IN FAHRENHEIT DEGREE-DAYS

	Height above M.S.L.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
	feet			degree-days						degree-days				
Westminster	27	61.4	560	470	324	152	60	28	28	66	211	414	508	3435
Camden Square	110	620	566	500	318	152	60	31	28	66	205	414	508	3468
Kensington Palace	81	626	563	479	327	161	54	31	34	69	229	420	520	3513
Regent's Park	129	620	578	482	336	164	66	31	34	81	213	417	517	3539
Kew Observatory	18	620	578	491	351	173	66	31	34	84	235	423	514	3600
Hampton	39	638	590	485	297	173	66	34	40	84	229	441	529	3606
Greenwich*	24	623	569	491	339	179	72	31	40	90	245	429	523	3631
London (Heathrow) Airport	82	641	590	494	351	188	75	34	40	87	247	441	550	3738
Bromley	213	644	593	503	363	197	81	37	43	96	253	447	541	3798
Dartford	17	638	596	497	363	209	90	37	43	99	253	441	541	3867
Croydon	220	656	599	512	375	203	81	34	43	96	259	432	544	3834
Southgate	221	674	605	515	354	203	84	34	43	96	256	450	553	3867
Wisle	105	659	584	503	366	203	99	46	52	126	274	471	559	3942
Addington	474	680	626	533	393	212	96	43	46	108	247	474	565	4023
Hampstead	450	677	623	563	384	212	99	52	52	103	265	468	568	4071

\*Greenwich Observatory, 149 feet (45.4 metres), 1951-52

Source of data: London, Meteorological Office, *Monthly weather report*, 1951-60.

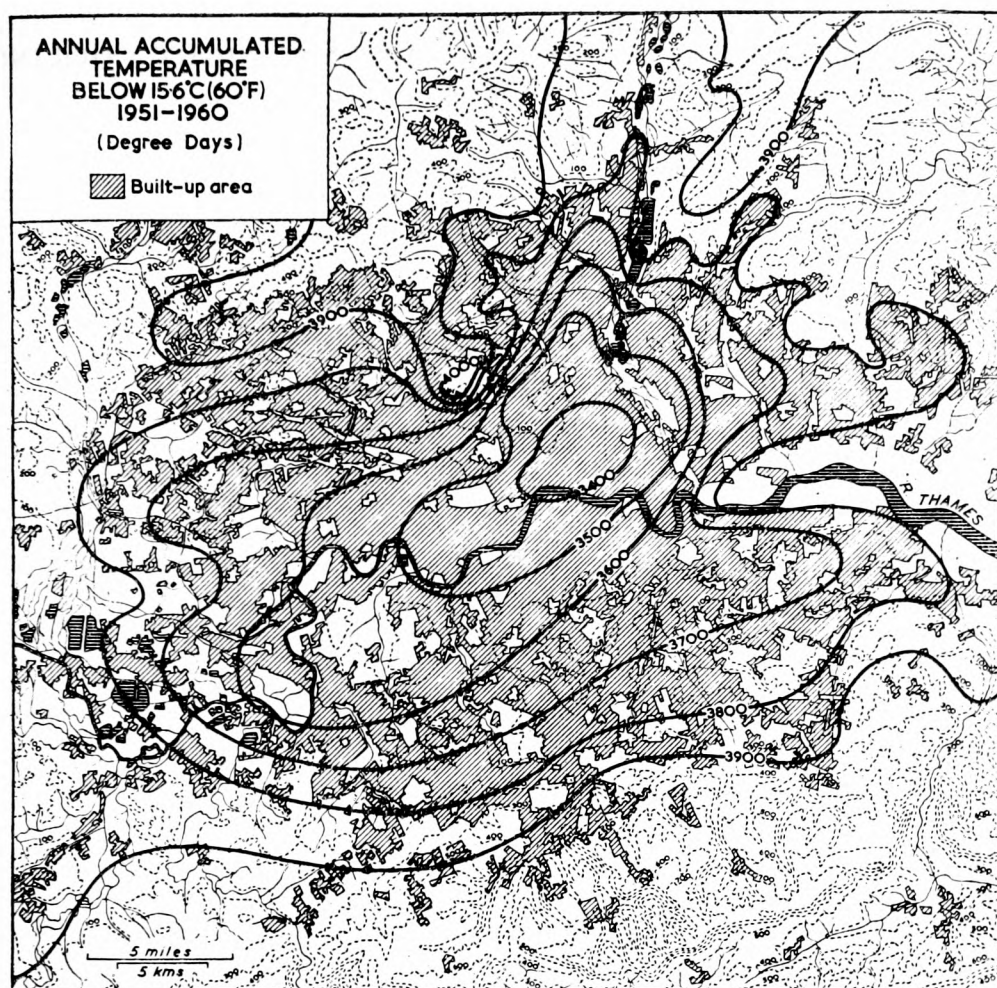


FIGURE 1—AN ACCUMULATED TEMPERATURE MAP OF THE LONDON AREA  
Isopleths are numbered in Fahrenheit degree-days

critical in determining the degree of local warming and for detailed studies of heating requirements, account must be taken of site influences upon solar radiation, temperatures and winds close to the buildings in question. But the picture is also complicated by the style of architecture and in most studies more regional climatic values have to be used. Nevertheless, attention should always be paid to the effects of the buildings themselves upon the climate outside their walls.

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## A METHOD OF FORECASTING A RADIATION NIGHT COOLING CURVE

By J. A. BARTHRAM

**Introduction.**—Articles, notably by Saunders,<sup>1,2</sup> have shown that the rate of decrease of temperature on radiation nights has a discontinuity during the evening, and that the subsequent fall of temperature is related to the strength of the geostrophic wind. This article describes a method of depicting these factors on a simple diagram, and with an assumption about the time of minimum temperature a cooling curve can be quickly drawn.

### Factors used in determining the cooling curve.—

*Temperature of discontinuity.*—Articles by Saunders and others<sup>3-6</sup> show that at a time which varies from month to month there is a check in the rate of cooling, and the temperature of this discontinuity ( $T_R$ ) is given by

$$T_R = \frac{1}{2}(T_{\max} + T_d) - k$$

where  $T_{\max}$  is the day maximum temperature, and  $T_d$  is the dew-point at the time of  $T_{\max}$ . The factor  $k$  varies between cases when there was or was not an afternoon inversion with a base below the height of the 850 mb level and also varies with location of site.

The following figures are suggested mean values of  $k$  for low-lying inland airfields:

- (a) with an inversion below 850 mb,  $k = 2^\circ\text{C}$
- (b) with no inversion below 850 mb,  $k = 1^\circ\text{C}$

They are based on values published in the articles mentioned, and on the author's experience at airfields so situated. Figure 1 is a diagram from which the discontinuity equation can be solved for the values of  $k$  suggested. Each vertical line is given values for cases with and cases without an inversion, though individual stations may have to amend the values shown. For normal use a temperature range from, say  $-10^\circ\text{C}$  to  $25^\circ\text{C}$  would be displayed.

*Time of discontinuity.*—This time is related to the time of sunset and will also vary with location, and possibly with whether the ground is wet or dry. Figure 2 is a suggested monthly curve for low-lying inland airfields in the southern half of England near the meridian, based again on values from the articles previously mentioned. The values of time (GMT) of  $T_R$  at the beginning of the month are:

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1645	1745	1845	2015	2100	2130	2145	2130	2030	1900	1745	1700

*Subsequent cooling: the minimum temperature.*—The articles<sup>1-5</sup> also give details showing how the fall of temperature after  $T_R$  is related to the geostrophic wind speed and the value of  $T_R$ . It was found that acceptable means could be produced from the data given, and Figure 3 shows curves giving the night minimum temperature for a range of values of  $T_R$  and wind strength. Once again the graph is based on low-lying inland airfields, and significant amendments may be necessary for other locations.

*Time of occurrence of minimum temperature.*—Although there is generally a day-to-day variation in the time of occurrence of the minimum temperature ( $T_{\min}$ ), it has been found that the time of local sunrise gives a good approximation.

Dew-point ( $T_d$ ) at time of maximum temperature

With inversion 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20°C

No inversion 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20°C

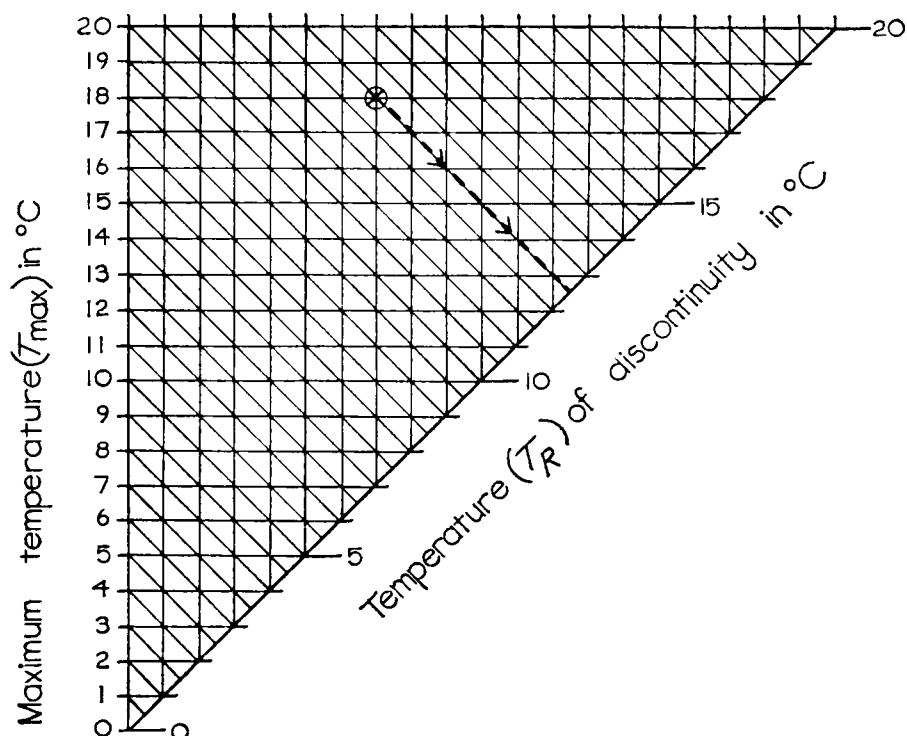


FIGURE 1—GRAPH FOR OBTAINING THE TEMPERATURE OF DISCONTINUITY FROM THE MAXIMUM TEMPERATURE AND THE DEW-POINT AT THE TIME OF MAXIMUM TEMPERATURE

Example:  $T_{\max} = 13^\circ\text{C}$ ,  $T_d = 11^\circ\text{C}$  with inversion give  $T_R = 12.5^\circ\text{C}$ .

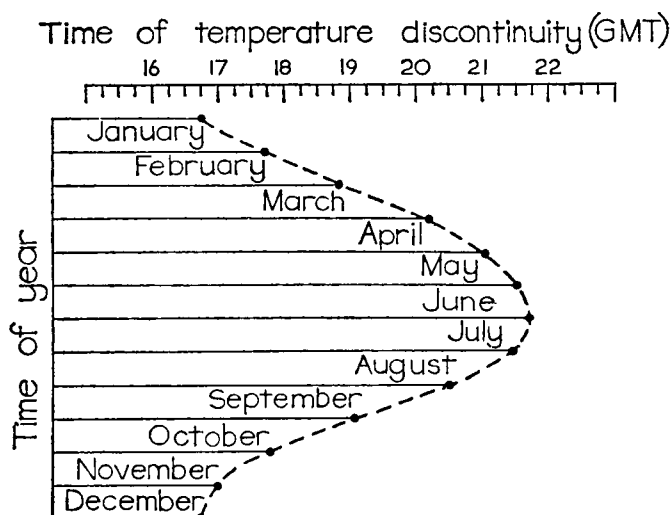


FIGURE 2—MONTHLY CURVE OF TIME OF TEMPERATURE DISCONTINUITY  
The curve is based on data for low-lying airfields and is dependent on the time of sunset.

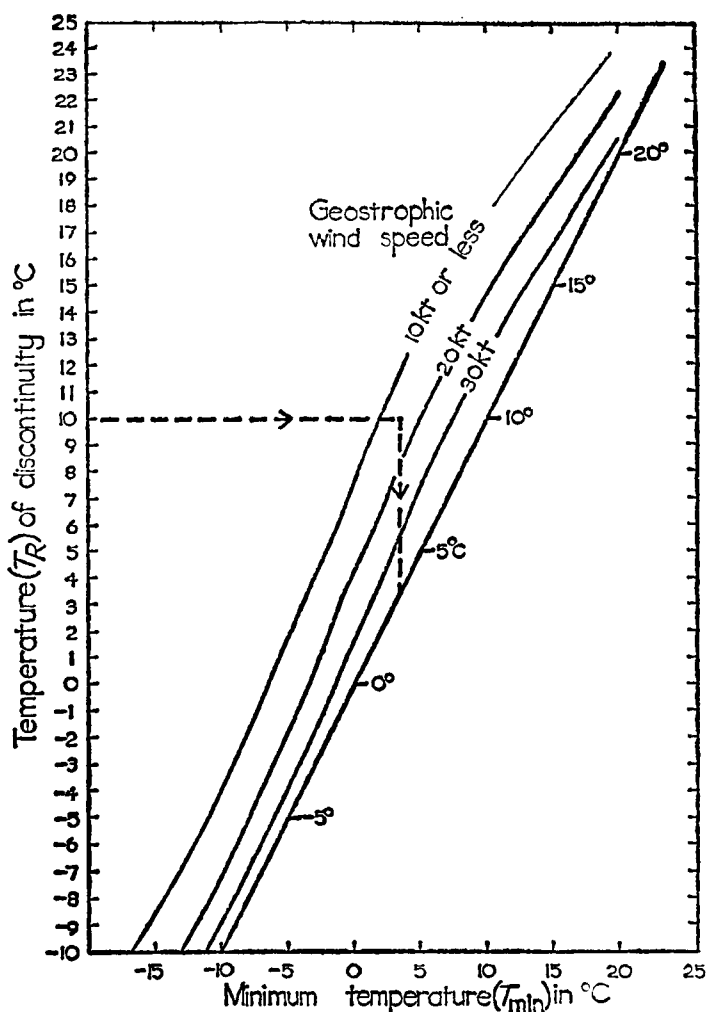


FIGURE 3—GRAPH FOR OBTAINING THE MINIMUM TEMPERATURE FROM THE TEMPERATURE OF DISCONTINUITY FOR VARYING GEOSTROPHIC WIND SPEEDS

Example:  $T_R = 10^\circ\text{C}$  and wind speed = 15 kt give  $T_{\min} = 3.5^\circ\text{C}$ .

### Forecasting a cooling curve.—

*Features of the diagram in Figure 4.*—Section 2, the central part of Figure 4, has a horizontal time-scale and a vertical temperature-scale. On this part the cooling curve is drawn. In the lower part of this section are drawn the curves of time of discontinuity and time of minimum temperature.

In section 1, on the left, is a reproduction of Figure 1—reduced in size and detail—for finding the temperature of discontinuity. Section 3, on the right, is the graph (shown in detail in Figure 3) for determining the minimum temperature from the temperature of discontinuity and the geostrophic wind speed.

*Method of positioning  $T_R$ .*—The method of positioning  $T_R$  is shown in Figure 4. Plot the maximum temperature at its time of occurrence in section 2, run back along the  $T_{\max}$  isotherm to the appropriate dew-point in section 1, and then follow the sloping grid lines to the main diagonal. Take this value,  $T_R$ , horizontally across until it cuts the vertical from the time of discontinuity. Plot this point.

*Method of positioning  $T_{\min}$ .*—To plot  $T_{\min}$  the value of  $T_R$  already obtained is carried horizontally across the diagram in Figure 4 until it cuts the curve of the appropriate geostrophic wind speed in section 3. Follow a vertical line through

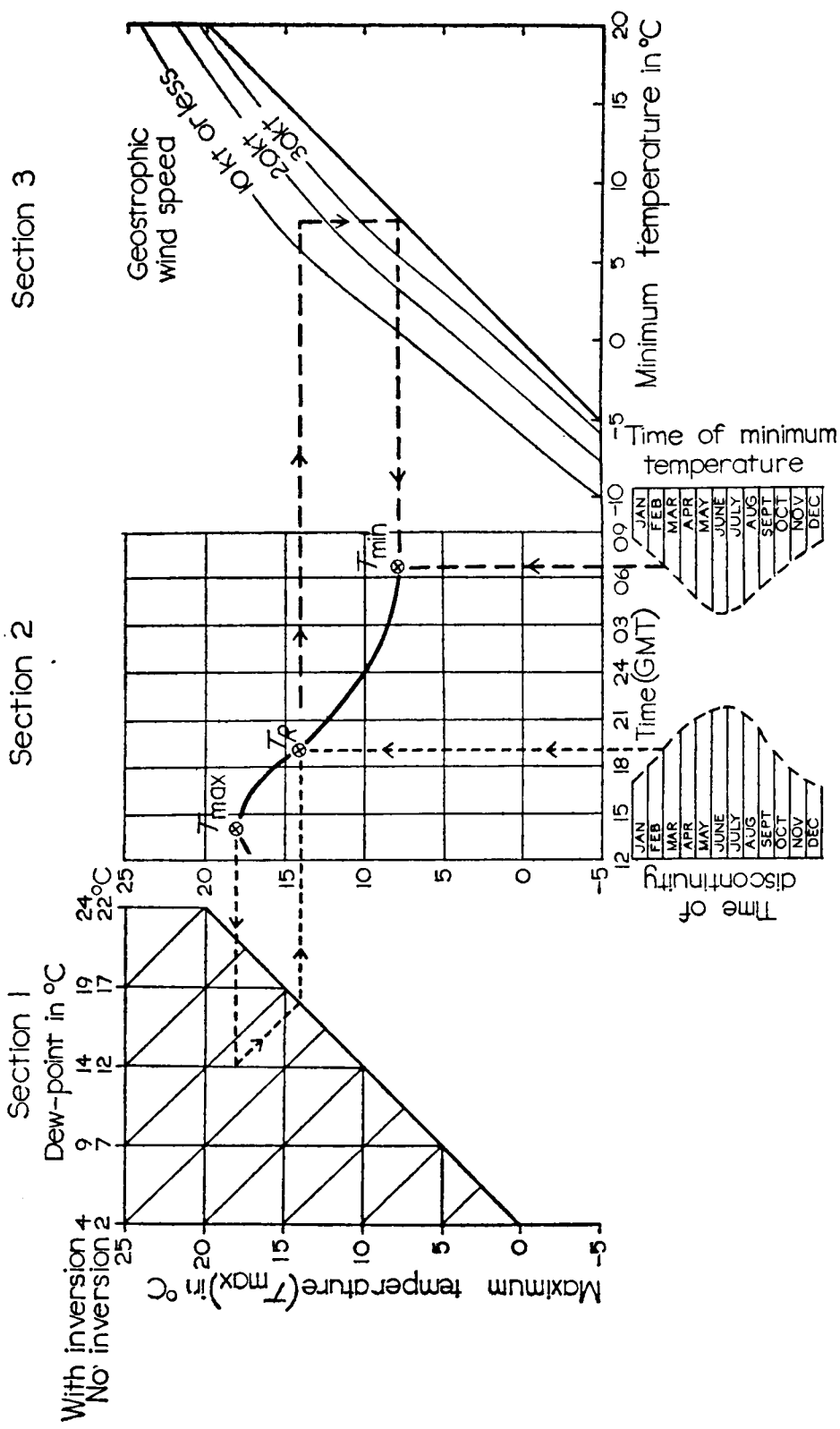


FIGURE 4—DIAGRAM FOR FORECASTING A COOLING CURVE ON RADIATION NIGHTS  
 Example: date = 3 March,  $T_{max} = 18^{\circ}\text{C}$  at 1400 GMT,  $T_d = 12^{\circ}\text{C}$ , no inversion, and wind speed = 15 kt.

here to the main diagonal. This is the minimum temperature. Run back along the horizontal isotherm of  $T_{\min}$  until it meets the vertical from the time of minimum temperature, and this point is plotted.

*The cooling curve.*—The key points of  $T_{\max}$ ,  $T_R$ , and  $T_{\min}$ , of the cooling curve on radiation nights are now plotted. By joining freehand with the usual ‘opposing curves’ a forecast of the night’s temperatures is quickly obtained. The shape of the ‘opposing curves’ is soon assessed with experience in use.

An example of a forecast curve is shown on Figure 4. Here the maximum temperature was taken as  $18^{\circ}\text{C}$ , the dew-point as  $12^{\circ}\text{C}$ , on a day in early March without an inversion. The  $T_R$  is plotted as  $14^{\circ}\text{C}$  at 1900 GMT, and using a geostrophic wind speed of 15 knots the minimum temperature appears as  $7.5^{\circ}\text{C}$  plotted at 0630 GMT.

**Discussion.**—A statistical check on the accuracy and usefulness of the curve drawn is not easy. Almost every radiation night has its own irregularities, with the actual temperature fluctuating around the forecast profile.

At Laarbruch, Germany, a check over the past year showed that only about one in every eight forecast curves was considered misleading, the remainder being broadly classified as useful. The most likely cause of failure is the difficulty of assessing a representative dew-point in inhomogeneous air. The minimum temperatures forecast were within plus or minus  $2^{\circ}\text{C}$  on all occasions described as ‘useful,’ and on half of these occasions the forecast was within  $1^{\circ}\text{C}$ .

The drawing of this cooling curve gives an early assessment of the time the fog-point is likely to be reached. Also hourly plots of actual temperature alongside the forecast profile draw attention to the occasions when this forecast time may require amendment. The probable time of air frost is also readily obtained.

Some places experience a continuing fall of temperature after fog has formed. Figure 5 gives the result of an investigation during 1957 and 1958 at Wyton, Huntingdonshire. An additional detail such as this may be included on the diagram Figure 4, and the forecast curve amended after the expected fog-point is reached. This perhaps rather unusual feature is important when, although the fog-point is significantly above  $0^{\circ}\text{C}$ , an air frost must still be considered.

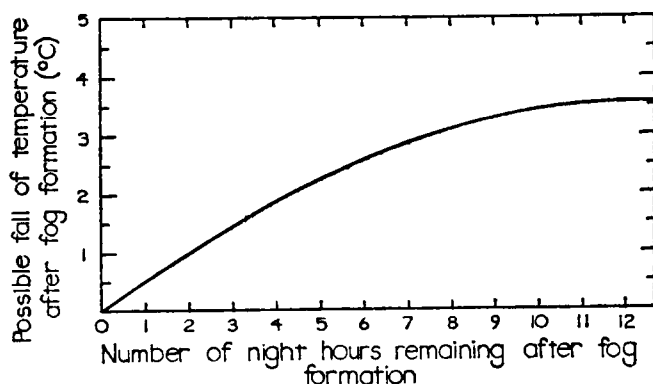


FIGURE 5—POSSIBLE FALL OF TEMPERATURE AFTER THE FORMATION OF RADIATION FOG



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## REVIEW

*Keoeit—the story of the aurora borealis*, by W. Petrie, 10 in × 7½ in, pp. xii + 134, illus, Pergamon Press Ltd., Headington Hill Hall, Oxford, 1963, Price: 35s.

For whom is this book intended? It is very difficult to decide. The style of writing seems to vary from section to section, even from paragraph to paragraph, which gives the impression that it has grown up from a set of notes which the author has enlarged. The prologue states that the book is aimed primarily at the non-scientist and the earlier chapters sound faintly like someone talking down to a 12-year old. Later on a much greater familiarity with Advanced Level Physics would be necessary for its full understanding.

The book starts off with an interesting account of the aurora in history, but we are told only what the ancients thought it looked like, and the reader has to wait until Chapter IV before his curiosity about its actual appearance can be satisfied. This is somewhat characteristic of the whole book; the author assumes that the reader has a passing acquaintance with all the topics discussed.

Despite the fact that the aurora “has long attracted the attention of man” Chapter II is an apology for its study. It is not, apparently, the fascination for the aurora which compels people to study it, as the author’s prologue would imply, but the cold needs of telecommunications. In this chapter the reader is irritated by the needless digression on the ionized layers in the atmosphere. Chapter III is purely technical, and describes the instruments used to study the aurora. The human eye gets a mention but hardly in due proportion; a discussion of the response of the eye to different levels of intensity of light would have been much more useful to the layman than descriptions of radar installations.

At last in Chapter IV the reader is to be told what the aurora actually looks like. After saying that it defies description the author takes his own words to heart and makes a very poor attempt compared with the build-up in the earlier chapters. The so-called description seems to have been taken bodily from the *Atlas of Auroral Forms*, and amounts to no more than a technical classification of forms. The next chapter deals with “the Habitat of the Aurora”, and gives details of the height and geographical extent of the aurora. The transatlantic origins of the book become obvious when one notices that although there is a map of North Amercia showing a highly idealized auroral zone, Europe is not so privileged, and the British reader would get no clear idea of where to go to see the aurora.

After dealing with temporal and spatial variations the writer goes on to discuss light and sound in Chapter VII. Here, it seems, he is more confident and his style more relaxed. He is now writing on a topic he understands, but

unfortunately the lay reader will find the technicalities getting too involved; band spectra, Doppler-shifted hydrogen lines and the rest. Finally we go into deep waters discussing the relatives of the aurora and their causes.

The general impression given by this book is that the author has taken on more than he can manage. He wants to write for the layman, but cannot explain first ideas. For example, on page 15 he discusses the necessity for "fast" lenses when photographing the aurora. He seems unequal to the task of describing what this implies to all his readers; he abdicates by saying "those familiar with cameras will appreciate..... the camera has an f number of 0.71". Those who are unfamiliar with cameras are left behind. As the book progresses, more and more basic knowledge is assumed. On page 51 we get the first reference to "particle belts" to correct an impression given by an accompanying diagram, but with no explanation. The Van Allen belts are not properly introduced until the last chapter.

The book is well produced with diagrams and some good photographs in black and white. A novel feature is the collection of coloured paintings aimed at giving a more realistic impression of the aurora as seen. The diffuse nature of the forms comes over well, and this seems to be the best effort in this direction in any popular work on the aurora. Credit for the paintings, however, goes to the author's wife.

G. M. THOMAS

*Behind the scenes at London Airport*, by Norman Wymer, 8 in  $\times$  5½ in, pp. 82, illus., Phoenix House Ltd., 10-13 Bedford Street, Strand, London, W.C.2, 1963. Price: 10s. 6d.

The link between meteorology and aviation is a very strong one. During the past 50 years, the needs of flying have led to many demands from the meteorological services, but this has been no onesided business relationship. Aviation has made a profound contribution to meteorology itself, not only in the form of direct observations, but more importantly in the stimulus that it has given both to the setting up of surface and upper air observation and networks and to the undertaking of theoretical studies. The association of meteorology and aviation is thus in a true sense a partnership and it has been a very profitable one to both sides.

Despite increasing applications of meteorology today to other fields, aviation still remains by far the biggest customer. It is therefore very much to the advantage of every meteorologist to see to it that he knows and understands something about the world of aviation, for any partnership will be more fruitful if each member of it is well informed about the needs and activities of the other.

The stated intention of this book (which is one of a series) is "to satisfy young people's curiosity about the inside working of everyday enterprises." It is thus not aimed directly at adult readers, though it could certainly be read with profit by many who have had little personal contact with civil aviation. Moreover, there are few adults who are not involved from time to time with the curiosity of the younger generation, and in trying to provide answers find themselves singularly ill-equipped for the task. In these situations it is most useful to know a book that may be recommended to, and read by the inquirers themselves.

Having given a brief history of London (Heathrow) Airport and of civil aviation in England, the author continues with a survey of the functions of some of the main departments concerned with the running of the airport and then gives an account of the airlines who use it. This is followed by some information on modern civil aircraft, their development, equipment and maintenance. Succeeding chapters are on Freight and Mail, Air Crews and Air Traffic Control, whilst to conclude there is a description of a flight followed through from pre-flight planning stage to the maintenance hangar after final touchdown.

References to the Meteorological Office are mostly brief, but following one of them it is pleasant to see recorded the opinion of the Vice-President of the American Air Line Pilot's Association that Heathrow is operationally "as close to Utopia as you can get from a pilot's viewpoint". Undoubtedly the operational side of the Airport, including its meteorological services, is high in international esteem, and the striking thing about this is that such a reputation should have been established in the short time that Heathrow has been open for civil air traffic. The photograph of the 1946 Passengers Waiting Room in a dilapidated marquee is a vivid reminder of the changes that have taken place in well under 20 years.

There are two major pitfalls for books of this kind that set out to provide information for the young; the style can be bad or irritating to the point where the reader loses interest, or the facts provided can be incorrect. On the whole this book has successfully avoided both those traps. The style has the merit of being simple and straightforward, and is completely devoid of any talking down to the reader, whilst the author has obviously gone to a good deal of trouble to inform himself about his subject. He has consulted not only a number of the Airlines and other organizations concerned with the running of the Airport, but also the Ministry of Aviation.

It is therefore a pity that errors have crept in, but a few must be recorded. It is very doubtful whether bonding the aircraft structure (p. 42) reduces the risk of the aircraft being struck by lightning; it would be better to refer to reducing the danger when the aircraft is struck. Icing (p. 42) may form in cloud *above*, not below, the freezing level, and in the same paragraph it would have been better to refer to ice 'on the hinges of control surfaces' rather than "on the hinges of wings". Although the intended contrast with turbulence in cloud is reasonably clear, to say that "above the clouds the weather is usually calm" is not a statement that any pilot or meteorologist can accept.

The description of basic aircraft instruments (p. 41) though simplified is probably adequate except that the periscopic sextant is for use in astronavigation and thus enables the pilot to determine his latitude not his altitude. The simplified version of the quadrantal altitude procedure (p. 61) is probably acceptable, but the example given of its working is quite incorrect; if North America were substituted for the Mediterranean all would be well. The description of Instrument Landing System (ILS) on pp. 68-69 is wrong. Two transmitters at the ends of the runway give the localizer beam and glide path and operate the cockpit instruments. The marker beacons have nothing to do with this, being used in conjunction with the radio compass to give distances from the end of the runway or as a joining facility.

In the description of meteorological pre-flight procedures (p. 72) there are a few turns of phrase which would grate on the ears of a professional meteorologist; similarly the aviation specialist would note the slip in the caption to one of the photographs in which Quantas are alleged to operate a Comet. However, these are quite minor points and could easily be rectified in a future edition along with the other errors noted.

The book is attractively produced, and is well illustrated with 6 line drawings and over 40 photographs. It should also fulfil its stated aim, and it is hoped that it will enjoy the success it deserves.

R. J. OGDEN

551.594.221:629.13

## LETTER TO THE EDITOR

### Lightning strike 23 April 1964

During the afternoon of Thursday, 23 April 1964, a Varsity aircraft of the Meteorological Research Flight, Farnborough, was flying in a large cumulonimbus situated south of Bedford. The base of the cloud was at 2500–3100 feet with patches of stratus at 1200 feet. A thunderstorm was in progress with frequent lightning and heavy rain. At 1410 GMT, when the aircraft was at 3000 feet in heavy rain just below the cloud base, a brilliant flash of white light and a loud bang was observed. The inside of the aircraft was then illuminated with a shimmering whitish-blue light for a couple of seconds from the starboard side.

The pilot, on the other hand, reported that the loud bang momentarily preceded the flash. He then saw a ball of blue light about the size of a football on the starboard wing tip. This ball lasted for about two seconds before vanishing.

There were several more flashes of lightning, but none in the immediate vicinity of the aircraft.

After landing, a number of small burns were found on both the starboard and port wing tips and also on the underneath of the fuselage. The navigation light on the starboard wing tip had been smashed and the aircraft compass when tested indicated an error in reading of about 10 degrees.

G. T. VIDLER

*Meteorological Research Flight, Farnborough.*

## AWARDS

The Council of the Royal Society of Arts has awarded a Silver Medal to Dr. R. C. Sutcliffe, C.B., O.B.E., F.R.S., for his paper on 'Advances in Weather Forecasting' which was read to the Society on 15 April 1964.

### Hunt Trophy

The Hunt Trophy is awarded annually by the Guild of Air Traffic Control Officers to the individual or organization considered to have made the most outstanding contribution to Air Traffic Control in the preceding year. The trophy itself is a silver tray (about 10 inches in diameter) and is inscribed with the names of the recipients in the various years. It was originally presented to the Guild in 1958 by Captain V. A. M. Hunt, C.B.E., B.A., F.R.Ae.S., who is the Director of Control (Operations) in the National Air Traffic Control Service,

and who at that time had the responsibility for Air Traffic Control in the Ministry of Aviation.

The award in 1964 was made to the British Ocean Weather Ships and was accepted by the Director-General of the Meteorological Office on behalf of the Ocean Weather Ships on Friday, 17 April 1964 at the Annual Dinner of the Guild. The Master of the Guild made the presentation and read the following citation:

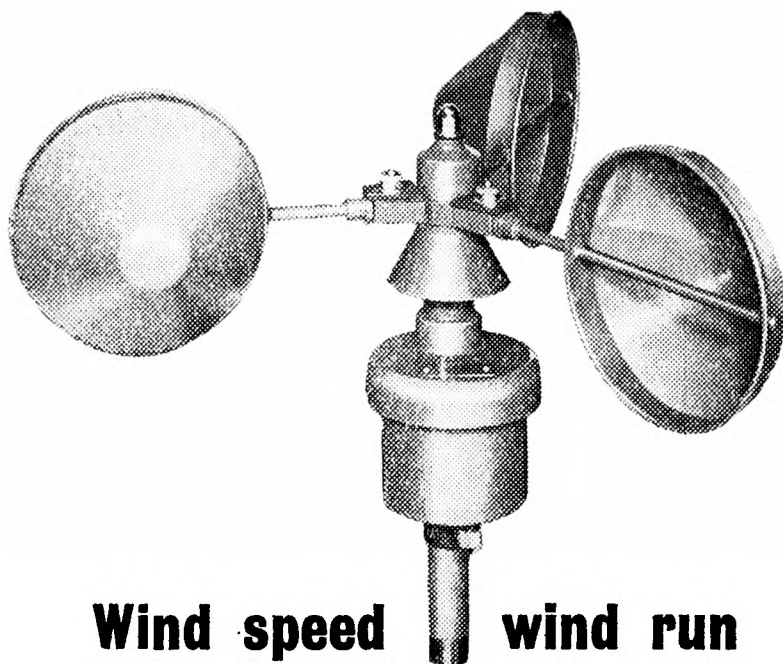
“While appreciating that the first function of the Ocean Weather Ship Service is to provide meteorological data which itself is of immense value to International Aviation, it has long been evident to Transatlantic aircrews, and to Control Officers at Oceanic Area Control Centres, that the services to Air Traffic Control in respect of communications relay, radar fixing of aircraft, and Alert of Search and Rescue action, often carried out under very difficult conditions and with equipment not specifically designed for the task have been outstanding.

A bond has grown up between Weather Ship Officers, typified by those of the United Kingdom Weather Ships, Oceanic Controllers and Air Pilots, which it is desired to perpetuate by the award this year of the “Hunt” Trophy to the U.K. Ocean Weather Ships Service.”

Previous recipients have been:

- 1959 School of Air Traffic Control. (Ministry of Transport and Civil Aviation.)
- 1960 Royal Air Force. (In recognition of the setting up of the United Kingdom Air Traffic Service Branch in the RAF.)
- 1961 G. J. H. Jeffs, C.V.O., O.B.E. (One of the original Air Traffic Control Officers *circa* 1920, and lately Airport Commandant, London Airport.)
- 1962 (No award this year.)
- 1963 School of Air Traffic Control. (International Aeradio Ltd.)

The trophy will be exhibited at the Ocean Weather Ship Base at Greenock after a short period of display at the Meteorological Office Headquarters, Bracknell.



**Wind speed | wind run**

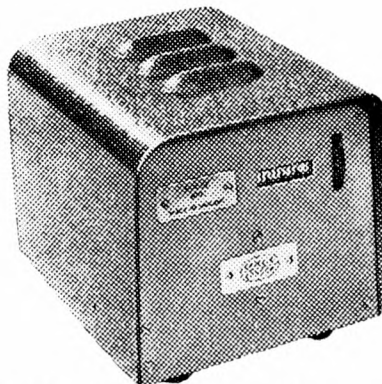
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# THE METEOROLOGICAL MAGAZINE

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## SOME EVIDENCE FOR THE WINDBORNE SPREAD OF FOWL PEST

By C. V. SMITH

**Introduction.**—Fowl pest is a respiratory disease initiated by a virus. Although a virus may exist outside of a body cell, the processes necessary for the growth and reproduction of the virus only occur after it has penetrated a cell. The factors which determine whether virus or host cell will dominate are the subject of current research. If the virus enslaves the cell, the cell then lends itself to the multiplication of the virus at the expense of its own growth and economy. The cell may suffer deterioration or its genetic pattern may be dramatically altered. If the host cell dominates, the viral invader may take up residence within the cell without affecting the cell adversely.

With infectious diseases, the inoculation of one individual by another may commonly be by an airborne route. This article examines whether meteorological conditions were suitable for such a route in the widespread outbreaks of fowl pest in Bedfordshire and neighbouring counties in the early part of 1960 and 1962.

Whilst the diameters of virus particles are of the order 0.01 microns, they are commonly found, in the free atmosphere, to be associated with particulate matter (such as dust and dried saliva) having a diameter of a few microns. Broadly speaking, we can expect such fine particles suspended in the air to follow the movement of the air. Their movement is also affected to some extent by Brownian and turbulent diffusion and by the existence of local temperature, vapour pressure and electrical gradients. However, these smaller-scale processes, together with those of impaction and direct condensation, are only likely to be of importance when removal of the particles from the atmosphere is under consideration.

An exposed surface in a broiler house will show a visible dust collection in a matter of hours. Modern intensive units may have a through-put of one to two million cubic feet of air per hour. If the houses in which the initial outbreaks occurred may be regarded as continuous point sources of infectious dust particles, then Pasquill<sup>1</sup> has given a method for estimating the dispersion of this windborne material for distances of up to 100 kilometres.

**The technique and criteria adopted.**—A schematic diagram of a plume from a source at ground level is shown in Figure 1. The angle AOB gives a measure of the lateral spread and is defined by the arc APB, the points A and B

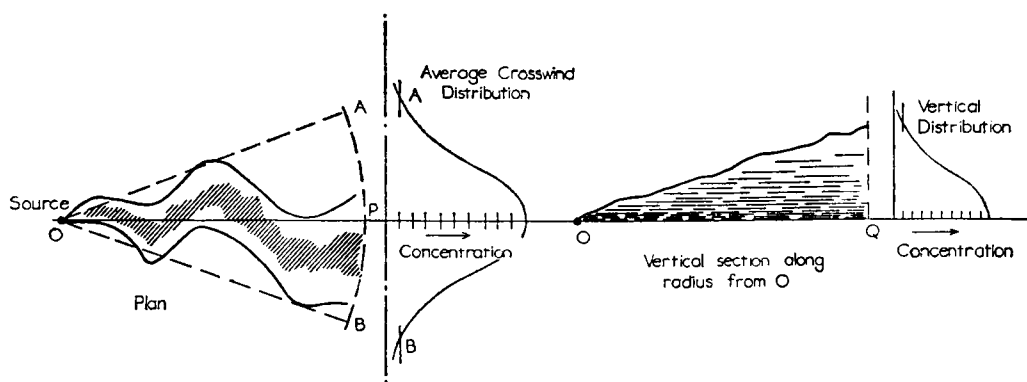


FIGURE 1—SCHEMATIC DIAGRAM OF A PLUME FROM A SOURCE AT GROUND LEVEL

being chosen to locate concentrations of one-tenth of the axial (or peak) concentration. The vertical spread is similarly defined as the height at which one-tenth of the ground concentration is reached.

Relationships are available to determine the concentrations at various distances and heights downstream, provided the rate of release of material at the source is available. Since the source strengths in question must be regarded as unknowns, and since even a single virus can multiply rapidly given the right environment, attention has been confined to locating the axes and lateral spread of the dust plumes. The information necessary to do this comes from weather maps and from the fine structure shown by routine records of wind speed and direction.

Information supplied on the outbreaks stated simply the sites and the dates on which confirmation of the disease was obtained. The data were perhaps biased towards occurrences within counties, with Bedfordshire as the main centre of interest.

The earliest date of confirmation within the information presented was taken to indicate the primary source of infection. In general, it was assumed that the source was destroyed on the day following the date of confirmation of the disease. A period of 8 days (including the date of confirmation) was taken as the interval during which windborne infection could spread from a primary source. For subsequent outbreaks, it was necessary to allow for an incubation period after the arrival of the infection and for a rather more variable period before the outbreak was confirmed by laboratory tests. (The date of confirmation depended upon how quickly the disease became obvious, how quickly it was then reported and how soon laboratory tests could confirm.) Only at sites where fowl pest was confirmed within 6 to 14 days of the arrival of air from a source of infection was the new outbreak taken as attributable to that source. Subsequent (secondary) sites of the disease were themselves additional sources of infection. Such sources were considered as operative from the fourth day after the arrival of a 'trajectory' from an earlier source up to the date of confirmation.

The wind record at Cardington was taken as representative of the areas of interest and the orientation and lateral spread from sources were only obtained for one hour (1200 to 1300 GMT) of each day.



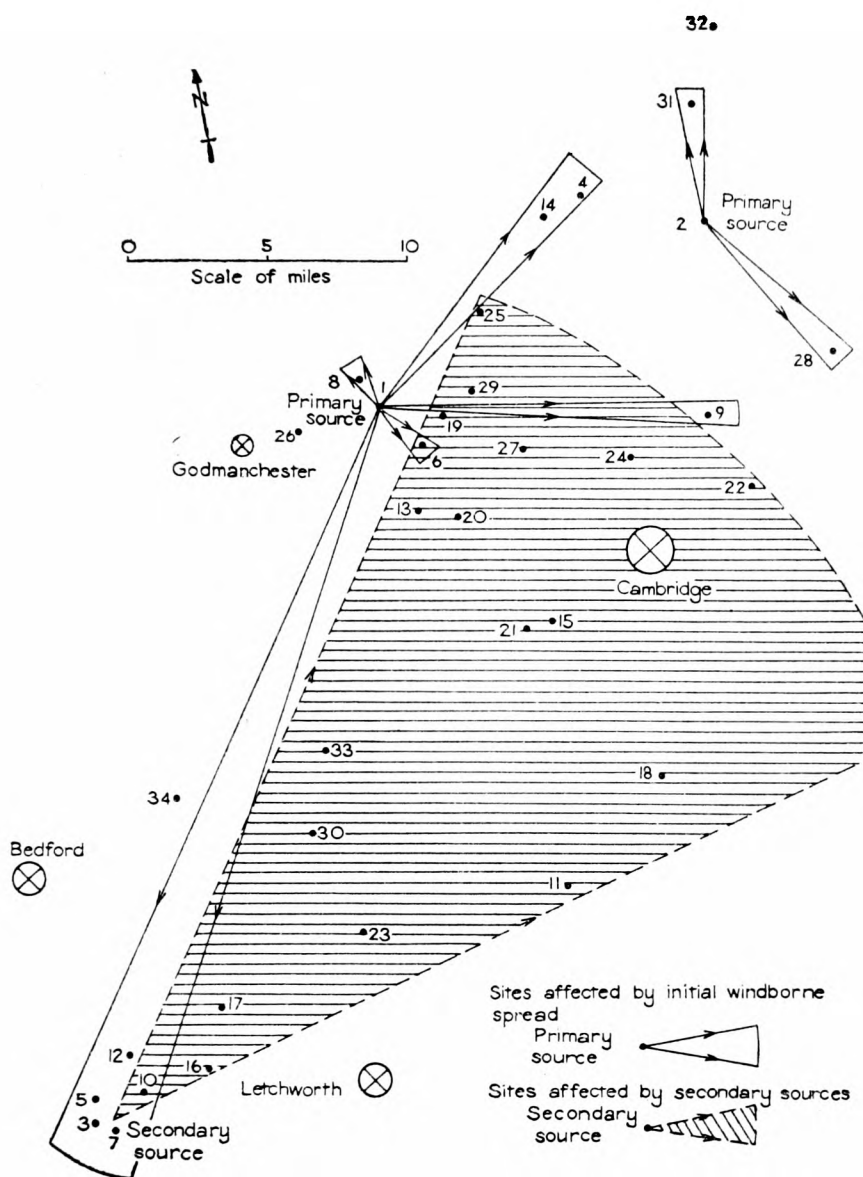


FIGURE 2—SITES AND EXAMPLES OF THE SPREAD OF FOWL PEST IN THE SPRING OF 1962

For identification of site numbers see Table I.

### The outbreaks.—

(i) *March and April 1962.*—Figure 2 is a map of the area showing sites of the outbreaks. Table I lists the locations and dates of confirmation of the outbreaks. In addition, Table I lists the outbreaks (indicated by an asterisk) attributable to various sources.

A primary source in the vicinity of St. Ives over the period 15 to 23 March only 'explains' the outbreak at Fen Drayton, but a primary source near St. Ives over the period 21 to 29 March (6 to 14 days before the outbreaks at Little Thetford and Greenfield) accommodates a far greater number of subsequent occurrences. The result of treating secondary sources is also shown in Table I.

TABLE I—SOURCES OF INFECTION AND SITES OF SUBSEQUENT OUTBREAKS ATTRIBUTABLE TO A WINDBORNE SPREAD

Sources and dates on which the location was acting as a source														
Site number	Location	Date of confirmation of outbreak	Primary sources			Secondary sources							Site number	
			St. Ives 15.3.62 to 23.3.62 Source	St. Ives 21.3.62 to 29.3.62 Source	Little Thelford 27.3.62 to 4.4.62 Source	Greenfield 28.3.62 to 4.4.62 Source	Witcham 29.3.62 to 4.4.62 Source	Flitton 28.3.62 to 5.4.62 Source	Ten Drayton 31.3.62 to 5.4.62 Source	Pulloxhill 28.3.62 to 6.4.62 Source	Needingworth 1.4.62 to 6.4.62 Source	Water-beach 31.3.62 to 6.4.62 Source		Silsoe 28.3.62 to 7.4.62 Source
1	St. Ives	23.3.62												1
2	Little Thelford	4.4.62												2
3	Greenfield	4.4.62		*										3
4	Witcham	4.4.62		*										4
5	Flitton	5.4.62		*										5
6	Fen Drayton	5.4.62	*											6
7	Pulloxhill	6.4.62		*										7
8	Needingworth	6.4.62		*										8
9	Waterbeach	6.4.62		*										9
10	Silsoe	7.4.62		*									*	10
11	Royston	8.4.62		*									*	11
12	Clophill	8.4.62		*									*	12
13	Boxworth	8.4.62		*									*	13
14	Sutton	10.4.62		*						*			*	14
15	Comberton	10.4.62		*						*			*	15
16	Gravenhurst	11.4.62		*						*			*	16
17	Shefford	12.4.62		*						*			*	17
18	Fowlmere	12.4.62		*						*			*	18
19	Swavesey	12.4.62		*						*			*	19
20	Lolworth	12.4.62		*						*			*	20
21	Tot	13.4.62		*						*			*	21
22	Stow-Cum-Quay	13.4.62		*						*			*	22
23	Hinxworth	14.4.62		*						*			*	23
24	Histon	14.4.62		*						*			*	24
25	Earith	15.4.62		*						*			*	25
26	Hemingford	16.4.62		*						*			*	26
27	Long Stanton	16.4.62		*						*			*	27
28	Burwell	16.4.62		*						*		*	*	28
29	Over	16.4.62		*						*		*	*	29
30	Wrestlingworth	17.4.62		*						*		*	*	30
31	Chittisham	17.4.62		*						*		*	*	31
32	Littleport	17.4.62		*						*		*	*	32
33	Gamlingay	20.4.62		*						*		*	*	33
34	Great Barford	21.4.62		*						*		*	*	34

An asterisk indicates that an outbreak occurred at the location shown on the left.

(ii) *March and April 1960.*—As before, a map of the area is shown (Figure 3) and the locations and dates of confirmation of the outbreaks are listed (Table II). In addition, the subsequent outbreaks attributable to various sources are shown.

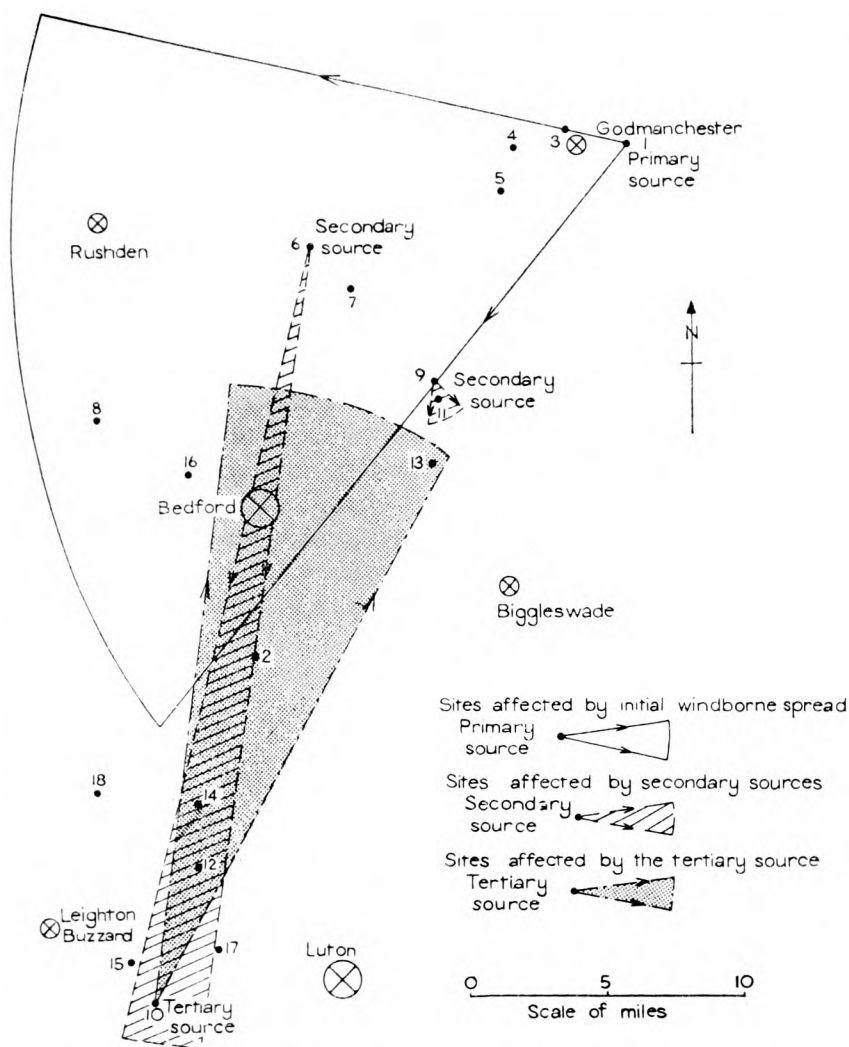


FIGURE 3—SITES AND EXAMPLES OF THE SPREAD OF FOWL PEST IN THE SPRING OF 1960

For identification of site numbers see Table II.

### Discussion.—

(i) *The results.*—The windborne spread of infection is obviously a possibility. The mechanical transport of infectious dust particles by people and vehicles moving between sources and subsequent seats of infection cannot be ignored. Another possibility is that fowl-pest carriers are likely to be present in any large flock and that their presence remains hidden until such times as the biological resistance of the birds becomes lowered, perhaps by diet deficiencies, perhaps by environmental stress associated with inadequate ventilation systems, i.e. with draughty or dusty and ammoniacal atmospheres.

TABLE II—SOURCES OF INFECTION AND SITES OF SUBSEQUENT OUTBREAKS ATTRIBUTABLE TO A WINDBORNE SPREAD

Site number	Location	Date of confirmation of outbreak	Sources and dates on which the location was acting as a source										Site number
			Primary source	Secondary sources						Tertiary sources			
			Hemingford	Huntingdon	Brampton	Buckden	Portenhall	Chawston	Eaton Bray	Tingrith	Houghton Regis		
1	Hemingford	25.3.60	to 17.3.60	23.3.60 to 2.4.60	24.3.60 to 2.4.60	20.3.60 to 2.4.60	26.3.60 to 4.4.60	29.3.60 to 4.4.60	30.3.60 to 8.4.60	9.4.60 to 17.4.60	20.4.60 to 23.4.60	1	
2	Houghton Conquest	2.4.60	*	Source			*					2	
3	Huntingdon	2.4.60	*	*	Source							3	
4	Brampton	2.4.60	*	*								4	
5	Buckden	2.4.60	*	*	Source	Source						5	
6	Portenhall	4.4.60	*	*	*	*	Source					6	
7	Little Stoughton	4.4.60	*	*	*	*						7	
8	Carlton	4.4.60	*	*	*	*						8	
9	Chawston	4.4.60	*	*				Source	Source			9	
10	Eaton Bray	8.4.60					*	*				10	
11	Wyboston	12.4.60										11	
12	Toddington	15.4.60						*	*			12	
13	Great Barford	16.4.60							*	*		13	
14	Tingrith	17.4.60							*	Source		14	
15	Stanbridge	22.4.60							*			15	
16	Stanbridge	4.5.60									*	16	
17	Bromham	22.4.60										17	
17	Houghton Regis	23.4.60								*	Source	17	
18	Houghton Regis	3.5.60										18	
18	Woburn	28.5.60										18	

An asterisk indicates that an outbreak occurred at the location shown on the left.

If in 1962, a source of infection is assumed in the St. Ives area over the period 21 to 29 March (6 to 14 days before the first outbreak in Bedfordshire), then a total of 29 of the 33 later outbreaks can be 'explained' with the restrictive criteria and with examination of the situation for only one hour of each day. Any one site is commonly affected by more than one source.

In 1960, with Hemingford as the primary source, the outbreaks up to the 12 April are fairly adequately covered. Thereafter the linkage is a little tenuous but, if pursued, then some 15 out of 19 later outbreaks are 'explained' by the airborne route. Taking both years together, the windborne dispersion of infectious material can account for some 85 per cent of all outbreaks.

(ii) *Preventive measures.*—A uniformly high standard of hygiene and animal husbandry would help and vaccines are now generally available. An alternative is to remove the virus particles from the atmosphere, but to do this would require a change in the ventilation systems of most of our present poultry houses.

Much depends on the particle size. Little elimination of particles of virus dimensions is likely to be achieved by conventional filtration or scrubbing techniques. Once inhaled, the particles, because of their dimensions, are unlikely to escape from the lungs and if 'soluble' they will have rapid access to the blood-stream. In the free atmosphere, the removal of such particles may be slow, being primarily dependent upon the processes of direct condensation, Brownian movement and impaction. Since, however, the viruses are more usually associated with larger dust particles, complete sterilization is likely to be obtained by an efficient air filtration system of the type employed in operating theatres and other places where airborne organisms are unwanted. Such an arrangement would imply a plenum ventilation system.

Sterilization of the incoming air by means of radio-active sources might also be considered.

The use of prophylactic aerosol sprays within the house does not appear to recommend itself. The capture of dust particles by the droplets from such a spray is probably only obtained by impaction, i.e. direct collision, and this process is not likely to be efficient. An evaporating droplet, in fact, repels dust particles.

**Acknowledgement.**—The author would like to thank Mr. G. Duncan, Veterinary Officer of the Ministry of Agriculture, Fisheries and Food, Bedford, for supplying information on the outbreaks.

#### REFERENCE

1. PASQUILL, F.; The estimation of the dispersion of windborne material. *Met. Mag., London*, 90, 1961, p. 33.

551.5:061.3

## SIXTEENTH SESSION OF THE EXECUTIVE COMMITTEE OF THE WORLD METEOROLOGICAL ORGANIZATION

By C. W. G. DAKING, B.Sc.

The sixteenth session of the Executive Committee, the first full session since Fourth Congress in April 1963, took place in the beautifully appointed Headquarters of the World Meteorological Organization (WMO) in Geneva from 26 May to 12 June, 1964. The President of the Organization, Dr. A. Nyberg of Sweden, in opening the session paid tribute to Dr. F. W. Reichelderfer, a past

President of WMO, and to Dr. P. D. McTaggart-Cowan both of whom had relinquished their membership of the Executive Committee since the previous session. The President then welcomed Dr. R. M. White, Dr. Reichelderfer's successor as Chief of the U.S. Weather Bureau and Mr. Elliot Coen, acting President of Regional Association IV, both of whom were now interim members of the Executive Committee. There was thus a full attendance of members, now 21, as approved by Fourth Congress and in addition, the Committee had the benefit of the presence of the Chairman (also the President of the Commission for Aerology (CAe)) of the WMO Advisory Committee, Dr. G. P. Cressman and Mr. A. Silva de Sousa, outgoing President of the Commission for Aeronautical Meteorology (CAeM). Representatives of the United Nations Educational, Scientific and Cultural Organization (UNESCO) were present for the discussion on the International Hydrological Decade.

Every effort had been made by the Secretary-General to reduce the agenda on this occasion and this enabled the Committee to complete its tasks in 16 days. In doing this it was helped considerably by the provision of interpretation and translation facilities, in the four working languages of WMO, i.e. English, French, Russian and Spanish as approved at Fourth Congress.

The highlights of the session were the detailed and prolonged work on the World Weather Watch and the New Development Fund, subjects which are closely interrelated. Discussions on these subjects lasted over several days and involved the study of many documents. They indicated an urgent need for work to be begun by the WMO Planning Unit on such questions as the location and functions of World and Regional Centres, global communications networks and observational systems. In this connexion a schedule for completion of the various phases of planning was drawn up which provides for completion of planning by February 1967 in time for the complete World Weather Watch implementation plan to be submitted to Fifth Congress. Resolutions on the subject of World Weather Watch covered such matters as the need to extend the use of the Automatic Picture Transmission system for satellite data, the desirability of obtaining data especially from sparse data areas through increased provision of aircraft reports, upper air observations from mobile ships and the use of horizontal sounding balloons tracked from the surface or by satellite. Both France and U.S.A. intend to carry out pilot projects in the southern hemisphere using horizontal sounding balloons for obtaining upper air data. WMO is to appeal to the International Air Transport Association and the International Civil Aviation Organization (ICAO) to make greater efforts to provide Members with aircraft reports particularly over oceanic and uninhabited areas now that aircraft are equipped with automatic navigation devices and have the ability to determine upper winds more accurately than in the past.

With regard to the New Fund, discussion centred on the plan for utilization and operation of the fund which had been approved in principle by Fourth Congress, for the development of meteorological organization leading to improved networks and communications ultimately benefitting all who depend on meteorological data for their work be it operational or research. A tentative programme for the Fourth Financial Period was drawn up which provisionally allocates the funds available as follows—one-half to improving facilities, i.e. networks and communications, one-tenth to education and training not qualifying for assistance under the United Nations (UN) programmes and

four-tenths to surveys and studies in connexion with the World Weather Watch, e.g. new observation techniques and global telecommunication systems. A great deal of the detailed work on this complex subject was done by a working group whose membership included the President, the Secretary-General, and Dr. White and Sir Graham Sutton. A Panel of the Executive Committee (EC) is scheduled to meet in October 1964 to examine proposals submitted for projects to be approved for 1965. All Regions are represented on this Panel whose membership includes the President and the two Vice-Presidents and M. André Viaut (France), Mr. W. J. Gibbs (Australia) and Sir Graham Sutton. The composite plan for operation of the New Fund as finally agreed by the EC (only one member dissenting) is to be forwarded to Members for their approval by postal ballot after which, it being assumed that a two-thirds majority in favour will be obtained, the Panel can get to work and set the machinery in motion for projects to be carried out in 1965.

Quite unexpectedly the subject of sessions of Technical Commissions and Regional Associations gave rise to fierce controversy. It having been agreed that as a host country for the Commission for Maritime Meteorology (CMM)-IV was not forthcoming, the Commission should meet in Geneva, the question of working languages was immediately raised and some argued that interpretation and documentation should be provided in all four working languages. Fourth Congress Abridged Report was quoted from freely both in Working Committees and at Plenary meetings but certain members remained unconvinced that Congress had provided funds for the use of the four working languages only at Congress and at sessions of the EC. In the end, it was agreed that the Secretary-General should take all possible steps with host countries and Members concerned to find means of alleviating the situation and should attempt to prepare a general scheme with regard to the use of four working languages taking into account budgetary implications and assessing the consequences both for WMO and for Members. The cost at the WMO Headquarters of interpretation and translation of all documents in four languages for a session of CMM lasting 15 days was estimated by the Secretary-General to be about £7500. It was therefore decided that at CMM-IV interpretation will be in two languages only, but that draft decisions and final decisions would be made available in four languages if required, all other documents being in two languages.

Considerable attention was devoted to clarification of certain of the General Regulations and during the discussion on this matter a most unfortunate discrepancy between the English and French texts in Article 13(a) of the Convention came to light. The English text includes the words "to conduct the activities of the Organization in accordance with *the intention of* such decisions"—that is, the decisions of Congress. The words in italics have been omitted from the French text. Various methods of remedying the situation were discussed but eventually it was decided to consult the legal expert who had assisted WMO in the revision of the Convention before Fourth Congress, and request him to consider the matter and report to the EC at its 17th session. The Working Group on the Convention set up by Congress is also to be informed of the matter and of the expert's opinion.

The Committee noted with great appreciation the first report of the WMO Advisory Committee established by Fourth Congress. Various parts of the

report were considered under relevant agenda items. The Committee endorsed the list of principal research projects which should be undertaken and prepared an 'action list' allocating follow-up action by Members, Technical Commissions, the Secretary-General and so on, as considered appropriate. This report contained a statement about the modification of weather and climate, to the effect that before large-scale modifications are attempted, the consequences must be predicted. This was endorsed by the EC and the President of CAe was requested to prepare a report on this subject. It transpired that recent events at a session of the Committee on Space Research (COSPAR) had emphasized the need for close co-ordination between WMO and other organizations concerned with the science of meteorology and a Resolution was passed which authorized the President to discuss with the President of the International Council of Scientific Unions (ICSU) arrangements for the co-ordination of the relevant programmes of WMO and ICSU. In order to achieve the objective desired it is probable that joint meetings between the WMO Advisory Committee and the relevant body or bodies of ICSU will be arranged.

Under the Technical Programme of the WMO the Committee discussed such matters as the plan for use of the WMO projects funds for the rest of the Fourth Financial Period, symposia to be supported during 1965, the financing of sessions of working groups in 1965 and scientific problems to be discussed at EC-XVII. With regard to symposia to be supported in 1965 the Secretary-General was requested to endeavour to organize a symposium on meteorological data processing and the Committee agreed to give substantial support to symposia on:

(a) Meteorological results of the International Indian Ocean Expedition (with UNESCO)—Bombay;

(b) Hydrological network design (with the International Association of Scientific Hydrology)—Canada;

(c) Polar meteorology (with the International Association of Meteorology and Atmospheric Physics);

and to various other projects, e.g. agrometeorology, comparison of instruments, and network and communications surveys.

The Committee considered that the scientific discussion held during its 16th session had been most beneficial—Numerical Weather Prediction and prospects for the future presented by Dr. Döös of the Swedish Meteorological Service—and agreed that further scientific subjects should be discussed at future sessions. The following two subjects were selected for the 17th session—

(a) the use of radar for assessments of areal rainfall

and (b) the synoptic use of meteorological satellite data and prospects for the future.

Fourth Congress approved the use of the International Meteorological Organization (IMO) Funds to pay an honorarium for a lecture to be delivered at each session of Congress. The EC having taken into account the fact that WMO is planning to have a global observation system, decided that the IMO lecture to be delivered at Fifth Congress should be devoted to the general circulation of the atmosphere. A list of three scientists who were to be invited, in order of priority, to prepare and present the lecture was drawn up by a Working Group and accepted by the Committee. The IMO Prize for 1964



was awarded to Dr. F. W. Reichelderfer, until October 1963, Chief of the U.S. Weather Bureau. Readers will recall that the 1963 recipient was Dr. R. C. Sutcliffe, Director of Research in the Meteorological Office.

With regard to the collection and processing of marine climatological data the Committee supported a Japanese proposal that each Responsible Member as defined in Resolution 35(Cg-IV) should publish the summaries relating to its area of responsibility at its own expense. The Secretary-General was requested to ask the Members concerned whether they would be willing to accept this task and provide the necessary funds.

The EC studied with interest the steps which have been taken since Fourth Congress towards the expansion of the training activities of the Organization. The Committee noted that in certain respects the implementation of the WMO plan for training of meteorological personnel in the developing countries of Africa had encountered difficulties which originated mainly from the lack of students with adequate qualifications who wished to take up meteorology as a profession. The Committee agreed that the question of meteorological training in Africa could be studied again at the next session of Regional Association I (Lagos, February 1965), in the light of the progress achieved, the difficulties encountered and the experience gained so far. The Secretary-General was therefore directed to submit to the fourth session of Regional Association I a full report on this question. The Committee considered that the immediate requirements of the developing countries should be met by training personnel at Class II level rather than persons of a high scientific standard (University graduates). It was mentioned that, as an interim measure, the training of Class II and III meteorologists should be carried out on a regional basis and within the region, while the training of Class I meteorologists could be provided by the countries having adequate facilities.

The Committee noted with appreciation the report of the Secretary-General on the action taken to implement the decision of Fourth Congress regarding the International Year of the Quiet Sun (IQSY) meteorological programme. It was decided that the WMO/IQSY Fund should be used for the publication of IQSY meteorological data which would not otherwise be published. The Secretary-General was requested to examine this matter and to bring forward specific proposals to a future session of the EC. The International Union of Geodesy and Geophysics (IUGG) representative spoke with appreciation of the speedy action taken by WMO in developing and introducing the STRAT-WARM scheme. He considered it very likely that scientists would wish to continue this scheme after the end of IQSY and suggested that a decision to this effect might be taken by the EC at its 17th session. The Committee decided to refer this suggestion to the President of CAE for consideration.

With regard to the International Hydrological Decade beginning in 1965, it was noted that the Intergovernmental Meeting of Experts convened by UNESCO in April 1964 had fully recognized that WMO would play an important role in the implementation of the Decade Programme. It was decided that WMO should concentrate on the following activities:

- (i) Preparation and distribution of guidance material on hydrometeorological practices including questions of standardization of instruments and methods of observation;

- (ii) Assistance to Members in the establishment and expansion of basic hydrometeorological networks and related services;
- (iii) Training of manpower required to meet the expansion of national hydrometeorological data gathering and other services;
- (iv) Promotion of research and widespread dissemination of hydrometeorological knowledge;

and that an EC Panel of Experts should be formed to consider and promote the programme of WMO participation in the Decade and to maintain, through the Secretary-General, close collaboration with the Co-ordinating Council of UNESCO for the Decade and with appropriate bodies of ICSU, so that WMO would be fully informed on developments of the whole project of the International Hydrological Decade.

Some attention was paid to questions concerning the structure and operation of WMO. The EC noted the report presented by the Standing Advisory Committee on Technical Matters on steps to improve the structure and operation of the Organization regarding scientific and technical matters. The Committee agreed that there was a need for speeding up the technical work of the Organization and that this question should be further studied with the following two purposes in view: (*a*) to improve the present machinery within the existing regulations and the WMO Convention; and (*b*) to prepare proposals for consideration by Fifth Congress. With regard to the immediate problem of improving the technical and scientific activities of WMO the EC agreed that there was a particular need for the preparation of guidance material in the following two fields: (*a*) planning and carrying out of symposia supported by WMO, and (*b*) establishment and activities of working groups of Regional Associations and Technical Commissions.

The EC examined separately the two volumes of the provisional final report of the Third Session of CAeM, and its decisions on the recommendations of the simultaneous meetings with the MET/OPS Divisions of ICAO have been included in three separate EC Resolutions. These contain a mass of detail but also some important questions of policy. Among the latter are approval by the EC for the setting up of a CAeM Working Group to consider procedures for compiling aviation forecasting techniques and practices and for highlighting subjects on which research is urgently needed, so that Members may consider subjects for their research programmes which have especial importance for aviation. The President of CAeM is to consider the research aspects in consultation with the President of CAe and to submit detailed terms of reference of the Working Group to the President of WMO for consideration prior to their approval. The joint meeting with ICAO had recommended that the exchange of upper air data up to 10 mb now in progress during the IQSY period should be continued after the IQSY ends so that data may accumulate for high levels for the purpose of carrying out preparatory studies necessary for the planning of supersonic operations. This proposal was supported and endorsed in a separate Resolution which is to be brought to the attention of all Members. The Committee supported the wish of the CAeM to meet in sessions, quite separate from, and as an additional feature to, the simultaneous meetings with the appropriate technical bodies of ICAO, as provided by the WMO/ICAO working arrangements. These separate sessions should not be split up in individual short meetings convened while the simultaneous meetings are in

progress. The separate sessions should be held immediately before or immediately after the simultaneous meetings, preferably after, and their duration could be of the order of one week. Their purpose would be to consider technical and scientific matters in the field of aeronautical meteorology, as distinct from procedural and organizational matters.

There was a disappointing development regarding Antarctic Meteorology. Fourth Congress had provided for the setting up of a Standing Committee on the Antarctic to deal with operational matters in that area. This Committee was to have acted as a Regional Association for the Antarctic. At the request of certain delegations at Congress, the relevant Resolution contained a clause which prevented the setting up of the Standing Committee until all Members of WMO which are signatories of the Antarctic Treaty had signified their approval. Unfortunately, at the meeting of the Antarctic Treaty Powers held in Brussels at the same time as EC-XVI, one delegation declined to give approval for the formation of a WMO Standing Committee for reasons which remain shrouded in mystery to the writer. It was decided that, in these circumstances, the EC should set up a Working Group whose terms of reference were virtually the same as agreed for the Standing Committee at Fourth Congress and that it should report to the EC with its recommendations on operational and research questions and that it should be composed of members nominated by the Permanent Representatives of countries which are signatories of the Antarctic Treaty.

This session of the EC was particularly arduous and heavy burdens fell on those members whose services are amongst the leading ones in the world, notably on Sir Graham Sutton who is one of the few 'elder statesmen' left on the Committee. His experience and knowledge of legal and administrative niceties pertaining to WMO enabled the Committee to extricate itself from some awkward situations. Towards the end of the session the weather became warm and very humid—conditions which were trying indeed for the Bracknell contingent, and also for some others used to high temperatures coupled with low dew-points. The Secretary-General and his staff worked with their customary skill in preparing the 118 documents for the session (in four languages). Somehow the translators, typists and duplicator operators managed to keep up to date—a commendable performance. Relaxation was provided on several occasions in the evenings thus enabling members and their advisers to reduce the tensions built up during some of the meetings. All the same it was good to touch down at London (Heathrow) Airport on the return journey after a quick and comfortable flight.

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## **NOTE ON WEATHER OBSERVATIONS AT EFFORD, LYMINGTON, HAMPSHIRE**

By O. S. WELFORD

One of the chain of Ministry of Agriculture, Fisheries and Food experimental horticulture stations is at Efford which is situated 2 miles north of the western end of the Solent, halfway between Southampton and Bournemouth. The site was chosen for its high light intensity which is of benefit to the culture of early tomatoes. However, a wide variety of vegetable crops is also grown, as well as the main types of soft fruits—strawberries, black currants, and raspberries. There

is also an area of apples and pears. Other crops such as chrysanthemums and lettuce are grown in glasshouses or in unheated Dutch-light structures and frames.

It can thus readily be appreciated that much depends on weather conditions, especially in the spring when the land is prepared for outdoor crops and also in midsummer when good weather is vital for soft fruit picking. Again, winter sunshine is important for the production of early tomatoes.

Weather observations have been taken daily at Efford since March 1953 thus giving continuous data for 11 years. General observation suggested that a study of the measurements might produce evidence of some interesting variations from long-term averages. Such departures if they persist may be of great importance to growers and also be of interest to meteorologists studying climate and to agricultural scientists and advisory officers of the National Agricultural Advisory Service.<sup>1</sup>

The Efford observations under review are those for January 1954 to December 1963, and the long-term averages used for comparison are the provisional rainfall averages for 1916–50 and the provisional averages of bright sunshine (for simplification referred to as sunshine) for 1931–60 for Efford, and provisional temperature averages for Bournemouth (Hurn) for 1921–50 as supplied by the Meteorological Office.

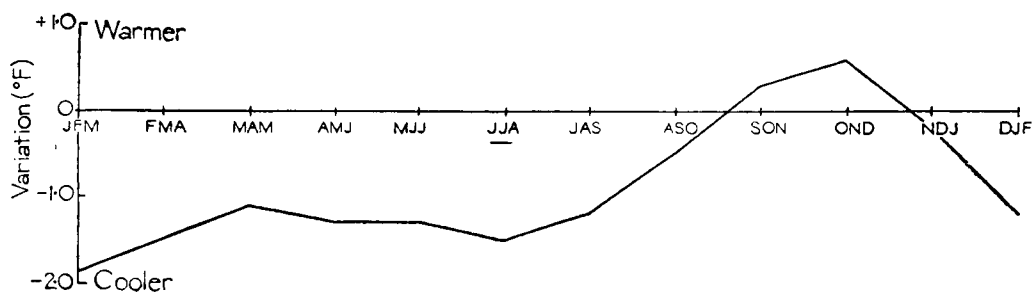
Table I shows for each month the mean daily temperature, the mean monthly rainfall and the mean daily hours of sunshine for the period 1954–63 compared with their respective long-term averages.

TABLE I—AVERAGES FOR EACH MONTH OF TEMPERATURE, RAINFALL AND SUNSHINE AT EFFORD COMPARED WITH THE LONG-TERM AVERAGES

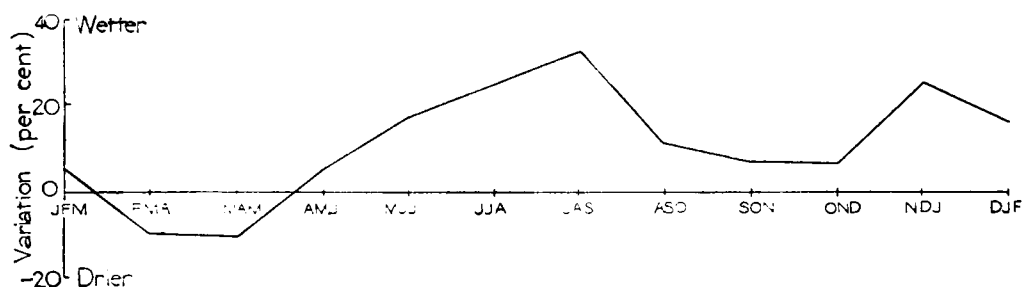
	Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean daily temperature (°F)	1921–50	40.9	41.1	44.5	48.5	53.4	59.0	62.5	62.4	58.8	52.1	45.5	41.5	50.9
	1954–63	39.0	38.8	43.3	47.5	52.3	57.8	61.0	60.7	58.2	52.9	46.0	42.0	50.0
Mean monthly rainfall (inches)	1916–50	2.3	2.1	2.1	1.7	1.8	1.8	1.9	2.3	2.2	4.0	3.0	3.0	28.2
	1954–63	3.3	1.8	1.9	1.6	1.7	2.3	2.2	3.0	3.1	3.2	3.6	3.7	31.3
Mean daily sunshine (hours)	1931–60	2.13	2.95	4.45	6.50	7.32	7.83	6.99	6.89	5.32	3.89	2.36	1.80	4.88
	1954–63	2.15	2.93	4.45	5.97	7.47	7.70	7.14	6.39	5.36	3.99	2.34	1.84	4.82

**Daily temperatures.**—In Figure 1(a) the 3-monthly moving averages of the Efford 10-year means are compared with those of the period 1921–50. This curve confirms the comparisons shown in Table I which show that the months January to September are cooler than expected. Once October comes into the reckoning the picture changes to show that the late autumn and early winter are warmer than average. The months showing the largest deviation from normal are February (2.3°F lower), July (1.5°F lower) and August (1.7°F lower). These serve to keep the January–March and February–April periods in the spring much cooler, by 1.9°F and 1.5°F, and in midsummer the June–August period is 1.5°F cooler. In contrast October shows an upward trend (0.8°F higher) as does November (0.5°F higher) and December (0.5°F higher). The periods from September to November and from October to December are therefore warmer than expected by 0.3°F and 0.6°F, respectively.

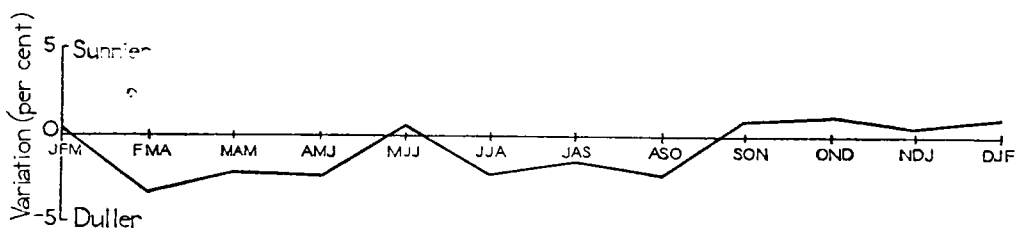
Extreme screen temperatures recorded over the 10-year period were 86°F maximum and 12°F minimum, with 10°F as the lowest grass minimum. These



(a) Temperature: variation in °F based on 3-monthly moving averages of mean daily temperature.



(b) Rainfall: percentage variation based on 3-monthly moving averages of mean monthly rainfall in inches.



(c) Sunshine: percentage variation based on 3-monthly moving averages of mean daily hours of sunshine.

FIGURE 1—VARIATION OF EFFORD 1954-63 AVERAGES FROM THE LONG-TERM AVERAGES

The long-term average is used as the zero line in each case. The months are identified by their initial letters.

minimum temperatures occurred on 26 January 1963, the grass minimum being over 4 inches of snow. The average frequencies of air and ground frost for each month are given in Table II. (On 1 January 1963 the definition of air frost was changed from a screen reading of '32°F or below' to 'below 32.0°F, and the definition of ground frost was changed on 1 January 1961 from a grass minimum reading of '30.4°F or below' to '32°F or below' and on 1 January 1963 to below 32°F'.)

TABLE II—AVERAGE MONTHLY FREQUENCY OF AIR AND GROUND FROST AT EFFORD (1954-63)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
	<i>average number of occasions</i>												
Air frost	14	11	7	2	0	0	0	0	0	1	4	8	47
Ground frost	17	14	12	7	2	0	0	0	0	2	7	12	73

Air frosts in May have occurred on two occasions only; in September air and ground frosts have been recorded once only during the 10 years.

Soil temperatures are recorded daily at depths of 4 inches, 8 inches and 2 feet, and Table III shows the monthly means at these depths. There are no long-term averages for comparison.

TABLE III—MEAN SOIL TEMPERATURES AT 0900 GMT AT EFFORD (1954-63)

Depth	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	<i>degrees Fahrenheit</i>											
4 inches	37.6	37.5	41.3	47.5	54.3	60.5	63.3	62.0	57.8	52.3	44.6	40.5
8 inches	38.7	38.4	42.2	47.6	54.2	59.5	62.6	61.6	58.3	52.7	45.8	41.6
2 feet	41.8	41.8	43.6	48.3	53.4	58.3	61.5	61.9	60.0	55.5	49.7	44.9

Extreme soil temperatures reached during the 10-year period were 22.9°F in January 1963 and 71.8°F in July 1959, both at the 4-inch depth. A study of the soil temperature figures shows that those at the 8-inch depth follow closely the average daily temperatures for each month at Efford (cf. Table I).

**Monthly rainfall.**—In Figure 1(*b*) an attempt has been made to express the variation of the 1954-63 average monthly rainfall from the long-term average as a percentage of the 1916-50 average. Using the 3-monthly moving averages of the latter period as a base, those of the Efford 10-year means are plotted as a percentage. The resulting curve confirms the impression given by the figures in Table I of a drier spring and a wetter summer than the long-term average.

The annual average increase of the Efford 10-year figure over that of 1916-50 is 11.1 per cent. The range of the Efford rainfall lies between 25.7 inches in 1962 to 46.2 inches in 1960. These extremes were spread over 141 days of rain (0.01 inches or more) in 1962 and 199 days in 1960. The average number of rain days per year is 151. The average number per month does not vary greatly from month to month. Even for the driest months February to May the average number is 11, while for the wettest ones, August to January, it does not exceed 15. Heavy falls occur generally in late autumn, but some may do so during thundery conditions in midsummer. Since 1954 the heaviest daily falls recorded were 2.46 inches on 19 October 1955 and 2.42 inches on 23 June 1960.

**Sunshine.**—Mean daily hours of sunshine in each month are shown in Table I. In Figure 1(*c*) the 3-monthly moving averages of the Efford monthly means have again been used for comparison with those of the 1931-60 long-term ones. Using the latter as the base the former are expressed as a percentage, giving a curve similar in general shape to the rainfall one of Figure 1(*b*) but with a less pronounced deviation from the long-term average. But, even so, it may be seen that though the spring months are drier than expected they are surprisingly duller, a result which is probably related to the tendency to dry easterly winds at this season. A further interesting trend is for the winter months, though wetter than average, to be sunnier than expected. This latter fact is very important for glasshouse crops where light intensity is a limiting factor, for example in the production of early tomatoes. Experience at Efford has also shown that the drier, cooler and duller than average springs have created conditions for land preparation for seed sowing which have proved more difficult than expected.

This short review of the weather data at Efford Experimental Horticulture Station seeks to show trends which may or may not persist. It is hoped that it may provide a basis for further study.

**Acknowledgements.**—The author is indebted to Mr. W. H. Hogg, Senior Meteorological Officer of the National Agricultural Advisory Service, Bristol, for his advice on the presentation of the data and to the observers at Efford, Messrs. Bullock, Cheston, Slater and Lewis for their assistance.

#### REFERENCE

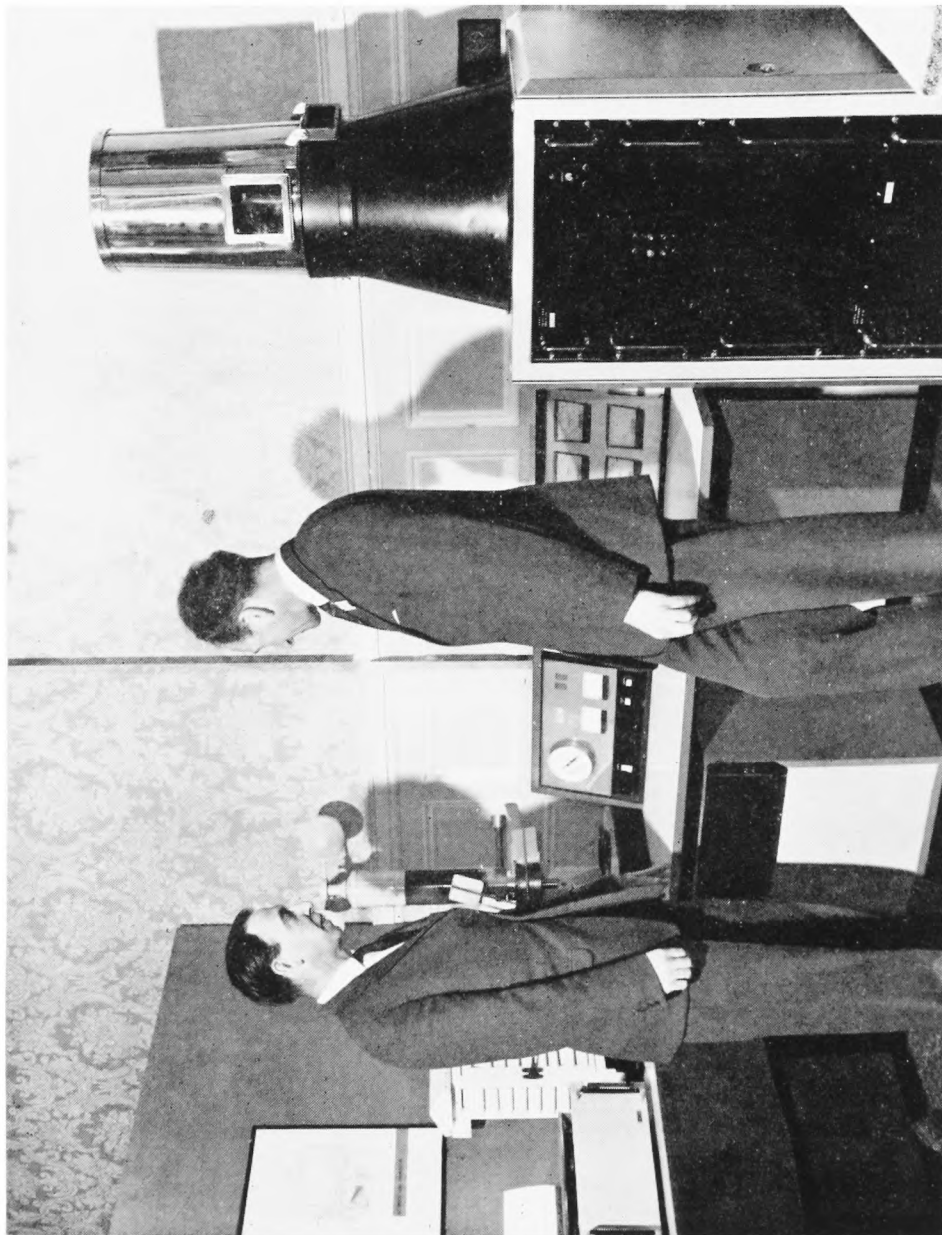
1. SMITH, L. P.; Progress report on agricultural meteorology. *N.A.A.S. Quart. Rev., London*, No. 62, 1963, p. 81.



*Photograph by R. K. Pilsbury*

**PLATE I—THE AUXILIARY REPORTING STATION AND KEY CLIMATOLOGICAL STATION  
OF ROSS-ON-WYE WHICH BEGAN REPORTING IN 1859**

Pictured above is Mr. Parsons to whom we send our congratulations on completion this year of 50 years of observing work and our thanks for the excellent contribution he has made to our meteorological records.



*Photograph by courtesy of EMI Electronics Ltd.*

**PLATE II—THE AUTOMATIC WEATHER STATION AT EMI ELECTRONICS' SYMPOSIUM  
AND EXHIBITION IN LONDON, 26-28 MAY 1964**

Dr. N. E. Rider (left) of the Meteorological Office, Bracknell, and Dr. Karl Newman of EMI Electronics Ltd's telemetry division discussing the automatic weather station which attracted so much interest at the exhibition.





*Photograph by J. Paton*

PLATE III—TURBULENCE AT 80 KM SHOWN BY NOCTILUCENT CLOUD, 0214 GMT,  
25 JULY 1950

Previously a brilliant aurora accompanied the cloud which remained stable until about 0206 GMT when this 'fuming' began.

*To face p. 273*



*Photograph by courtesy of BEA*

**PLATE IV—PRESENTATION OF METEOROLOGICAL OFFICE AWARDS AT THE HEAD-  
QUARTERS OF THE GUILD OF AIR PILOTS AND AIR NAVIGATORS ON 15 JULY 1964**

Dr. A. C. Best, C.B.E., Director of Services of the Meteorological Office presenting a brief case to Captain R. P. Ellis of BEA (see page 285).

## FORECASTING DRY SPELLS OF THREE DAYS OR MORE IN SOUTH-EAST ENGLAND FROM NOVEMBER TO APRIL

By C. A. S. LOWNDES

**Introduction.**—In a recent paper<sup>1</sup> it was shown that the highest proportion of the dry spells at London which occur in the months November to April is associated with a spread of high pressure from the south-west or west of the British Isles and that many of the longer spells are associated with a spread of high pressure from the north-east or east, particularly in the five months November to March. In an earlier paper<sup>2</sup> the synoptic types associated with dry spells at London were classified into Types I to IX and for the months May to October rules were described<sup>3</sup> for forecasting dry spells at London and in south-east England associated with a spread of high pressure from the south-west of the British Isles (Type V). The basic predictors were a mobile upper trough between 60°W and 50°W and surface pressure above normal at the Azores. It was decided, in the first instance, to determine whether similar predictors were applicable in the winter months. It became clear from a study of 500-millibar troughs between 70°W and 40°W that, as in the summer months, many of the Type V spells began one or two days after a trough became situated between 60°W and 50°W. Many of the spells associated with a spread of high pressure from the north-east of the British Isles (Type I) also began one or two days after an upper trough became situated between 60°W and 50°W. The two synoptic evolutions were as follows:

*Model SW.*—The upper trough between 60°W and 50°W generally progressed across the Atlantic at about 10 degrees of longitude per day and weakened. At the same time, a surface high moved from south-west of the British Isles to the region of the British Isles.

*Model SW-NE.*—The upper trough between 60°W and 50°W generally progressed at 10 to 20 degrees of longitude per day and rapidly weakened. At the same time, a surface high moved from the Azores region towards the British Isles, losing its identity as it linked across the British Isles with a high over Scandinavia. The high over Scandinavia then moved to a position to the east or south-east of the British Isles with a ridge persisting over the British Isles.

In forecasting either model, the surface pressure level at the Azores was not a sufficiently precise predictor and the position and central pressure of the surface high were used. It was found necessary to invoke further predictors, in particular a measure of the zonal flow across the Atlantic (zonal index).

**Data extracted.**—For the 14 years 1949 to 1962, all occasions when a 500 mb trough was situated between 60°W and 50°W were noted and the following data extracted. All upper air data were obtained from 500 mb charts.

(i) *Upper air data.*—

- (a) The maximum negative height anomaly at 45°N on the trough axis between 60°W and 50°W.
- (b) The latitude of the centre of the belt of flow around the base of the trough.
- (c) The latitude at which the flow on the eastern flank of the trough changed from a south-westerly to a south-easterly (if applicable).
- (d) The spacing from the trough between 60°W and 50°W to the next upwind trough.

(e) The 500 mb height at Lajes (Azores) minus that at Keflavik (Iceland) (a measure of the zonal index).

(ii) *Surface data.*—(a) The position and central pressure of all surface highs with a central pressure of 1020 mb or more in the Atlantic–European sector between longitudes 50°W and 50°E and from latitude 20°N to 70°N. (The central pressure of the high was taken to be that of the closed isobar nearest the centre with isobars at 4 mb intervals).

(b) The dates of the beginning and end of all dry spells of three days or more in south-east England. A dry spell was defined as a period when none of a group of 11 stations in south-east England, for which 12-hour totals of precipitation are given in the *Daily Weather Report*, had more than a trace of precipitation. The 7 stations, Kew, London Airport, Felixstowe, Gorleston, Mildenhall, West Raynham, and Boscombe Down were available throughout the 14-year period. The other 4 varied but came from the following group of 9 stations: Thorney Island, Hurn, Lympne, Tangmere, Calshot, Cranfield, Gatwick, Cardington and Wittering. On a few occasions, when it was clearly illogical to split a dry spell, a small amount of precipitation over a short period was allowed. This usually involved up to 0.2 millimetres provided by moist airstreams from the sea affecting coastal stations or by wet fog at night.

**Model SW: the critical values of the predictors.**—For Model SW, a study was made of occasions when a 500 mb trough was situated between 60°W and 50°W and at the same time a surface high was situated in an area between longitudes 50°W and 5°W and latitudes 20°N to 70°N (see Figure 5).

*The intensity of the trough between 60°W and 50°W.*—The intensity of the trough between 60°W and 50°W was not critical. Dry spells which began within three days were associated with troughs with negative anomalies at 45°N ranging from 3 decametres in April to 37 decametres in January. However, some very flat troughs were not associated with dry spells. On these occasions, as in the summer months, the flow around the base of the upper trough was centred north of 46°N. For troughs associated with dry spells, the flow around the base of the trough was centred south of 47°N for the months November to March and south of 49°N for April.

*The flow on the eastern flank of the trough.*—The flow ahead of troughs which were associated with dry spells was usually south-westerly or south-south-westerly. On occasions when the flow became south-easterly, south of latitude 53°N, no dry spell followed. Examples of this type of trough are shown in Figures 1 and 2. The 500 mb chart for 1200 GMT on 3 January 1959 (Figure 1) shows the trough associated with a classic blocking system and the flow ahead of the trough becoming south-easterly at 50°N. On this occasion, the block persisted in much the same position for several days. An intense surface high persisted over Greenland, a surface high south-west of the British Isles moved to Spain, and the British Isles remained under the influence of a cyclonic northerly type. The 500 mb chart for 1500 GMT on 22 January 1952 (Figure 2) shows the flow ahead of the trough becoming south-easterly at 49°N. On this occasion, an intense surface high rapidly developed over southern Greenland and a surface high north of the Azores made no progress towards the British Isles, which remained under the influence of a northerly cyclonic type.

*The spacing to the next upwind trough.*—On occasions when a dry spell followed within three days, the spacing from the trough between 60°W and 50°W to the

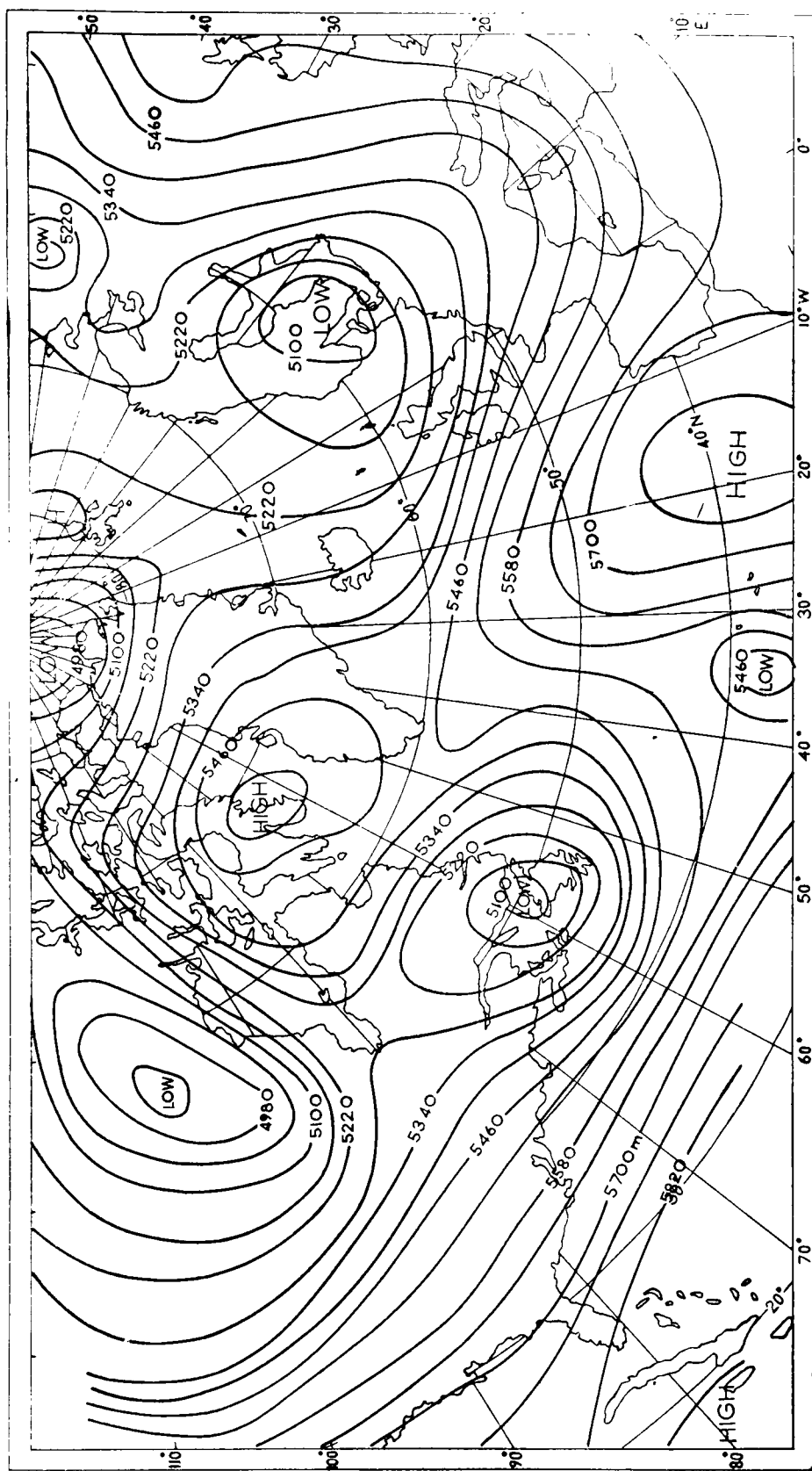


FIGURE 1—THE FLOW ON THE EASTERN FLANK OF THE TROUGH  
500 mb contours at 1200 GMT on 3 January 1959

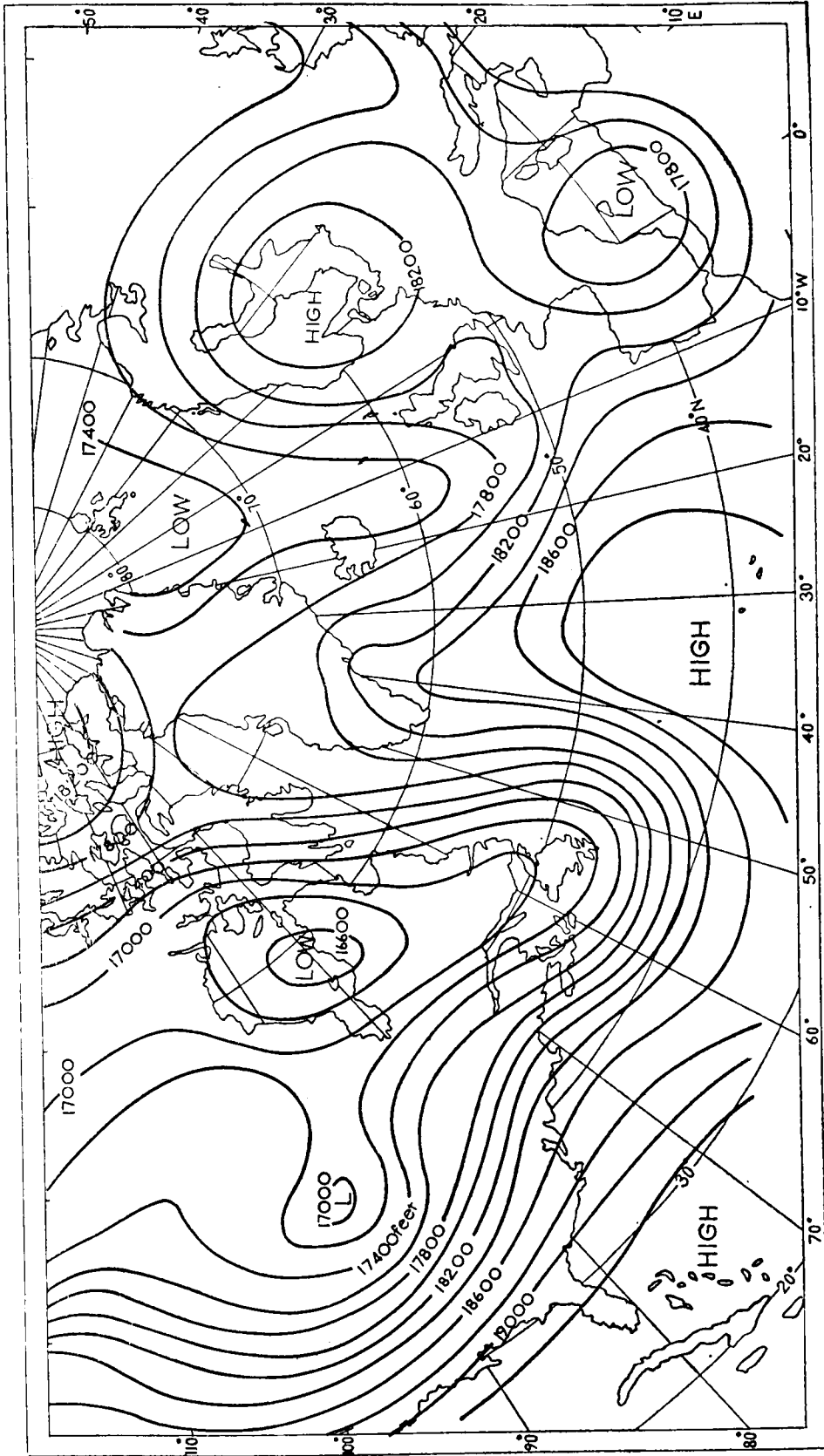


FIGURE 2—THE FLOW ON THE EASTERN FLANK OF THE TROUGH  
500 mb contours (feet) at 1500 GMT on 22 January 1952

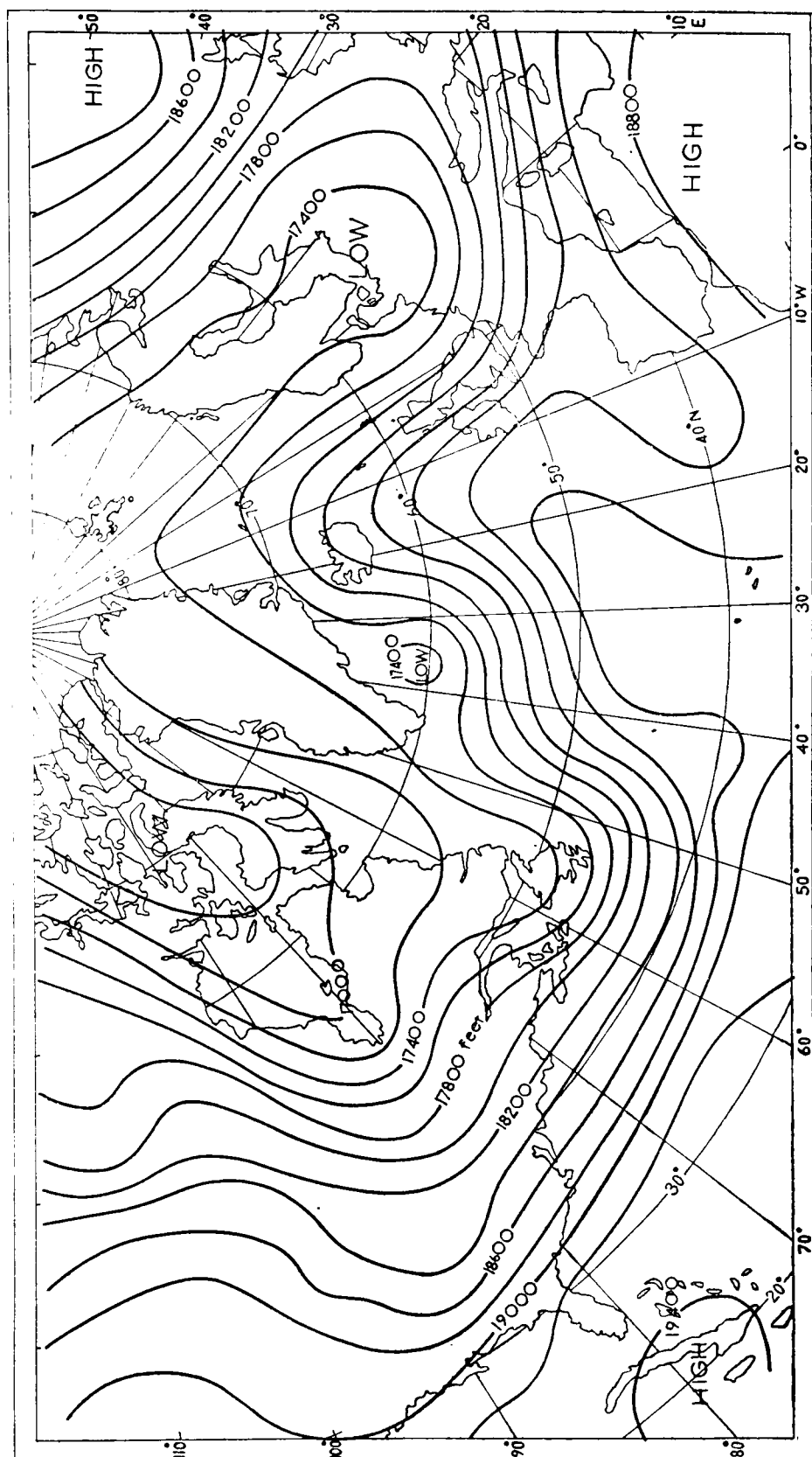


FIGURE 3--THE SPACING TO THE NEXT UPWIND TROUGH  
500 mb contours (feet) at 1500 GMT on 11 November 1952

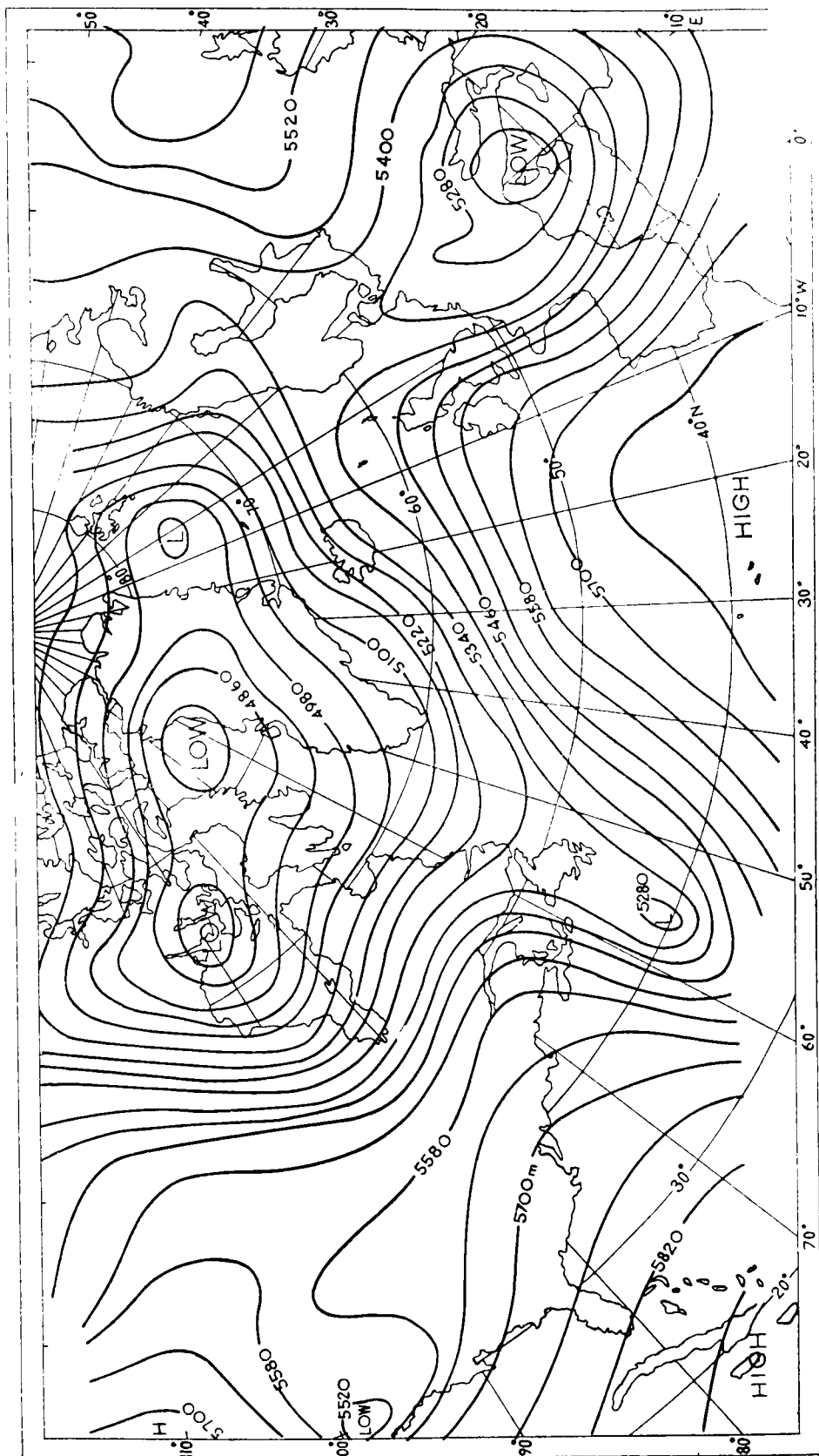


FIGURE 4—THE SPACING TO THE NEXT UPWIND TROUGH  
500 mb contours at 0000 GMT on 13 January 1958



next upwind trough was  $32^\circ$  of longitude or more. On many occasions when no dry spell followed, the spacing was less than  $30^\circ$ . Examples of this type of situation are shown in Figures 3 and 4. The 500 mb chart for 1500 GMT on 11 November 1952 (Figure 3) shows the trough between  $60^\circ\text{W}$  and  $50^\circ\text{W}$  closely followed by another trough less than  $30^\circ$  upwind. During the following 48 hours, the trough between  $60^\circ\text{W}$  and  $50^\circ\text{W}$  ran forward quickly as a weak feature to north of Iceland and the following trough replaced it between  $60^\circ\text{W}$  and  $50^\circ\text{W}$ . A surface high north of the Azores was stationary and fronts associated with a depression near Iceland crossed the British Isles bringing rain. The 500 mb chart for 0000 GMT on 13 January 1958 (Figure 4) again shows a second trough less than  $30^\circ$  upwind with the trough between  $60^\circ\text{W}$  and  $50^\circ\text{W}$  partially cut off. Within 36 hours, the trough had almost completely cut off in low latitudes with the main flow around a shallow trough at  $50^\circ\text{W}$  in high latitudes. A surface high moved from the Azores to a position south-west of the British Isles, intensifying from 1028 to 1040 mb, but fronts associated with depressions which moved across Iceland to Spitsbergen swung south-eastwards across the British Isles bringing some rain to most districts.

*The zonal flow across the Atlantic (zonal index).*—A measure of the zonal flow across the Atlantic, when the trough was situated between  $60^\circ\text{W}$  and  $50^\circ\text{W}$ , was found to be a useful predictor. The index used was the 500 mb height at Lajes in the Azores minus that at Keflavik in Iceland. On nearly all occasions when a dry spell occurred, the zonal index was less than 60 decametres. On occasions when the index was 60 or more, the surface high to the south-west of the British Isles often extended a ridge over France or Spain with cyclonic westerlies bringing rain to the British Isles.

*The orientation of the surface high.*—On five occasions when other factors were favourable and no dry spell occurred, the surface high to the south-west of the British Isles was elongated in a north-south direction.

**Model SW: a summary of the critical values of the predictors.—**

- (i) The flow around the base of the trough between  $60^\circ\text{W}$  and  $50^\circ\text{W}$  must be centred south of  $47^\circ\text{N}$  ( $49^\circ\text{N}$  for April).
- (ii) The flow ahead of the trough must not become south-easterly, south of latitude  $53^\circ\text{N}$ .
- (iii) The spacing to the next upwind trough must not be less than  $30^\circ$  of longitude.
- (iv) The zonal index must be less than 60 decametres.
- (v) The surface high must not be elongated in a north-south direction.

Including only those occasions when the above conditions were satisfied, a diagram was plotted (Figure 5) showing the positions of surface highs with a central pressure of 1020 mb or more. If a dry spell of three days or more began within three days, a dot was plotted. A dry spell of two days was indicated by a dot within a circle. If no dry spell began within three days, a cross was plotted. The numbers next to the plots are the last two figures of the central pressure of the high in millibars. Occasions when a dry spell was associated with Model SW-NE are not included. An area enclosing many of the dry-spell plots is shown to the south-west of the British Isles. All of the highs within the area which were associated with dry spells of three days or more had a central pressure of 1028 mb or more. Of the 30 dry spells of three days or more associated with the highs within the area, 3 began on the same day that the trough

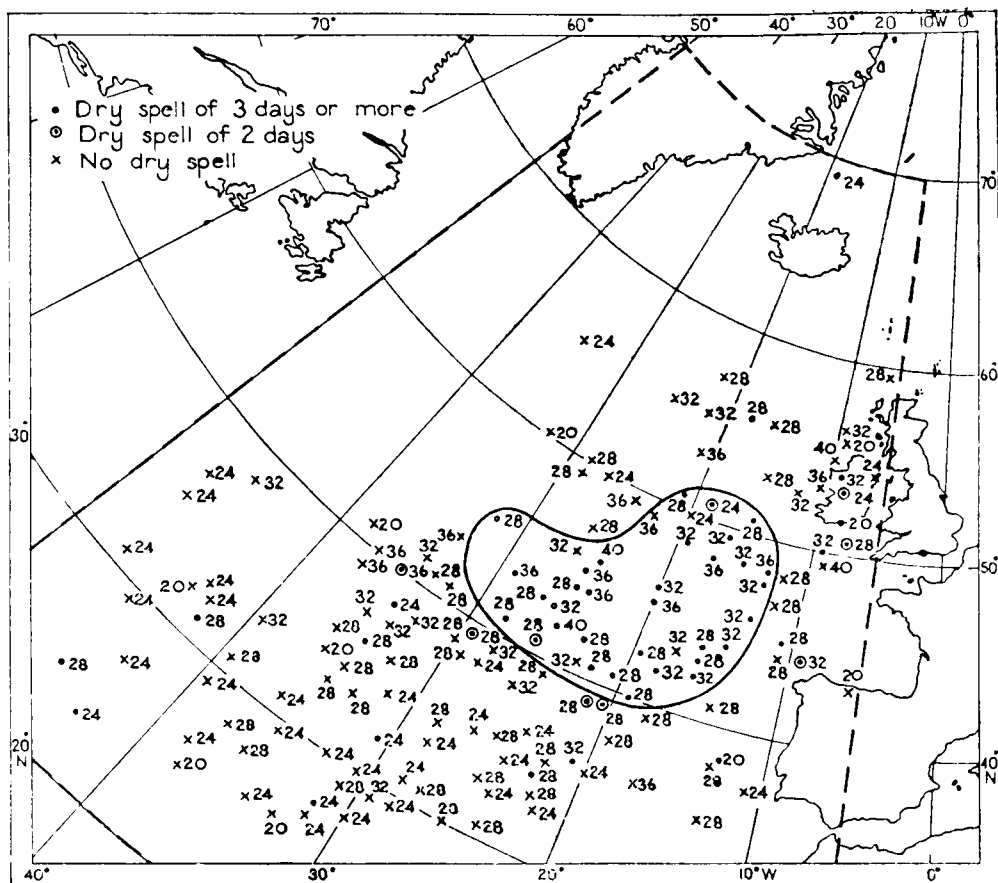


FIGURE 5—MODEL SW: POSITION AND INTENSITY OF SURFACE HIGHS  
The central pressures of the surface highs are given in mb omitting the first two figures.

reached longitudes  $60^{\circ}\text{W}$  to  $50^{\circ}\text{W}$ , 12 began one day later, 12 began two days later and 1 began three days later. Two spells had begun already and continued for a further three days. One high was associated with a continuation for a further three days of 1 of the 30 spells. There were four occasions when a high of 1028 mb or more within the area was not associated with a dry spell, two of which were in December. As none of the occasions when a dry spell followed was in December, there is no evidence that Model SW is of use in this month.

**Model SW: the tracks taken by the surface highs.**—Figure 6 shows the tracks taken by the surface highs from their initial positions within the specified area to their positions three days later. The highs generally moved in a north-easterly direction over or to the south of the British Isles. After three days, most of the highs were positioned east or south-east of the British Isles, some over the British Isles and a few to the south or south-west. The tracks of two highs are not shown. On one occasion in April after a small depression had moved south-eastwards across the British Isles, a high formed to the north-west and moved over the British Isles linking with the high which had persisted to the south-west. On the other occasion, also in April, the high to the south-west moved towards the British Isles and weakened as a new high formed to the north of the British Isles.

**Model SW: the effect of a second surface high in the Atlantic-European sector.**—On 18 of the 30 occasions there was no other surface high in the Atlantic-European sector. On 4 occasions another high was situated

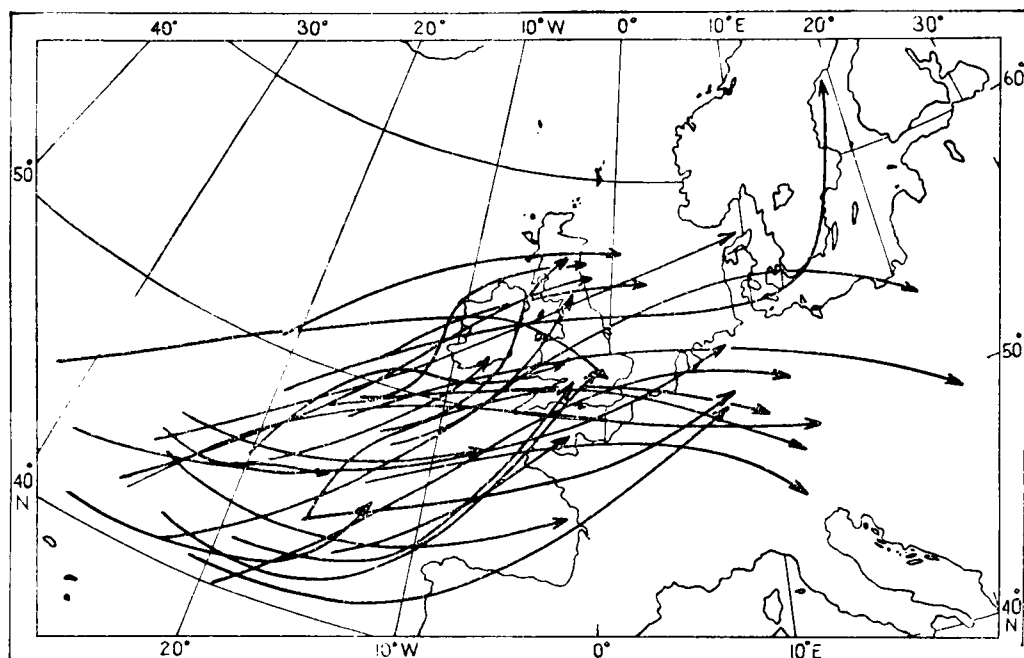


FIGURE 6—MODEL SW: TRACKS OF SURFACE HIGHS OVER THREE DAYS

over Russia, on 2 occasions over France and on 1 occasion over Scandinavia, the Baltic states, the Balkans, Italy, to the north of the British Isles and to the west of the British Isles. The high to the south-west of the British Isles lost its identity by linking with the other high on only 2 occasions. On 1 occasion the high to the south-west linked with a high over Scandinavia, transferring the centre of high pressure to the British Isles and on the other occasion merged with a high to the west before moving across the British Isles.

On 1 occasion when other factors were favourable and no dry spell occurred, a second high was centred near Iceland.

**Model SW: rules for forecasting dry spells in south-east England in November and from January to April.—**

(i) Take note of each chart on which a 500 mb trough is situated between  $60^{\circ}\text{W}$  and  $50^{\circ}\text{W}$ .

(ii) If a surface high with a central pressure of 1028 mb or more is situated within the specified area to the south-west of the British Isles (see Figure 5) a dry spell is likely to begin in south-east England within one or two days. Occasionally, the dry spell may have begun already and a continuation for a further three days is likely. This procedure applies provided that (a) the flow around the base of the trough is centred south of  $47^{\circ}\text{N}$  ( $49^{\circ}\text{N}$  for April), (b) the flow ahead of the trough does not become south-easterly in a latitude south of  $53^{\circ}\text{N}$ , (c) the spacing to the next upwind trough is not less than  $30^{\circ}$  of longitude, (d) the zonal index is less than 60 decametres, (e) the surface high is not elongated in a north-south direction and (f) another high is not situated in the region of Iceland. Another high may be situated in any other part of the Atlantic-European sector.

**Model SW-NE: the critical values of the predictors.—**For Model SW-NE, a study was made of occasions when a 500 mb trough was situated between  $60^{\circ}\text{W}$  and  $50^{\circ}\text{W}$  and at the same time a surface high was positioned

in an area between longitudes  $50^{\circ}\text{W}$  and  $5^{\circ}\text{W}$  and latitudes  $20^{\circ}\text{N}$  to  $50^{\circ}\text{N}$  and another high in an area between longitudes  $5^{\circ}\text{W}$  and  $50^{\circ}\text{E}$  and latitudes  $50^{\circ}\text{N}$  to  $70^{\circ}\text{N}$  (see Figure 7).

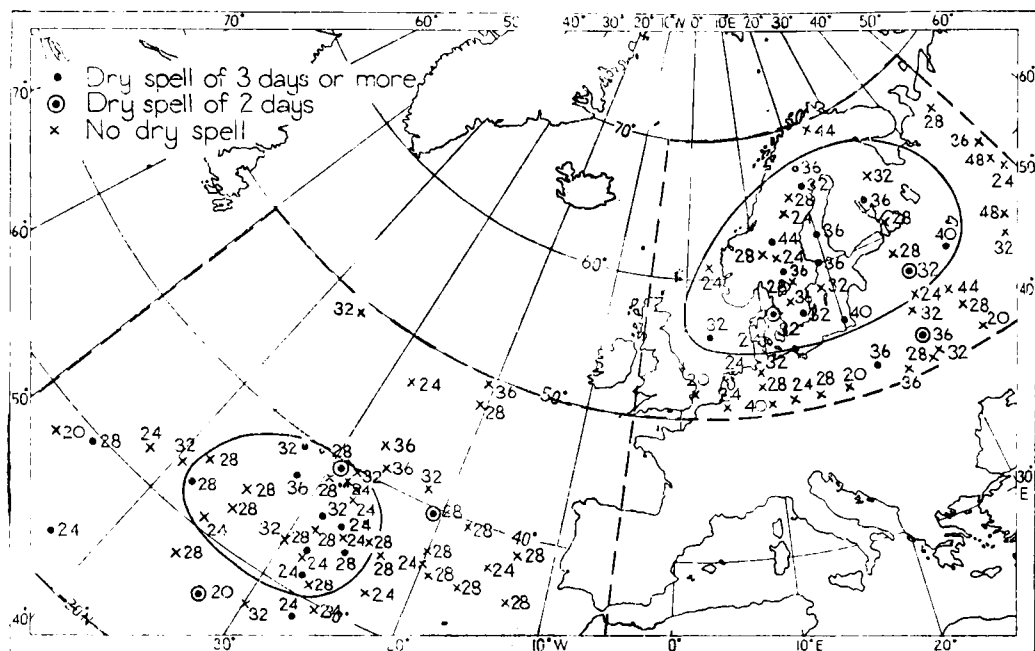


FIGURE 7—MODEL SW-NE: POSITION AND INTENSITY OF SURFACE HIGHS  
The central pressures of the surface highs are given in mb omitting the first two figures.

*The intensity of the trough between  $60^{\circ}\text{W}$  and  $50^{\circ}\text{W}$ .*—The intensity of the trough was not very critical. Dry spells were associated with troughs with negative anomalies at  $45^{\circ}\text{N}$  ranging from 9 decametres for April to 31 decametres for January. However, some flat troughs were not associated with dry spells. On these occasions, the flow around the base of the trough was centred between  $44^{\circ}\text{N}$  and  $52^{\circ}\text{N}$ . For troughs associated with dry spells, the flow was centred between  $36^{\circ}\text{N}$  and  $43^{\circ}\text{N}$ .

*The east-west spacing between the surface highs.*—On occasions when a dry spell followed, the east-west spacing between the high to the south-west of the British Isles and the high to the north-east varied between  $32^{\circ}$  and  $68^{\circ}$  of longitude. On 4 occasions when no dry spell occurred, the spacing was  $74^{\circ}$  or more.

#### **Model SW-NE: a summary of the critical values of the predictors.—**

(i) The flow around the base of the trough between  $60^{\circ}\text{W}$  and  $50^{\circ}\text{W}$  must be centred south of  $44^{\circ}\text{N}$ .

(ii) The east-west spacing between the surface highs to the south-west and north-east of the British Isles must be less than  $70^{\circ}$  of longitude. Including only those occasions when the above conditions were satisfied, a diagram was plotted (Figure 7) showing the positions of surface highs with a central pressure of 1020 mb or more.

Occasions when a dry spell associated with Model SW followed are not included. Most dry-spell plots fall within the smaller areas indicated. Figure 8 shows the areas modified to include only those occasions when one high was

situated in one area and one in the other. The dry spells of three days or more were associated with a high of 1032 mb or more in the north-east area and a high of 1024 mb or more in the south-west area. Of the 7 dry spells of three days or more associated with the highs, 2 had already begun and continued for a further three days after the trough reached longitude  $60^{\circ}\text{W}$  to  $50^{\circ}\text{W}$ , 3 began one day later and 2 began two days later. One occasion was associated with a continuation for a further three days of one of the 7 spells. On one occasion in December when a high of 1032 mb was situated in each area, no dry spell followed. As none of the occasions when a dry spell followed was in December, there is no evidence that Model SW-NE is of use in this month.

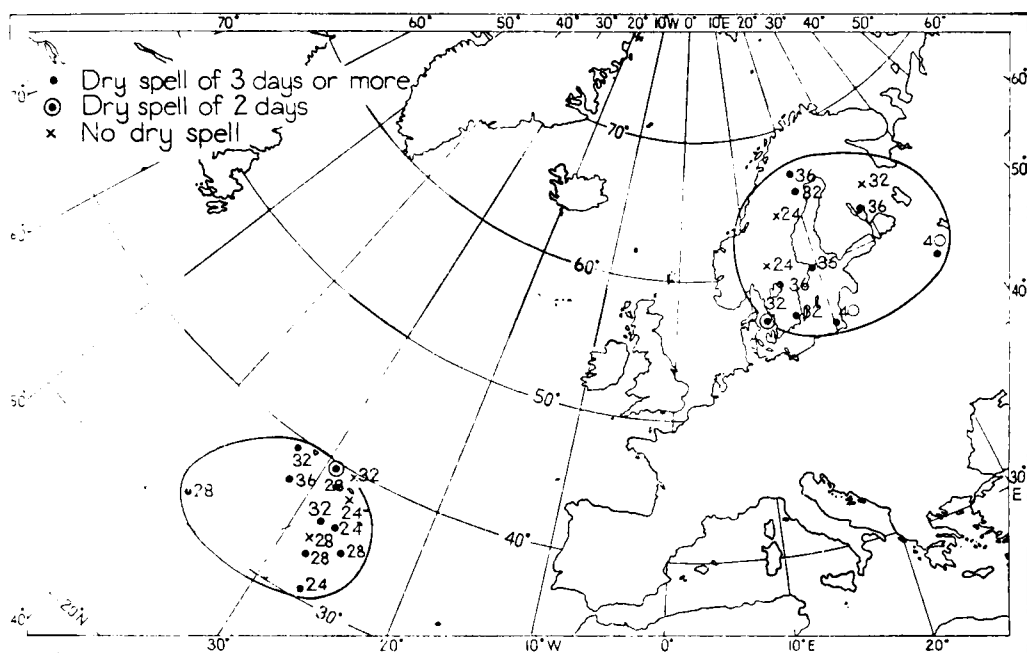


FIGURE 8—MODEL SW-NE: POSITION AND INTENSITY OF SURFACE HIGHS ON OCCASIONS WHEN A HIGH WAS SITUATED IN EACH AREA AT THE SAME TIME

The central pressures of the surface highs are given in mb omitting the first two figures.

**Model SW-NE: the effect of a third surface high in the Atlantic-European sector.**—On all occasions associated with a dry spell of three days or more, there was no third surface high in the Atlantic-European sector. On one occasion, associated with a dry spell of only two days, there was a complex high to the east of the British Isles with a small surface high cell over Scandinavia and the main cell of the same intensity over the Balkans.

On one occasion when other factors were favourable and no dry spell occurred, a third high was situated to the west of the British Isles.

**Model SW-NE: rules for forecasting dry spells in south-east England in November and from January to April.**—

- (i) Take note of each chart on which a 500 mb trough is situated between  $60^{\circ}\text{W}$  and  $50^{\circ}\text{W}$ .
- (ii) If a surface high with a central pressure of 1024 mb or more is situated in the south-west area and a high with a central pressure of 1032 mb or more is situated in the north-east area (Figure 8) a dry spell of three

days or more is likely to begin in south-east England within one or two days. On other occasions, the dry spell may have begun already and a continuation of at least three days is likely.

This procedure applies provided that (a) the flow around the base of the trough is centred south of 44°N, (b) the east-west spacing between the surface high to the south-west and the high to the north-east is less than 70° of longitude, (c) the high in the north-east area is not part of a complex high with the main cell to the south of the area and (d) a third high is not situated to the west of the British Isles.

**The proportion of dry spells forecast.**—Table I shows the number of spells of three days or more which actually occurred during the period 1949 to 1962 with figures in brackets indicating the number which would have been forecast by the two models.

TABLE I—THE NUMBER OF DRY SPELLS WHICH OCCURRED AND THE NUMBER

Synoptic type	FORECAST (1949 TO 1962)								Total
	I(NE)	II(E)	III(SE)	IV(S)	V(SW)	VI(W)	VII(NW)	VIII(N)	
	<i>number of spells</i>								
November	1(1)	2(0)	1(0)	—	4(4)	5(0)	—	—	13(5)
December	2(0)	1(0)	1(0)	2(0)	1(0)	2(0)	—	—	9(0)
January	2(1)	3(1)	1(0)	1(0)	4(4)	2(1)	1(0)	1(0)	15(7)
February	2(0)	1(1)	3(0)	1(0)	3(2)	1(0)	2(0)	—	13(3)
March	3(2)	2(0)	—	2(0)	6(4)	2(1)	2(0)	2(0)	19(7)
April	2(2)	1(0)	1(0)	—	13(12)	1(0)	4(1)	—	22(15)
Total	12(6)	10(2)	7(0)	6(0)	31(26)	13(2)	9(1)	3(0)	91(37)

Figures in brackets indicate the number of spells which would have been forecast by the two models.

The rules would have forecast 26 of the 31 Type V dry spells of three days or more which actually occurred and 6 of the 12 Type I spells. They would also have forecast 2 of the 10 Type II spells, 2 of the 13 Type VI spells and 1 of the 9 Type VII spells. Of the 91 spells of all types 37 would have been forecast. A forecast of a dry spell of three days would have been wrong on four occasions though on two of them the weather was dry for two days.

Table II shows the number of spells of three days or more which actually occurred in each individual year with figures in brackets indicating the number which would have been forecast.

TABLE II—THE NUMBER OF DRY SPELLS WHICH OCCURRED AND THE NUMBER

Synoptic type	FORECAST IN INDIVIDUAL YEARS								Total
	I(NE)	II(E)	III(SE)	IV(S)	V(SW)	VI(W)	VII(NW)	VIII(N)	
	<i>number of spells</i>								
1949	1(0)	—	2(0)	—	4(4)	—	1(0)	—	8(4)
1950	—	1(0)	1(0)	—	4(3)	—	1(0)	—	7(3)
1951	—	2(1)	—	—	—	1(0)	—	—	3(1)
1952	—	—	—	1(0)	1(1)	2(0)	1(0)	—	5(1)
1953	1(1)	1(0)	3(0)	—	2(2)	1(0)	—	—	8(3)
1954	1(1)	1(0)	—	1(0)	3(2)	—	—	2(0)	8(3)
1955	1(0)	1(0)	—	—	1(1)	2(1)	1(0)	—	6(2)
1956	1(1)	—	—	—	4(4)	1(0)	1(0)	—	7(5)
1957	2(1)	2(0)	—	1(0)	—	1(0)	1(0)	—	7(1)
1958	2(2)	—	—	—	3(3)	—	1(0)	1(0)	7(5)
1959	—	2(1)	—	—	4(3)	2(1)	—	—	8(5)
1960	1(0)	—	—	1(0)	—	—	1(1)	—	3(1)
1961	2(0)	—	1(0)	1(0)	2(2)	2(0)	—	—	8(2)
1962	—	—	—	1(0)	3(1)	1(0)	1(0)	—	6(1)
Total	12(6)	10(2)	7(0)	6(0)	31(26)	13(2)	9(1)	3(0)	91(37)

Figures in brackets indicate the number of spells which would have been forecast.

The two models would have been of most use in 1956, 1958 and 1959 when 5 spells in each year would have been forecast. They would have been of least use in 1951, 1952, 1957, 1960 and 1962 when only 1 spell a year would have been forecast.

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#### NOTES AND NEWS

##### **Meteorological Office awards to captains and navigators of civil aircraft**

At the headquarters of the Guild of Air Pilots and Air Navigators in South Street, Mayfair on Wednesday 15 July, two senior pilots received presentation briefcases for their long and meritorious service in the provision of weather reports from aircraft. The awards go to Captain T. M. Bulloch, D.S.O., D.F.C., commander of Boeing 707 flights with BOAC, and Captain R. P. Ellis, of the BEA Vanguard fleet (see Plate IV).

Both Captain Bulloch and Captain Ellis started their air careers with the Royal Air Force. Ulster-born Captain Bulloch, aged 48 and living at Burnham, Bucks, is a Master Air Pilot of almost 30 years' flying experience. He served with Coastal Command on U-boat hunting over the Atlantic and had five confirmed sinkings to his credit before joining BOAC in 1945.

Captain Ellis, also a Master Air Pilot, is 49 and lives at Ruislip, Middlesex. He joined BEA in 1946 after six years' war service and is today a Senior Captain 1st Class of the Vanguard fleet flying the Line's domestic trunk routes. He is an Upper Freeman of the Guild of Air Pilots and Air Navigators.

Dr. A. C. Best, C.B.E., Director of Services, Meteorological Office, presented the briefcases on behalf of the Director-General of the Meteorological Office, and emphasized how the demands of aviation stimulated the development of techniques of forecasting for longer routes, for greater heights and with greater precision.

The first-hand knowledge of upper weather conditions that pilots and navigators meet along their scheduled flight routes is most valuable when reported back to the Meteorological Office and enables the official forecasters to build up more accurate meteorological maps for following flights, and it is on such accurate weather patterns that the safety and economic operation of civil aircraft is dependent.

For their valuable weather reporting services and for the best series of weather reports in the past year, the following captains and navigators have been awarded books by the Director-General, Meteorological Office: Captains J. R. Payne, J. R. Affleck, P. Bray and T. M. Mackenzie of BEA; Captains L. H. Levene and P. Seigel of British United Airways; and Captains S. T. R. Beal, S. W. Gooch, J. C. O. Granett and J. E. Sayce of BOAC. Similar awards go to BOAC navigators M. T. Rogers, D. E. Campbell, G. S. Turner, and G. T. Leggett, and to D. A. Barbour of British United Airways.

## REVIEW

*Wind-driven ocean circulation*, edited by Allan R. Robinson. 9½ in × 6½ in, pp. 161, *illus.*, Blaisdell Publishing Company, New York, 1963. Price: \$3.75.

Since the atmosphere and the oceans are both fluids moving on the surface of the rotating earth, it is hardly surprising that the meteorologist is often on familiar ground in considering the general circulation of the oceans. The fundamental equations are those he knows; ideas on scale of motion, vorticity and geostrophic balance apply equally to both. There are differences, of course. The motions of the atmosphere are more complex than those of the oceans, and exhibit turbulence of a kind and on a scale that defies precise enough description for incorporation into a satisfactory theory of the general circulation. On the other hand, oceanic circulations present their own particular problems, notably perhaps, the awkward boundary conditions which must be applied in any mathematical solution.

This book brings together eight previously published original papers on the theory of the general circulation of the oceans, and ends with notes by the editor which in effect review the subject. The first paper was written in 1947 by Sverdrup who computed the strength of equatorial counter-currents in a baroclinic ocean from the known wind stress, while the last dates from 1961 when Carrier and Robinson described a relatively sophisticated model that accounted for many of the observed features of the large-scale oceanic circulations. Despite this span of 14 years and although eight authors are represented, the papers are remarkably coherent, developing logically from one another so as to constitute a compelling account of the growth of ideas in a difficult field of geophysical study. The meteorologist may well be surprised to find what strides were made, and this without the use of the electronic computer which dominates atmospheric studies. He will be encouraged to look again at some of his own apparently intractable problems.

The idea of publishing together papers by various authors which are already available elsewhere can be good, but obviously the material must be carefully chosen if a useful purpose is to be served. The choice here will please meteorologists at least; they will be happy to have these important papers in a field closely allied to their own in such a convenient volume.

A. GILCHRIST

## METEOROLOGICAL OFFICE NEWS

**Retirement.**—The Director-General records his appreciation of the services of:

*Mr. Leonard Dods*, Principal Scientific Officer, who retired from the Meteorological Office on 22 June 1964 after 38 years service.

This bare statement will but poorly express feelings of regret in all who knew Mr. Dods, on the departure of a well-loved colleague.

Leonard Dods joined the Meteorological Office in 1926 and spent the first six months of his career in the World Climatology Division, then at South Kensington. He was then posted to the Forecast Division, M.O.2, and, like several of his colleagues who joined the Office in the late twenties, made his first acquaintance with synoptic meteorology through the rather mundane duties which fell to the lot of a Junior Professional Assistant in those days. However he was soon promoted to Senior Professional Assistant with some



forecasting responsibilities. Short spells of duty at Cardington (in the former Airship Services Division), Larkhill, and longer ones at Eskdalemuir and Malta followed, but in 1939 he returned to what came to be regarded as his home ground, the Forecast Division at Headquarters, as a Senior Forecaster. Here he stayed throughout the war years, a difficult period when data were scarce and often unreliable, the demands for forecasts increased enormously and the responsibility attaching to a senior forecasting post was heavy and fraught with anxiety. Night duties for forecasters were introduced in the early wartime days at Dunstable and on one of these Mr. Dods, by his prompt action at considerable personal risk and some injury, saved the wooden building then occupied from almost certain destruction by fire which had started unobserved. His colleagues of those days remember with gratitude his level-headedness in difficult situations, his unfailing cheerfulness and his willingness to take more than his share of the burden of duties. He never spared himself, and it came as no surprise that his health suffered; in 1947 he was taken off shift duties and posted as Head of the Special Investigations Branch, M.O.9, at the Kingsway Headquarters. Since then Assistant Directors in charge of M.O.9 have come and gone but Leonard Dods has remained so that to many minds he and M.O.9 have been one and the same.

In M.O.9 he has shown the same kind, helpful and self-effacing spirit. He will be missed, not only for his personal qualities but because in appealing to precedent for guidance in the now Met.O.9 his colleagues will in future have to search through thick files and dusty papers instead of simply asking 'Doddie'.

A. G. F.

## RESEARCH METEOROLOGIST

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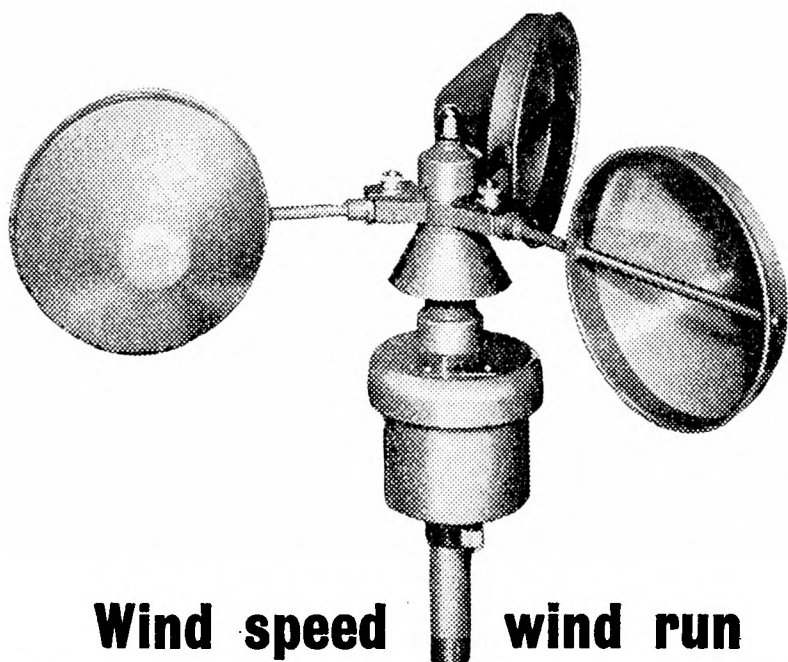
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quoting RC 283/383/04 and giving full name, age and qualifications.



## Wind speed      wind run

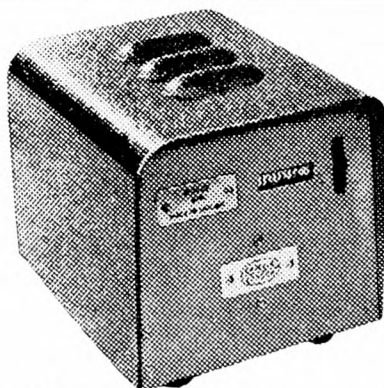
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# THE METEOROLOGICAL MAGAZINE

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## SEISMOLOGY AT ESKDALEMUIR OBSERVATORY

By L. JACOBS

The primary purpose of establishing a new observatory at Eskdalemuir,<sup>1,2</sup> Dumfriesshire, in 1908, was so that geomagnetic records could be obtained in a place free from local disturbances, such as were affecting Kew Observatory when electric tramways were extended to the area at the beginning of this century.<sup>3</sup> Shortly afterwards, in July 1910, seismological recording with the then new Galitzin instruments was started at Eskdalemuir, the installation being supervised by Prince Galitzin himself. When geomagnetic recording was finally abandoned at Kew, the Galitzin seismographs were transferred there, in 1925, from Eskdalemuir and, after a period of recording in the basement at Kew, when the records were much disturbed by strong winds rocking the building, were placed, in 1937, in a new vault<sup>4</sup> in which recording has continued up to the present time.

Interest has grown in recent years in the study of seismology, both from the general point of view of the scientific study of the structure of the earth's crust mantle and core in connexion with the understanding of earthquakes, and recently because seismic observations offer the best prospects for the detection of underground nuclear explosions which involves the difficult problem of distinguishing man-made explosions from earthquakes. Recent research has been directed to the refinement of instrumentation—fundamentally under the influence of electronics with the possibility of converting the data into a format suitable for computer work. There has also been the application of new processing techniques to well-known principles, e.g. by the United Kingdom Atomic Energy Authority (UKAEA) when analysing the results of the cross array of seismometers in the Eskdalemuir area.<sup>5</sup> It is worth noting that no new principle has emerged for recording earth movements; new seismometers, like all the older instruments, respond to the difference between the movement of the suspension point of a heavy pendulum and the much smaller movement of the pendulum itself. The usual conversion of the relative movement to a trace on a seismogram is by arranging for this relative movement to be that between a coil and a magnetic field, the current induced in the coil passing through a galvanometer, the light spot deflected by the galvanometer mirror giving rise to photographic recording on a seismogram on a rotating drum. The change in modern times, as just indicated, is to process the current by electronic means,

but the photographic recording is still an excellent and convenient method and, as will be seen later in this article, is that used for the new equipment recently installed in a new vault adjacent to Eskdalemuir Observatory.

The inadequacies of seismological technique began to be realized at the Geneva Conference of Experts in 1958,<sup>6</sup> when the first proposals were drawn up for a world-wide system for the detection of nuclear explosions. These shortcomings were further demonstrated when the analysis of underground tests in the United States, in the autumn of 1958, revealed a number of unsatisfactory features in the proposed detection system. Following this the Americans proposed, in 1959, a programme to improve the instrumentation of the seismograph stations of the world. It was realized that in order to hasten basic research in seismology, the instrumentation of the world network of seismograph stations must be improved and standardized in the same manner as the standardization of meteorological instrumentation.

In 1960 a committee of American seismologists was formed by the National Academy of Sciences and the National Research Council, to advise the Government Agencies on the choice of instruments and to determine the basis for selecting the stations to receive the equipment. This group of seismologists met in April 1960 to establish detailed specifications for the instruments. Their recommendations were:

“....electromagnetic seismometers recording through galvanometers with conventional photographic recording drums will be most satisfactory. The same drum rates, direction of paper transport and ground motion combinations are recommended for all the stations. It is further recommended that high quality clocks and radio receivers be supplied with the seismograph so that all stations will have time service of uniformly high quality.”

About this time the UKAEA was looking, in Scotland, where the seismic ‘noise’ level is much smaller than in southern England, for a suitable area to install the seismic array later described by Thirlaway.<sup>5</sup> The team making the test decided that the area around Eskdalemuir was very suitable and the central point of the array was fixed at about 4 km north-east of the Observatory. In tests for ‘noise’ level the best point near the Observatory itself was found to be on a rising piece of ground at Mass Knowe (Plates I, II and III) which is about  $\frac{1}{4}$  mile distant from each of various sources of ‘noise’—Davington Burn to the west, the minor road to the east, the activities at Nether Cassock Farm to the north and the general movement of staff in the Observatory grounds to the south, where there is also the ‘noise’ disturbance due to the roots of trees on the periphery moving in the shallow soil.

The International Seismological Summary Committee, at its Paris meeting in July 1961, pronounced the international requirement that all countries should work towards the ideal of a world network, having stations at intervals of about 1000 km. A circle of 1000 km centred in southern Scotland includes the whole of Ireland and the Low Countries and substantial areas of France, Germany and Scandinavia, so that one first class station at the centre of this circle is a sufficient United Kingdom contribution in relation to land areas. This point and the general need to have a first class station in a low ‘noise’ area were the main reasons why the Council of the Royal Society recommended, in January 1962, that Eskdalemuir Observatory be developed as the main recording base in the United Kingdom to provide for routine recording to international standards, for the development and operation of special instruments constructed

by other organizations and for the study of local earthquakes. (It is appropriate to recall that it was a Committee of the Royal Society which selected the site for the Observatory in the early years of the century.) It was agreed that the Meteorological Office should arrange for the return of seismological work, on an increased scale, to Eskdalemuir Observatory; this was particularly appropriate since Gassiot Fellowships<sup>7</sup> in seismology and geomagnetism had recently been approved for the Meteorological Office and also since the Seismic Research Group was being set up at the Royal Observatory, Edinburgh.<sup>8</sup>

In September 1961 the American offer was received of the gift of the standard American seismograph system for Eskdalemuir Observatory—one of about 125 stations to be so equipped over the world. This offer was accepted and it was planned that the equipment would occupy about a third of the space in the new vault at Eskdalemuir on the best available position at Mass Knowe described above, the remainder of the vault to be available for other seismic equipment. It so happened that there was a disused quarry in the required area; it was ascertained by local inquiry that there had never been any blasting which might have disturbed the underlying rock. After detailed planning, including consideration of features of other modern vaults, the vault was built in the latter half of 1963 without, of course, any blasting; it is of reinforced concrete, the interior being some 36 feet  $\times$  20 feet  $\times$  7½ feet high; the top is covered smoothly with some 3 feet of earth and the rough reedy grass is growing over. By making the excavation in the existing quarry in the side of a hill, the entrance to the vault (Plate III) has a normal doorway without steps; the underlying solid rock formation is Silurian shale (greywacke). A special feature of the vault is wire heating on the ceiling, controlled by a variable mains transformer, so that not only are there no abrupt changes of temperature, but the air remains stable so that disturbance to the instruments is as small as possible. There are also independently supported bridges for staff to walk on without affecting the piers on which instruments stand. (The vault is centred within a sheep-proof fenced compound, of about 230  $\times$  220 feet, to eliminate disturbance due to sheep movements.)

The 'noise' level in the new vault was compared with that at Kew. In the first winter of measurements, for periods 0.125 to 0.25 seconds the 'noise' level at Eskdalemuir was about ½ millimicron (1 millimicron is 10<sup>-9</sup> metres) compared with about 45 millimicrons at Kew; for periods 1 to 2 seconds the comparable figures are 20 and 75 millimicrons; as the period increases the figures approach until at periods 4 to 8 seconds the 'noise' level at Eskdalemuir is greater, 1.2 microns, as against Kew, 0.25 microns; presumably because Eskdalemuir is closer than Kew to the source of microseisms generated by waves in the Atlantic.

The American equipment was installed by two technicians from the U.S. Coast and Geodetic Survey, the agency responsible for equipping stations all over the world, in February/March 1964. There are short-period (about 1 second) and long-period (about 30–100 seconds) seismometers all recording via mirror galvanometers on photographic paper on rotating drums. Each seismometer records three components, vertical, north–south horizontal and east–west horizontal (Plates IV and V). Timing is controlled by a crystal oscillator in conjunction with a radio receiver (Plate VI). The installation was completed in time to record the severe Alaskan earthquake on 28 March 1964. Because of a large amount of microseism activity during the setting-up period the initial magnifications of the seismographs were set at 12,500 for the

short period and 750 for the long period, but these were later doubled. (At Kew the short-period vertical seismometer has a magnification of up to 3000 and the Galitzin instruments have a magnification of about 400–500.) Eskdalemuir thus became the 95th station of those planned for the world network. The seismograms from all these stations are sent at regular intervals to the U.S. Coast and Geodetic Survey Seismological Data and Analysis Center in Washington where they are copied on to microfilm and later returned to the station; microfilms or full-size copies of seismograms from all stations in the network are available, at a small charge, to scientists in any part of the world for independent research studies. An example of a seismogram is shown in Figure 1. The complete seismogram is 3 feet long and about 1 foot broad. The record starts on the top line, goes from left to right and resumes left to right on the second line and so on. The trace carries time marks at each minute (with special identifying marks at the hours and main synoptic hours). The portion displayed (about 2/3 original size) gives the trace for 12 minutes of each of 24 hours. The small movements over most of the trace are normal background microseisms but after the arrival of the shock wave from the Japanese earthquake at 0414 GMT (lower left) there are marked oscillations. At the end of the bottom line of the trace appears a large loop which is caused by a calibration check.

For future requirements of data logging of the recordings by electronic equipment in the vault, a 25-core shielded cable leads underground from the new vault all the way to the southern part of the Observatory grounds where a new surface laboratory for seismology is to be built; the cable path was chosen so that no interference is likely to be caused by the mains cable. The data can thus be logged on equipment in the laboratory and tapes from this equipment can be processed by electronic computers.

Thus a significant start has been made in re-establishing seismological work at Eskdalemuir. It was agreed at the Berkeley, California, meeting of the International Union of Geodesy and Geophysics in August 1963 that a new International Seismological Research Centre be established in Edinburgh and that the International Seismological Summary unit, located at Kew Observatory for many years, should be transferred to Edinburgh<sup>9</sup> when the present plan for dealing with the backlog of work is completed. Dr. P. L. Willmore, Senior Research Fellow in Seismology at the University of Edinburgh was appointed Director of these two new seismological groups. Dr. Willmore and his group are developing seismic equipment for recording on magnetic tape and expect to take advantage of the fact that the low 'noise' level in the vault at Eskdalemuir will enable such equipment to be operated at much higher sensitivity than at most other places in the United Kingdom. The spare space in the vault is, of course, available for use by other research workers in seismology.

In addition to the vault already completed at Eskdalemuir, it is planned, as stated above, to have a new surface laboratory; an extra married quarter and a hostel extension are also to be provided and at the same time there is to be an augmented water and electricity supply and a central oil-fired boiler house with underground ducts to lead the heating to all official and domestic buildings.

The annual report of the Meteorological Committee for the year ending 31 March 1928 has an interesting entry (p. 22):

"In order to commemorate the connection of four eminent physicists with the Eskdalemuir Observatory, it was decided by the Meteorological

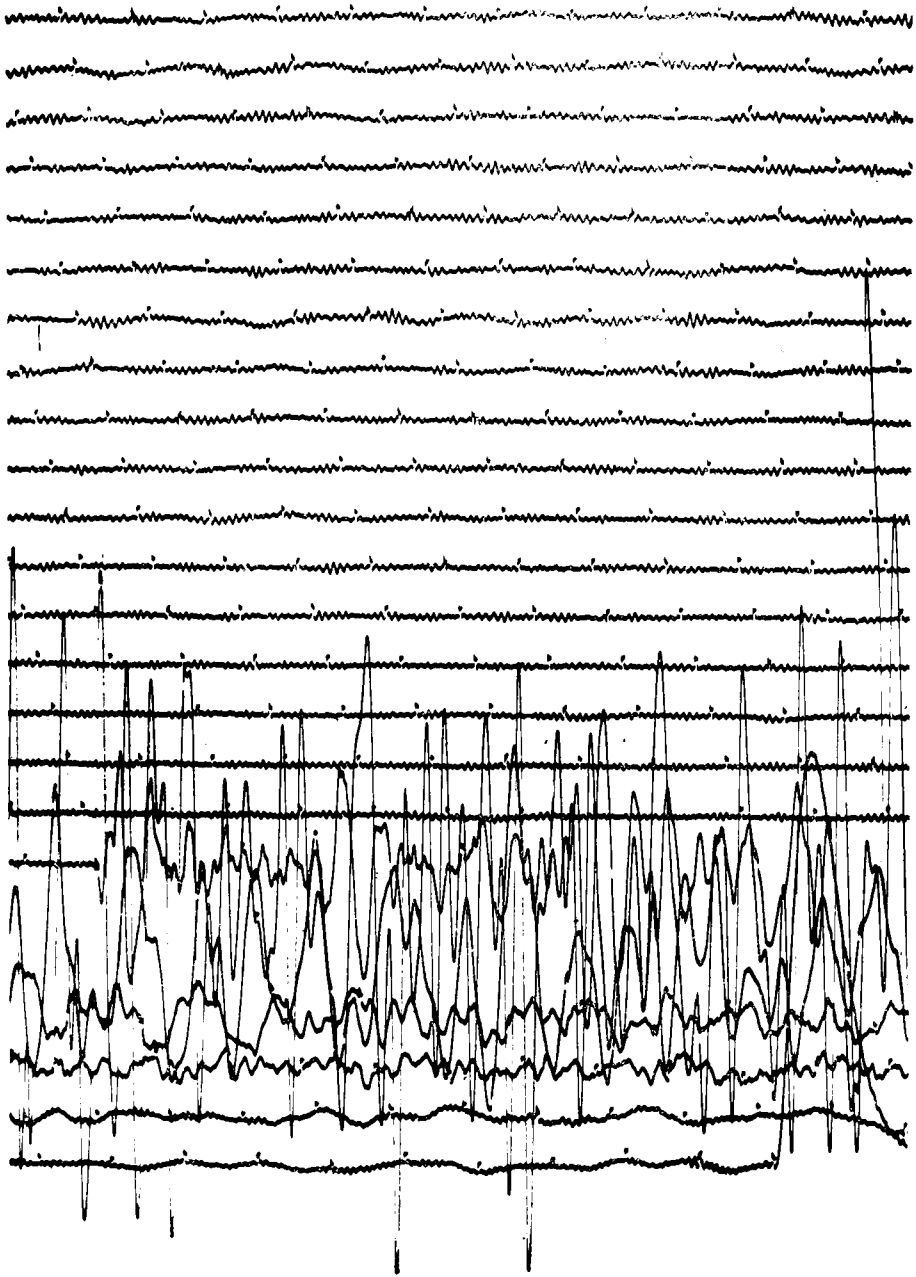


FIGURE 1—PORTION OF THE ESKDALEMUIR NORTH-SOUTH LONG-PERIOD SEISMOGRAM FOR 16 JUNE 1964 SHOWING THE ARRIVAL OF THE SHOCK WAVE, FROM THE JAPANESE EARTHQUAKE, AT 0414 GMT

Committee to give the four residential houses the following names: Superintendent's House, Rayleigh House, Assistants' House, Schuster House and the two houses recently erected for members of the staff Glazebrook House and Shaw House."

Rayleigh House and Schuster House, the present hostel, were two of the original buildings erected in 1908 when the Observatory was looked after by the National Physical Laboratory (the Meteorological Office took over in July

1910). The new buildings to be erected are to be named after former members of the Observatory staff, thus: the new hostel after George W. Walker, the first Superintendent at Eskdalemuir, who wrote *Modern seismology* (1913) and was responsible for organizing an important geomagnetic survey of the British Isles; the new married quarter after L. F. Richardson, Superintendent at Eskdalemuir in 1913–16, when he drafted his account of numerical forecasting; and the seismological laboratory after A. W. Lee, the well-known research seismologist who wrote many papers and rewrote Milne's classical book on *Earthquakes and other earth movements*—he was also at Eskdalemuir for a short time.

It is planned, at the end of 1964, to cease seismological recording at Kew with the older, much less sensitive equipment (although the short-period vertical seismometer, of greater sensitivity, may be left in use). The issue of the Kew Seismological Bulletin will then cease, being replaced by a seismological bulletin for Eskdalemuir based on analysis of the new standard seismograms.

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## THE SUPERSTANDARD PROPAGATION OF RADAR WAVES AT GIBRALTAR

By C. J. STAPLEY

**Introduction.**—In 1960 the author began a series of routine observations of radar echoes received from targets beyond the normal radio horizon of the radar equipment used at the Gibraltar radiosonde station. The radar in use was the normal Meteorological Office wind-finding radar<sup>1</sup> which has a wavelength of 10 cm and a peak power output of 350 kW. This article gives a short description of the procedures adopted by the author and the results obtained, and is preceded by a brief explanation of some of the terms used in radio meteorology.

**Refractive index.**—The index of refraction  $n$  in dry air has the same value over almost the whole of the electromagnetic spectrum, being the same for radio and light waves. In the atmosphere  $(n-1)$  is of the order of  $300 \times 10^{-6}$ . In order to avoid small numbers in calculation  $(n-1) \times 10^{+6}$  is sometimes denoted by  $N$  where  $N$  is the number of millionths in  $(n-1)$ . Thus,

$$N = (n-1) \times 10^6 = Kp/T$$

where  $K$  is a constant which has a value of 79 for wavelengths greater than 2 cm,  $p$  is the air pressure in mb,  $T$  is the temperature in °K.

However, when water vapour is added to the dry air the value of  $N$  for the mixture becomes dependent on frequency. It can be shown that since water



molecules are polar in nature they have different responses to different frequencies. With the high frequencies of light waves they become electrically polarized; with the lower frequencies of radio waves, in addition to becoming polarized, the water molecules reorientate themselves rapidly and so follow the electric field changes. As a result the index of refraction of water vapour is greater for radio frequencies than for optical frequencies. For radio waves of wavelengths greater than 2 cm the index of refraction for atmospheric air can be calculated from the expression

$$N = (n-1) \times 10^6 = (79/T) \times (p - e/7 + 4800 e/T)$$

where  $e$  is the vapour pressure in mb.

**Modified refractive index.**—Theoretical work<sup>2</sup> shows that for rays with small inclination to the horizontal a modified refractive index can be used which allows the curvature of a ray to be considered relative to a flat earth. The refractive index  $n$  is modified to  $n + h/R$  where  $h$  is the height above the earth's surface and  $R$  the radius of the earth. In practice  $(n + h/R - 1) \times 10^6$  is denoted by  $M$  where  $M$  is the number of millionths in  $(n + h/R - 1)$  and is sometimes said to be measured in  $M$ -units and referred to as the M.R.I. (modified refractive index).

**Types of duct.**—The modified refractive index  $M$  may be calculated from associated radiosonde ascents. Typical examples of curves showing the lapse of  $M$  with height are shown in Figures 1(a) and (b) and such curves are more

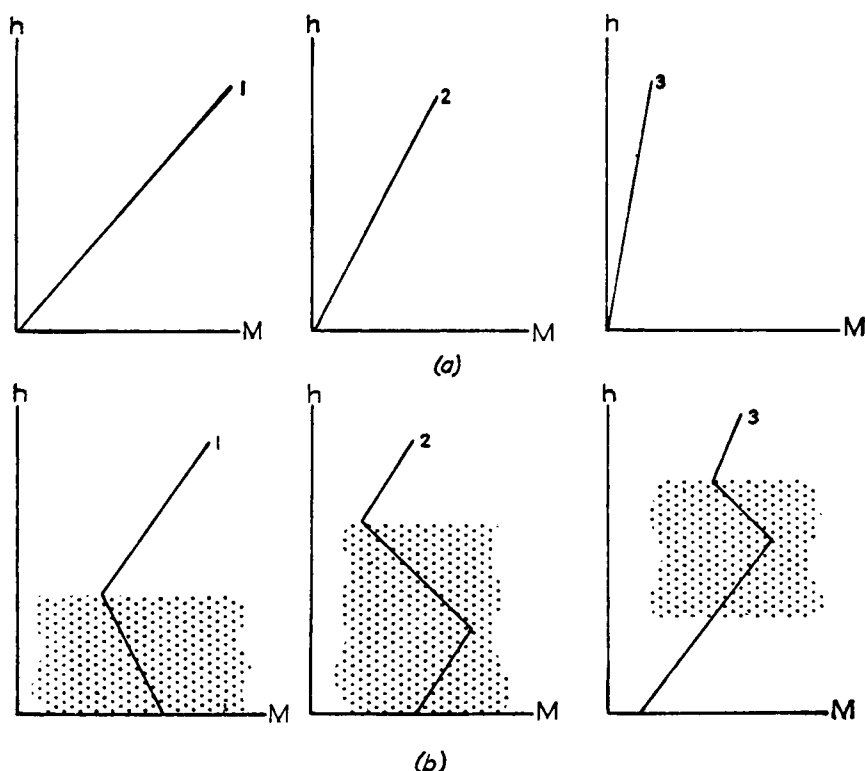


FIGURE 1—TYPES OF HEIGHT VARIATION OF THE MODIFIED REFRACTIVE INDEX ( $M$ - $h$  CURVES)

(a) 1. Substandard type, 2. standard type, 3. transitional type.

(b) Superstandard types with ducts shown by stippling.

1. Simple Surface duct, 2. Ground-based S duct, 3. Elevated S duct.

fully discussed elsewhere.<sup>2</sup> For super-refraction it is necessary for  $M$  to increase with height less rapidly than usual. If  $M$  actually decreases with height a duct is formed in which rays from a transmitter within the duct may be trapped. The rays may be returned from a reflecting object also in the duct. If the duct exists over a great distance then echoes may be received from objects which are normally well out of radar range. Various types of duct are shown in Figure 1(b).

**Radio horizon.**—Under standard propagation conditions the radio horizon  $d$  is given in km by  $d = 4.1 \sqrt{H}$  where  $H$  is the height in metres of the aerial above sea level. The radar equipment at Gibraltar is situated close to the sea on the Mediterranean side of the colony and the aerial height is approximately 6 m above sea level thus giving a standard radio horizon of 10 km. If the height of a ship is taken to be 20 m then the maximum range at which such a target could be located by the radar under standard conditions is given by

$$d = 4.1 (\sqrt{6} + \sqrt{20}) = 28 \text{ km.}$$

**Procedure.**—Searches for echoes from ships beyond the standard radio horizon were normally made immediately preceding or following a radiosonde wind or radar-wind ascent, the method of search being to rotate the radar aerials from 40 degrees to 180 degrees in azimuth, the elevation being kept at zero degrees. This method gave the radar beam a long sea track. In order to check that the radar equipment continued to operate at the same level of efficiency throughout the observations, several permanent echoes up to a range of 87 km were located before every search. This check on performance in conjunction with routine field strength measurements showed that the radar performance did not deteriorate to any appreciable extent during the period of the observations.

At all times while the searches were being carried out the radar presentation unit was set on automatic gain control and the azimuth and elevation signals were aligned both optically and with the error sensing unit<sup>1</sup> before the readings were recorded.

**Relationship between super-refraction and the variation of modified refractive index with height.**—From 4 July 1960 until 25 July 1961, 113 sets of readings were made, resulting in recorded observations of over 600 separate echoes from ships at ranges beyond the standard radio horizon and echoes from distant land on 34 occasions. Ranges of ship echoes below 36 km were not recorded though many were observed.

Curves of  $M$  against  $h$  were drawn for observations made near the time of a radiosonde ascent, values of temperature and humidity used in the computation of  $M$  being taken from these ascents. Two methods were used for computing the first  $M$  point. In one case the station screen temperatures (wet and dry) were used and the other more successful method used the sea temperature and a relative humidity of 90 per cent (see Table I). The usefulness of  $M$ - $h$  curves in forecasting super-refractive conditions is shown in Table II. The surface values

TABLE I—SUCCESS IN FORECASTING SUPER-REFRACTIVE CONDITIONS

Temperature used to compute first $M$ value	Number of forecasts of super-refractive conditions	
	Correct	Wrong
Sea	55	19
Station	42	32

of  $M$  used in the plotting of the curves considered in Table II were computed by using the sea temperature taken at the eastern side of Gibraltar and a relative humidity of 90 per cent. By doing this the initial decrease of  $M$  in the surface layers may be representative of the conditions along the path of the beam over the sea.

TABLE II—SUPER-REFRACTION AND TYPES OF  $M$ - $h$  CURVES

Type of $M$ - $h$ curve plotted at time of observation (See Figures 1 and 2)	Number of occasions on which echoes due to super-refraction were recorded	Number of occasions on which echoes due to super-refraction were not recorded
Standard	5	2
Substandard	4	9
Superstandard		
(a) Simple Surface duct	33	8
(b) Ground-based S duct	3	1
(c) Elevated S duct	6	0
(d) Transitional	2	1

In the drawing-up of all the  $M$ - $h$  curves the values of  $M$  were plotted at the surface height, 25 m and thereafter at intervals of 50 m up to a maximum height of 1000 m. This resulted in all types of  $M$ - $h$  curves being recorded. The curves called transitional in this article are those in which the value of  $M$  at any point increases with height at a rate less than standard but does not become of negative slope (see Figure 1(a)).

**Limitations of radiosonde measurements.**—It can be seen from Table I that the forecasting of super-refractive conditions in coastal waters could be very misleading if no account is taken of the sea temperature when computing the surface  $M$  value.

Some of the wrong forecasts can perhaps be explained in the following manner. Where super-refractive conditions were known to exist and yet no echoes from ships were recorded, it is possible that no ships were in the vicinity to give reflections. In the instances in Table II where curves are seen to be standard or substandard and yet echoes from beyond the normal radio horizon were received, the limitations of the Radiosonde Mk 2B for giving detailed structure for this type of work must be considered.

The sampling rate of any particular element of pressure  $p$ , temperature  $T$ , or humidity  $U$  on the radiosonde is approximately 6 seconds per 18-second cycle of  $p$ ,  $T$  and  $U$ . This represents approximately 120 ft out of a layer of 360 ft covered by one complete cycle of  $p$ ,  $T$  and  $U$ .

If at the time of launch the switch on the sonde is at the beginning of the  $U$  signal, no temperature will be recorded during the first 200 ft of the ascent. This, coupled with the inherent lag of the type of hygrometer used, could very easily mean that a shallow duct existing near the surface would not be recorded by the sonde. Since a duct of only 10 ft in depth will allow a 10-cm wave to be propagated over long distances, such points as those mentioned above could be of much importance in the forecasting of super-refractive conditions.

The foregoing is only theoretical and the author cannot say that the sonde has failed to register a shallow duct which may have existed near the surface. In practice the sonde has proved reliable in recording the existence of a well-defined duct of the Simple Surface type.

**Side lobes.**—It was appreciated that during the observations the energy contained in the transmitter side lobes could also be extended in range when

super-refractive conditions were in evidence. A check was made to ascertain the exact position of these side lobes on the radar equipment. This check showed that the side lobes existed at 15 degrees and 30 degrees in elevation and at 21 degrees and 45 degrees in azimuth. For a reference signal input to the aerials of one micro-microwatt the energy in these side lobes was less than the energy in the main lobe by 25 decibels (dB), 43 dB, 25 dB and 25 dB. It can be seen from these measurements that a signal, under standard propagation conditions, would have to be of considerable power in order to be picked up on a side lobe and give a signal to noise ratio of 3 : 1, the figure at which the set is normally operated.

To test the location of ships in these side lobes the paraboloids were rotated until a ship was located in the main beam, the paraboloids were then moved to the side-lobe positions and a check made to see if the ship under observation showed up on the display unit. These tests were carried out under all propagation conditions.

**Side-lobe reception.**—The investigation into the effectiveness of ship location by means of side-lobe reception showed that under normal propagation conditions ships could be located by this means up to a maximum range of 5400 m. When super-refractive conditions were in evidence side-lobe reception became much more marked.

Under super-refractive conditions it was found that when a Ground-based S duct was present, ranges in excess of the standard radio horizon were recorded for side-lobe reception, the maximum range recorded being 57,000 m. The echo received at this range showed up in both azimuth side lobes but at the 15-degree position only in elevation. On the day that the side-lobe reception at 57,000 m occurred attempts to receive echoes on side lobes at ranges of 76,220 m and 78,850 m were unsuccessful.

On other occasions when a Ground-based S duct was present, echoes were observed in elevation and azimuth side lobes at ranges of 44,000, 49,500, 32,000 m; and, in elevation side lobe only, 21,000 m.

When an Elevated S duct was present the maximum range at which side-lobe reception took place was found to be 15,500 m. This was in the 21-degree azimuth position but not at all in elevation.

When a Simple Surface duct was present no instances of side-lobe reception were recorded during the period of observations.

**Interference echoes.**—At times during the normal radiosonde ascents, when super-refractive conditions were known to exist, difficulty in following the radar reflector suspended from the weather balloon has been encountered by the radar operators. This difficulty takes the form of interference from numerous echoes, apart from the one being followed. The interference swamps the indicator tubes and has taken place at elevations up to 30 degrees. The source of these echoes can sometimes be ascribed to the mountainous terrain over which the balloon is passing. On many occasions however the balloon track is over the sea and the unwanted echoes are most certainly from ships, and have the characteristic appearance of such echoes. The only explanation that can be offered is that the unwanted echoes are due to side-lobe reception. These occurrences are only noticed during operational soundings and in consequence further investigation is not always possible. On 19 August 1960 one such echo appeared on the coarse range tube at a range of 60,000 m during the 1700

GMT radar-wind ascent. When this echo was first noticed the paraboloids were at an elevation of 30 degrees. Shortly afterwards the balloon burst; the echo was then strobed and found to be at a range of 60,000 m and at zero degrees in elevation. This echo was without doubt the result of reflection from a ship and is assumed to be the result of side-lobe reception. The range at which it occurred however is greater than any recorded during the investigation mentioned earlier, and the ducts in evidence at 1100 GMT and 2330 GMT on this day were not the type, in the experience of the author, to give good side-lobe reception. Figures 2(a) and (b) show the  $M$ - $h$  curves for the 1100 GMT and 2330 GMT ascents on 19 August 1960 together with the associated temperature and dew-point curves.

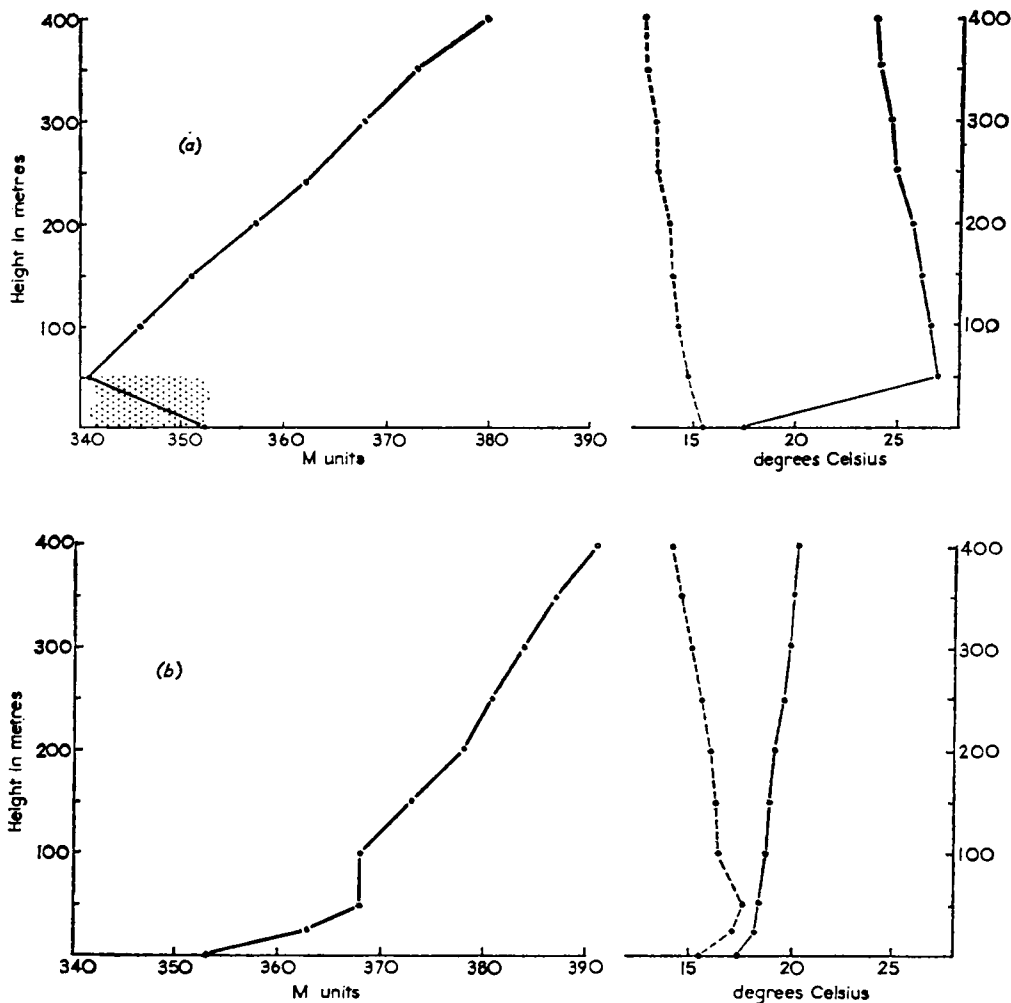


FIGURE 2—HEIGHT VARIATION OF THE MODIFIED REFRACTIVE INDEX, TEMPERATURE AND DEW-POINT ON 19 AUGUST 1960

(a) 1100 GMT (b) 2300 GMT  
 — Modified refractive index, - - - dew-point, — temperature.  
 Stippling shows the ducts.

**Land echoes.**—Echoes having a slight to-and-fro movement have been received from land on 34 occasions, presumably from North Africa. From calculations and with reference to a 1:2,000,000 scale map the echoes appear to be reflections from the Middle Atlas mountains, the Saharan Atlas and the

coastal region around Oran. The distances involved range from 416 km to 464 km. These echoes are not seen on the radar unless super-refractive conditions are in evidence. For these echoes to have come from the areas mentioned they must necessarily be Multiple Time-base echoes.

**Ducts over land and sea.**—On a number of occasions the positions of the received echoes have been plotted and it has been seen that the radar beam has sometimes travelled over the sea and then over part of the Spanish coast to be reflected from ships in the Bay of Malaga (see Figure 3). Since the distances involved are greater than the standard radio horizon it would appear that the

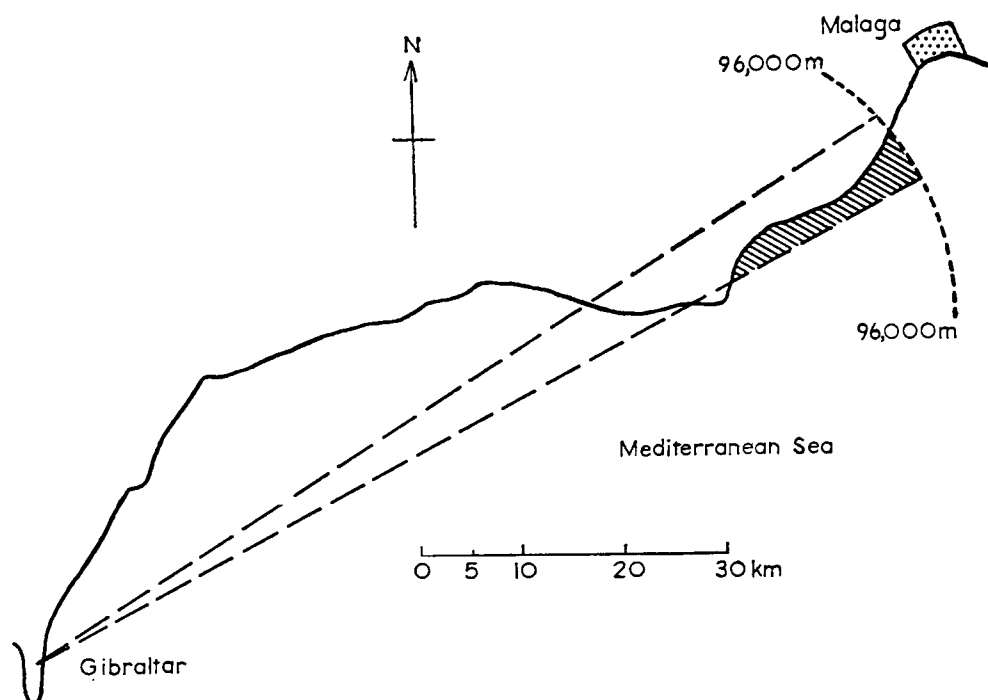


FIGURE 3—PLAN OF THE COASTAL REGION AROUND MALAGA

Hatching shows the area from which ship echoes were received.

duct in which the beam has travelled existed over the coast as a continuation of the duct existing over the sea. When these reflections took place there was no apparent loss of signal strength. The shaded area in Figure 3 shows the region from which these echoes have been received. The number and conditions under which these echoes were received are shown in Table III.

In the instances where ships have been located in the Bay of Malaga (Table III) it will be seen that in general the duct has been of the Simple Surface type. During August 1960 when most of these events occurred, the wind conditions were such that during the day a sea breeze prevailed although at night the wind was always from the land. Such a wind régime is normal for this area during the hot summer months. Ducts over the sea may be enhanced by the high surface-humidity over the very warm inshore waters, and during the day may be carried inland by the sea breeze thereby providing continuity of the duct from Gibraltar to the Bay of Malaga across the intervening promontory. At night the sea breeze dies away and the radiation cooling over the land would lead to a gradual destruction of the duct from the surface upwards. From the observations it would appear that at 2300 GMT the destruction process is still far from complete.

TABLE III—ECHOES FROM THE BAY OF MALAGA

Date	Time (GMT)	Wind at Malaga Direction	Speed <i>knots</i>	Type of duct	Number of echoes received
8 Aug. 1960	0001	NW (land breeze)	10	Simple Surface	1
13 Aug. 1960	2300	NW (land breeze)	10	Simple Surface	1
19 Aug. 1960	1100	SE (sea breeze)	10	Simple Surface	6
19 Aug. 1960	2230	NW (land breeze)	10	(Transitional)	1
20 Aug. 1960	1100	SE (sea breeze)	10	(Not known)	1
20 Aug. 1960	1630	SE (sea breeze)	10	(Not known)	2
27 Aug. 1960	1100	SE (sea breeze)	10	Simple Surface	2
4 Feb. 1961	1120	W	5	Simple Surface	1
5 Feb. 1961	2120	W	10	Simple Surface	1

The westerly wind in February 1961 may be considered as a wind from the sea on to the promontory and would contain the ducts which are probable over the sea. Average sea temperatures suggest that the structure shown in Figure 6 is reasonable near the Malaga area.

**Occurrences during winter.**—During the winter months November to March, 30 sets of observations were made. It was found that super-refraction occurred on 23 occasions during this period.

**Ducts with no temperature inversion.**—On a number of occasions it was noticed that a radio duct had formed in a layer of air in which there was no temperature inversion. At such times, however, there was a most noticeable drop in dew-point with height.

These examples occurred only in winter at times when a large number of echoes due to super-refraction were recorded, especially those thought to be Multiple Time-base (MTB) echoes. Table IV gives details of these events and

TABLE IV—ECHOES WITH NO TEMPERATURE INVERSION THROUGH THE DUCT

Date	Type of duct	Rate of fall of dew-point through duct	Type of echoes received
15 Nov. 1960	Simple Surface	very rapid	ships
16 Nov. 1960	and Elevated S shallow	steady	none
19 Nov. 1960	Simple Surface	fairly rapid	ships
5 Feb. 1961	(Transitional) Simple Surface	rapid*	many ships and MTB
9 Feb. 1961	Simple Surface	rapid	many ships and MTB
11 Feb. 1961	Simple Surface	rapid	none
12 Feb. 1961 (0030 GMT)	Simple Surface	rapid	MTB
12 Feb. 1961 (1130 GMT)	Simple Surface	rapid	many ships and MTB
13 Feb. 1961	Simple Surface	rapid	none
14 Feb. 1961	Simple Surface	very rapid	none
24 Feb. 1961	Elevated S	steady†	none
28 Feb. 1961	Simple Surface	very rapid	MTB
28 Mar. 1961	Simple Surface	rapid	ships and MTB

\*Isothermal through duct, †temperature inversion present (see Figure 4).

MTB is the abbreviation for Multiple Time-base.

shows that it is not absolutely necessary to have a temperature inversion in order that a duct may be formed. Since there is invariably a temperature inversion layer over the sea surface in this region during the summer months the author is unable to say that ducting would occur without such an inversion. In the winter, however, an inversion layer over the sea is not always present and results show that on a good many occasions ducting did take place without an inversion being present at the surface. It was when this type of ducting took place that some of the best echoes due to super-refraction were recorded, especially those thought to have come from land beyond the normal radio horizon. An *M-h* curve drawn when there was no inversion present at the surface is shown in Figure 4.

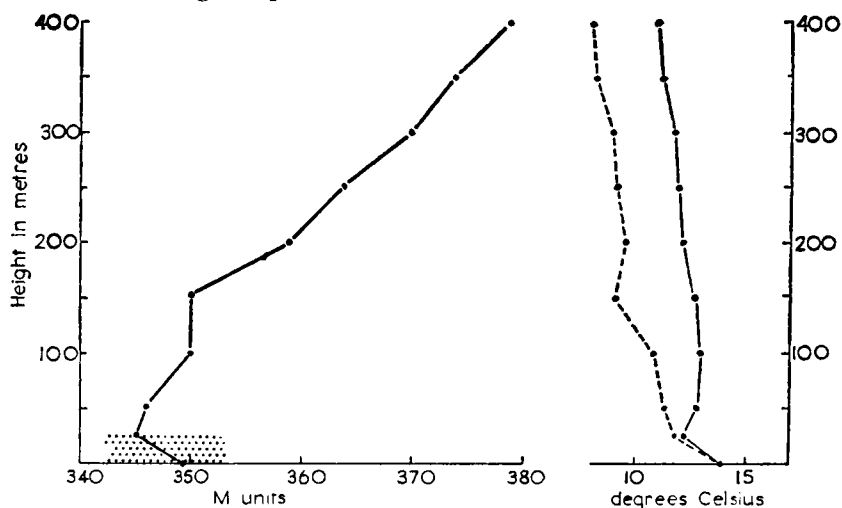


FIGURE 4—HEIGHT VARIATION OF THE MODIFIED REFRACTIVE INDEX, TEMPERATURE AND DEW-POINT FOR 2330 GMT ON 24 FEBRUARY 1961  
 — Modified refractive index, - - - dew-point, — temperature.  
 Stippling shows the duct.

**Further examples of ducts.**—A selection of *M-h* curves is shown in Figures 5, 6, 7 and 8 together with an account of the type of echoes recorded on the days that these curves were plotted. Referring to Figure 7 it will be seen that the transmitter was lower than the duct; in such a case ducting cannot take place as the beam will enter the duct at an angle too great to allow it to be trapped. However the presence of the duct serves to bend the transmitter beam closer to the earth's surface than would normally be the case so that distant land echoes somewhat beyond normal range could well be recorded. In the case under consideration no ship echoes at all were seen but echoes from distant land were.

**Conclusions.**—These observations have shown that the super-refraction of radar waves can take place when a lapse of dew-point exists without an inversion of temperature within the air structure in which the duct is formed.

The propagation of side lobes is greatly enhanced when super-refractive conditions are in evidence. This could cause some misleading information to be recorded by ships' radars in coastal waters.

It would appear that Gibraltar is an ideal place to carry out investigations of this type. Super-refractive conditions seem to be the rule rather than the exception for this area and no matter what the season of the year, extension of radar ranges will be much in evidence.



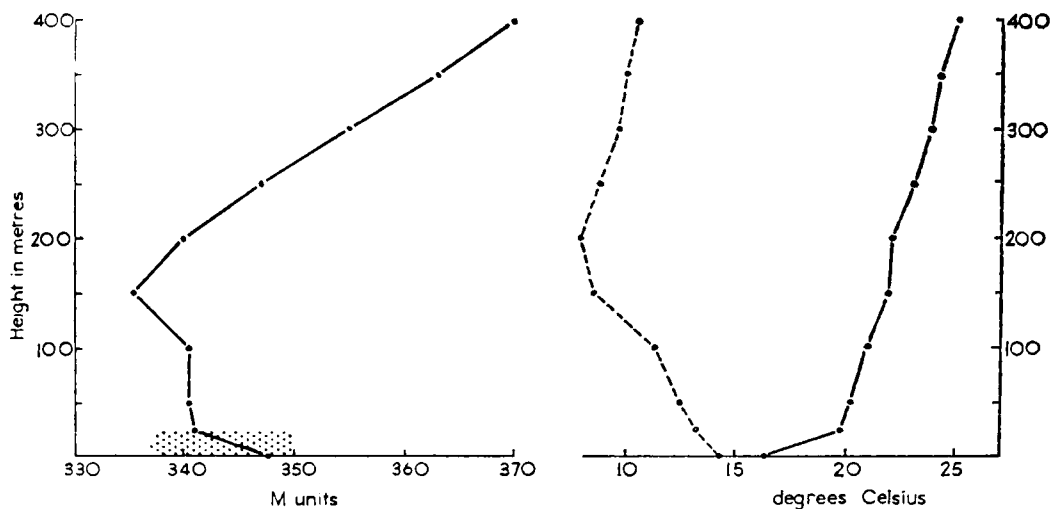


FIGURE 5—HEIGHT VARIATION OF THE MODIFIED REFRACTIVE INDEX, TEMPERATURE AND DEW-POINT FOR 2300 GMT ON 5 JULY 1960

— Modified refractive index, - - - dew-point, ——— temperature.  
Stippling shows the duct.

The following types of echoes were received on this day:

- (i) Ship echoes up to a range of 95,830 m;
- (ii) Multiple Time-base echoes from North African coast in the vicinity of Oran.

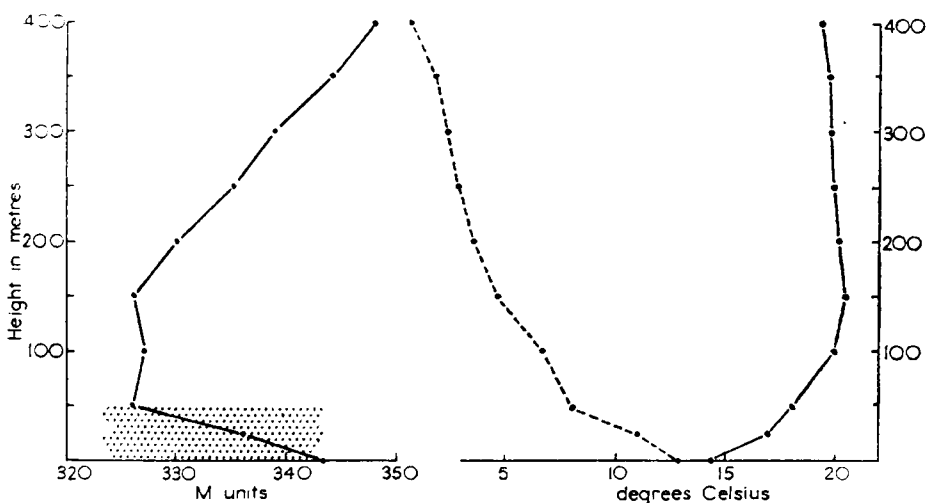


FIGURE 6—HEIGHT VARIATION OF THE MODIFIED REFRACTIVE INDEX, TEMPERATURE AND DEW-POINT FOR 1130 GMT ON 5 FEBRUARY 1961

— Modified refractive index, - - - dew-point, ——— temperature.  
Stippling shows the effective duct.

The following types of echoes were received on this day:

- (i) Ship echoes up to 96,000 m;
- (ii) Multiple Time-base echoes from North African coast in the region of Puerto Capaz.

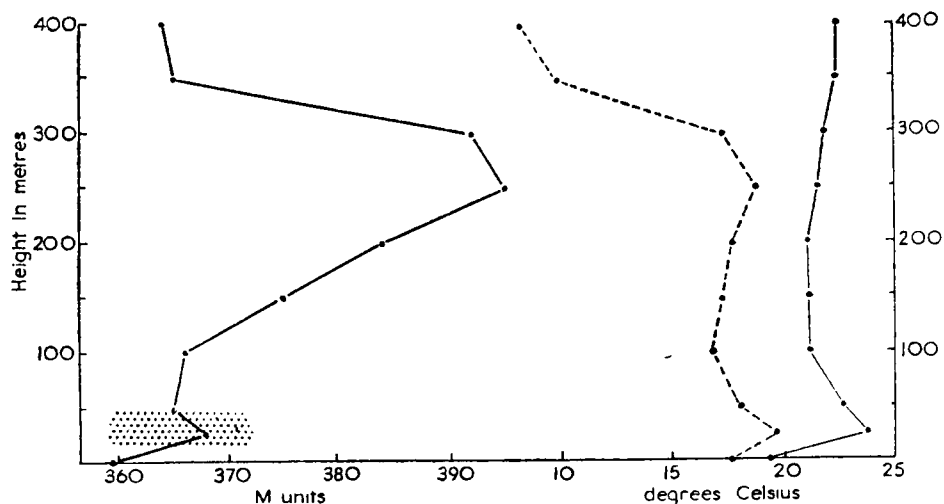


FIGURE 7—HEIGHT VARIATION OF THE MODIFIED REFRACTIVE INDEX, TEMPERATURE AND DEW-POINT FOR 1130 GMT ON 21 JULY 1961

— Modified refractive index, - - - dew-point, — temperature.

Stippling shows the effective duct.

The following types of echoes were received on this day:

- (i) Ship echoes—nil seen beyond normal radio horizon;
- (ii) Multiple Time-base echoes from all along North African coast.

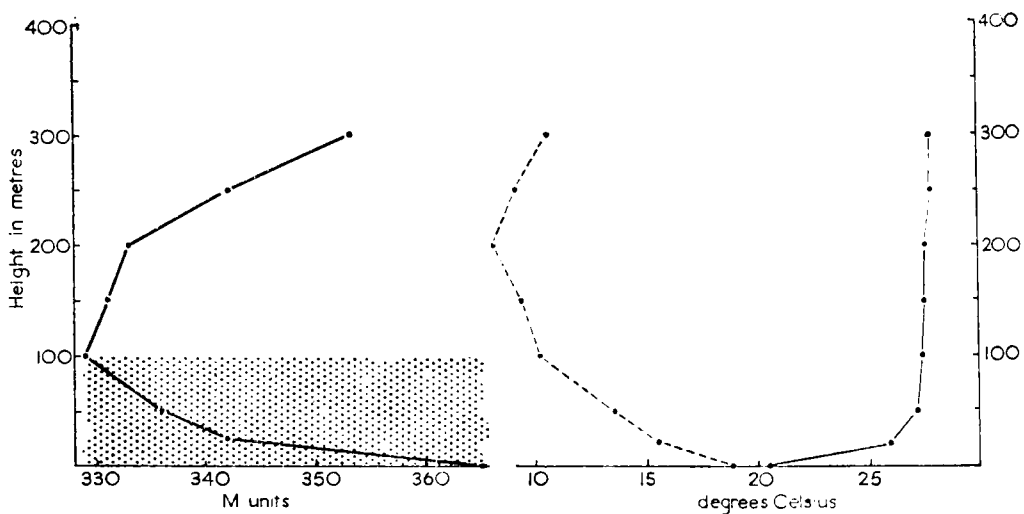


FIGURE 8—HEIGHT VARIATION OF THE MODIFIED REFRACTIVE INDEX, TEMPERATURE AND DEW-POINT FOR 1130 GMT ON 20 JULY 1961

— Modified refractive index, - - - dew-point, — temperature.

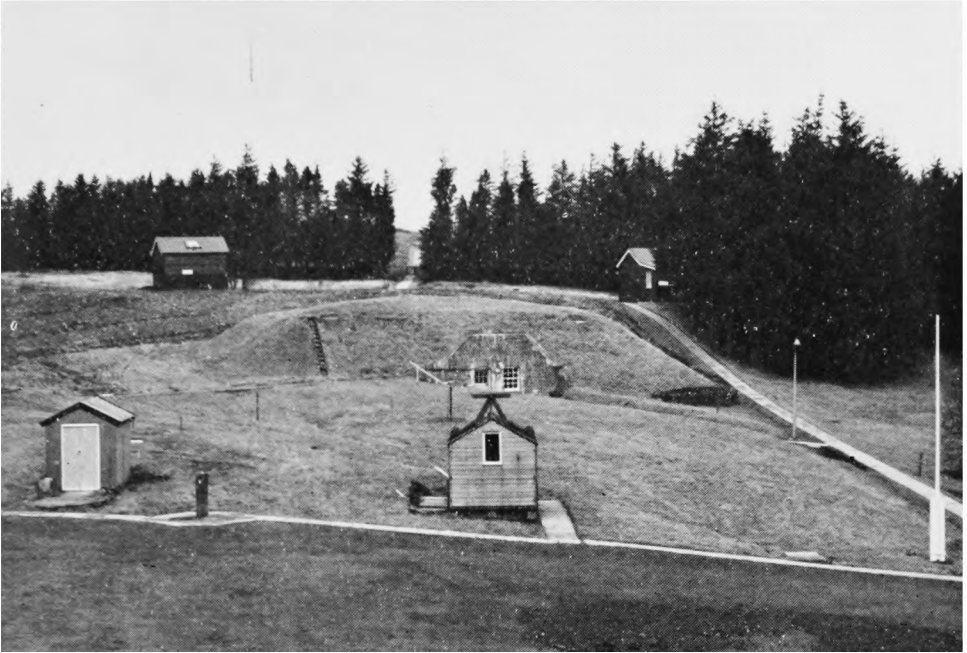
Stippling shows the duct.

The following types of echoes were received on this day:

- (i) Ship echoes up to 96,000 m;
- (ii) Multiple Time-base echoes from all along North African coast.

#### REFERENCES

1. London, Meteorological Office. Handbook of meteorological instruments. Part II. London, HMSO, 1961, pp. 46-56.
2. London, Meteorological Office. Meteorology of radio propagation. London, HMSO, 1953.



*Photograph by A. E. Dawson*

**PLATE I—THE NORTHERN PART OF THE OBSERVATORY GROUNDS AT ESKDALEMUIR**

The chambers containing the magnetographs are under the mound in the centre; absolute magnetic observations are made in the huts near the trees. The seismological vault is about 300 yd beyond the trees and along the path shown in the background (see page 290).



*Photograph by B. J. Gerst*

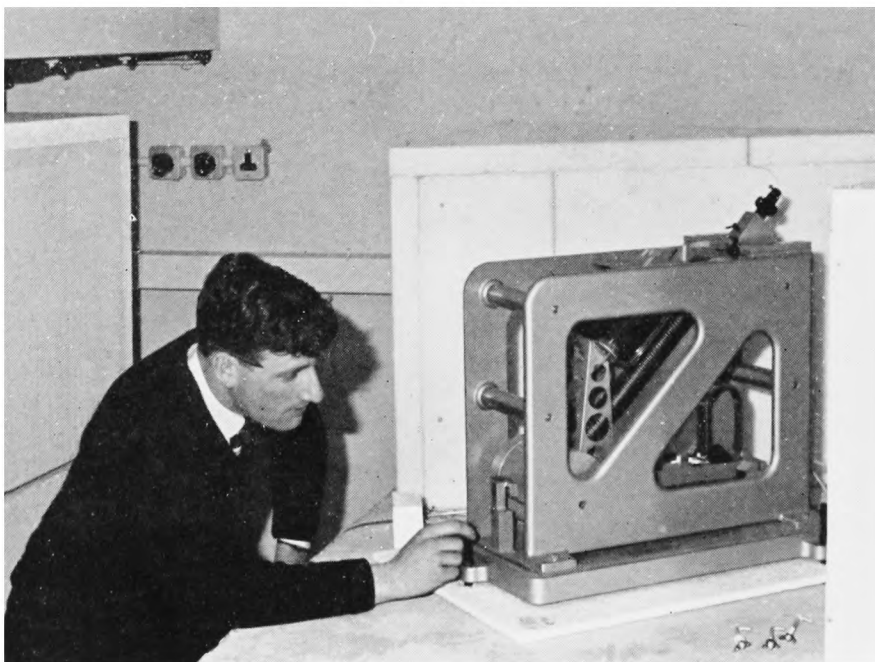
**PLATE II—THE APPROACH TO THE NEW SEISMOLOGICAL VAULT AT MASS KNOWE  
NEAR ESKDALEMUIR OBSERVATORY**

The entrance to the vault, in the hillside, is at the left beyond the gate (see page 290).



*Photograph by B. J. Gorst*

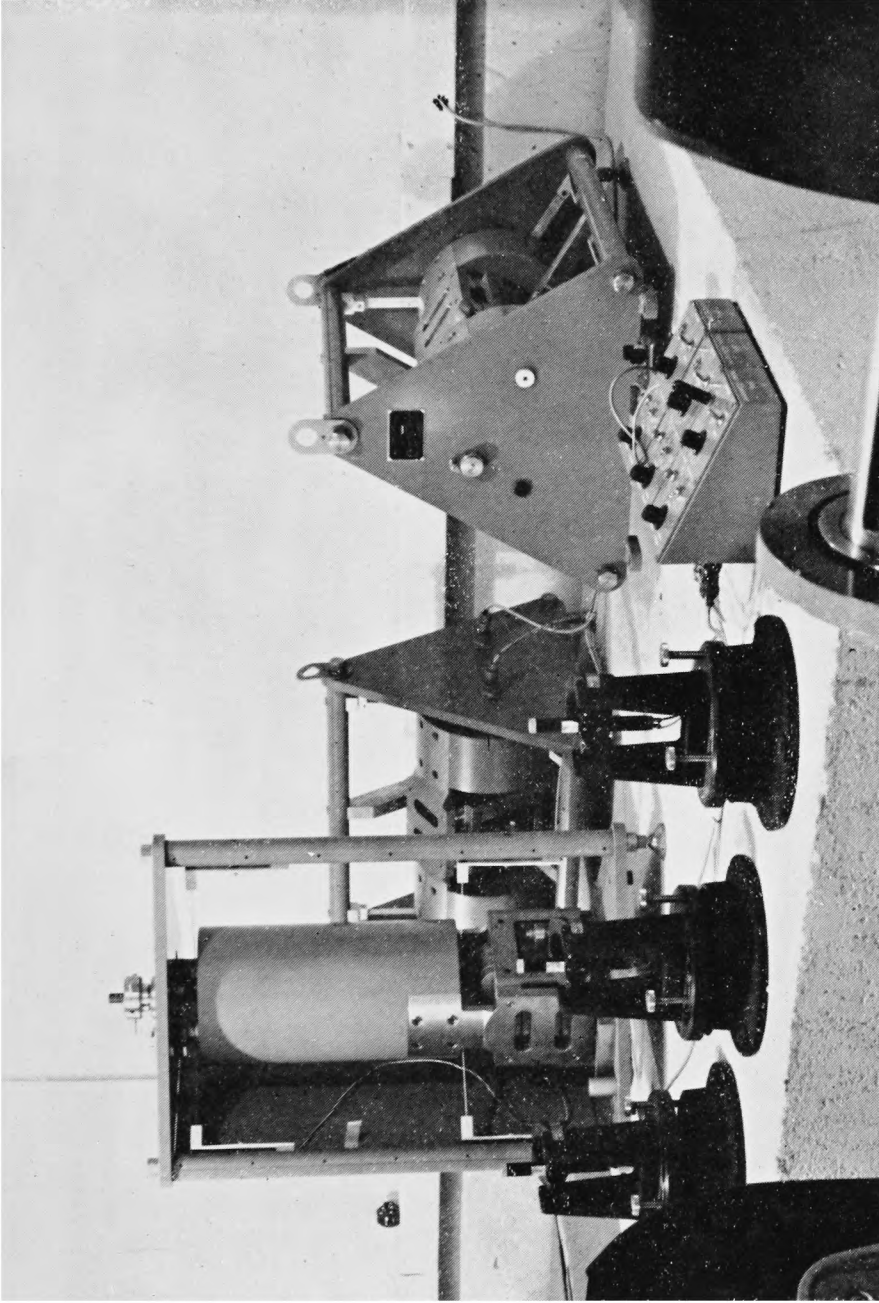
PLATE III—THE ENTRANCE TO THE NEW SEISMOLOGICAL VAULT AT MASS KNOWE  
(See page 290.)



*Photograph by B. J. Gorst*

PLATE IV—THE ADJUSTMENT OF THE LEVEL OF THE LONG-PERIOD VERTICAL  
SEISMOMETER AT ESKDALEMUIR

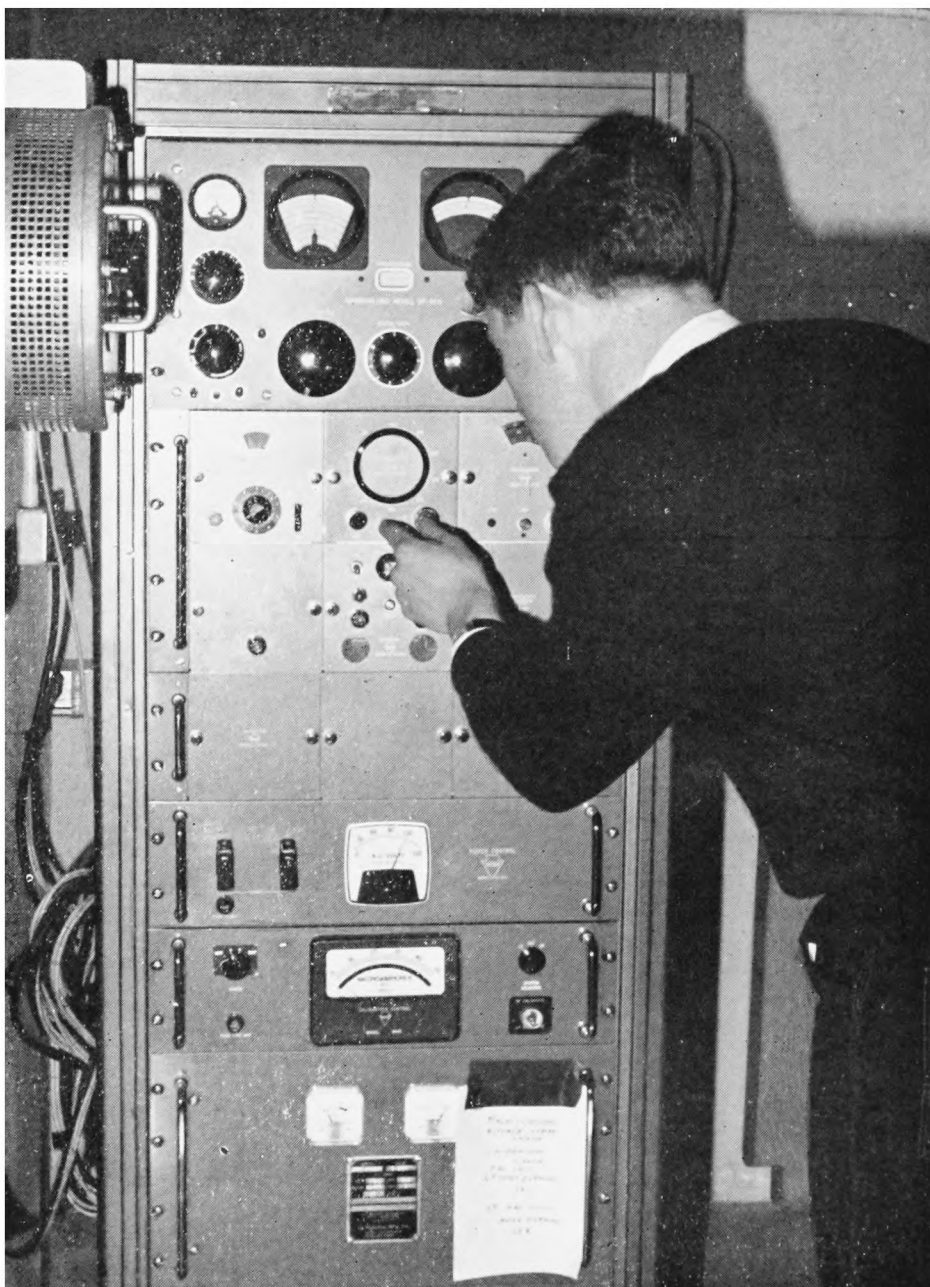
The long-period seismometers are normally enclosed in a metal cover surrounded by an expanded polystyrene cover to eliminate air currents (see p. 291).



*Photograph by A. E. Dawson*

PLATE V—THE SHORT-PERIOD SEISMOMETERS WITH GALVANOMETERS AND CONTROL  
BOX AT ESKDALEMUIR

The vertical component instrument (the tallest one) is 36 inches high. (These instruments are normally enclosed in a metal container to eliminate air currents.) (See page 291.)



*Photograph by B. J. Gorst*

PLATE VI—THE MAIN CONTROL PANEL FOR THE SEISMOLOGICAL INSTRUMENTS  
AT ESKDALEMUIR

The crystal clock error is being adjusted to zero as a daily routine after changing charts. The variable mains transformer used to control the heating of the vault can be seen to the top left (see page 291).

# THE YEAR-TO-YEAR VARIATION OF THE FREQUENCY OF FOG AT LONDON (HEATHROW) AIRPORT

By P. J. WIGGETT, B.Sc.

A study of the variation from year to year of the incidence of fog at London (Heathrow) Airport indicates that the frequency of occasions with visibility in the range 220–1100 yd has decreased significantly, whilst the frequency of thick fog (visibility less than 220 yd) is little changed during the period 1946–63.

In recent years members of the staff at Heathrow engaged on local forecasting have become aware of a decrease in frequency of fog at the Airport. This note reviews the evidence of the observational record to date to determine the magnitude of this decrease, and to see if any significant trend in the frequency is discernible. Previous notes<sup>1,2</sup> concerning fog at Heathrow have discussed at length the diurnal and annual variation of this element. Here, by contrast, the primary concern is to describe the year-by-year variation.

The record of visibility at Heathrow extends from early 1946 to the present. These data have been summarized on a monthly basis into the frequency of occasions with visibility in the ranges, less than 45 yd, 45–105 yd, 110–210 yd, 220–430 yd, 440–1090 yd for the eight main observational hours (0001, 0300, 0600.....2100 GMT). Inevitably, changes in recording and coding practices have occurred during this period, and consequently the classification of a few borderline cases in the early years prior to January 1949 is in doubt. However, the number involved is too small to have any significant influence on the final conclusions.

As Davis<sup>1</sup> has already shown, fog frequency at Heathrow is at a maximum in late autumn/early winter and falls to a minimum during the summer half of the year, April to September. The monthly summaries have been divided into 12-month periods July to June and the frequency totals for each of the 'years' from July 1946 to June 1963 derived. Thus, any variation in fog frequency due to persistence or other factors may be related to a specific fog season, and an arbitrary splitting of the winter maximum in the frequencies is avoided.

Table I gives the 12-months (July–June) totals for each of the visibility ranges considered.

TABLE I—12-MONTH (JULY TO JUNE) TOTAL OF 3-HOURLY OBSERVATIONS OF VISIBILITY WITHIN CERTAIN RANGES AT LONDON (HEATHROW) AIRPORT FOR THE YEARS 1946–63

Visibility yards	Year (12-month period commencing July)																
	1946	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
	<i>number of 3-hourly observations</i>																
440–1090	133	114	100	90	82	85	114	93	62	64	84	65	94	42	47	64	71
220–430	23	27	33	37	19	19	45	25	12	17	15	18	38	15	15	18	19
110–210	20	16	25	37	14	15	32	25	15	10	23	17	35	15	18	13	10
45–105	34	26	53	21	12	27	36	39	21	26	30	21	47	23	14	18	28
< 45	10	13	19	17	7	13	31	8	3	16	7	5	28	18	3	6	22

These values have also been combined to give the frequency of occasions with visibility below specific limits in fog, the results being shown in Figure 1. On this basis the variation of frequency shows three marked maxima corresponding with the foggy winters of 1948–49, 1952–53, 1958–59. During these periods the frequencies in the upper ranges increase to approximately twice



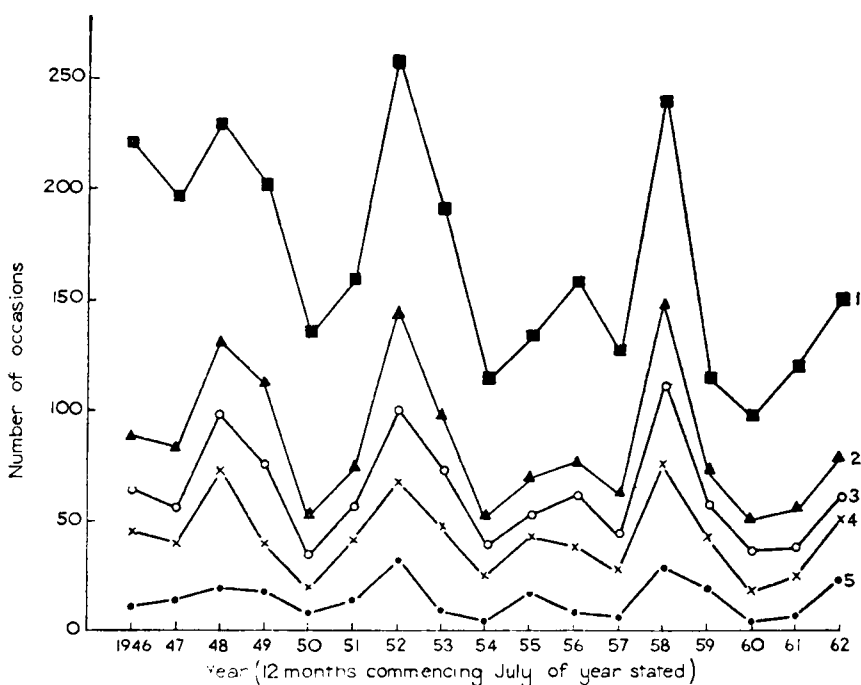


FIGURE 1—YEAR-TO-YEAR VARIATION OF FREQUENCY OF VISIBILITY AT LONDON (HEATHROW) AIRPORT

1—Visibility less than 1100 yards: 2—Visibility less than 440 yards: 3—Visibility less than 220 yards: 4—Visibility less than 110 yards: 5—Visibility less than 45 yards.

the value observed in the intervening years, whilst in the lowest range the amplitude is even greater being as much as 10 times the minimum values.

The variation of frequency for each range of visibility does not always conform to the pattern indicated in Figure 1, e.g. the first maxima for the ranges 110–210 and 220–430 yd both occurred in the winter of 1949–50, see Table I. Further, it is evident that the frequency of fog in the upper ranges has suffered an overall decline during the period thus confirming the impressions of the local forecasters at Heathrow. By contrast, the decrease in the lower ranges is much less pronounced, whilst the frequency of visibilities below 110 yd has remained virtually unchanged apart from the year-to-year variation.

The striking difference between the trend in the upper and lower ranges is emphasized in Figure 2 which shows 5-year running means for each range starting with the 5 years July 1946 to June 1951. For the range 440–1090 yd the mean frequency has dropped by nearly 40 per cent and a similar though less dramatic trend is evident in the middle ranges, the decline being about 10 per cent for visibilities between 45 and 105 yd. The values for the lowest range betray no significant trend. The best-fitting straight lines to each group of 5-year means have also been derived and are given in Table II.

TABLE II—EXPRESSIONS FOR BEST-FITTING STRAIGHT LINES TO 5-YEAR RUNNING MEANS OF VISIBILITY FREQUENCIES WITHIN CERTAIN RANGES

Visibility yards	Expression
440–1090	$f_1 = 100.9 - 3.37t$
220–430	$f_2 = 28.5 - 0.85t$
110–210	$f_3 = 22.9 - 0.34t$
45–105	$f_4 = 29.3 - 0.21t$
< 45	$f_5 = 14.1 - 0.15t$

Where  $f_1$  to  $f_5$  represent the 5-year mean frequency centred at  $t$  years after 1948.



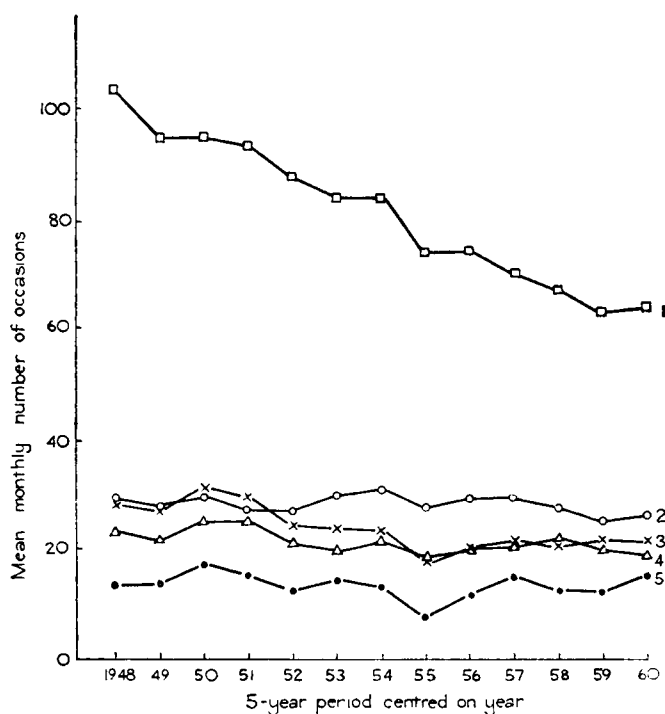


FIGURE 2—RUNNING 5-YEAR MEANS OF ANNUAL FOG FREQUENCY AT LONDON (HEATHROW) AIRPORT

1—Visibility 440–1090 yards: 2—Visibility 220–430 yards: 3—Visibility 110–210 yards: 4—Visibility 45–105 yards: 5—Visibility <45 yards.

For example, the 5-year mean frequency of visibility between 110 and 210 yd centred on 1958 can be expressed approximately as  $22.9 - 3.4 = 19.5$  occasions, whilst the 5-year mean is decreasing at the rate of 3.4 occasions in 10 years. The expressions in Table II show that although the means in all ranges are declining, the rate differs greatly. The rate for the range 440–1090 yd is over 20 times as great as that in the lowest range. In terms of numbers of occasions, the mean decline in the lowest range is of little significance amounting as it does to less than 2 occasions in 10 years.

The distinction between smoke and water fog at Heathrow has been commented upon by Evans<sup>2</sup> who came to the conclusion that visibilities in the range 440–1090 yd were due largely to smoke pollution, though occasions arise when visibilities reported in this range relate to water fog that is in the process of formation or dispersal. Since the frequency of visibilities in the ranges below 440 yd shows the least decline, it is reasonable to assume that the frequency of water fogs has been similarly least affected. Thus the drop in frequency in the upper ranges must be directly related to a decrease in smoke pollution. This is in agreement with the steady decrease of smoke pollution in the London area since 1955 reported by Warren Spring Laboratory, Department of Scientific and Industrial Research.<sup>3</sup>

Finally, the monthly frequencies have been meaned by months and the results are given in Table III.

TABLE III—MEAN MONTHLY FREQUENCY OF 3-HOURLY OBSERVATIONS OF VISIBILITY  
WITHIN CERTAIN RANGES FOR THE YEARS 1946-63

Visibility yards	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
440-1090	12.5	10.9	10.7	2.1	1.2	0.3	0.4	0.6	2.5	12.3	13.8	15.2
220-430	3.8	2.5	2.3	0.4	< 0.1	0.2	< 0.1	0.6	1.3	3.6	3.8	4.6
110-210	3.6	2.5	1.2	0	0.4	0.2	< 0.1	0.5	1.4	3.3	2.3	4.5
45-105	4.3	1.4	1.8	0.2	0.2	0.1	0	0.2	0.9	5.6	5.9	7.4
< 45	1.9	0.8	1.0	< 0.1	0	0	0	0	0.1	1.7	3.2	4.6

Here it is evident that the maximum fog frequency occurs in December, whereas Davis<sup>1</sup> using data from only four years found that November was the foggiest month. Although these data are summaries of 3-hourly as opposed to hourly observations of the earlier analysis, a comparison of the two sets of data shows a difference of at most 5 per cent of the mean value and in general 3 per cent of the mean value. Such a small correction would not alter the above inference.

**Conclusion.**—The year-to-year frequency of fog at Heathrow has declined over the last 17 years whereas there is little change in the frequency of thick fog. The improvement in the higher ranges is seen as primarily the result of the reduction of smoke pollution in the London area in recent years, though the possibility that it is also in part the result of a variation of some synoptic or climatic factor cannot be ignored.

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2. EVANS, D. C.; A second report on fog at London Airport. *Met. Mag., London*, **86**, 1957, p. 333.
3. London, Department of Scientific and Industrial Research, Warren Spring Laboratory. Report for 1963. London, HMSO, 1964, p. 3.

551.577.21:551.577.37:519.2

## THE RELATIONSHIP BETWEEN POINT AND AREAL RAINFALL IN PROLONGED HEAVY RAIN

By F. BURNS

**Summary.**—In two circular areas of 100 square miles each, it was found that on occasions of heavy rain the average difference between the rainfall reading at the centre of the area and an estimate of the areal rainfall was small.

**Introduction.**—It was required to investigate how far rainfall at a particular station was representative of that of the surrounding area, on occasions when falls of rain were heavy enough to result in a risk of flooding. The appropriate rates of rainfall were assumed to be of the order of 1 inch in 12 hours or less, or 1½ inches in 24 hours or less. The two areas studied were Glasgow and Edinburgh.

**Glasgow area.**—This contains a high density of long-established rainfall stations, and has relatively little variation in terrain as shown in Figure 1. The period used was 1939-61 and the number of stations within the circular area for any particular year varied from 15 to 23.

A continuous rainfall-record was available at Renfrew (or Abbotsinch) but other stations in the area reported only 24-hour rainfall amounts at 0900 GMT. Consequently, Renfrew's hourly records were examined; firstly, to identify occasions when considerable amounts of rain fell with few, if any, breaks; secondly, to select from them the occasions when practically all of the rain was

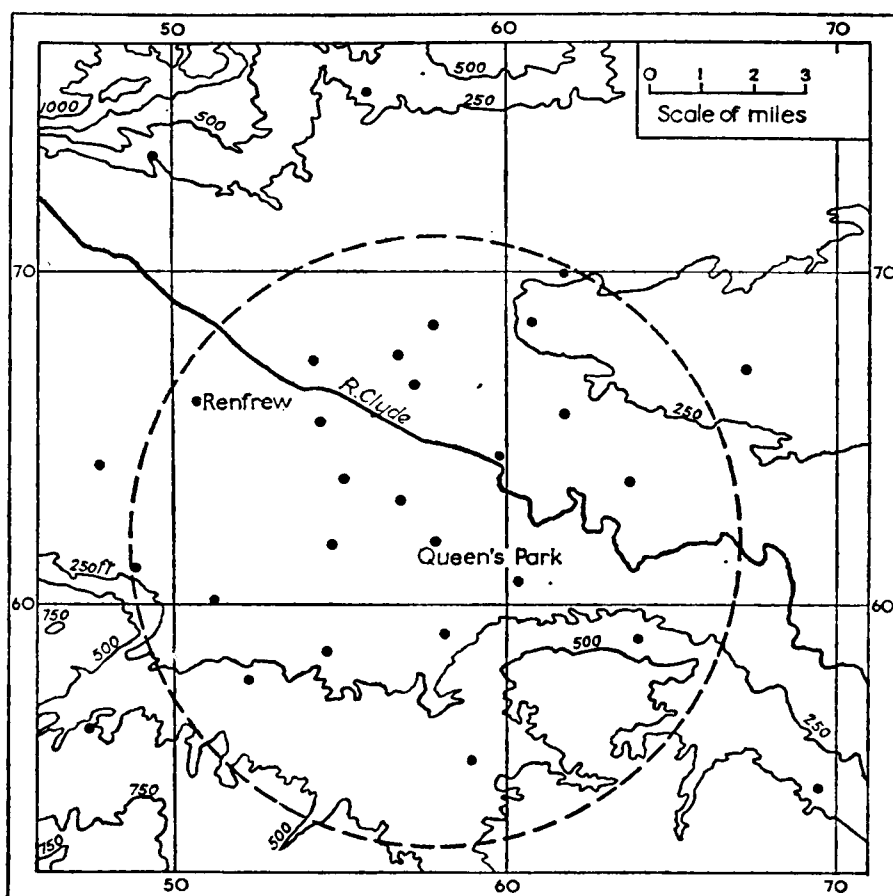


FIGURE 1—POSITIONS OF RAINFALL STATIONS AROUND GLASGOW

• Rainfall station. Contour heights are in feet.  
National Grid lines are shown.

confined to discrete periods of 24, 48 or 72 hours. The *Daily Weather Report* of the Meteorological Office\* was also consulted to ensure that the only cases used were those in which the rain was caused by features on a synoptic scale, e.g. by depressions, slow-moving fronts, etc. rather than by showers or thunderstorms. In all, 36 such instances were found; in these, no rain, or only very small amounts, fell outside the heavy rain period.

For each selected case, the total amounts of rain were plotted for every station in the area, and a circle, centred on Queen's Park, drawn to represent 100 square miles. Isohyets were then drawn at 0.1-inch intervals, and the areas between each successive isopleth within the circle measured by a planimeter. From these planimeter readings, the areal rainfall for each interval (the area between 0.1 inches and 0.2 inches, for example, was allocated a mean value of 0.15 inches), and finally that for the circular zone was calculated. This areal estimate for each occasion is tabulated in Table I, together with the approximate duration of the rainfall, the Queen's Park and Renfrew rainfalls, and the areal rainfalls as a percentage of the rainfalls at both Queen's Park and Renfrew. In Tables I and II, the 'days' quoted are strictly 24 hours beginning at 0900 GMT on the dates indicated.

\*London, Meteorological Office. *Daily Weather Report*.

TABLE 1—DATA FOR GLASGOW AREA

Date	Approximate duration at Renfrew hours	Queen's Park rainfall inches	Areal rainfall inches	Renfrew rainfall inches	Areal rainfall compared with	
					Queen's Park per cent	Renfrew per cent
4 Dec. 1961	17	1.29	1.26	1.52	98	83
27-28 Sept. 1961	15	1.09	1.10	1.40	101	79
7-8 Aug. 1961	20	2.20	2.24	2.31	102	97
13-14 Sept. 1960	27	1.27	1.39	1.50	109	93
4-5 July 1960	12	0.84	0.87	1.20	104	73
12-13 May 1960	12	1.28	1.28	1.16	100	110
26 Oct. 1959	13	1.36	1.44	1.13	106	127
27-28 July 1958	17	1.59	1.74	1.80	109	97
28 Feb.-1 Mar. 1958	34	1.65	1.65	1.92	100	86
24 Nov. 1954	10	0.88	0.85	1.00	97	85
16-18 Oct. 1954	58	3.32	3.41	3.03	103	113
1-3 Dec. 1953	47	2.47	2.56	2.36	104	108
19 Dec. 1951	15	0.81	0.93	1.19	115	78
6 Sept. 1950	10	1.19	1.26	1.24	106	102
10-11 Sept. 1950	30	1.74	1.77	1.80	102	98
17-18 Oct. 1949	17	0.85	1.06	1.34	118	79
24-25 Oct. 1949	21	1.46	1.51	1.41	103	107
7 Aug. 1949	18	2.37	2.12	2.57	89	82
6-7 Jan. 1949	24	1.48	1.57	1.41	106	111
6 June 1948	12	1.25	1.41	1.14	113	124
12 Oct. 1947	12	0.97	0.92	1.10	95	84
15-16 Sept. 1947	12	1.09	1.10	1.02	101	108
5 Apr. 1947	12	1.16	1.06	1.14	91	93
13 July 1945	12	0.64	0.67	1.02	105	66
19-20 Oct. 1944	13	1.28	1.23	1.07	96	115
4 Nov. 1944	22	1.89	1.75	1.55	93	113
4-5 Feb. 1943	24	1.39	1.28	1.65	92	78
3 Oct. 1943	24	1.68	1.63	1.90	97	86
10 Dec. 1942	13	0.68	0.78	1.18	115	66
23 May 1941	15	1.10	1.27	1.32	115	96
15 Aug. 1941	17	1.35	1.37	1.15	101	119
19-20 Aug. 1940	4	1.08	0.93	1.02	86	91
8-9 Oct. 1940	36	1.44	1.56	1.92	108	81
14 Jan. 1939	12	0.92	0.86	1.01	94	85
6 Feb. 1939	12	0.80	0.82	0.98	103	84
7 July 1938	12	0.69	0.82	1.14	119	72

The differences (areal estimate minus rainfall at Queen's Park) are plotted against Queen's Park rainfall in Figure 2, and the graph indicates a fairly even scatter about the mean difference of 0.026 inches, with a slight tendency towards reduced scatter with increasing rainfall. The standard deviation is 0.10 inches.

To give an indication of how the difference (areal estimate minus station rainfall) would vary if the station were chosen near the edge of the circular zone, the mean difference (areal estimate minus rainfall at Renfrew) was calculated. Its value is -0.086 inches, with a standard deviation of 0.22 inches.

**Edinburgh area.**—A similar study was carried out for the Edinburgh area with Turnhouse and Firhill in place of Renfrew and Queen's Park. For the period 1948-63, examination of the continuous rainfall-record at Turnhouse revealed 34 occasions of 'heavy rain'—as defined earlier. The circular zone was centred on Firhill Tank, Colinton, and the number of stations in the zone varied from 15 to 28 (Figure 3).

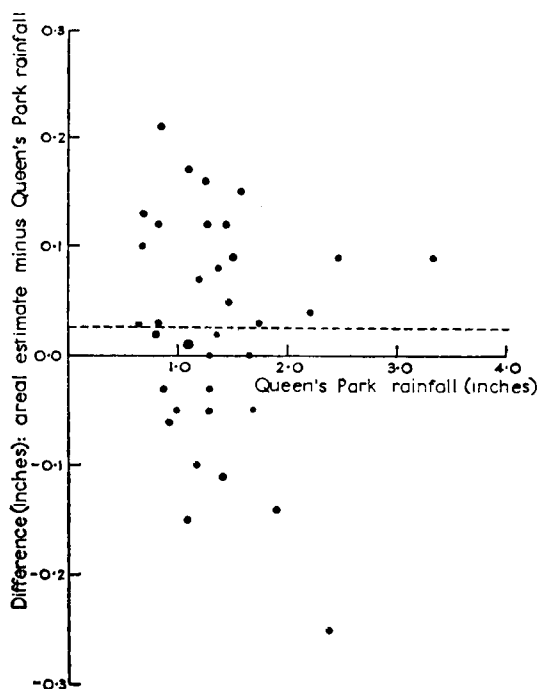


FIGURE 2—DIFFERENCE BETWEEN AREAL ESTIMATE AND QUEEN'S PARK RAINFALL  
FOR VARIOUS VALUES OF QUEEN'S PARK RAINFALL  
----- Mean difference, equal to 0.026 inches.

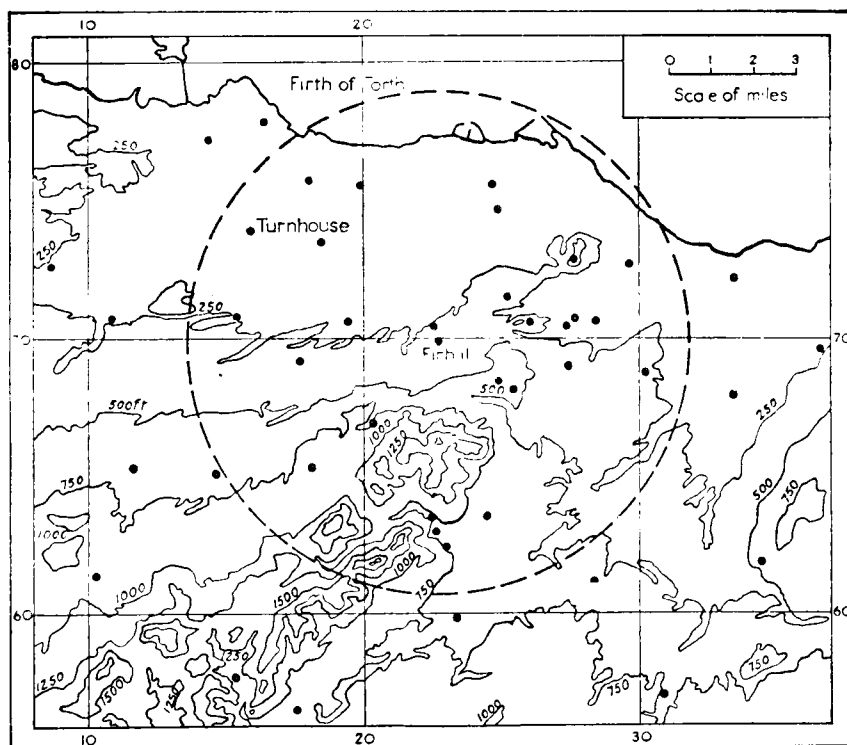


FIGURE 3—POSITIONS OF RAINFALL STATIONS AROUND EDINBURGH  
· Rainfall station. Contour heights are in feet.  
National Grid lines are shown.

Topographically, the Edinburgh area is markedly different from the Glasgow one, with a pronounced ridge in the south-south-west. Here, as there were no stations above 800 feet reporting daily readings, the isohyets over the higher ground (which reaches about 1800 feet) were based on values obtained by adding 25 per cent per 1000 feet to the reading reported from the nearest daily station. This figure is the average increase of the annual rainfall in the area per 1000 feet, and may not be true for daily rainfall; however as the area above 800 feet is only about 10 per cent of the whole, the value adopted will not greatly affect the final figures.

For the Edinburgh area Table II gives the information corresponding to Table I. The mean difference (areal estimate minus rainfall at Firhill) is  $-0.144$  inches, with a standard deviation of  $0.26$  inches (Figure 4). If the extreme case, for 7-8 August 1948, is omitted, the mean difference and standard deviation are reduced respectively to  $-0.114$  and  $0.19$ . There is a tendency for the Firhill observation to increasingly over-estimate the areal rainfall as the

TABLE II—DATA FOR EDINBURGH AREA

Date	Approximate duration at Turnhouse hours	Firhill rainfall inches	Areal rainfall inches	Turnhouse rainfall inches	Areal rainfall compared with Firhill	
					per cent	Turnhouse per cent
22-23 Nov. 1963	30	1.23	1.28	1.33	104	96
10 Nov. 1963	13	1.06	1.01	1.22	95	83
10-11 Sept. 1962	30	1.89	1.71	1.64	91	104
24 July 1962	14	1.20	1.14	0.92	95	124
20-21 July 1962	13	0.95	1.04	1.09	109	95
10 July 1962	12	1.37	1.26	1.22	92	103
7-8 Aug. 1961	34	2.88	2.45	2.30	85	107
12 July 1961	18	1.49	1.55	1.52	104	102
12-13 May 1960	14	1.12	1.02	1.23	91	83
27-28 July 1958	25	2.30	2.24	1.74	97	129
4-5 Nov. 1957	10	1.61	1.33	1.31	83	101
21-22 Jan. 1957	28	0.98	1.06	1.07	108	99
2-3 Sept. 1956	28	2.56	2.14	1.99	84	107
27-28 Aug. 1956	21	1.64	1.68	1.34	102	125
29 July 1956	13	1.70	1.47	1.43	87	103
11-12 June 1956	27	0.81	0.99	1.44	122	69
2-3 July 1955	24	1.47	1.48	0.91	101	163
16-17 Oct. 1954	30	1.58	1.40	1.31	89	107
14-15 Oct. 1954	19	1.63	1.71	1.69	105	101
3 Dec. 1953	21	2.11	1.73	1.61	82	107
16-17 Sept. 1953	16	1.67	0.97	1.19	58	81
7 Aug. 1952	22	1.35	1.11	1.00	82	111
21 Apr. 1952	18	1.15	1.14	1.13	99	101
6-7 Aug. 1951	29	2.86	2.75	2.83	96	97
22 July 1951	19	1.10	1.27	1.53	115	83
30 Apr.-1 May 1951	18	1.80	1.59	1.56	88	102
21 Nov. 1950	23	1.45	1.18	1.14	81	103
10-11 Sept. 1950	29	1.44	1.38	1.76	96	78
24-25 Oct. 1949	21	2.27	2.09	2.31	92	91
23 Oct. 1949	10	1.62	1.37	1.18	85	116
6-7 Jan. 1949	19	1.31	1.42	1.37	108	104
14-15 Sept. 1948	12	1.50	1.46	1.53	97	95
11-12 Aug. 1948	24	2.40	2.33	2.06	97	113
7-8 Aug. 1948	43	4.24	3.08	2.90	73	106

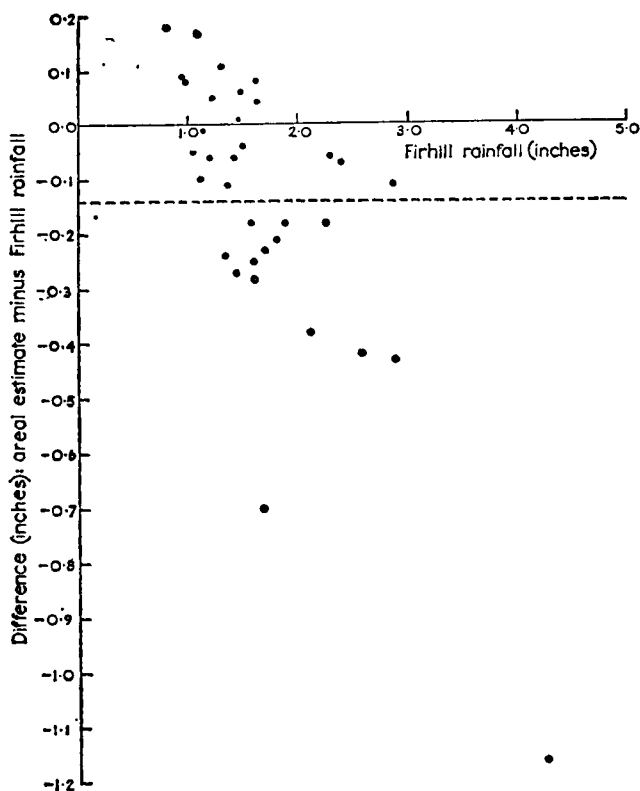


FIGURE 4—DIFFERENCE BETWEEN AREAL ESTIMATE AND FIRHILL RAINFALL FOR VARIOUS VALUES OF FIRHILL RAINFALL  
 - - - - Mean difference equal to -0.144 inches.

total fall increases. If Turnhouse—near the edge of the circular zone—is adopted as the base station, then the mean difference (areal estimate minus rainfall at Turnhouse) is 0.030 inches, and the standard deviation 0.21 inches.

551.515.3

## DUST WHIRLS AT IDRIS AIRPORT ON 31 MAY AND 1 JUNE 1964

By J. B. MCGINNIGLE

At 1229 GMT on 31 May 1964, a large and very well-developed dust whirl tracked across Idris Airport, position  $32^{\circ}41'N$   $13^{\circ}10'E$ , 14 n.miles south of Tripoli, North Africa. Its centre moved directly over the control tower and meteorological office area, causing some damage to and within the building. A window was broken when it was thrown against its frame and some items of radio equipment were thrown from a table adjacent to another window. A noise like a small explosion was heard at the time. The dust whirl was then observed to be tracking towards  $120^{\circ}$  at approximately 10 kt its base being about 50 yards in diameter while the top, estimated to be at about 2000 feet, appeared to be about 250 yards in diameter. As its track had been across mainly cultivated land, there was not a great deal of dust or sand in the vortex but its extent was clearly marked by a large number of pieces of paper and vegetation circling cyclonically at all heights. Sizable objects were easily kept aloft by the upcurrent. The circulation was observed for five minutes, by which time it was almost a

mile away and difficult to observe because of its transparency. With the passage of the dust whirl, the north to north-easterly sea breeze penetrated to Idris, its speed initially being 10 kt subsequently increasing to 15 kt.

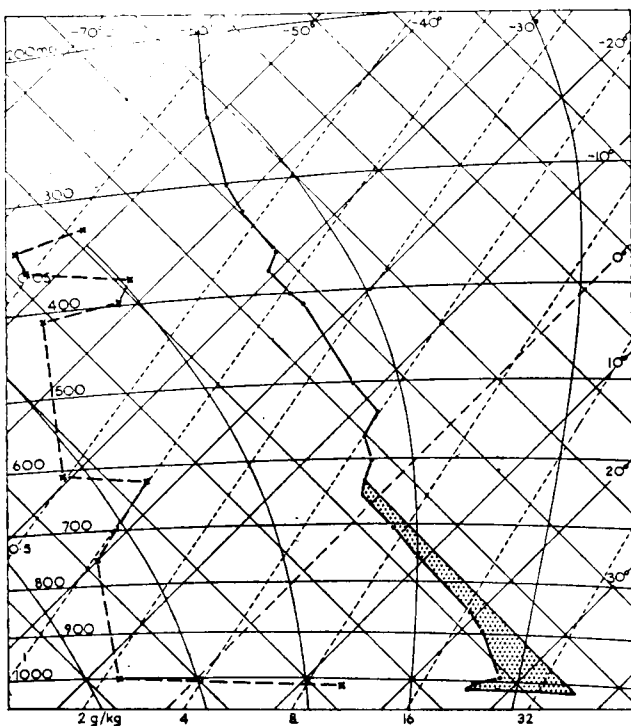
The next day, 1 June, a number of well-developed but considerably smaller dust whirls were observed at Idris between 1130 and 1400 GMT. Although none tracked near to the meteorological office, a typical example of one of these dust whirls was observed close to its source region and was subsequently followed for 14 miles as it moved northwards at about 40 kt approximately parallel to a road connecting Idris with Tripoli. The vortex circulation was again cyclonic at all heights. The source region was a small area of sandy ground, surrounded by trees and other fairly dense vegetation, and the vortex contained large quantities of sand. As it moved overland, mainly over sandy ground, the vortex was at all times clearly visible and did not vary much in size or intensity.

**Meteorological situation and observations.**—On 31 May 1964, pressure was slack over the Idris area and the air mass was very dry and unstable as can be seen from the 1200 GMT upper air ascent (Figure 1(a)) from Wheelus Field, situated 17 n.miles north-north-east from Idris, near to the Mediterranean coast. The low-level inversion on this ascent was due to the penetration of the northerly sea breeze into Wheelus Field around 1000 GMT. At Idris, however, the air temperature quickly rose to 36°C at 1200 GMT with a relative humidity of 13 per cent. The sea breeze was expected to penetrate to Idris between 1200 and 1400 GMT, and to take up its normally recorded direction and speed of north-easterly, 15 kt. As indicated in Figure 1(a), a convection path superimposed on this ascent using the Idris 1200 GMT air temperature and dew-point follows the dry adiabat to 630 mb, where the condensation level and the normal upper level of convection are coincident. A large positive energy area exists, as marked on Figure 1(a).

At the time of passage of the dust whirl, the meteorological office barograph showed an instantaneous fall and rise of 3.5 mb; the M.S.L. pressure reading at 1200 GMT was 1010.2 mb and the pressure indicated at the vortex passage was 1006.7 mb. At 1245 GMT, ground temperature readings were taken by placing a thermometer, shielded from the direct rays of the sun, with its bulb about 1 ft above the surface. The temperature of three representative types of ground was measured and the results were: rough grass 41.2°C, sand 43.2°C, tarmac chip road 45.0°C. An environmental lapse rate of between 5 and 9°C per 1000 ft existed in the first 4 feet of the air at this time, with a superadiabatic rate extending to at least 2000 feet, and a dry-adiabatic lapse rate to 10000 ft. The use of the ground temperatures as measured at 1245 GMT would indicate an even larger positive energy area than that shown in Figure 1(a).

On 1 June, the development of a complex depression over Algeria and Tunisia caused a strong southerly gradient over the area and the surface wind was increased overnight to become south-easterly 15–20 kt by 0700 GMT, gusts to 25–30 kt by 0900 GMT. Because of this strong surface wind, there was no sea-breeze penetration at either Wheelus Field or Idris on this day, and the air temperature at both stations increased rapidly during the morning to 38°C at Wheelus and 40.6°C at Idris at 1200 GMT, with a relative humidity of 8 per cent. Again Figure 1(b) shows the extreme dryness and instability of the air (1200 GMT ascent 1 June) but, in this case, the convection path using the





(a) 1200 GMT on 31 May 1964

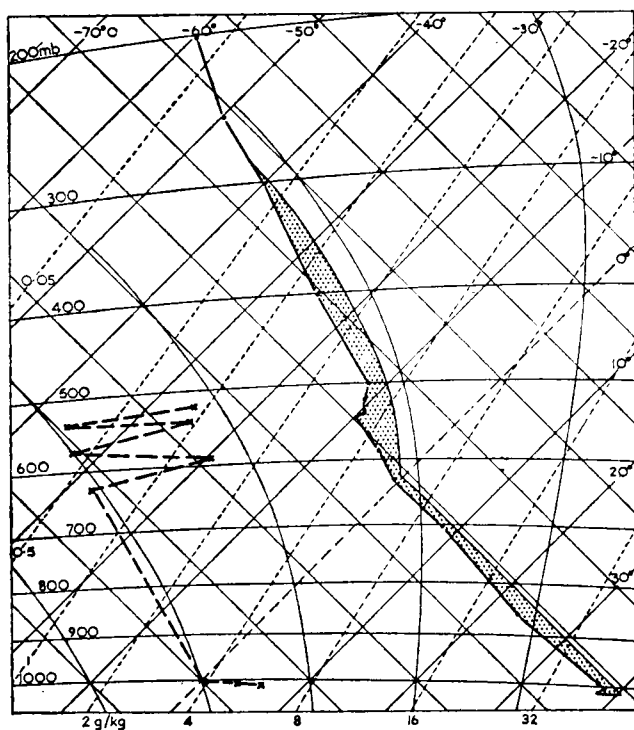


FIGURE 1—UPPER AIR ASCENTS FROM WHEELUS FIELD

(b) 1200 GMT on 1 June 1964

— Dry-bulb temperature, - - - dew-point temperature.

Positive energy areas are shown by stippling. Convection paths are based on the Idris surface temperature and dew-point at 1200 GMT on each date.

1200 GMT Idris air temperature and dew-point although extending to far higher levels than the previous day, is far closer to the environment temperature path thus producing a markedly smaller positive energy area than on the previous day. Also, although no ground temperatures were taken on 1 June, it is assumed that the much higher surface wind velocity would decrease the lapse rate between the ground and the 4-foot level. The use of an assumed ground temperature as above would therefore not increase the positive energy area as much as would the conditions of 31 May already described.

### Discussion and conclusions.—

(i) *Dust whirls of 1 June.*—On this day, the combination of the very marked instability and the extremely high air (and ground) temperatures over the whole land area produced ideal conditions for the maintenance of developed dust whirls. Because of the strong surface wind, ground temperatures would vary with the exposure, and the source region of the dust whirls, by virtue of its sandy surface and sheltered exposure, would undoubtedly have a higher ground temperature than the more cultivated and exposed ground which surrounded it. As can be seen from Figure 1(b), a superadiabatic lapse rate would exist only in the first few hundred feet of the 1200 GMT ascent of 1 June, using the recorded Idris temperatures for 1200 GMT. This would indicate that the height of the dust whirls would not exceed a few hundred feet and those observed were estimated not to be of greater vertical extent.

(ii) *Dust whirl of 31 May.*—The only dust whirl observed on this day was very large and passed directly over the meteorological office at Idris. It is very significant that its passage was immediately followed by the penetration of the sea breeze and this, coupled with its direction of movement, indicates that the dust whirl was associated with the sea-breeze front.

The combination of the very unstable air mass, large positive energy area and very high air and ground temperatures, further allied to the marked horizontal convergence of the sea-breeze front, would be highly conducive to the formation of a vigorous vortex which would develop on the front as a wave depression. The vortex would move along the sea-breeze front with the direction of the wind in the lower levels and the circulation would probably be maintained to a few thousand feet. The Wheelus Field ascent gives the wind at 2000 ft at this time as  $290^\circ$ , 8 kt. It is therefore suggested that this very large dust whirl was a small vigorous wave depression on the sea-breeze front.

## REVIEWS

*Einfluss der Karpaten auf die Witterungserscheinungen (Die II. Konferenz für Karpatenmeteorologie Budapest, 13–15 November 1961)*, edited by Dr. J. Kakas,  $6\frac{1}{4}$  in  $\times$   $9\frac{1}{2}$  in, pp. 297, *illus.*, Akadémiai Kiadó, Budapest V, Alkotmány Utca 21, 1963. Price: \$9.50.

This publication contains the lectures, reports and discussions of the Second Conference on The Meteorology of the Carpathians held at Budapest in 1961. The First Conference was held at Smolnice and it was proposed that a Third Conference should be held in 1963.

The papers are written in Russian or German and summaries are given in Hungarian and English. The summaries, for the most part, are detailed and

adequately represent the substance of the papers concerned. In general, the English summaries are written in a sound colloquial style and this, together with the fact that all figure and table captions have English translations, should enable the English reader who has no Russian or German to obtain a great deal of value from the papers.

The volume, although it contains papers of general meteorological interest, deals mainly with the effect on the weather of the Carpathian Mountains (and of the Danube basin as a whole since the two are closely linked geographically and meteorologically). It may be felt by the British reader that our own mountains are remote physically and in scale from the Carpathian Mountains but many of the problems of Alpine meteorology occur also in this country and the research devoted to the peculiarities of mountain weather and climate discussed in this volume may have fruitful application to mountain areas in Britain.

The first paper consists of a review of research work in hydrometeorology in the Ukrainian sector of the Carpathians, and is followed by a group of papers which discuss rainfall. The Bodolai family has produced many stimulating papers on the relationship between meso-scale rainfall distribution and synoptic situations and on this occasion Mme Bodolai presents a discussion on the effect of friction-induced vertical velocities on the spatial and temporal distribution of precipitation. D. Szepesi discusses the effect of mountain ranges in inducing 'additional' precipitation. He demonstrates that, in certain situations, although a föhn effect may result in 'negative' orographic precipitation 15 kilometres to the lee of a mountain ridge, 'positive' orographic precipitation may be discerned a further 15 kilometres downwind due to lee waves.

A further group of papers discusses snow measurements, avalanches (of which there are several photographs), duration and extent of snow cover, etc.

Another loosely-related group of papers deals with temperature conditions in the Carpathians, the mapping of temperature distribution (particular reference is made to the difficulty of mapping temperatures in mountains because of local pools of cold air in valley bottoms and temperature inversions), and advective influences as reflected by the frequency distribution of temperature anomalies.

Several papers deal specifically with synoptic meteorology. Three of these are rather specialized in that they discuss irruptions of cold air into the Danube basin and one of them considers the synoptic conditions which allow cold air to flow into the Pannonian Plain (that part of the Danube basin in which Belgrade is centred) simultaneously from two or more directions.

In a paper on methods for the investigation of orographically induced weather in the Carpathians, a wave-like distribution in 24-hour precipitation patterns, similar to the pattern which Parrey<sup>1</sup> discovered to the lee of the Peak District in England, is discussed.

W. Böer in a paper on synoptic climatology suggested that progress in dynamical climatology had been disappointingly slow since Bergeron first introduced the concept. Reasons for this and suggestions as to how further progress might be made were put forward by the author and by many speakers in the ensuing discussion.

The complexity of rainfall distribution in mountainous areas is illustrated in one of the most unusual rainfall maps the reviewer has seen. The map of annual rainfall (p. 228) is based on a network of more than 30 rain-gauges in an

area of 40 square kilometres to the south of Lunz and shows a marked rainfall maximum in the main river valley with amounts decreasing to minimal values on a plateau to the west and on a ridge to the east. Such a distribution is quite contrary to that usually observed in Britain.

Several papers discuss radiation-balance and water-budget in Carpathian areas. In one of these papers, on the roles played by radiative and advective influences in the climatic pattern of Hungary, the ratio of the amount of precipitation which forms run-off to the amount which is returned to the atmosphere as evaporation is derived for various catchment areas of central Europe and also for the neighbourhood of London. Unfortunately, the ratio of 1:1 (p. 242) for the London area given is incorrect. For the major catchment the Thames to Teddington (an area of about 10,000 square kilometres) the ratio is about 1:2 and for the drier Lee at Feildes Weir (about 1000 square kilometres) it is nearer 1:3.

In the final paper, W. Lászlóffy stresses the interdependence of the states of the Danube basin hydrologically and meteorologically and puts forward a number of proposals for international collaboration. Dr. Dési, in the preface, also stresses this need, as, indeed, do many of the authors in the body of the volume.

The present work is a most happy example of international co-operation. Naturally, authors from Hungary, the host country, provide the greatest number of papers, but at least one paper appears from each of the following countries associated with the Carpathians and the Danube: Russia, Yugoslavia, Czechoslovakia, Poland, East Germany, Austria and Romania.

The standard of production of the volume is far higher than for most published proceedings of conferences and symposia and reflects great credit on the editors and on the Publishing House of the Hungarian Academy of Sciences. The reproduction of figures and photographs is excellent, the print is clear (and of a reasonable size), and misprints, the curse of multilingual proceedings of symposia, appear remarkably few.

J. GRINDLEY

#### REFERENCE

1. PARREY, G. E.; Unexpected rainfall at Watnall, 18 May 1958. *Met. Mag., London*, **89**, 1960, p. 71.

*The physics of lightning*, by D. J. Malan. 8½ in × 5½ in, pp. xvi + 176, *illus.*, English Universities Press Ltd., 102 Newgate Street, London, E.C.1, 1963. Price: 25s.

The appearance of a textbook covering, even if briefly, almost every aspect of the physics of lightning and its associated phenomena, is of obvious importance. This work undoubtedly achieves at least two of the writer's three aims, in providing material both for the general reader and for the student intending to take up work on lightning research. For the third of the purposes stated in the author's preface, the provision of a useful reference book, achievement is more doubtful. The work suffers to some extent by being dated, a fault almost inevitable in a textbook dealing with a continuously advancing subject.

Where references to other publications are given, they are far from complete, being limited to 12 published documents in a field which has produced an extensive volume of material.

The practical aspects of damage arising from lightning are mentioned only briefly. While the very real hazard to aircraft, arising from the violent turbulence associated with clouds from which lightning discharge is possible, could be accepted as being outside the subject of the physics of lightning as such, any reference to the effect of lightning in aircraft should include the risks associated with damage to ancillary equipment, such as radio, and not be limited to wing-tip to wing-tip strikes. The reasons for the usual immunity from damage from such strikes is also worthy of mention.

In dealing with lightning flash counters, the basic problem of knowing the area over which the count is made, or, if the area is world wide, of ensuring that each flash is counted only once, is not explained. No reference is made to the important international local lightning flash counter accepted as a standard by the International Radio Consultative Committee (CCIR).

Both the specialist in lightning physics and the meteorologist will find particular interest in the location of thunderstorms by radio direction finding, and descriptions are given of the two systems in regular use. Unfortunately there is no critical discussion of the relative merits and shortcomings of the two methods, while the lack of up-to-date detail is exemplified by reference to the stations of the British Sferics Network—the list is incomplete and one station mentioned has been closed for the past 10 years.

This book, while filling an undoubted requirement, would benefit from revision on points of detail and amplification in several important aspects. Despite this it forms a welcome introduction to a subject of great interest and importance.

A. L. MAIDENS

## OBITUARY

It is with deep regret that we heard of the death of Mr. H. A. Scotney on 30 June 1964. Mr. Scotney, Senior Experimental Officer, retired on 30 November 1958 after 33 years in the Office. Our sympathy is extended to his widow and son.

## CORRIGENDA

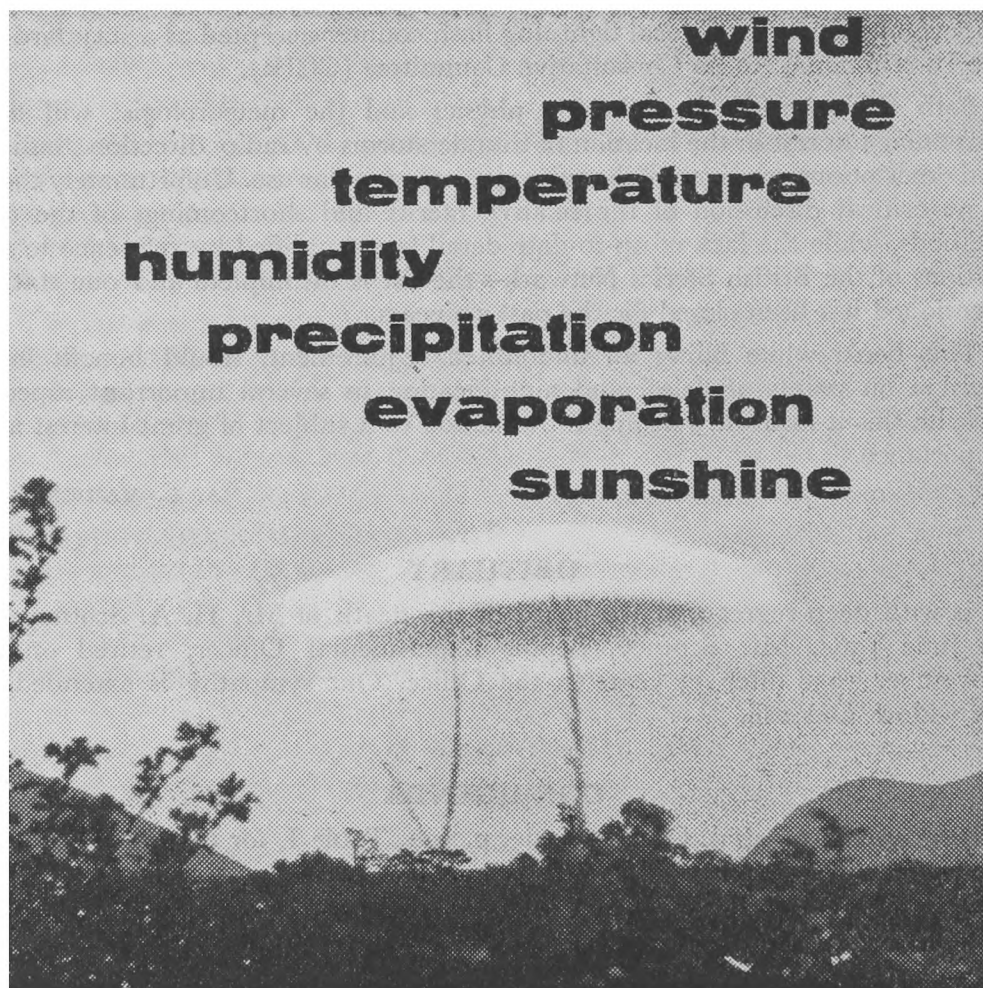
*Meteorological Magazine*, October 1963, p. 302, Table I, for the Fordingbridge values substitute the following:

	<i>NW</i>	<i>N</i>	<i>E</i>	<i>S</i>	<i>ACW</i>	<i>W</i>	<i>CW</i>	<i>C</i>	<i>AC</i>	<i>U</i>
Fordingbridge	1.0	0.3	2.5	4.6	0.3	3.3	2.8	4.3	0.6	4.8

*Meteorological Magazine*, June 1964, p. 171, in the bold subheading, for “stratosphere” read “troposphere.”

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# THE METEOROLOGICAL MAGAZINE

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551.582.2(676.1):551.588.2

## A LOCAL CLIMATIC STUDY IN TYPICAL DISSECTED TOPOGRAPHY IN THE SOUTHERN REGION OF UGANDA

By P. A. HUXLEY and M. BEADLE\*  
Makerere University College

**Summary.**—The kind and magnitude of diurnal local climatic change at Makerere University College Farm are described with the aid of diagrams for two occasions chosen as representing likely extreme weather conditions.

As the topography of the Farm is typical of a large part of the agriculturally important area of south and south-western Uganda similar differences in local climate are likely to be experienced throughout this region.

**Introduction.**—Makerere University College Farm (latitude  $0^{\circ}28'N$ , longitude  $32^{\circ}37'E$ , maximum altitude 3950 feet above M.S.L.) is situated in the southern, lake-shore region (the south and south-west part of Buganda) of Uganda about 11 miles north of Kampala. Originating from a raised peneplain the present topography is highly dissected and characterized by small, often flat-topped hills with the land sloping away to swamps in the valleys; these swamps eventually drain northwards into the Nile system. The amplitude of relief is moderate, with a difference in height between hilltops and valleys of about 300–400 feet which increases somewhat towards the north-west of the region (Singo County), but elsewhere it can be less where pedimentation has been active (Pallister<sup>1</sup>). The vegetation is typically short-grass savanna on the summits and hill slopes, long grass (*Pennisetum purpureum*) and scattered trees on the pediments, with papyrus (*Cyperus papyrus*) a dominant species in many of the swamps; the area is intensively cultivated however (see Plate I). A more detailed summary of the physiography of this region can be found in Radwanski.<sup>2</sup>

During the course of early development at the Farm, a meteorological site was established, and detailed accounts of the weather experienced have been published annually for 1961 onwards (Huxley<sup>3</sup>). This meteorological site is located on top of the ridge running north–south through the middle of the farm, the boundaries of which extend down to the swamps on either side. Although the relative relief is not great, it was obvious that local climatic differences existed, and some measure of the magnitude of these was considered desirable as a preliminary to further investigation on how such variations could affect crop plants and farm animals.

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\*Now Climatologist at the Nuffield Unit of Tropical Animal Ecology, Queen Elizabeth National Park, Uganda.

**Methods.**—With the limited resources available, it was felt that such a study would best be accomplished by 24-hour surveys along a 'transect' across the Farm from the eastern to the western boundary. The range of elevation experienced was 210 feet (Figure 1). Dry-bulb and wet-bulb temperatures

# SECTION (composite)

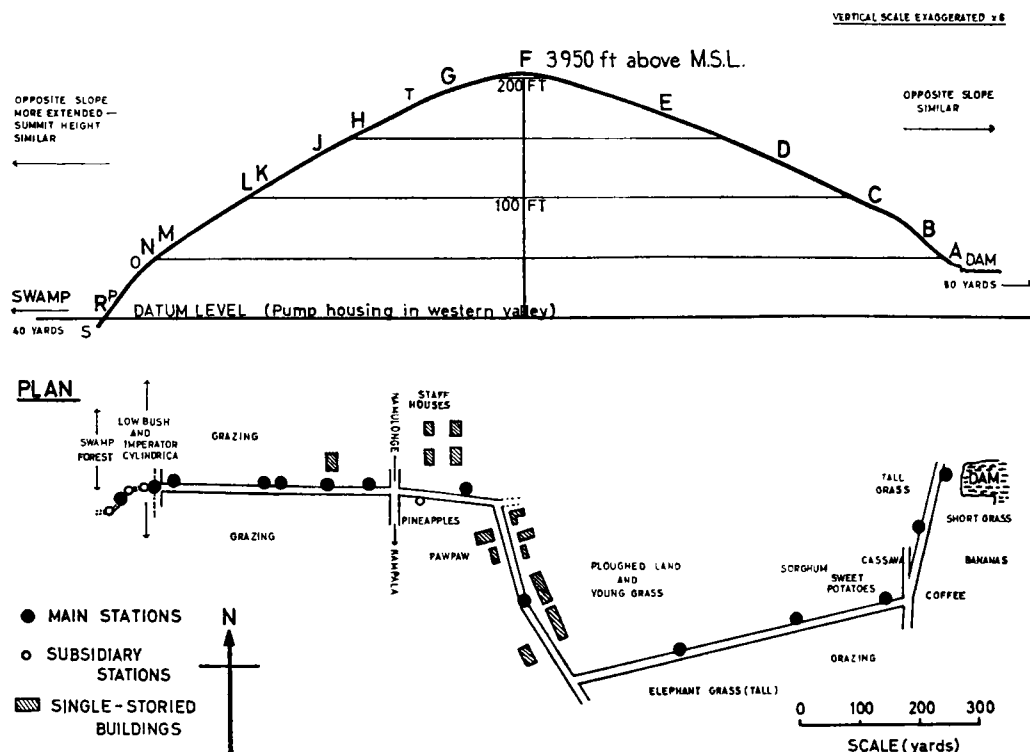


FIGURE 1—PLAN AND COMPOSITE SECTION SHOWING POSITION OF STATIONS AT WHICH RECORDS WERE TAKEN

were measured with a whirling psychrometer at approximately 3 feet above ground level; mean wind speed on the ridge site, wind direction, cloud amount, and dew occurrence were also recorded.

These observations were made during several 24-hour periods of which two have been selected here as representing the possible extremes of local weather conditions. Along the transect, data were obtained successively from not less than 10 stations, which were a few yards to the side of a farm track in most cases. At any one time several psychrometer readings were taken at each station, so as to ensure accuracy, and during daylight hours the psychrometer was shaded from direct solar radiation. Relative humidities and dew-points were calculated using a Mark V Meteorological Office humidity slide-rule. Both cloud amount and mean wind speed were estimated hourly, the latter with the aid of a cup-counter anemometer situated at 2 metres above ground level on top of the ridge. The presence of dew was estimated by examining adjacent short grass and scoring on an arbitrary scale of five degrees.

**Results and conclusions.**—Figures 2, 3 and 4 show dry-bulb temperatures, relative humidities, and dew-points (as well as the presence of dew) respectively.



Figures 2(a), 3(a) and 4(a) refer to a survey carried out on 8 to 9 December 1960, and Figures 2(b), 3(b) and 4(b) to one on 8 to 9 March 1961. Cloud amounts, wind direction and hourly mean wind speed are shown at the right side of Figures 2(a) and (b).

(i) *Dry-bulb temperatures.*—

8–9 December 1960, (Figure 2(a)).—A relatively large amount of cloud and a breeze during the afternoon maintained fairly even temperatures over the whole transect; conditions became almost isothermal at sunset. At this time wind speed decreased somewhat, and a little later the sky cleared. Radiative cooling did not take place to any degree during the night however, as extensive cloud soon developed, and temperatures remained relatively high in all areas overnight. The diurnal temperature ranges experienced on the ridge and lower western slope were only 9°C and 13°C respectively. At dawn, cloud largely dispersed, the wind increased and there was a relatively evenly distributed rise in temperature over the transect.

8–9 March 1961, (Figure 2(b)).—In sharp contrast to the previous occasion this period was virtually cloud-free, although winds were quite strong. However, conditions are seldom calm in this region and the mean run of wind at the meteorological site is about 60 miles per day. On the ridge a seldom-exceeded maximum temperature of 33°C was reached during the afternoon, and in the more sheltered low-lying parts temperatures were higher still. In the late afternoon temperatures decreased more rapidly in the western swamp than at higher stations, and subsequently with a clear sky and reduced wind speed this effect was reinforced—almost certainly by the katabatic flow of cold air down the slopes. The accumulation of cool air on the lower slopes was disturbed shortly after midnight when the wind became slightly stronger again. This may have been due simply to mixing from higher levels, or it could have been partly caused by a release of latent heat of condensation consequent on dew formation (Monteith<sup>4</sup>). Later in the night temperatures continued to decrease in the lower areas; this was markedly so near to sunrise when conditions became virtually calm. The minimum temperature recorded in the western swamp reached 8°C; on the ridge it was 15°C—a lower temperature than this is seldom recorded there. The diurnal temperature ranges on the ridge and the lower western slope during this period were 17°C and 27°C respectively.

(ii) *Relative humidity* (Figures 3(a) and 3(b)).—The close dependence of this parameter on temperature is well illustrated by the similarity in isopleth patterns for the respective diagrams; it is seen best when comparing figures 2(b) and 3(b). During the day, in both surveys, there was little difference in relative humidity between the lower sites and the ridge but, as expected, overnight in the second survey a marked increase in relative humidity occurred at the lower sites as temperatures dropped. The generally low relative humidity which occurred during the afternoon of 8 March represents an extreme for the locality.

(iii) *Dew-points and the presence of dew.*—

8–9 December 1960 (Figure 4(a)).—The variation between dew-points over the whole area was not more than 2.5°C at any one time. A slight rise commencing in the afternoon continued until about 0300 hours (note: all times are East African Standard Time, i.e. GMT + 3 hours) and examination of the

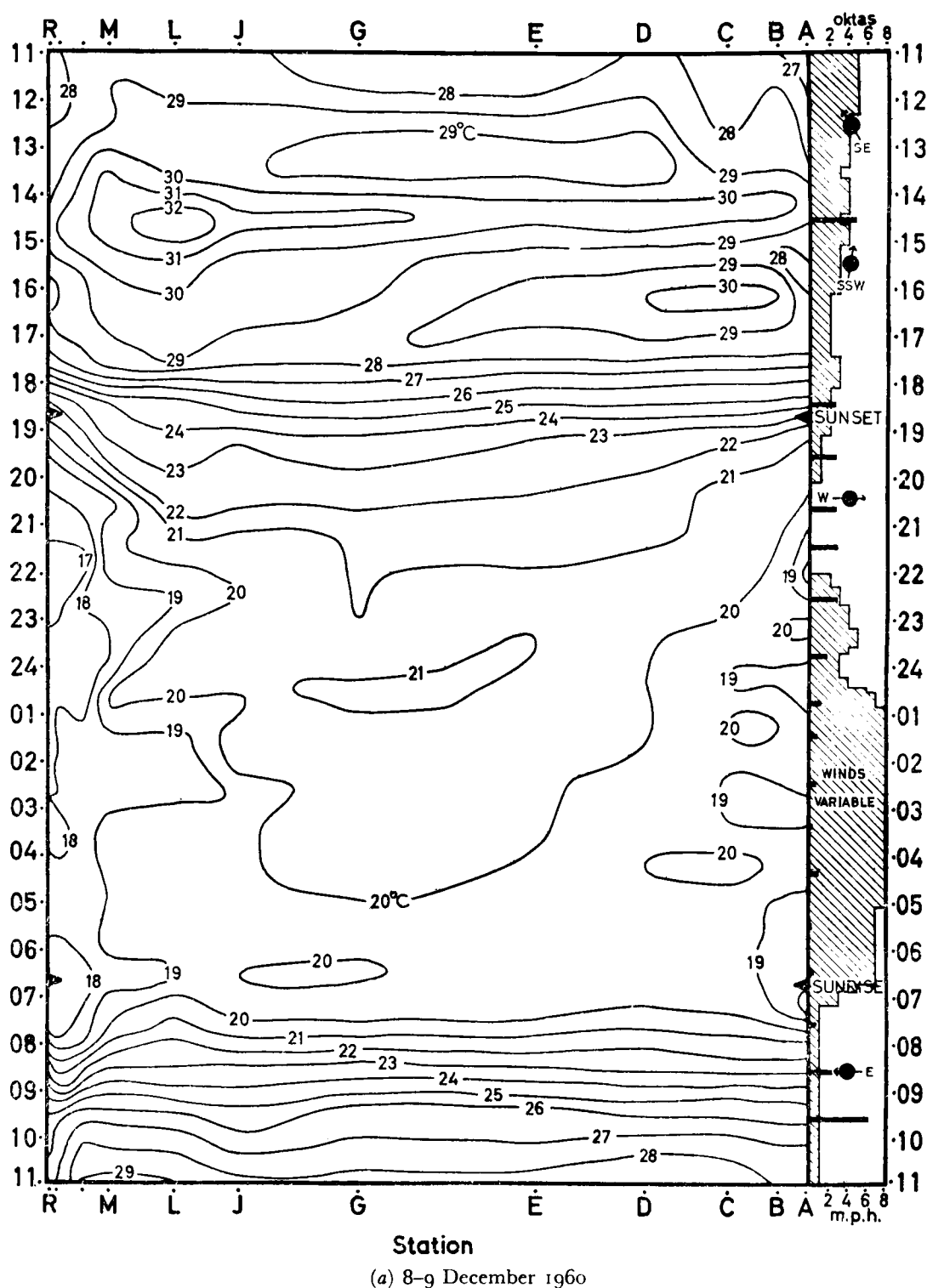
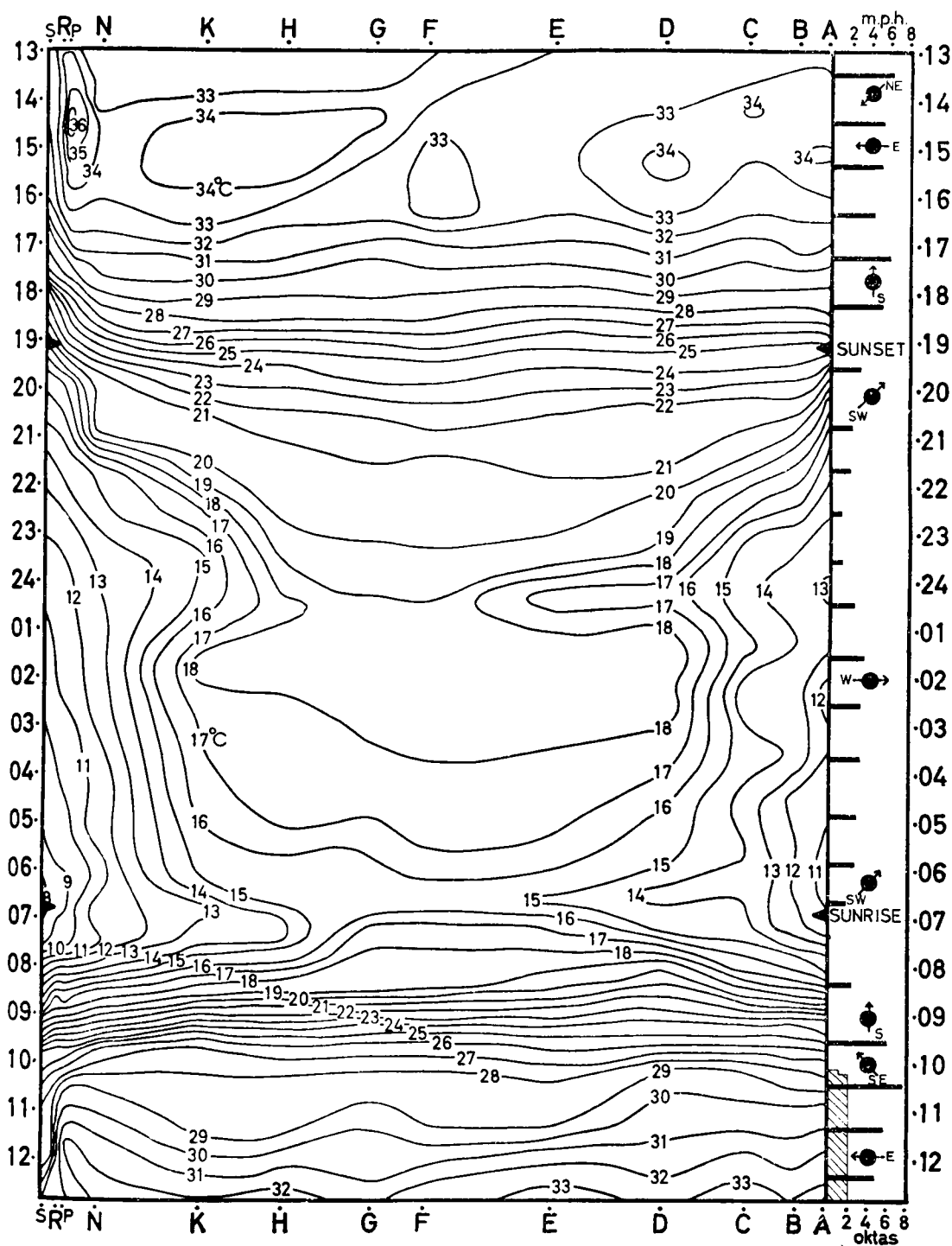


FIGURE 2—CHANGES IN DRY-BULB TEMPERATURE ALONG THE TRANSECT THROUGH-  
OUT A 24-HOUR PERIOD

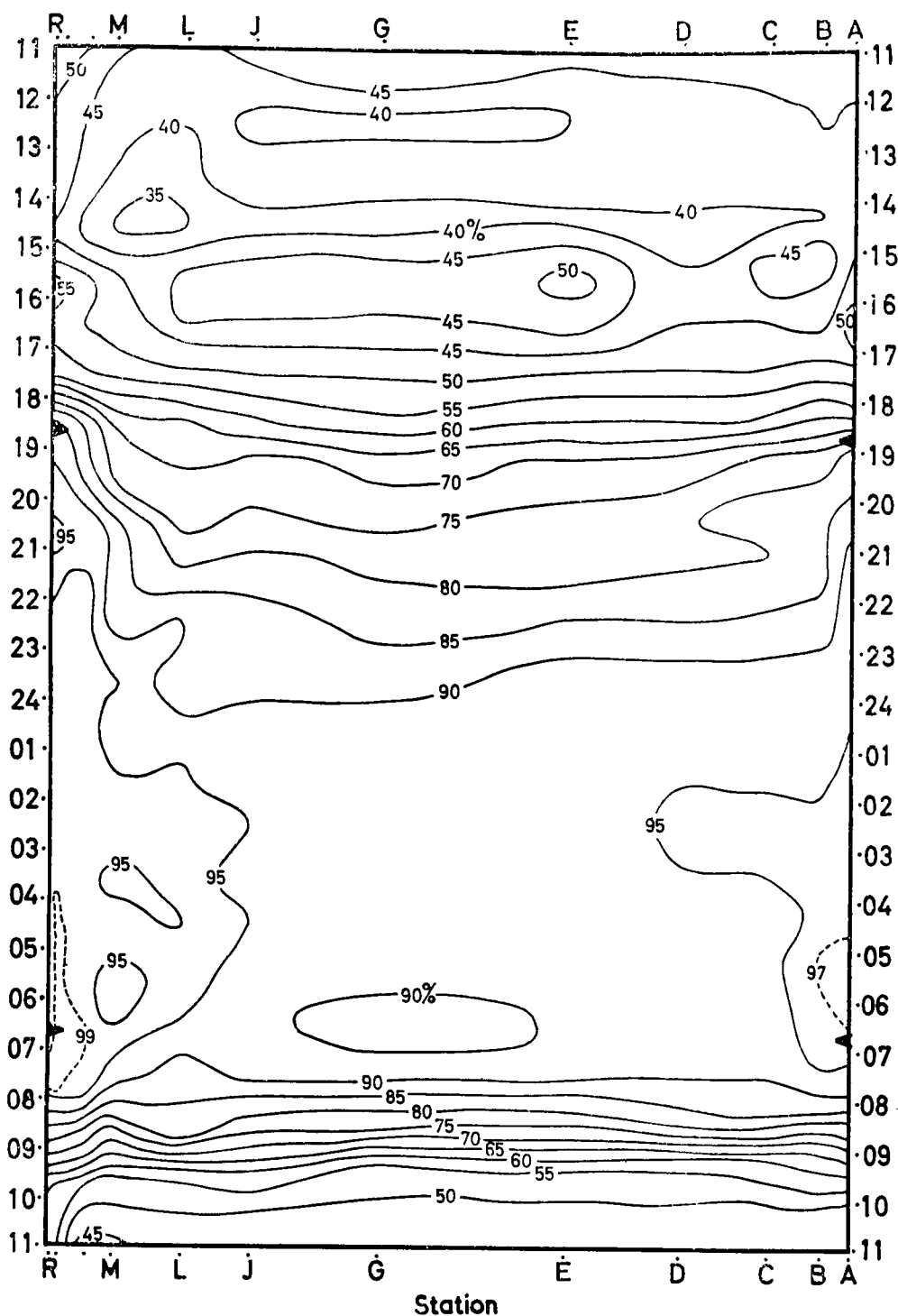
Local times are shown against the vertical axis; cloud amounts are shown by hatching; wind speeds are shown by bars and the major changes in direction by arrows. Stations at which records were taken are shown in Figure 1.



(b) 8-9 March 1961

FIGURE 2—CHANGES IN DRY-BULB TEMPERATURE ALONG THE TRANSECT THROUGH-OUT A 24-HOUR PERIOD

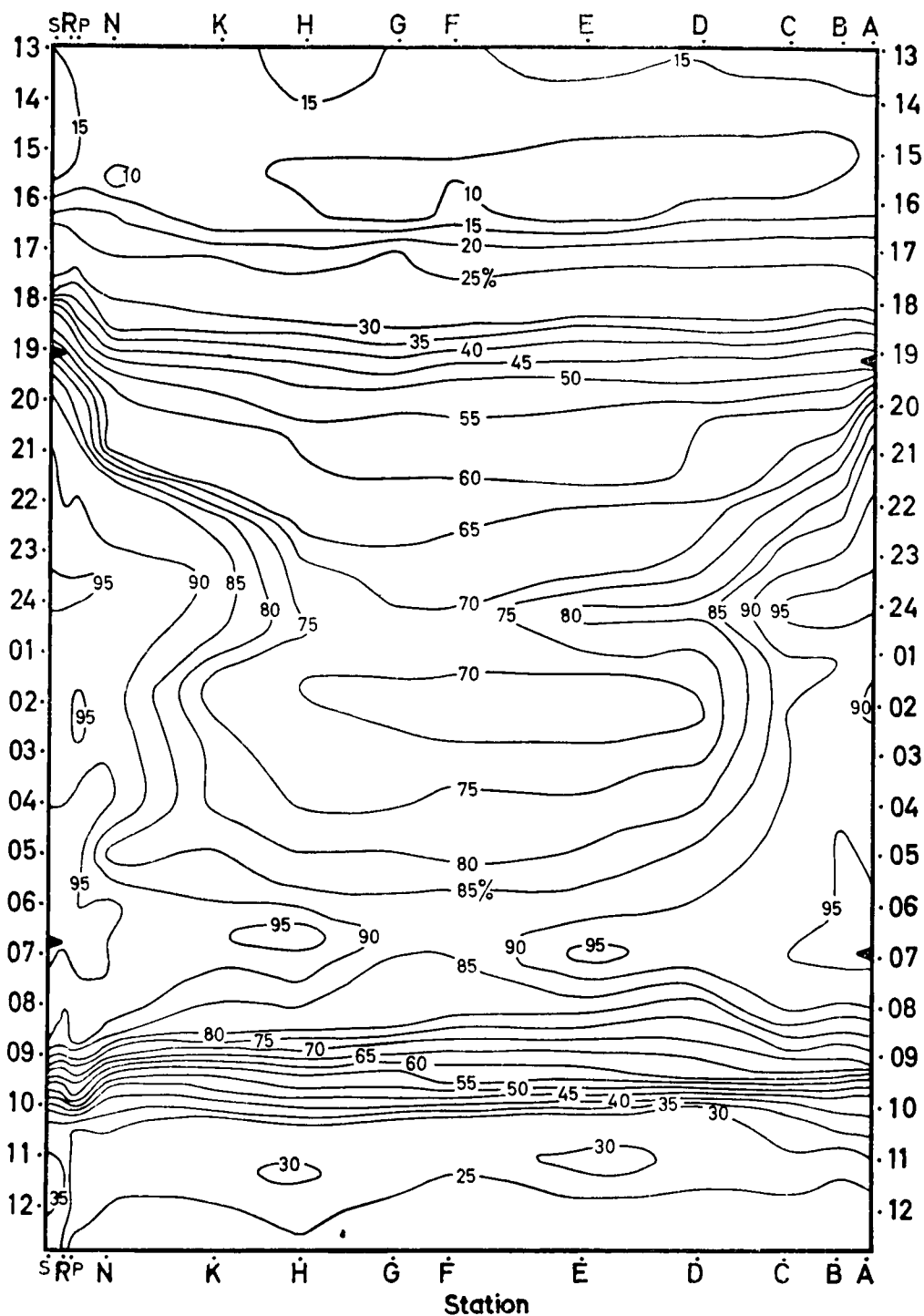
Local times are shown against the vertical axis; cloud amounts are shown by hatching; wind speeds are shown by bars and the major changes in direction by arrows. Stations at which records were taken are shown in Figure 1.



(a) 8-9 December 1960

FIGURE 3—CHANGES IN RELATIVE HUMIDITY ALONG THE TRANSECT THROUGHOUT A 24-HOUR PERIOD

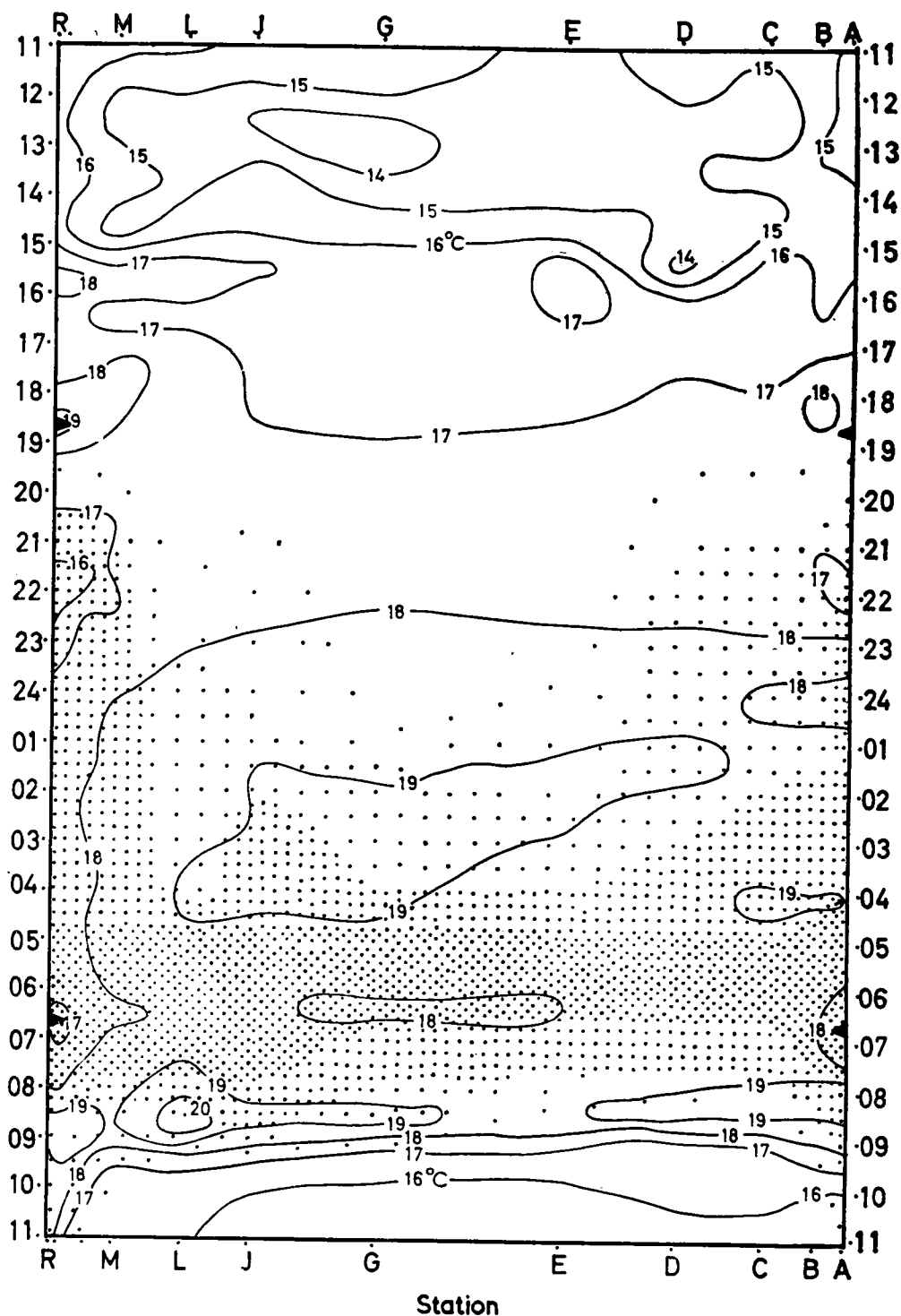
Stations at which records were taken are shown in Figure 1.



(b) 8-9 March 1961

FIGURE 3—CHANGES IN RELATIVE HUMIDITY ALONG THE TRANSECT THROUGHOUT A 24-HOUR PERIOD

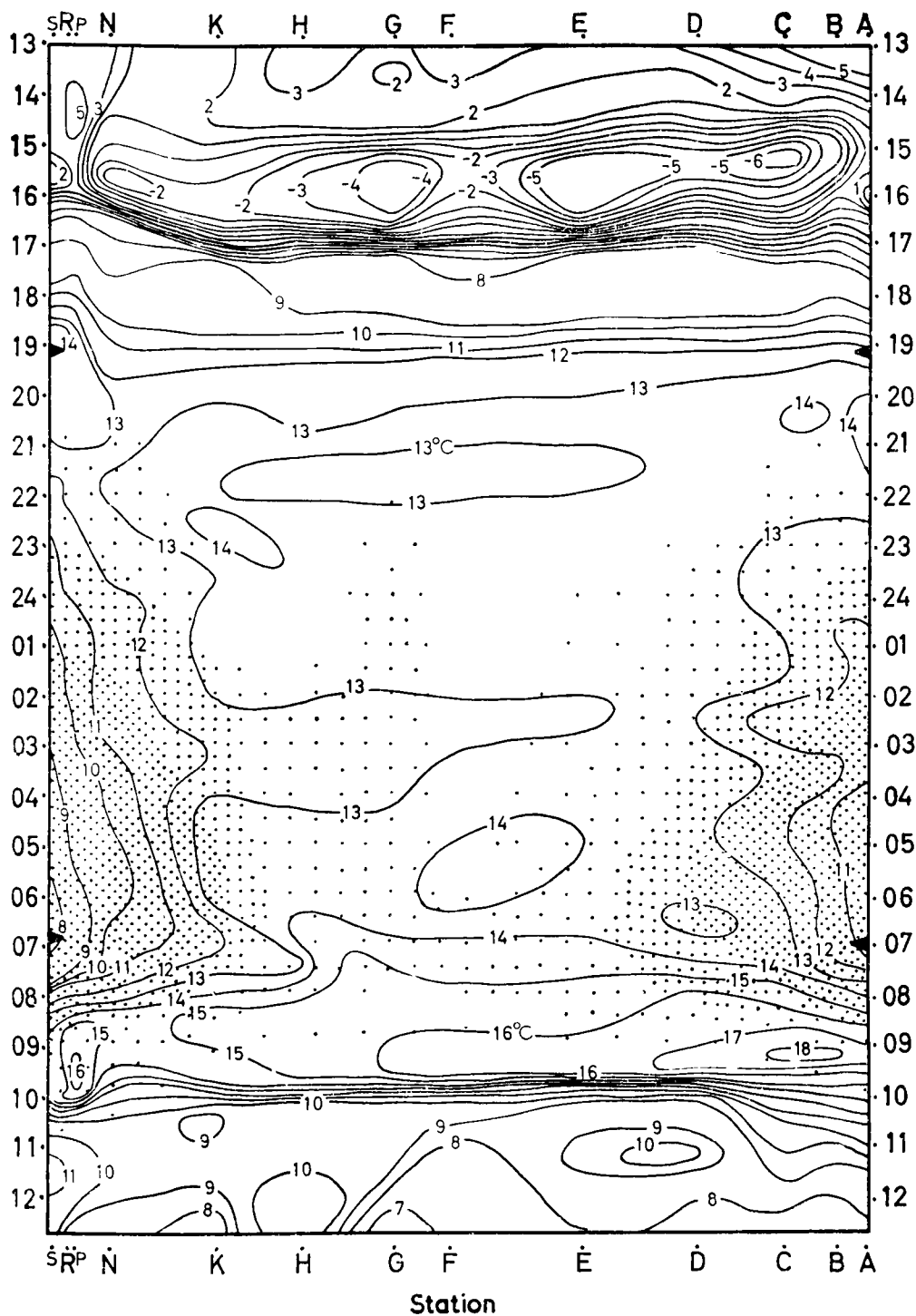
Stations at which records were taken are shown in Figure 1.



(a) 8-9 December 1960

FIGURE 4—CHANGES IN DEW-POINT ALONG THE TRANSECT THROUGHOUT A 24-HOUR PERIOD

The occurrence of dew on short grass was also recorded on an arbitrary scale of five degrees, i.e. nil, trace, light, medium and heavy. The last four degrees are represented on the diagram by an increasing number of dots. Stations at which records were taken are shown in Figure 1.



(b) 8-9 March 1961

FIGURE 4—CHANGES IN DEW-POINT ALONG THE TRANSECT THROUGHOUT A 24-HOUR PERIOD

The occurrence of dew on short grass was also recorded on an arbitrary scale of five degrees, i.e. nil, trace, light, medium and heavy. The last four degrees are represented on the diagram by an increasing number of dots. Stations at which records were taken are shown in Figure 1.

synoptic situation showed that this was partly due to the incursion of a slightly moister air mass over the whole district. No marked reduction in dew-point occurred in areas where heavy dew-fall was observed. It seems probable, therefore, that most of this dew was formed by distillation from the lower, moist layers of soil and vegetation, but because dew-point was measured only at one level, 3 feet above ground, precise conclusions on moisture exchange are not possible. After dawn, as the wind increased and mixing with drier, upper air presumably took place, dew-points dropped somewhat. Dew was present throughout the night over a large part of the farm, and 'light dew,' or more, was observed on short grass from 0200 to 0800 hours on the ridge, and from 2100 to 0800 hours on the lower slopes.

8-9 March 1961, (*Figure 4(b)*).—On this occasion dew-point, which was initially low even in the western swamp and near the dam, became slightly lower during the early afternoon. At this time most vegetation over the farm was wilting, even on the elevated margins of the swamp. Wind was from the north-east as is usual at this time of the year (Henderson<sup>5</sup>), but by late afternoon a southerly lake-breeze component became apparent. During this period dew-point rose rapidly over the whole transect. The lake-breeze component could feasibly account for some increase in dew-point at this time, but reference to the synoptic situation showed that, in addition, the rise might well have been partially or wholly due to the passage of a belt of moist air which at one time had been associated with an easterly pressure wave. No marked convergence or divergence of air masses was apparent during this period. On the ridge dew-point remained fairly constant during the night, but in the lower regions it dropped steadily in those parts where heavy dew was observed. This suggests that, on this occasion, true dew-fall was occurring. After dawn there was a slight increase in dew-point, presumably as dew evaporated into the lower atmosphere, followed by a drop as the easterly wind component increased and mixing occurred again. 'Light dew' was present from about 2200 to 0930 hours on the lower slopes, and it even occurred for a short period on the ridge.

(iv) *Additional minimum temperature records*.—In order to ascertain the extent to which night minimum temperatures over a period differed from ridge to swamp, minimum thermometers were established at six stations on the western slope. These thermometers were placed 3 feet above ground level in open-ended, asbestos-pipe screens (Lake<sup>6</sup>). Records were kept for 24 nights in early 1961 (*Figure 5*). During this time the weather was generally hot and dry, but some rain fell and cloudy nights occurred also. The diagrams show clearly that during such a period the difference in night minimum temperature from ridge to swamp commonly exceeded 6°C, and the minimum screened temperature in the western swamp fell to about 10°C quite often. On several occasions the warm zone remained below the ridge top, and the marked inversions that occurred on the nights of 22 February and 6 March suggest that distinct stratification of the air can occur, as has been reported elsewhere (Weise<sup>7</sup>).

**Discussion.**—The topography of the site on which these observations were made is similar to that experienced over a large part of the south and south-west of Uganda. Elsewhere in this region relative relief may be somewhat greater, and the exposure different, but the surveys reported here are likely to indicate the kind and approximate magnitude of local climatic changes which may be expected under similar weather conditions. It is clear that the variations in



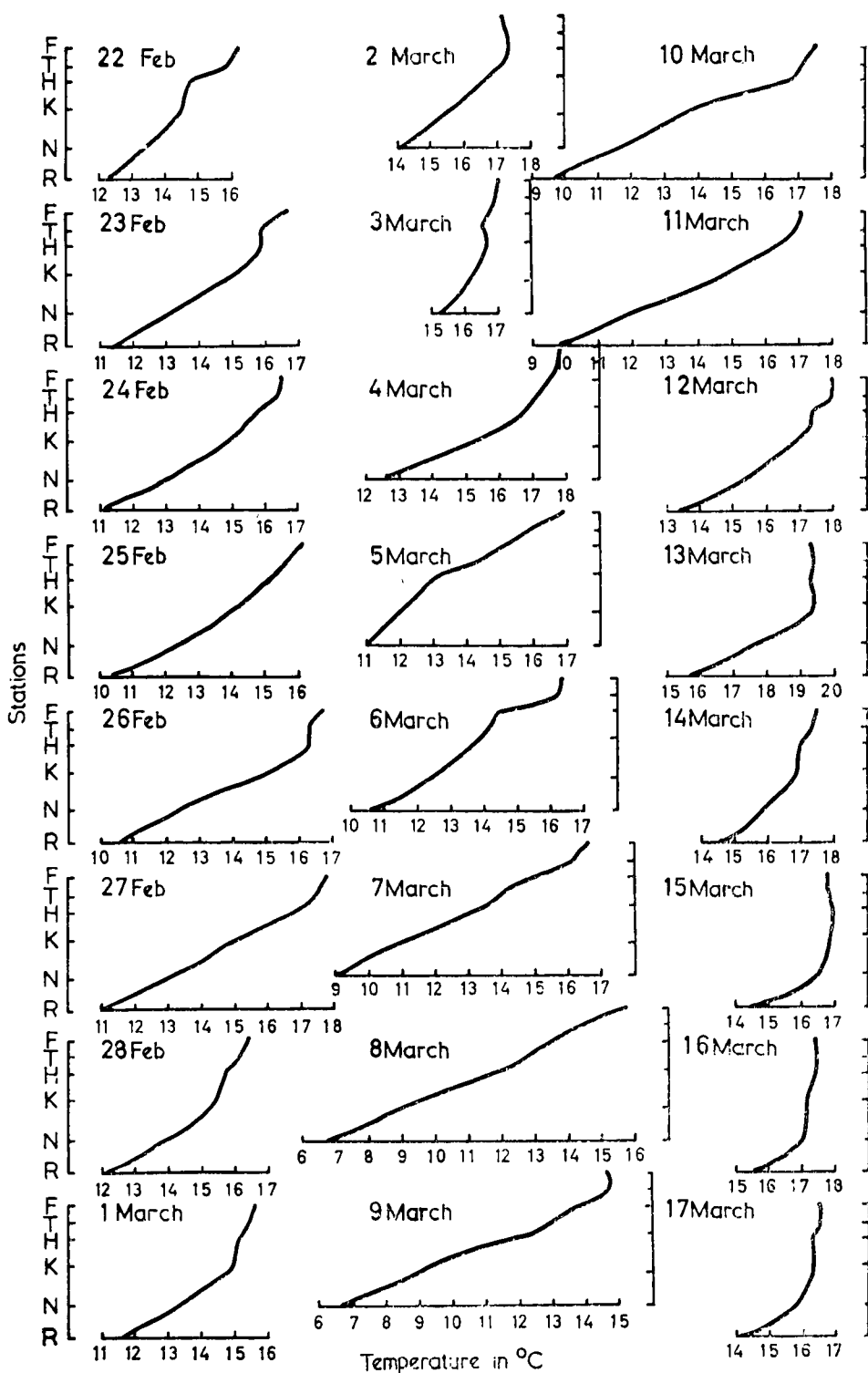


FIGURE 5—SCREENED NIGHT-MINIMUM TEMPERATURES AT A HEIGHT OF 3 FEET AT SIX STATIONS ON THE WESTERN SLOPE DURING EARLY 1961

Stations at which records were taken are shown in Figure 1 and were at the following heights above the datum line: F, 205 feet; T, 175 feet; H, 150 feet; K, 108 feet; N, 48 feet; R, 0 feet.

Stations at which records were taken are shown in Figure 1.

topography, although comparatively modest, are sufficient on occasion to cause quite large differences in local climate, particularly at night. This clearly needs to be borne in mind when interpreting the records from meteorological sites in the region.

Observations taken during the first survey emphasize the lack of local climatic difference which is apparent over varied relief during the periods in which much cloud and wind occur, but the most striking feature of the study is the large difference in range of diurnal temperature change which can be experienced between ridge and lower slopes when cloud is absent and wind is light.

Conditions were little influenced by the presence of water in the dam or by dense vegetation in the western swamp, and during the day dew-point was only slightly higher at or near to these sites. The higher dry-bulb temperatures experienced during the night of the second period in the eastern as compared with the western valley were unlikely to be due to the presence of a body of water in the former site because, during the night of the first period when conditions were cloudy and there was unlikely to be much katabatic flow of cold air, the temperatures in both valleys remained similar. The temperature difference on the second occasion was more likely to be due to dissimilarity in the rate of cold air accumulation caused by disparity in elevation, extent of the respective slopes, and the contribution of cold air from areas adjacent to the Farm (Figure 1).

Aspect had only a small effect on day temperature as is to be expected in an equatorial region (Geiger<sup>8</sup>). The high temperatures experienced near the bottom of the western valley during the afternoon of the second period were almost certainly attributable to the sheltered situation there. In the first period, during somewhat cloudy conditions, the western slope achieved a temperature only 2°C higher than the eastern slope by mid-afternoon. The prevalence of windy conditions throughout most daylight hours at this site makes it unlikely that this difference would often be exceeded greatly. At Kiambu, Kenya, Kirkpatrick<sup>9</sup> noted that an easterly slope warmed up about one hour quicker than level ground, but even on days of continuous sunshine a westerly slope of gradient 20° had a maximum temperature only about 2.0 to 2.5°C higher than an easterly one.

Dew is invariably recorded each morning on short grass even on the ridge (Huxley<sup>3</sup>) and it is clear from the two surveys that relatively copious amounts are likely to be found in the lower areas throughout most nights. The agricultural importance of dew in this region has yet to be determined but, even though climatically 'humid', seasonal periods of aridity occur and rates of potential transpiration can be high. In both surveys, dew had disappeared some two hours after sunrise, but it is not unusual on other occasions to find it persisting on crops until 1000 or 1100 hours. Dew-point measured at 0900 hours in the thermometer screen on the ridge almost always approximates to the recorded minimum temperature, hence it seems likely that a proportion of the observed dew may often be true dew-fall. The results of the second survey provide evidence that this was certainly so in the lower areas on that occasion. The contribution which true dew-fall can add, in quantitative terms, to the water balance can only be slight (Slatyer and McIlroy<sup>10</sup>) and in this respect it is probably of small importance except in arid regions. Nevertheless, even

elsewhere, dew may well have a significant effect on crop growth, as it restores plant turgidity early in the night and it can delay the onset of water stress the following morning.

The lower-lying areas in this region are not preferred for domestic settlement, partly because of the greater prevalence of mosquitoes and other insect pests near the swamps, but also because of the physical discomfort engendered by the greater extremes of temperature and the higher relative humidities experienced as compared with more elevated sites. With the likelihood of increasing land pressure and the need for greater agricultural productivity, lower areas, which at present remain either unproductive or unused, are likely to be developed agriculturally. Thus there is now a need to investigate the influence of these local climatic variations on the growth and yield of crops, the prevalence of pests and diseases, and the comfort and behaviour of farm animals.

**Acknowledgement.**—The assistance of the Director of the East African Meteorological Department and his staff in providing and interpreting information about the synoptic meteorology is gratefully acknowledged.

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551.5(09):551.507.352

## 202 METEOROLOGICAL RECONNAISSANCE SQUADRON

By R. F. M. HAY, M.A.

The disbandment of No. 202 Meteorological Reconnaissance Squadron ends more than two memorable decades of intimate and valuable co-operation between an operational squadron of the Royal Air Force and staff of many branches of the Meteorological Office. Over the past 18 years this Squadron has made over 4000 sorties with great regularity, entailing nearly 40,000 hours of flying mostly over the open oceans. On a number of occasions it has been given publicity by the Press and by television, and as recently as May 1964 the BBC ran a Northern Ireland schools' radio programme on the work of the Meteorological Office and of 202 Squadron.

A brief mention of the history of the Squadron before its formal association with the work of the Meteorological Office began in the Second World War, is not out of place here, since it forms a worthy prelude to the events to be described. The formation of the Squadron dates back to October 1914, when it

began its operational life as No. 2 Squadron Royal Naval Air Service at Eastchurch flying 70-hp Short Biplanes. Photographic reconnaissance for the historic Zeebrugge raid was among its achievements in the First World War. The Squadron was disbanded in 1921; however within a few years (1 June 1929) No. 481 (Coastal Reconnaissance) Flight in Malta was redesignated as No. 202 Squadron. In September 1939 the Squadron was moved to Gibraltar (flying Catalinas and Sunderlands) and in the next five years was credited with the sinking of three enemy submarines and with a share in sinking or damaging three others. It was also a Catalina of No. 202 Squadron which picked up General Mark Clark from a submarine after his clandestine visit to Algiers to meet French Resistance leaders.

Meteorological flights have continued to provide synoptic observations of the highest quality and intrinsic value for weather forecasting and other scientific purposes over many years. So today some effort is required to recall the grim situation which obtained quite early in the second war, when the enemy's tactical successes effectively denied vital meteorological information over immense areas of land and ocean to our national meteorological services; and so made the provision of air meteorological reconnaissance indispensable. Early in 1939 the Meteorological Office was looking for means of obtaining weather information at sea to replace ships' reports, always liable to be completely suppressed in war, and concluded that the best arrangement would be to have its own special flights for that purpose. However the shortage of operational aircraft delayed developments until late in 1940, when three flights using Blenheim III aircraft were established within Coastal Command, at Bircham Newton, St. Eval and Aldergrove. During the remaining years of the war these flights were successively re-equipped with Hudson, Hampden, Ventura and Halifax aircraft, the last named being the standard aircraft for meteorological reconnaissance squadrons by the end of the war. In the same period, ranges of 200 miles with the Blenheim aircraft were extended up to 900 nautical miles, aircraft establishments were increased on some flights to provide for two sorties daily, and additional flights were operated from airfields as far apart as Bircham Newton, Brawdy, Tiree, Wick, Reykjavik, the Azores and Gibraltar. This effort was not achieved without many setbacks due to mechanical troubles and shortage of aircraft, which were overcome with the aid of Coastal Command and later the United States Army Air Force, both of which lent aircraft of their squadrons to the meteorological flights.

A Meteorological Air Observer Section of the Royal Air Force (General Duties Branch) was formed in September 1942, and had achieved a fine record of active service by the end of the war. It was recruited from experienced staff of the Meteorological Office who were then trained in making observations from aircraft. Officers were posted to meteorological flights in June 1943, and non-commissioned officers (NCO's) followed not long afterwards. Since 1948 the section has been staffed by volunteer Scientific Assistants. Over a long period, occasions when a member completed 400 sorties have been marked by a celebration within the Squadron. Master Pilot F. Radina and Master Signaller J. Stratton were among those who achieved this target, while during his several tours of duty with the Squadron the present Flight Commander, Flight Lieutenant Ignatowski, AFC, DFM, had logged 397 sorties by the date of the Squadron's disbandment and received a L. G. Groves Memorial Award in 1963. In a short account few individual names can be included, and a

mention of four Air Meteorological Observer Leaders, Flight Lieutenant Cayhill, Flight Lieutenant Parsons, Flight Sergeant McCubbin and Flight Sergeant Hunt, implies that there were many others who also performed their duties with outstanding success and contributed in no small measure to the fine performance and high morale of the Squadron as a whole. Flight Sergeant Hunt was also a recipient of a L. G. Groves Memorial Award in 1959.

Flight plans of the reconnaissance squadrons were gradually extended until the existing triangular tracks were devised in which the first and third legs were flown at a low level (950 mb) and the second leg at a higher level (500 mb). Routine eye and instrument observations were made every 50 miles on the flights, besides observations of wind by multiple drift, and sea-level pressure was determined at every 200 miles on the low-level legs and at the positions of the soundings to 500 mb. Determination of sea-level pressure involved descent to about 50 feet estimated above the sea surface in the early days, but after radio altimeters were fitted to the aircraft, a descent to about 200 feet only above the sea surface was required.

Towards the end of the war No. 202 Squadron performed anti-submarine duties at Castle Archdale in Northern Ireland, prior to being disbanded for a few months during 1946 and then being redesignated as a meteorological reconnaissance squadron at Aldergrove. Halifax aircraft continued to be used for several years and during this period 32 crew members lost their lives in aircraft accidents. This toll of life exacted in peacetime, in the pursuit of weather observations from potential or actual storm areas at the meteorologists' request, demands recall and grateful mention here. The Squadron was re-equipped with Hastings aircraft in 1950, and the fact that these aircraft have been used ever since that date with no further loss of life is some tribute to the flying crews and to the suitability of the aircraft for this exacting task. Soon after the end of the war all the meteorological reconnaissance flights were disbanded with the exception of those from St. Eval ('Epicure'), Gibraltar ('Nocturnal') and Aldergrove ('Bismuth'), and after about 1950, No. 202 Squadron was left as the sole long-distance 'met recce' flight from a base in the British Isles.

During the last few years the Squadron had an establishment of five Hastings and their crews comprised captain, 2nd pilot, navigator, engineer, two signallers and two air meteorological observers. Sorties were made on five days a week on standard Bismuth tracks extending some 800 miles over the Atlantic, and ranged from the Biscay area through the Western Approaches to Icelandic waters. Choice of track to be followed was made by the forecasting staff at Headquarters, Bracknell, and was normally dictated by the need to cover an area where information was sparse or missing, or where confirmation or otherwise of bad weather or new developments was required. The flights were most often made into the worst possible weather conditions, and the regularity with which tasks were completed has always been a source of pride to the Squadron. With a view to reducing this bad weather hazard some of the Hastings were recently fitted with cloud collision radars, and the operational value of this equipment, apart from some teething troubles, had been clearly demonstrated by the time of the Squadron's disbandment.

The information provided over the years by the Bismuth flight of No. 202 Squadron has undoubtedly been of very great value for military and civil aviation interests at all times, and for operational forecasting for the general

public on certain occasions. A striking instance was provided by Mr. E. Gold, F.R.S., in his Symons Memorial Lecture delivered before the Royal Meteorological Society in April 1947, when he cited a meteorological reconnaissance made during the night of 7-8 January 1947, which, by penetrating close to the centre and there making an ascent to 500 mb, gave a detailed synoptic picture of one of the deepest Atlantic depressions for several years. On this occasion the meteorological observer was the son of a previous Symons Lecturer, Mr. F. Entwistle, and Gold added "I have included this chart because I regard this flight as one of the most notable achievements in meteorological observations and worthy of a high place in meteorological literature." Another important occasion was on 24 September 1957 when a Bismuth aircraft flew through the centre of hurricane CARRIE, the hurricane which had caused the loss of the sailing ship *Pamir* a short time earlier. Flight Lieutenant Dinnes, who was the captain of this aircraft, vividly recalled this occasion to the writer recently. Torrential rain and severe turbulence were encountered throughout the flight, and the aircraft captain's description makes it evident that he found the eye of the storm still in existence, and penetrated it in a position approximately  $51^{\circ}30'N$ ,  $14^{\circ}00'W$ , that is about 150 miles to the west-south-west of Ireland. He then flew within the eye for some time where he found the usual features of light winds and little cloud, apart from a few cumulus, with a characteristic surrounding amphitheatre of cloud extending to a great height. This flight was a normal sortie made on the standard track 'Bravo' at the request of the Central Forecasting Office, then at Dunstable.

Besides affording support for the forecasting services through so many years, the Bismuth meteorological reconnaissance aircraft have also acted on numerous occasions as a mobile aerial platform for experimental work by other government departments, notably the Atomic Energy Authority. Since 1948 each flight has sampled the air for radio-active dust, using a cylindrical filter of high collective efficiency carried on the aircraft. A representative sample of the dust content of the lower troposphere was thereby obtained, and at the end of each flight the filter with its collected dust was sent for analysis to the authority for whom the sampling programme was carried out. In this way the Squadron assisted the aim of measuring concentrations of radio-activity at various levels around the British Isles which, being situated far from test sites, form a suitable observation area for the study of contamination on a global scale. The aircraft observations therefore rank among the most important contributions to this problem, and the results were used in an American as well as a British report on the subject. The second series of nuclear weapon tests held at Christmas Island in 1958 afford another example of invaluable support given by personnel of 202 Squadron, as it were behind the scenes. On this occasion one officer and four NCO's from the cadre of air meteorological observers at Aldergrove were detached to Christmas Island. There they flew numerous sorties in aircraft of Shackleton and Canberra squadrons, and provided upper wind observations and cloud photographs over a large operational area. The procedures used in making and transmitting observations to base were similar to those used on normal sorties made by 202 Squadron from Aldergrove.

In this article an attempt has been made to place on record in a meteorological journal the remarkable achievements of this Squadron in the task of weather observing. While it may be premature to speculate on the effects to



Photograph by P. A. Huxley

PLATE I—VIEW WESTWARDS FROM THE TOP OF KABANYOLO FARM RIDGE SHOWING  
TYPICAL DISSECTED TOPOGRAPHY

(See page 321.)

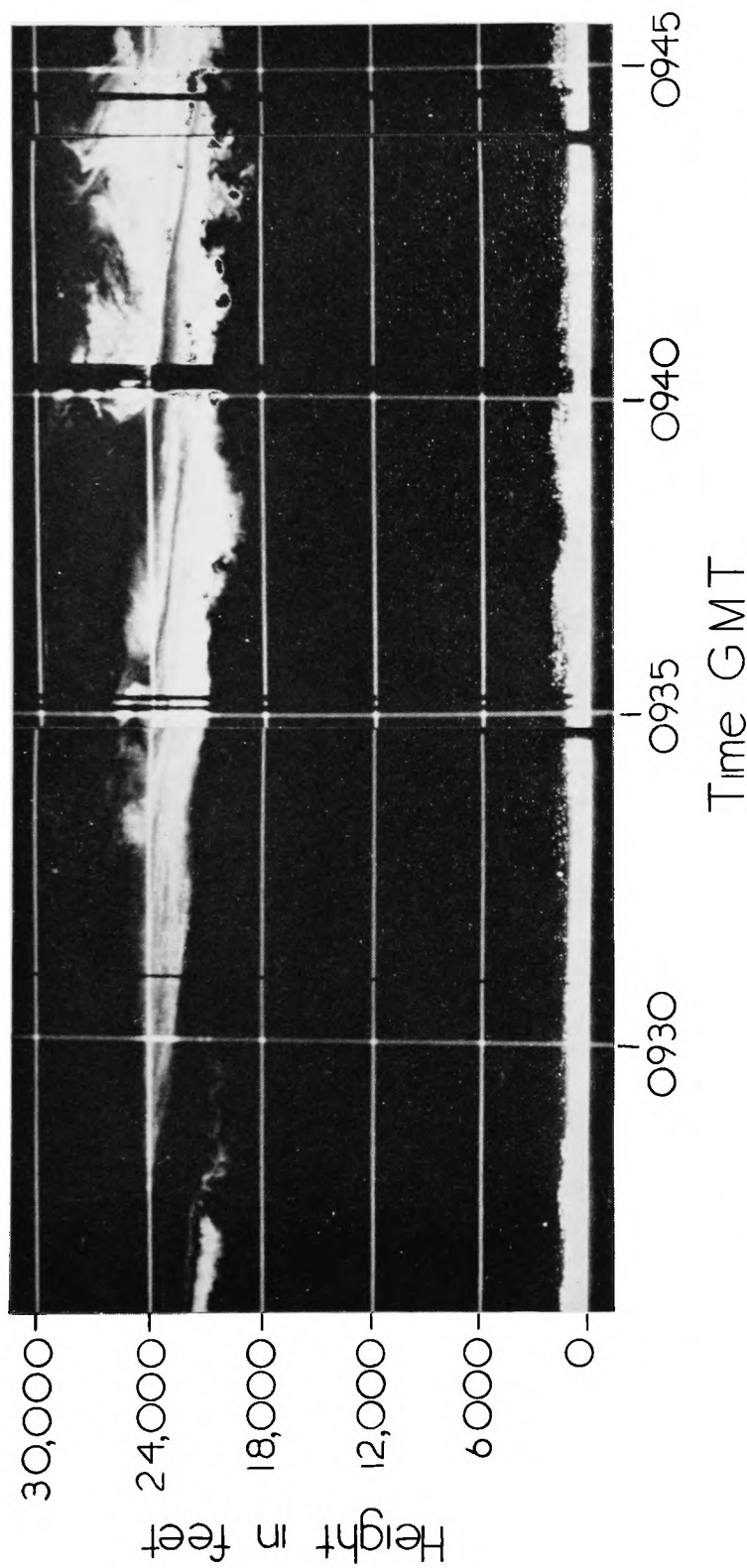


*Crown copyright*

PLATE II—THE 16-FT DIAMETER AERIAL OF THE 8.6-MM RADAR AT THE ROYAL  
RADAR ESTABLISHMENT, MALVERN

(See page 337.)

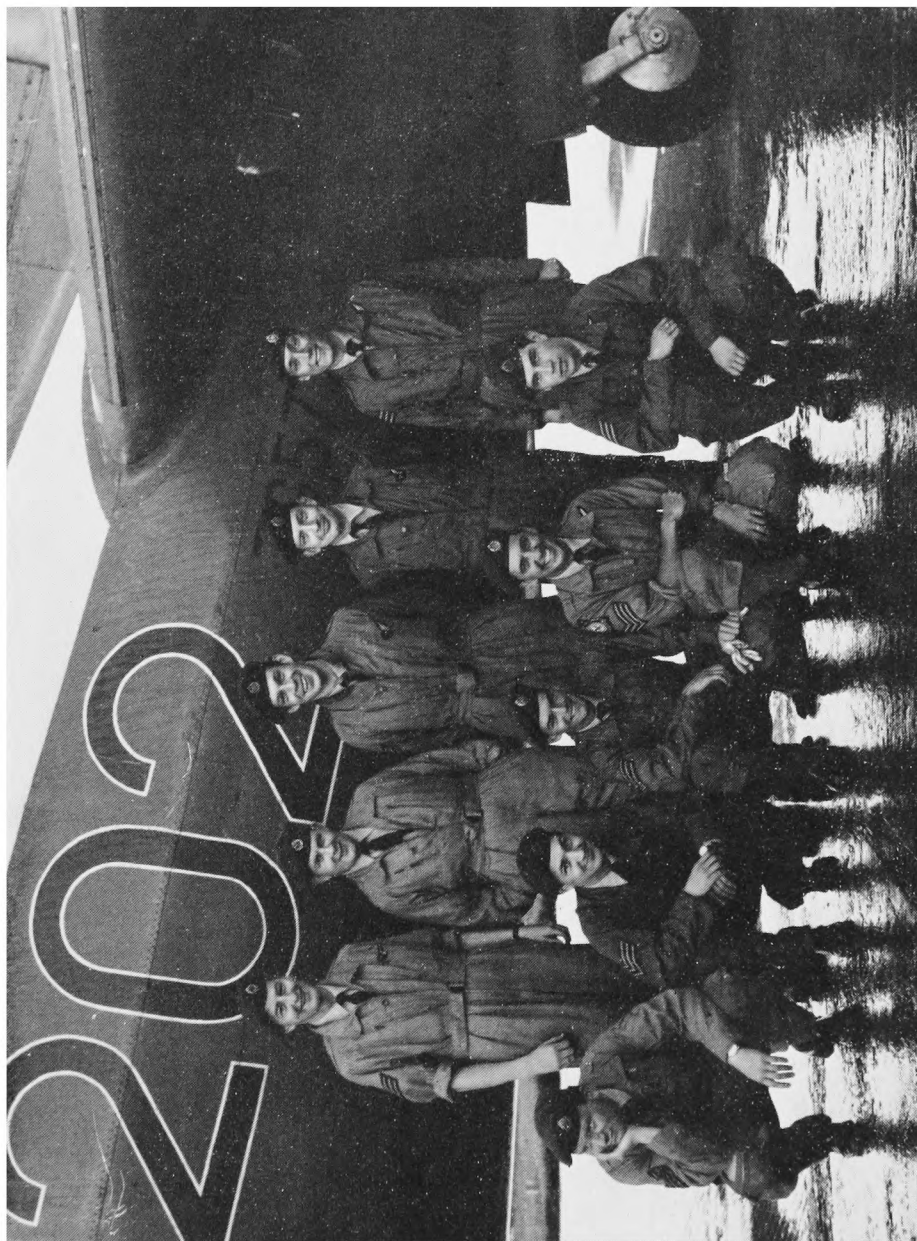




*Group copyright*

PLATE III—AN EXAMPLE OF A HEIGHT-TIME RECORD FROM THE 8.6-MM RADAR ON  
24 SEPTEMBER 1962, WITH ECHO BETWEEN 18,000 AND 30,000 FEET

The cloud was reported as 7/8 cirrus fibratus at first, but with cirrostratus predominating at 0945 GMT. There is clear evidence of fallstreaks in the echo (see page 340). At 0940 and 0945 2/8 to 3/8 of stratocumulus with its base estimated as 2000 ft passed through the zenith but was not detected by the radar. The vertical white lines are electronic time markers. The vertical black bands are caused by intensity measurement. The band of echo at the bottom of the record is the transmitter pulse, which prevents observation of the first 1000 ft. The spots of echo just above this are 'angels', probably the detection of insects passing through the radar beam.



*Crown copyright*

PLATE IV—MEMBERS OF 202 METEOROLOGICAL RECONNAISSANCE SQUADRON,  
ALDERGROVE, IN THE SUMMER OF 1964

Back row, left to right: Sergeants B. G. Young, J. M. Malcolm, M. W. P. Pain, A. A. J. Higgins, I. E. Stephenson.  
Front row, left to right: Sergeants R. E. Bywater, C. A. Brimacombe, D. W. M. Smithson, F. Garlick, B. Morris. 202 Squadron was disbanded on 31 July 1964. (See page 333.)

the community at large of losing the services of 202 Squadron, it will certainly be felt most severely by those responsible for forecasting weather at low levels over the oceans around this country. Over the years the Squadron performed an outstanding service to meteorology, fulfilling a requirement for on-the-spot observations from remote areas at short notice, with a promptness and flexibility that cannot be rivalled. The splendid reputation which it enjoyed throughout the Meteorological Office pays tribute to the fine spirit of co-operation of the aircrews and their devotion to duty. (See Plate IV).

## 551.501.81:551.508.85:551.576.2 CLOUD DETECTION WITH 8.6-MILLIMETRE WAVELENGTH RADAR

By W. G. HARPER, M.Sc.

**Summary.**—From an assessment with an 8.6-mm radar at Malvern it is concluded that about 50 per cent of high and low clouds, and 75 per cent of medium clouds in southern England give detectable echoes, provided that the equipment is maintained at high sensitivity. The small pulse-volume of the Malvern radar gives great detail in the echo patterns. It reveals fallstreaks, suggesting the presence of precipitation-sized particles, in a substantial proportion of the echoes, particularly at high and medium levels. It is concluded that 8.6-mm radar is often unreliable as an indicator of true cloud bases and tops. Some dense water fogs have given weak echoes, but the fog tops could not be defined. The effects of attenuation at 8.6-mm wavelength are discussed.

**Introduction.**—The move of the Meteorological Office Radar Unit from East Hill to Malvern in 1959 at the invitation of the Royal Radar Establishment made possible a series of meteorological measurements with specialized radar equipments.<sup>1</sup> These included a radar especially designed for use at millimetric wavelengths. Its special feature is its accurately contoured parabolic aerial 16 feet (4.9 m) in diameter (Plate II). At 8.6-mm wavelength this gives a radar beam only 8 minutes of arc in width to half-power points, making it suitable for a variety of meteorological studies. Since, apart from a short series of measurements at 8.6 mm by Roberts,<sup>2</sup> and an assessment of attenuation at 8.6 mm by Robinson,<sup>3</sup> no meteorological measurements at a wavelength shorter than 3 cm had been made in this country, the first use to which the radar was put was an assessment of the detectability of various cloud systems. The results are summarized in this paper, and the effects of attenuation are briefly discussed. Studies of selected radar records illustrating the exceptional resolution given by this radar in cloud detection will be published elsewhere, as will a further use of 8.6-mm radar, namely the measurement of rainfall, along an extended line, from the attenuation of the radar beam.

**Equipment and recording.**—Detailed comparison between visual and radar records was commenced in April 1961, on completion of the initial working-up of the equipment, and continued until October 1962. The radar was operated pointing vertically, to ensure that ranges of detection and the resolvable volume were as small as possible. At a height of 3 km the resolvable volume was 1100 m<sup>3</sup>, which by normal radar standards is exceptionally close resolution. Signals were displayed on a cathode-ray tube as an intensity-modulated display linear in height. By photographing this and applying a slow lateral displacement to the trace a height-time pattern of the precipitation passing overhead is built up, to which electronic height and time markers are added. Ten minutes' record was photographed on each 35-mm frame. The echo patterns have equal scales in the horizontal and vertical on this record if the cloud systems are moving through the beam with a wind speed of 36 knots. A range-amplitude display is available for intensity and calibration measurements.

To record cloud conditions a Wide-Angle Target Camera type GW<sub>1</sub> was installed as a sky camera, with automatic photography at 5-minute intervals, the shutter being triggered by the same circuit which provided time marks on the radar records. The angle of acceptance of the camera was 140 degrees, and it was usually tilted to bring in the horizon on a chosen azimuth as an aid to identification. The sky camera could not be used in precipitation or in poor light, and as a routine its records were supplemented by conventional meteorological observations of clouds and weather at intervals of 5 or 10 minutes and by the observer's estimates of cloud types affecting the zenith. Experience showed that the observer, with his ability to judge the angular velocity of clouds near the zenith, can determine cloud types of significance to the radar more efficiently than is possible even from 5-minute sky photographs. Much of the material was accumulated in the form of hourly runs. Analysis of 'occurrences' of detection and non-detection of cloud has been mainly from mounted prints from the radar height-time recorder and the sky camera, annotated with the observer's reports, and mainly for 5-minute intervals.

Much record had to be discarded from the comparison when the cloud, even though substantial in total amount, was not affecting the zenith. A further cause for discarding record has been that it was not felt possible to claim detection or non-detection of a low-cloud layer, e.g. stratus, when rain was falling through it from a medium-cloud layer above, for then precipitation echo blanketed the layer from which echo from the stratus cloud itself might have been detected; nor has it usually been possible in this case to claim detection of medium cloud either, for the low cloud usually prevented visual observation of the middle-level and high-level clouds present. Exclusion was the only possible course if the cloud type was not reported visually, since otherwise it would have biased the analysis towards detection.

**Calibration of the radar.**—The radar has been calibrated both against a standard metal sphere and against raindrop distributions measured with filter papers in steady light rain. The measured intensities in both cases were slightly lower than the theoretical values,<sup>4</sup> in the sphere experiments by an average of about 1 dB,\* in the filter paper comparisons by about 4 dB. The agreement however was sufficiently good to allow the adoption of the calculated level of 'best' performance of the radar. Neither method of calibration could be made daily, but it was possible to take account of short-term fluctuations in radar performance, e.g. those due to deterioration of valves and circuit components, by making regular measurements of the echo intensity from a ground target which has shown unusual stability. These measurements were made before and after each hourly run, or as soon as precipitation had ceased, and have proved a reliable guide to radar performance.

The present analysis includes all records made with radar performance up to 5 dB below its optimum as a compromise to obtain sufficient material. Five dB corresponds to a factor of 3 in radar reflectivity of precipitation targets, or to a factor of about 1.7 in height of detection. Thus an echo from altocumulus just detectable at 8000 ft with performance at its optimum would not be detectable above 4500 ft if the radar sensitivity had fallen by 5 dB.

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\*It is usual to express radar intensity ratios on a logarithmic scale. The ratio of two signal intensities  $P$  and  $Q$  is given in decibels (dB) by  $10 \log_{10}(P/Q)$ .

**Analysis.**—The result of an initial analysis of these records is given in Table I(a), with division of cloud types into genera according to the international cloud classification. The only exception to this has been the separation of cumulus humilis, cumulus mediocris and cumulus congestus because of their major differences in vertical development. It will be noted that stratus has been excluded from the table. This is because it was almost always reported either in conjunction with stratocumulus, without separate identification of amounts (it was then included as an entry under Sc) or as stratus fractus beneath precipitating altostratus or nimbostratus, when it was excluded because of the possibility of confusion with echo from rain falling through the stratus layer. At line 1 of the table are given the numbers of observations of each cloud type, at line 2 the numbers in which echo appeared to be associated directly with this cloud, and at line 3 the percentages of detection that these represent.

TABLE I—ANALYSIS OF DETECTION OF CLOUD TYPES WITH 8.6-MILLIMETRE RADAR  
(a) FOR INDIVIDUAL CLOUD TYPES, AND (b) GROUPED AS HIGH, MEDIUM AND LOW CLOUD

(a)	Cloud type	Ci	Cc	Cs	Ac	As	Ns	Sc	Cu hum	Cu med	Cu con	Cb
	Number of observations	121	2	32	250	178	34	286	149	219	40	0
	Number with echo	46	0	29	169	148	34	178	9	125	40	—
	Percentage detected	38	0	91	68	83	100	62	6	57	100	—
(b)	Cloud types	High Ci, Cs					Medium Ac, As			Low Sc, Cu		
	Number of observations	153					428			694		
	Number with echo	75					317			352		
	Percentage detected	49					74			51		

Notes.—(i) A few cases of cumulus fractus were included with cumulus humilis if humilis was the main cloud present but only fractus was overhead at the time.

(ii) Nimbostratus has been excluded from (b) because although it is by definition a middle-level cloud it usually extends down to quite low levels. In any case because of the rather small number of occurrences, its inclusion as medium cloud would only have raised the detection level from 74 to 76 per cent.

Detection ranges from 100 per cent for nimbostratus and cumulus congestus (and this would undoubtedly have applied also to cumulonimbus if any had passed overhead when the equipment was in operation, since this is essentially a precipitating cloud) to almost complete failure to detect cumulus humilis and cirrocumulus. The detection of the three types of cumulus shows a reasonable gradation, from 6 per cent for cumulus humilis to 57 per cent for cumulus mediocris and to 100 per cent for cumulus congestus. It is interesting that cirrostratus (91 per cent) is more readily detected than altostratus (83 per cent), and that both altostratus and altocumulus (68 per cent) are more readily detected than stratocumulus (62 per cent), despite the fact that the height of the lower cloud in each case should have aided detection. Some of the reasons for the trends shown by these figures may become apparent when the fine structure of these echoes and the evidence of particle size within them are described.

In Table I(b) the same observations are grouped as clouds at high, medium and low levels. It assumes that the individual cloud types were examined in proportion to their true frequency of occurrence. This seems preferable to an

analysis giving equal weight to each cloud type regardless of frequency. It shows about 50 per cent detection of high cloud and of low cloud, and about 75 per cent detection of medium cloud.

**Evidence for the occurrence of precipitation in the observed echoes.**

—Table I has not taken any account of the presence or absence of precipitation in the clouds, though this significantly affects the appearance and intensity of the echoes received. The very narrow beam (8 minutes of arc in width) and short pulse (0.2 microseconds giving a discrimination of 30 m in range) were of great value in the examination of these effects, often revealing a fine structure of fallstreaks where with a broader beam one would have inferred a structureless echo.

The occurrence of significant fallstreaks within the echoes, whether or not they were reaching the ground, has been taken as a criterion of the presence of precipitation (Plate II). This can probably be justified, for Findeisen<sup>5</sup> has shown that a water droplet of diameter  $20\ \mu$  in an environment with relative humidity of 90 per cent can fall only 3.3 cm before evaporating completely, a  $200\text{-}\mu$  droplet can fall 150 m, but a 2-mm raindrop could fall 40 km. Thus it seems likely that if fallstreaks are recorded which extend through at least 1 km in height, droplets of diameter at least  $200\ \mu$  or large ice crystals of comparable fall speed are present in them. An alternative criterion was a report of rain, snow, or drizzle at the ground, and cases of 'a few spots of rain in the wind' were included. These minimum criteria are reasonably closely related because  $200\ \mu$  is about the lower size limit for drizzle.

The results of this analysis are given in Table II where the third line of figures in both (a) and (b) gives percentages of echoes of each cloud type which gave evidence of precipitation (as defined above). It will be seen that 88 per cent and 94 per cent of echoes from altostratus and nimbostratus respectively showed precipitation effects. This is reasonable since these are by definition precipitating clouds, but surprisingly 50 per cent of cirrus echoes and 83 per cent of cirrostratus echoes contained fallstreaks. This suggests that cirrostratus should be classed with altostratus as essentially a precipitating cloud. Perhaps the most interesting result is the 68 per cent of altocumulus echoes showing fallstreak effects compared with 27 per cent of stratocumulus echoes, despite the shorter ranges at which the latter were measured. Overall, the percentage of echoes from high cloud with evidence of precipitation is much greater than the percentage from low cloud (Table II(b), line 3). This suggests greater efficiency of particle growth in the ice phase.

A calculation has been made to determine what proportion of non-precipitating cloud of each type was detected when clouds with evidence of precipitation were excluded (Table II(b) line 4). On this basis 40 per cent of non-precipitating low clouds were detected, 39 per cent of medium and 26 per cent of high clouds—substantially lower figures than those in Table I. To throw further light on these figures, levels of detection (similar to lines 3 and 4 in Table II(b)) were computed for two levels of sensitivity of the radar—at high sensitivity as already given in Table II and at a sensitivity lower on average by 6 dB. The effect will be described in terms of an increase of sensitivity of 6 dB; in the case of low cloud this was to increase substantially the detection of non-precipitating cloud (from 19 to 40 per cent), and to decrease the proportion of echoes containing evidence of precipitation (from 45 to 35 per cent). The effects on

TABLE II—STATISTICS OF THE OCCURRENCE OF PRECIPITATION IN CLOUDS AND OF DETECTION OF NON-PRECIPITATING CLOUD, (a) FOR INDIVIDUAL CLOUD TYPES AND (b) GROUPED AS HIGH, MEDIUM AND LOW CLOUDS

(a)	Cloud type	Ci	Cs	Ac	As	Ns	Sc	Cu hum	Cu med	Cu con
	Number of observations	121	32	250	178	34	286	149	219	40
	Number containing evidence of precipitation	23	24	115	130	32	48	0	47	29
	Percentage of echoes with evidence of precipitation	50	83	68	88	94	27	(0)	38	73
	Percentage detection of non-precipitating cloud only	23	(63)	40	38	(100)	55	6	45	(100)
(b)	Cloud types	High Ci, Cs				Medium Ac, As		Low Sc, Cu		
	Number of observations	153				428		694		
	Number containing evidence of precipitation	47				245		124		
	Percentage of echoes with evidence of precipitation	63				77		35		
	Percentage detection of non-precipitating cloud only	26				39		40		

Note.—Percentages are enclosed in brackets if based on fewer than 20 observations.

medium and high cloud were similar to each other but differed significantly from the effects on low cloud. In both cases the proportion of echoes containing evidence of precipitation increased (from 63 to 77 per cent for medium cloud, and from 53 to 63 per cent for high cloud), but the detection of non-precipitating cloud remained almost unchanged (a decrease from 43 to 39 per cent for medium cloud, an increase from 24 to 26 per cent for high cloud). A possible explanation of these figures is that all precipitating low clouds had already been detected at the lower sensitivity, so that improved performance resulted in strengthened echoes plus many previously undetected non-precipitating echoes; but that not all the precipitating medium and high cloud had been detected at the lower sensitivity, or had not been recognized as such (the larger pulse-volume at high levels would have contributed to this). The main effect of improved performance could then have been to reveal fallstreaks in echoes previously classed as non-precipitating. If this explanation is correct a further increase in sensitivity might reveal an even higher proportion of precipitating high and medium clouds. The figures given at line 4 of Table II(b) for high and medium clouds may therefore be over-estimates. In the case of low cloud however the increase in numbers of weak echoes at high sensitivity was very obvious, particularly with stratocumulus and cumulus mediocris. They are seen to have a distinctive appearance, with well-defined tops but weaker and ill-defined bases often merging imperceptibly into background noise. They are thought to be the true detection of non-precipitating clouds.

**Comparison with measured cloud droplet spectra.**—The plausibility of the detection of non-precipitating clouds at high radar-sensitivity has been tested by comparison with droplet spectra measured from aircraft in cumulus clouds by Durbin.<sup>6</sup> He analysed about 150 cloud droplet samples obtained by a magnesium oxide slide technique in 10 cumulus clouds ranging from 250 m to more than 2 km in vertical depth. All samples were taken at heights below the 0° C level. A mean spectrum has been taken for each of the 10 clouds, since there was little evidence in them of any systematic variation of droplet

spectrum with height, or with successive penetrations at a single height, and the echo intensity to be expected from them at a fixed range of 2 km, equal to the mean sampling height, and at the best sensitivity of the radar has been computed. The values are given in Table III, arranged in order of increasing echo intensity, positive values being above noise, negative values below noise. It is seen that 2 of the clouds would not be detected, 2 are marginal (less than 3 dB above noise), and the remaining 6 should all be detected. Also given are the reported vertical depths of the clouds; the maximum droplet diameters recorded in them; and the droplet sizes making the largest contribution to echo intensity per unit size range—these last show good correlation with echo intensity. It is of particular interest that cumulus numbers 1 and 7 would have been detected by the 8.6-mm radar by virtue merely of the water droplets 30  $\mu$  or less in diameter contained in them.

TABLE III—RADAR SIGNAL INTENSITY TO BE EXPECTED FROM EACH OF DURBIN'S 10 CUMULUS CLOUDS, COMPUTED FOR A RANGE OF 2 KILOMETRES

Durbin's cloud number	4	3	2	8	7	1	5	6	10	9
Echo intensity (decibels)	-10	-5½	+1½	+2½	+5	+9	+9½	+15	+22½	+26½
Depth of cloud (metres)	600	230	2130	760	1170	1870	690	290	1510	1520
Maximum droplet diameter detected (microns)	20	60	30	40	60	40	60	85	120	120
Droplet diameter contributing maximum echo (microns)	10	15	15-20	15-40	20-30	20-30	30-60	60-85	60-85	60-100

Durbin's cumulus distributions are approximately exponential, as had been found in cloud droplet distributions by Best,<sup>7</sup> i.e. roughly straight lines on a logarithmic plot of concentration. Cumulus numbers 3 and 4, which it was found would not be detected, have extremely small concentrations of 20- $\mu$  diameter droplets and steeply sloped distributions typical of fair weather cumulus. The Malvern radar would have needed to be 10 to 15 dB more sensitive to have detected them. Cumulus numbers 9 and 10 on the other hand have concentrations of 10- $\mu$  droplets smaller by a factor of about five than the fair weather cumulus, and a shallow slope extending to much larger droplet sizes, features which Weickmann and aufm Kampe<sup>8</sup> have found in cumulus congestus. The remainder are intermediate in slope and probably correspond roughly to cumulus mediocris. Four out of 6 would have been detected. These figures are in reasonable agreement with the detection of cumulus humilis, mediocris and congestus reported in Table I.

Echo intensities were also computed for the droplet spectra measured in layer clouds by Singleton and Smith.<sup>9</sup> The values are given in Table IV. Even their shallow layer clouds should be detected with the 8.6-mm radar, and the echo intensities are in sequence both with layer thickness and with the droplet sizes (per unit size range) contributing most strongly to the echo intensity, as was found for the cumulus spectra.

TABLE IV—RADAR SIGNAL INTENSITY TO BE EXPECTED FROM SINGLETON AND SMITH'S LAYER CLOUDS

Layer thickness (metres)	200-300	600	2000-2300
Echo intensity (decibels)	+12½	+16½	+30
Maximum droplet diameter detected (microns)	70	70	140
Droplet diameter contributing maximum echo (microns)	35-50	≥ 70	70-110



**Effects of attenuation.**—The echo intensities calculated for cumulus and layer clouds are those resulting from their cloud droplet content alone, since particles of precipitation size are outside the range of measurement of the magnesium oxide slide technique. Precipitation was in fact noted on the aircraft windscreen on some of the traverses through Durbin's cumulus numbers 9 and 10, and light rain was reported at the ground from the deepest layer clouds studied by Singleton and Smith. Precipitation within the pulse-volume will increase the echo intensity, but counteracting and possibly even greatly exceeding this will be the effect at millimetric wavelengths of attenuation by intervening precipitation. Absorption of energy by precipitation along the path of the beam will reduce echo intensities, and may prevent recording of the full vertical extent of cloud and precipitation, quite apart from the normal loss with increasing range of target. The absorption occurs on both outward and return paths. Robinson<sup>3</sup> found experimentally that at 8.6-mm wavelength, rain attenuation is given approximately by  $0.26R$  dB/km on a one-way path, where  $R$  is the rainfall rate in millimetres per hour. Attenuation by dry snow and ice crystals is negligible in comparison, but the attenuation by wet snow is quite high. Robinson, in one series of measurements in wet snow, found an attenuation two and a half times as great as in rainfall of equivalent rate.

One or two calculations of attenuation with a vertically-pointing 8.6-mm radar in typical rains will make its importance clear:

*Example 1*—In steady warm front rain of 2 mm/h with the 0°C level at 3 km, the attenuation up to the base of the melting layer would be about 3 dB. Attenuation through the melting layer should not add more than 0.6 dB, since the melting region is seldom more than 0.2 km deep, and attenuation in the snow above would be small, so that the total attenuation should not exceed 4 dB. This would probably not affect observation at lower levels, but might lose some of the snow echo otherwise detectable at high levels.

*Example 2*—In severe thunderstorms rainfall rates exceeding 50 mm/h over horizontal distances exceeding the beam width and extending through depths of 5 km or more would not be uncommon in this country. The attenuation through the first 3 km of this would be about 80 dB, sufficient to render undetectable even the heaviest precipitation at this and greater ranges, let alone cloud droplet distributions. Thus a grossly distorted height-time pattern can be expected in active thunderstorms. In lower latitudes this would be a frequent occurrence.

There are several other causes of loss at 8.6-mm wavelength, such as the absorption by cloud water droplets, by ice cloud particles, by water vapour and by other atmospheric gases. In addition there may be absorption by the skin of water on the aerial surface in heavy rain, loss due to precipitation particles comparable in size with the wavelength (for which the usual theory of radar back scattering does not strictly apply), and, at very short ranges only, the paralysis of the radar receiver while it is protected from the transmitted power-pulse. The combined effect of all these however is usually much smaller than the effect of rain attenuation at this wavelength. It is primarily rain attenuation which restricts the 8.6-mm weather radar to a vertically-pointing role.

**Comparison with the work of others.**—Some other evaluations of millimetric weather radars have been made, notably by Plank, Atlas and Paulsen<sup>10</sup> at 12.5-mm wavelength in Massachusetts, and by Wilk<sup>11</sup> at 8.6 mm

in Illinois. From the equipment parameters given in their papers it was calculated that, allowing for the longer wavelength, Plank's radar was about 7 dB less sensitive but that Wilk's radar could have been as much as 11 dB more sensitive than the Malvern equipment. This high performance was mainly due to the longer pulse employed and to the use of separate aerials for transmission and reception which allowed a lower noise level and smaller waveguide losses. With these values in mind it is of interest to compare their results for the detection of high, medium and low clouds with the ones reported in this paper (Table V). The figures follow the trend of the radar sensitivities, with the highest levels of detection reported by Wilk and the lowest by Plank *et alii*, but are nevertheless in broad agreement, despite these instrumental differences. The two values which differ most are the 87 per cent detection of low cloud by Wilk compared with the 51 per cent in the present analysis. It was found that there was a substantial difference in make up of the two sets of observations. Fifty-six per cent of the 694 low-cloud observations considered in this paper were cumulus clouds compared with only 7 per cent of Wilk's total of 269 low-cloud data. The 56 per cent probably weights the cumulus cloud too heavily (in particular the cumulus humilis which comprised 36 per cent of the cumulus clouds recorded) and the observation of fewer cumulus would have the effect of raising the overall level of detection. On the other hand, Wilk's cumulus clouds comprising only 7 per cent carry too little weight and his low-cloud detection of 87 per cent would undoubtedly have been less if cumulus clouds had been more strongly represented. For a high power 8.6-mm radar therefore, a low-cloud detection in the region of 60 to 80 per cent seems likely, depending on radar sensitivity.

TABLE V—COMPARISON OF ECHO DETECTION OF HIGH, MEDIUM AND LOW CLOUD WITH MILLIMETRIC RADARS IN AMERICA AND ENGLAND

Author	High cloud	Medium cloud <i>percentage detection</i>	Low cloud
Plank <i>et alii</i>	28	52	55
Harper	49	74	51
Wilk	54	75	87

Some sacrifice of sensitivity was necessary in the Malvern radar in order to achieve high definition: in fact its pulse-volume is 16 times smaller than Plank's and 85 times smaller than Wilk's. It is this which enabled assessment of the occurrence of non-precipitating as distinct from precipitating cloud. Plank *et alii* and Wilk did not attempt it perhaps because of poorer definition.

**Conclusions.**—Radar of 8.6-mm wavelength has the valuable ability to penetrate low-cloud layers and to detect a reasonable proportion of medium- and high-cloud systems, and this might in some circumstances be of overriding operational importance. However, the levels of detection found for high-sensitivity 8.6-mm radar, namely about 50 per cent of high cloud, 75 per cent of medium cloud and at best 60 to 80 per cent of low cloud, do not seem good enough to warrant its widespread operational use as a forecasting aid. It would not be possible to say with certainty from radar evidence alone that a particular aircraft flight level was clear of cloud.

These levels of detection might be acceptable if 8.6-mm radar could measure the heights of cloud bases and tops reliably, but evidence from the Malvern radar suggests that this is not often the case. The weak echoes from some shallow low clouds have clear-cut tops, and these, it is confidently thought, are also the

cloud tops and can be measured accurately, but the tops of echoes from medium and high cloud are rarely clear cut—an increase of sensitivity often reveals weak echo at a higher level. In addition, the radar evidence is that a large proportion of medium and high clouds contain embedded fallstreaks, giving a false indication of cloud base, so that there is uncertainty whether any of the echoes recorded at great heights represent true cloud-base measurement. Many of the echoes from low clouds certainly seem to be true cloud detection but, where these are detected at an intensity level only a few decibels above noise, there are grounds for thinking that the echo base does not coincide with the cloud base. The observations consistently suggest that the echo base is higher. A likely explanation is that the droplets in the base of the cloud though present in high concentrations are not detected because of their small size, but that higher in the cloud the droplets are larger and become detectable. Further evidence of the unreliability of 8.6-mm radar as an indicator of cloud base and top is that evidence of multiple-layered medium clouds was rarely seen, though it is reasonable to think that their occurrence cannot have been infrequent.

Nevertheless 8.6-mm radar often gives a good general indication of cloud structure, and shows that frequently precipitation is occurring aloft but is not reaching the ground. The frequent complexity of fallstreak patterns can give a fascinating indication of the variation of wind with height.

It would be of special importance if 8.6-mm radar could measure fog top. In some recent measurements with the Malvern radar, Harrold (unpublished) has recorded weak echoes from some denser water fogs, but has been unable to define the fog top. Other quite moderate fogs were not detected. A substantial increase in radar sensitivity, perhaps by as much as 20 dB, would probably be needed to improve significantly the levels of detection of cloud and fog. Technical advances, perhaps making use of shorter millimetric wavelengths, may make this possible in the future, but would not overcome pattern distortion caused by attenuation in heavy rain, a fault to which all millimetric radars are prone.

**Acknowledgements.**—The author is indebted to the Chief Scientist, Ministry of Aviation for the opportunity to evaluate the 8.6-mm radar, and wishes to thank Mr. J. R. Probert-Jones, now on the staff of Imperial College, London, Mr. H. W. Bahns of the Royal Radar Establishment, Mr. S. R. Smith of the Meteorological Research Unit at Malvern for the present high state of efficiency of the 8.6-mm radar and other staff of the Unit for their long hours of observation and analysis.

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## **SYMPOSIUM ON THE RESEARCH AND DEVELOPMENT ASPECTS OF LONG-RANGE WEATHER FORECASTING**

A symposium was held at Boulder, Colorado, under the joint sponsorship of the World Meteorological Organization and the International Union of Geodesy and Geophysics from 29 June to 4 July 1964, the purpose of which was to discuss the scientific basis for long-range weather forecasting. It was attended not only by meteorologists directly concerned with the preparation of long-range forecasts, but also by others engaged in fundamental studies of the general circulation of the atmosphere.

Papers were presented which described the statistical approach to long-range forecasting as applied in India, Germany, Japan, Sweden, Poland, and the U.S.A., but there seemed to be little general expectation that any substantial advance would come from the development of these methods. Even the refined method of 'empirical orthogonal functions' applied by Gilman to forecasting by correlation methods gave steadily deteriorating results when applied to independent data.

Several papers discussed the factors external to the atmosphere which might be responsible for long-term weather anomalies. Professor Willett (Massachusetts Institute of Technology) stressed the role of variations of solar radiation particularly in relation to 22- and 80-year cycles, but generally there was more emphasis on the part played by sea surface temperature, various aspects being discussed in papers by J. Namias, J. Bjerknes, J. S. Sawyer and H. Flohn.

The most encouraging session of the symposium was that devoted to numerical studies of the general circulation. Experiments in the U.S.A. in computing the large-scale behaviour of the atmosphere were reported by J. Smagorinsky, J. Adem, Y. Mintz and C. Leith. Although the calculations were made on a variety of different assumptions, all showed that important features of the general circulation could be closely simulated by numerical calculation. Studies of energy exchanges throughout the northern hemisphere by A. Wiin-Nielsen (U.S.A) and T. Murakami (Japan) confirm several important deductions from the numerical models of the atmosphere.

In the discussions which followed the presentation of papers there appeared to be a general agreement that the numerical studies of the general circulation could contribute much to establishing a firmer basis than now available for long-range forecasting. Although direct numerical forecasting beyond the first few days is not yet possible, it was generally expected that calculations from the current state of the atmosphere would ultimately be able to give useful guidance over a period of 2 to 4 weeks. Parallel calculations based on slightly different initial data would however be needed to establish the degree of predictability, and the range of variation to be expected. It also seemed to be

generally accepted that for periods of a month or more allowance would have to be made for variations in some factors external to the atmosphere—sea temperature, snow cover, evaporation from vegetation, etc.

It was also recognized that until numerical dynamical methods have been developed considerably further, empirical studies of the large-scale atmospheric circulation in relation to sea temperature, snow cover and other factors can play a useful part in aiding the long-range forecaster.

The meetings were arranged by Dr. P. D. Thompson of the recently formed National Center for Atmospheric Research in the U.S.A. and took place on the campus of the University of Colorado. The excellent arrangements both inside and outside the meetings aided materially the valuable exchanges of ideas which went on at the symposium.

J. S. SAWYER

## REVIEWS

*Cloud physics* edited by A. Kh. Khrgian.  $9\frac{1}{2}$  in  $\times$   $6\frac{1}{2}$  in, p. viii + 392, *illus.* (translated from the Russian by the Israel Program for Scientific Translation, Jerusalem). Oldbourne Press, 121 Fleet Street, London, E.C.4, 1964. Price: £6.

This book is a translation of a Russian book published in 1961 and represents the joint work of a number of Soviet scientists. It is unique among textbooks on this topic in dealing with the large-scale properties of clouds as well as with the microphysics of the formation of cloudy air. It is to be welcomed therefore as a book containing a wealth of practical information of value to the day-to-day practising meteorologist as well as to the research engineer or physicist. The authors have ranged widely in their reading and there is ample recognition of work done outside their own country as well as a useful summary of their own, based primarily on extensive flying by research aircraft. The bibliography contains reference to 254 publications in Russian, including Mason's *The physics of clouds*, and a further 378 in other languages. By and large the translation into American has been well done, but there are one or two instances where a too literal translation is misleading; thus it needs to be remembered that in talking about "low" and "high" cumulus clouds the authors intended the adjectives to refer to the vertical extent of the clouds and not to the height of the cloud base—"small" and "large" would have been better. The reviewer also puzzled somewhat over "frontal downpour clouds" before realizing that "downpour" meant "shower." The proof-reading has not been so well done and there are several small errors, perhaps the most serious of which to a casual reader would be the heading of the first column of Tables 23, 24, 25 as  $\text{g/cm}^3$  when  $\text{g/m}^3$  is intended.

The first chapter discusses the basic microphysics of condensation of water vapour on nuclei and their subsequent growth by diffusion and coalescence. This is followed by discussion of sublimation, the freezing of water droplets, and freezing nuclei. It is now familiar work and is dealt with more exhaustively in Mason's book.

The second chapter deals with the microstructure of clouds in terms of average drop-size distributions and water content and it would be better if the limitations of the measuring instruments were clearly expressed here rather than deferred until the eleventh and last chapter of the book.

After a short third chapter on the classification of clouds the next five chapters, which form the most valuable part of the book, discuss in some detail the structure and formation of cumulus, stratiform, altostratus and altocumulus, frontal and cirrus clouds. In the chapter on cumulus there is extensive reference to the American Thunderstorm Project and a reference to the aircraft "Meteor" which, although attributed to the U.S.A., was undoubtedly engaged in our own smaller thunderstorm investigation with pilots and observers from the Royal Aircraft Establishment. The section in this chapter on graupel and hail is disappointingly brief with no theories of formation and very little observational material.

A chapter follows on aircraft icing with a detailed discussion of the efficiency of catch of water droplets by cylinders and aerofoils. In the succeeding chapter on artificial stimulation of cloud and fog the accent is more on the dissipation of cloud and fog than on rain-making and it is clear that the claims for success in dissipation are more soundly based than are those elsewhere for enhancement of rain.

The concluding chapter describes various instruments for the capture of droplets and crystals and for the measurement of cloud water content from aircraft. It is interesting, but misleading, to read that the Meteorological Research Flight at Farnborough has four Hastings aircraft (only one) and the tropopause would need to be unusually low for this aircraft to explore the low stratosphere!

The book represents a good attempt to link the microphysics with the large-scale processes of cloud formation and dissolution and is a useful addition to meteorological literature.

R. F. JONES

*The problem of the professional training of meteorological personnel of all grades in the less-developed countries* by J. Van Mieghem. (World Meteorological Organization Tech. Note No. 50.) 11 in  $\times$  8 $\frac{1}{4}$  in, pp. x + 76, Secretariat of the World Meteorological Organization (WMO), Geneva, Switzerland, 1963. Price: Sw.F.4.

One of the primary aims of WMO is to encourage training in meteorology and to assist in co-ordinating the international aspects of such training.

With the emergence of several newly independent States during the last decade, WMO has given increasing attention to the training needs of the less-developed countries. In 1961 Professor Van Mieghem, who was Professor of Meteorology in the University of Brussels, and is now Director of the Meteorological Institute in Brussels, was engaged by the Organization, as a consultant, to assist in this task. He prepared three reports, of which this Technical Note is one.

The report underlines the essential requirements that all meteorological personnel, at the beginning of their careers, should be given a thorough training in the basic elements of meteorology. The level of such training will vary considerably from one grade to another, and assumes a prerequisite minimum knowledge of mathematics and physics appropriate to the grade.

It is recognized that there is a lack of uniformity in the grades of meteorological personnel employed by different national meteorological services. The report considers four classes, ranging from university graduates in mathematics

or physics (Class I) who would be engaged in highly scientific work, to Class IV personnel whose duties would mainly be concerned with the making and plotting of synoptic observations. Comprehensive syllabuses for each of these classes are given in detail in Annexes I to IV.

The establishment of national meteorological schools for the training of Class IV personnel is advocated, and of international regional centres for Class II and Class III personnel. The training of Class I personnel is considered to be a task for the Universities or for major meteorological schools of university level.

Attention is drawn to the need for instructional personnel to be both highly qualified and highly experienced, and for them to receive instruction in teaching methods.

Refresher courses and seminars are recommended to enable operational staff to keep abreast of new developments in the science.

Annexes V to VII summarize the comments on the report made by the Executive Committee of WMO, by Members of WMO, and by the Presidents of WMO Technical Commissions.

In publishing the report, the Executive Committee of WMO stresses that it should be considered as advisory material which would be useful to countries establishing or expanding their training facilities. W. R. GALLOWAY

## **OBITUARY**

### **Dr. M. Doporto**

We regret to record the death of Dr. M. Doporto, Director of the Irish Meteorological Service for the past 16 years. Dr. Doporto died suddenly in Dublin on 8 September, at the age of 62.

Dr. Doporto was well known to meteorologists in this country and elsewhere. A Spaniard by birth, he joined the Spanish Meteorological Service in 1921 and became officer-in-charge of the Weather Forecast Centre at Barcelona. The upheavals of the Civil War compelled him to leave his country, and in 1939 he joined the newly-formed Irish Meteorological Service. In 1948 he succeeded Mr. A. H. Nagle as Director.

Dr. Doporto was a scholar of distinction whose work lay mainly in dynamical meteorology. He dealt with the hydrodynamical equations of motion and the cellular structure of atmospheric circulations and in 1943 predicted the existence of a second isopycnic layer near 25 km, which was subsequently verified.

He was a member of the Board of Dublin Institute for Advanced Studies and maintained a lively interest in his subject to the end.

Dr. Doporto was a prominent figure in the world of international science and at the time of his death was Chairman of the Finance Committee of the International Union of Geodesy and Geophysics. He was a frequent and sometimes highly critical speaker at the Congresses of the World Meteorological Organization, of which he may rightly be regarded as one of the 'founding fathers.'

As one who often debated with Dr. Doporto in the business meetings of WMO, I shall miss him greatly. Although he always spoke his mind frankly and pressed his points with fervour, he was invariably courteous and outside the

meeting room was the most friendly and entertaining of colleagues. He was a man who was regarded with respect and affection by all who knew him, and the meetings in Geneva will never be quite the same without him.

Dr. Doporto leaves a widow and three sons, to whom we send our deepest sympathy.

O. G. SUTTON

## LETTER TO THE EDITOR

### Solar halo

Unusual solar haloes were seen at Lerwick Observatory on the morning of Sunday, 14 June 1964. The phenomena were remarkable both on account of the brilliance of the unusual phenomena that were visible as well as the complete absence of some of the more common halo phenomena.

The halo system was first seen at 0950 Universal Time (UT): all except the  $22^\circ$  halo had disappeared by 1020 UT. The elevation of the sun was  $47^\circ$  at 1000 UT.

The accompanying sketch (Figure 1) shows what was seen at the Observatory by the observer Mr. L. S. Leslie. The common  $22^\circ$  halo was bright except in the east where it was faintly seen inside a very bright part-circumscribing elliptical halo (*Observer's handbook*<sup>1</sup>) which extended from a point level with the sun on the east side to the highest point of the  $22^\circ$  halo, with which it made contact, and thence partly over to the west side. Another member of the staff, Mr. J. Cubin, from a point 2 km away, saw the whole of this circumscribing elliptical halo and estimated the semi-major axis to be  $26^\circ$ . The lower contact arc was very bright,

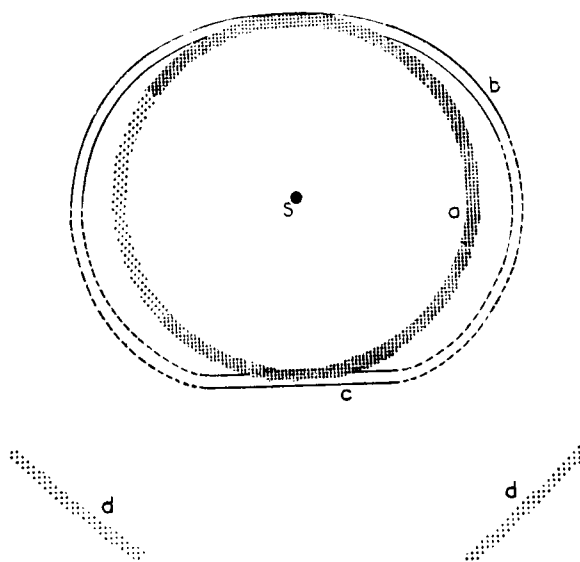


FIGURE 1—DIAGRAMMATIC SKETCH OF THE SOLAR HALO PHENOMENA SEEN AT LERWICK ON 14 JUNE 1963

- a  $22^\circ$  halo round the sun S,
- b, c upper and lower arcs of contact,
- d, d' infralateral tangent arcs of the  $46^\circ$  halo.

The pecked lines joining b and c show how another observer saw them joined together to form a circumscribing halo which was approximately elliptical with a semi-major axis estimated as  $26^\circ$ .



and appeared almost straight—presumably the  $22^\circ$  halo, the elliptical halo and the lower arc of contact (which is concave downwards) were superimposed and gave the appearance of a straight arc.

In addition there were two very bright and almost straight streaks below the sun and on either side, as shown in Figure 1. These are not mentioned in the *Observer's handbook*, but the *Compendium of meteorology*<sup>2</sup> describes these as the infralateral tangent arcs of the  $46^\circ$  halo (which was not visible at all).

Except at the lower arc of contact, which was mainly red and yellow, all these arcs and haloes showed almost the complete range of spectral colours; certainly from red to green and with an impression of blue. There were no mock suns, sun pillars,  $46^\circ$  halo or any white (reflection) halo. During the Aberdeen meeting of the Royal Meteorological Society on 29–30 June there was some discussion on what practical use could be made of observations of solar halo phenomena. The general opinion was that unusual haloes occurred because unusual atmospheric conditions allowed unusual ice crystal formation to take place.

*Meteorological Office, The Observatory, Lerwick.*

R. A. HAMILTON

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## NOTES AND NEWS

### Retirement of Michael J. Morley

When the Republic of Ireland came into being in 1922 the Meteorological Office continued to administer the Irish meteorological stations and especially to maintain the Valentia Geophysical Observatory at Cahirciveen, Co. Kerry. Not until 1936 was the Irish Meteorological Service formed, and it was a few years after that before sufficient staff had been recruited to take over completely.

Michael Morley was among the assets taken over. A native of Cahirciveen, he had started work at Valentia Observatory under L. H. G. Dines in 1915. Twenty-four years later he helped to found Shannon Airport and was then transferred to Dublin Airport. It is in his 25th year of service there that he has reached the age of retirement.

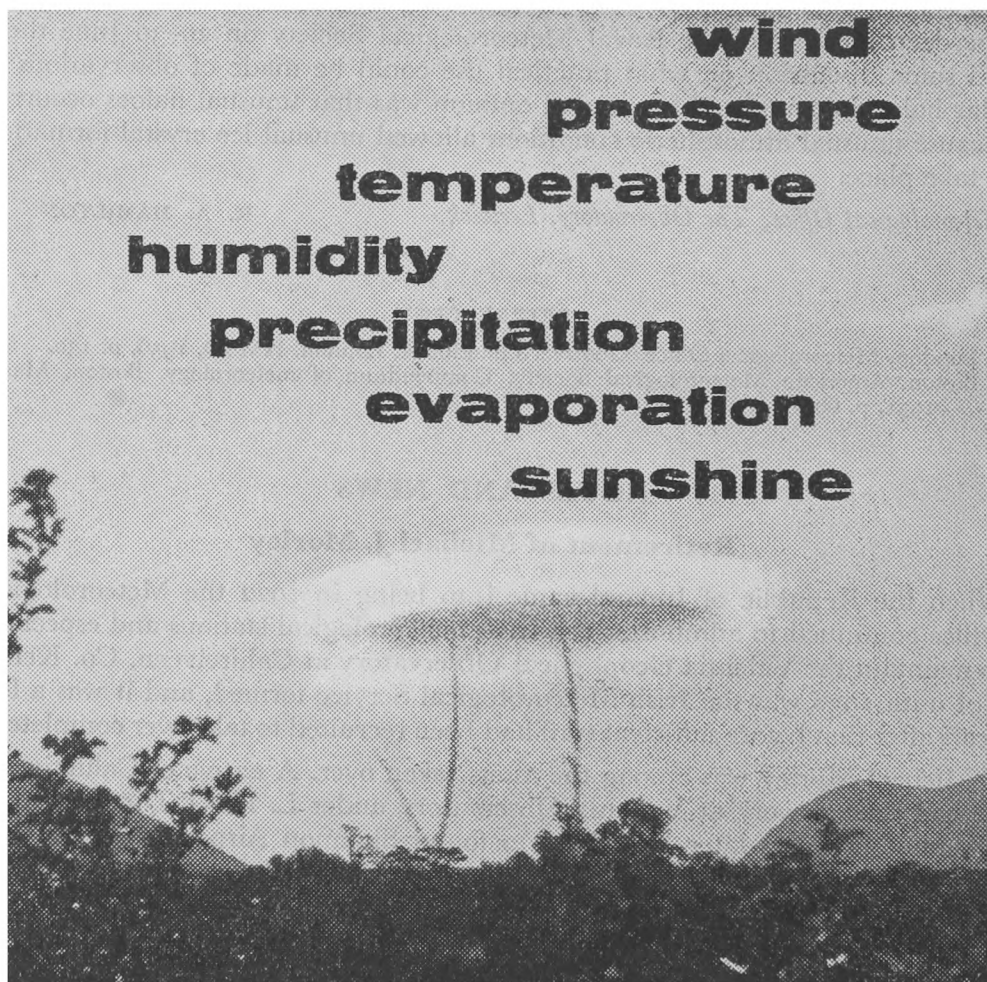
His flair was, and is, instruments. Many, many men have learned from him the art of humouring temperamental anemographs and sulky ceilometers. Those men, whether working with him, or under him, or over him, have all imbibed more than mere technique. They have learned that even in the routine of airport meteorology the job can be a vocation. The Irish Meteorological Service is still young, but through Michael Morley it is linked to the old tradition established by such dedicated men as FitzRoy, Scott, Dines and Shaw.

We join all his past and present colleagues in wishing him a long and happy retirement.

F.E.D.

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## A COMPARISON OF SNOW PREDICTORS

By C. J. BOYDEN

**Summary.**—Whether precipitation is likely to be in the form of rain or snow is normally determined by means of an index of atmospheric temperature. Six such predictors are examined, some discussion being included on how precipitation changes the magnitude of the predictor itself. On the assumption that the magnitude is accurately forecast, an assessment is made of the success of each predictor. The best are found to be (i) the height of the freezing-level and (ii) the 1000–850 mb thickness combined with the sea-level pressure.

**Introduction.**—In general the methods used in forecasting weather depend on how far in advance the forecast is required. Forecasting for the next day is dominated by broad-scale considerations, but for a few hours ahead there is greater emphasis on current trends. A predictor which is not very closely related to whether precipitation will be in the form of rain or snow is acceptable in the longer-period forecast. A more sensitive predictor is desirable when the forecast period is short enough for the predictor itself to be forecast with fair precision.

At British stations the decision as to whether rain or snow is the more likely is commonly based on the forecast 1000–500 mb thickness, which was investigated by Murray<sup>1,2</sup> and Lamb.<sup>3</sup> This is a crude predictor because the form of precipitation is determined by the lowest levels of the atmosphere and at least nine-tenths of the layer up to 500 mb has little or no bearing on the problem. As was pointed out by Murray, the justification for using such a deep layer is that the 1000–500 mb thickness is a standard parameter in synoptic analysis. Its success as a snow predictor is due to the degree of consistency, during precipitation, of the temperature lapse rates in the lower half of the troposphere. Because of this the temperature of the lowest layer, on which the thawing of snow-flakes depends, is moderately well indicated by the mean temperature of a much deeper layer.

It is obvious that the thickness of a shallower layer must be a more precise predictor. The 1000–700 mb layer, for example, excludes nearly half the irrelevant part included in the 1000–500 mb layer. It appears to be the less widely used of the two simply because the drawing of a 1000–700 mb chart may not be justified by other forecasting commitments.

The 1000–850 mb thickness is still better as a predictor of the form of precipitation because the melting layer extends through as much as one-quarter of its

depth. Mineeva<sup>4</sup> has studied the relationships between the critical stage of snow, the 1000–850 mb thickness and the temperatures near the ground and the 850 mb level.

Murray<sup>1,2</sup> and Heissat<sup>5</sup> are among those who have also related the form of precipitation to the height of the freezing-level as well as to the screen temperature.

The purpose of the present paper is to compare the success of six predictors of the form of precipitation. To a large extent this success is evaluated on the assumption that the magnitude of the predictor at the time of the precipitation is known; how easily each predictor can be forecast has not been studied. Some discussion is included, however, on the interdependence of the predictors and on the extent to which the magnitude of the predictor is controlled by the precipitation.

**Observations used.**—The investigation was based on observations made during the four winters 1955–56, 1957–58, 1961–62 and 1962–63, when snow fell more frequently than usual over the British Isles. The months used were December to March and all observations came from the radiosonde stations Lerwick, Stornoway, Shanwell, Long Kesh, Aughton, Hemsby, Crawley and Camborne. Every 0000 GMT and 1200 GMT observation was extracted provided there was precipitation at the time the radiosonde was launched. (The observation times were 0300 GMT and 1500 GMT in the 1955–56 winter).

The few observations of ice pellets were excluded from the analysis because the definition of the associated code figures for present weather is not specific enough for our purpose. The total number of observations remaining was 1406, of which 1030 were made during rain, 300 during snow, and 76 during sleet (a mixture of rain and snow). No distinction was made in the analysis between showery and non-showery types.

Most of the analysis was carried out for each station separately, midnight and midday observations also being kept apart. This showed that for most purposes it was satisfactory to treat all observations collectively. Climatological differences between the north and south of the British Isles in winter did not seem to justify modifications in relationships intended to be used by forecasters. Variations in the elevation of stations above sea level were likewise not a serious complication since, with the exception of Crawley at 144 m, all are within 90 m of sea level.

**The melting of falling snow.**—Above the freezing-level (meaning the level of the 0°C isotherm, a term preferred by some writers) a cloud is likely to consist of supercooled water drops as well as ice crystals. This suggests that when precipitation is falling through the freezing-level some of it may at times be in the form of rain. However, out of 170 occurrences of precipitation at the ground when the freezing-level was also at the ground, only 3 were reported as rain and 4 as sleet, the remaining 163 falls being of snow. Thus when the freezing-level is at any height above the ground it is reasonable to assume that virtually all the precipitation originating above the freezing-level and reaching the ground as rain was initially in the form of snow. The part of the atmosphere below the freezing-level determines whether there will be rain or snow at the ground. The part above the freezing-level determines the number, size and structure of the snow-flakes falling through the freezing-level; these are characteristics which do not appear to be relevant to the forecasting of the form of precipitation at the ground.

The heat required to warm a snow-flake as it falls into a warmer environment is very small relative to the heat transfer which takes place during melting, evaporation and condensation, and can be neglected in thermodynamical considerations.

Each snow-flake may be regarded as a wet-bulb thermometer of irregular shape, falling at a speed which Langleben<sup>6</sup> has shown to be largely independent of its size, at least until melting is nearly complete. Melting cannot begin before the temperature of the surface of the snow-flake exceeds  $0^{\circ}\text{C}$ , that is to say before the wet-bulb temperature of the surrounding air exceeds  $0^{\circ}\text{C}$ . When precipitation begins the snow-flakes may fall through air with a comparatively low relative humidity, in which case melting does not begin at the freezing-level but at some distance below it. Below the freezing-level but above the melting layer the air is cooled by evaporation from snow-flakes and the freezing-level descends until, if saturation is reached, it coincides with the original  $0^{\circ}\text{C}$  wet-bulb isotherm.

Nevertheless, this distinction between dry-bulb and wet-bulb temperatures is rarely an important one in relation to the melting of snow except in showers which are too short-lived to have much effect on an initially low relative humidity. On these occasions the showers may be of snow even when dry-bulb temperatures are such that rain seems the more likely. The conclusion that humidity is usually unimportant is based on a comparison made between the degrees of saturation before and during precipitation. It was not possible to ascertain the changes in a moving parcel of air, so the following method was adopted. Using routine upper air soundings the depression of the dew-point below the dry-bulb temperature, both at the 850 mb level and at the ground, was noted during precipitation. These figures were compared with the readings 12 hours earlier at the same station, provided there was no precipitation at that time. Selection of the occasions was made in this way to exclude most of the highly subsided air through which precipitation was unlikely to fall for a long time. The comparisons were made for Long Kesh and Hemsby and there was close agreement between the two stations, the median dew-point depression decreasing from  $3.2^{\circ}\text{C}$  to  $1.0^{\circ}\text{C}$  at 850 mb and from  $1.7^{\circ}\text{C}$  to  $0.7^{\circ}\text{C}$  at the surface. This decrease in dew-point depression was due not only to evaporational cooling but also to the cooling by the melting of snow and often to the arrival of air with a higher relative humidity. If evaporational cooling is taken to be the sole cause it can be assumed that the wet-bulb temperature was unchanged. The corresponding decrease in dry-bulb temperature would average about  $0.7^{\circ}\text{C}$ , the equivalent decrease in 1000–85 omb thickness being 3–4 metres. If the comparison could be made over a shorter period than 12 hours there is little doubt these figures would be smaller. In considering the probability that snow will melt it is therefore justifiable for the forecaster to examine dry-bulb temperatures without regard to humidity, as well as to ignore the effect of evaporational cooling on the 1000–850 mb thickness and probably on the height of the freezing-level.

**Temperature changes caused by the melting of falling snow.**—The temperature structure of the melting layer and the underlying atmosphere was first noted by Findeisen.<sup>7</sup> Melting of the snow begins just below the freezing-level and is completed within about 300 metres of it. The latent heat of fusion is abstracted from this layer, which therefore cools towards  $0^{\circ}\text{C}$ . The cooling

induces instability in the underlying air, an adiabatic lapse rate therefore progressively spreading downwards in it. As the melting layer becomes colder it is less effective in melting snow-flakes, so as time goes on the snow is able to fall to a lower level before being completely melted. Thus both the melting layer and the unstable layer below it move slowly down through the atmosphere while precipitation continues. If the base of the melting layer reaches the ground the rain there turns to sleet and then to snow, but this stage is not commonly reached because of the advection of warmer air possessing a higher freezing-level.

A fairly reliable estimate of the temperature structure from the freezing-level to the ground can be made by considering the variation of mean lapse rate with the height of the freezing-level. Figure 1 shows this relationship, the mean lapse rate ( $^{\circ}\text{C}/\text{mb}$ ) being the surface temperature divided by the pressure difference between the ground and the freezing-level. The curve shows a moderate lapse rate when the freezing-level is high and an increasing lapse rate with lowering freezing-level until this is about 50 mb above the ground. Below this level there is a fairly rapid decrease in lapse rate with decreasing height.

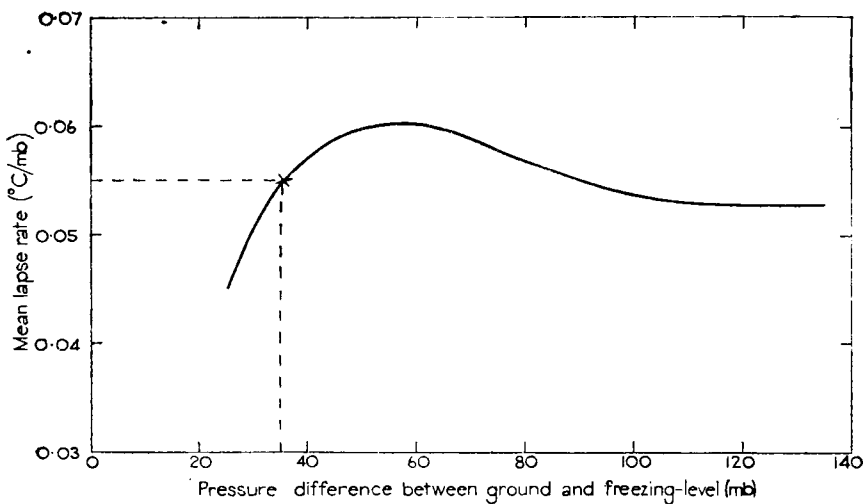


FIGURE 1—VARIATION OF THE MEAN LAPSE RATE FROM THE GROUND TO THE FREEZING-LEVEL DURING PRECIPITATION

The cross corresponds to an equal probability of rain, sleet or snow.

These variations of lapse rate can be explained by reference to Figure 2, where ABCD, EFG, HJ and KL depict upper air temperatures beneath four different freezing-levels during precipitation. AB is a melting layer, and in consequence of the cooling at B the layer BC has become unstable. The cooling has had no effect below C, so the mean lapse rate, as measured between A and D, can be described as moderate. Curve EFG is similar to ABC, but the unstable layer has reached the ground, so the lapse rate between E and G is relatively high. HJ represents the situation in which the melting layer just extends to the ground, giving an equal probability of rain, sleet or snow. The mean lapse rate in HJ is markedly less than in EG because there is no unstable layer. Curve KL indicates only partial melting of each snow-flake and the precipitation at the ground would almost certainly be snow.

The lapse rate in a melting layer depends on the initial lapse rate and the amount of snow subsequently melted at each level. If the temperature at a particular level is well above freezing-point the melting is rapid and so therefore is the

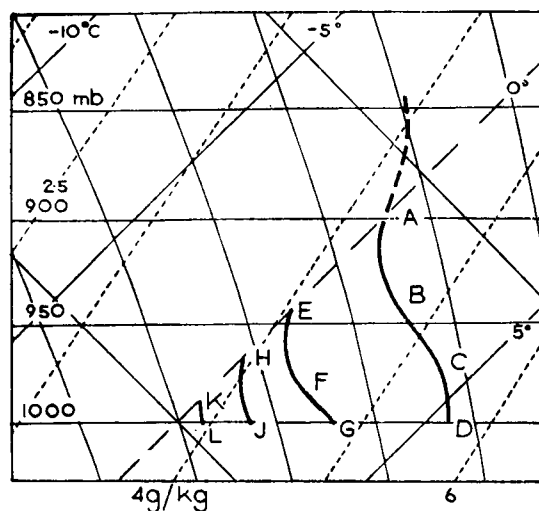


FIGURE 2—THE TEMPERATURE PROFILES BELOW VARIOUS FREEZING-LEVELS cooling of the air. As the air becomes colder its effectiveness in melting the snow is reduced, as also is its own rate of cooling. Thus a fair degree of uniformity is to be expected in the lapse rate of a melting layer whatever its height. Since the heat required to melt a given mass of snow involves the integrated product of the depth and positive temperature of the melting layer, a degree of uniformity would also be expected in the depth of the melting layer.

It was found that rain, sleet and snow occurred with equal frequency when the freezing-level was 35 mb above the ground, so this was taken as the mean depth of the melting layer. Figure 1 shows the corresponding mean lapse rate to be  $0.055^{\circ}\text{C}/\text{mb}$  which is close to saturation and gives a mean temperature difference of nearly  $2^{\circ}\text{C}$  between the base and top of the melting layer. When the freezing-level is so low that a complete melting layer does not exist, the lapse rate within it cannot easily be measured. In Figure 1 extrapolation of the curve to the left suggests the lapse rate is small in an incomplete melting layer. This implies that when there is a complete melting layer the lapse rate is likely to be smallest in its upper part (see Figure 2). This variation of lapse rate is to be expected since, because the melting layer sinks during precipitation, the upper part of the layer has been a thawing agent for longer than the lower part. Moreover, there is a turbulent upward transfer of heat to the base of the melting layer.

That there is a fair degree of uniformity in the depths and lapse rates of melting layers was also shown by an analysis of occasions when sleet was falling. This form of precipitation indicates that there is an almost complete melting layer with its base at the ground. The freezing-level heights showed a pronounced mode between 30 and 40 mb, and less than 20 per cent of melting layers were as deep as 50 mb. The corresponding uniformity of mean lapse rate was confirmed by 76 per cent of surface temperatures (reported in whole degrees Celsius) being either  $1^{\circ}\text{C}$  or  $2^{\circ}\text{C}$ . These temperatures were controlled to some extent by the snow cover on the ground but this could not have been a major factor since there was no comparable peak in the distribution of surface temperatures during rain or snow.

**The lowering of the freezing-level in precipitation.**—On general grounds one might expect that the greatest departure from a uniform depth and mean lapse rate of the melting layer would occur when the precipitation

was prolonged. A separate analysis was therefore made on occasions when the precipitation was reported as continuous. Somewhat unexpectedly the lapse rates fitted fairly well the curve of Figure 1. This suggests that the profiles of Figure 2 do not change substantially during prolonged precipitation. Nevertheless the base of the melting layer must sink through the atmosphere as cooling proceeds and the melting power of a particular layer of air decreases. The implication is that the top of the melting layer—the freezing-level—must descend correspondingly, presumably through turbulent mixing across the freezing-level.

To confirm that the top of the melting layer descends, an examination was made of a sample of 25 upper air soundings made in continuous rain which was moderate at the time of launch. On 80 per cent of occasions the mean lapse rate in the 40 mb above the freezing-level was less than in the 40 mb below it. Moreover a stable layer near the freezing-level was reported much more often just above it than just below it. Thus, on a routine tephigram, the evidence that heat has been used to melt snow is most likely to be seen as a relatively stable layer just above the freezing-level (the broken line above A in Figure 2). The active melting layer (AB) may be accompanied by too small a change of lapse rate to be mentioned in the upper air report.

On the assumption that during continuous rain at the ground the temperature lapse rate for some distance down from the freezing-level remains unchanged, an estimate can be made of the rate of lowering of the freezing-level in terms of the rate of rainfall. The temperature profiles for different air columns shown in Figure 2 may now be regarded as successive profiles in the same column of air through which precipitation is falling. Although there is some variation in the profiles (corresponding to lapse-rate variations in Figure 1), it may be assumed as a first approximation that the mean temperature change between two nearby curves is equal to the temperature change in the region just below the freezing-level.

Let  $p_g$  = pressure at the ground in mb,

$p_f$  = pressure at the freezing-level in mb,

$R$  = rainfall from the melting of snow-flakes in mm,

$\Delta T$  = mean temperature fall in °C in the layer from the freezing-level to the ground, caused by the melting of snow,

$\Delta p_f$  = lowering of freezing-level accompanying the mean temperature fall  $\Delta T$ .

Lumb<sup>8</sup> has shown that

$$R = 0.056 \Delta T (p_g - p_f). \quad \dots (1)$$

In the derivation of this result it was assumed that the air was saturated initially and allowance was made for the latent heat of condensation.

Taking 0.05°C/mb as the mean lapse rate, we may write  $\Delta T \simeq 0.05 \Delta p_f$ .

Equation (1) then becomes

$$\Delta p_f \simeq \frac{360R}{p_g - p_f}. \quad \dots (2)$$

Thus for a rainfall rate of 1 mm/h a freezing-level about 50 mb above the ground lowers by about 7 mb/h. With a freezing-level 100 mb above the ground the rate of lowering is more than half this figure, perhaps 4–5 mb/h, since, as is seen from ABCD in Figure 2, the rate of cooling is more pronounced in the upper part of the layer. When the freezing-level is less than 50 mb above the ground its rate of descent is uncertain because of changes in lapse rate.



**Snow predictors and their assessment.**—The relative merits of the following predictors were investigated:

- (i) Height of the freezing-level above the ground;
- (ii) Screen temperature;
- (iii) 1000–850 mb thickness;
- (iv) 1000–850 mb thickness adjusted for sea-level pressure and station height;
- (v) 1000–700 mb thickness;
- (vi) 1000–500 mb thickness.

All these predictors are well known apart from (iv), which is presented for the first time.

No way of forecasting sleet appears to be known, though a few comments on this are given later in the paper. In computing the probabilities of snow an occurrence of sleet was therefore counted as half to snow and half to rain.

Sufficiently low values of any of these predictors give a 100 per cent probability of snow and when they exceed critical values it is certain that snow will not reach the ground. Apart from the difficulty of forecasting it, a predictor can be classified as a good predictor if it satisfies two requirements. The first is the obvious one that its magnitude should be associated with the expected form of precipitation on a high proportion of occasions. The second is that there should not be a wide range of values of the predictor in which one form of precipitation is not much more likely than the other.

The extent to which each predictor met the first requirement was found simply by establishing the critical value for which snow and rain were equally probable, and then adding together the number of occasions when rain occurred at a lower value and when snow occurred at a higher value. This is the number of failures shown in Table I.

TABLE I—NUMERICAL VALUES OF EACH PREDICTOR CORRESPONDING TO DIFFERENT PROBABILITIES OF SNOW, TOGETHER WITH UNCERTAINTY RATIOS AND NUMBERS OF TIMES THE PREDICTOR FAILED

Predictor	Mean level of predictor for given snow probability <i>per cent</i>					Uncertainty ratio <i>per cent</i>	Number of failures
	90	70	50	30	10		
Height of freezing-level above the ground (gpm)	12	25	35	45	61	9	54
Surface temperature (°C)	−0.3	1.2	1.6	2.3	3.9	11	62
1000–850 mb thickness (gpm)	1279	1287	1293	1297	1302	16	75
1000–850 mb thickness adjusted for sea-level pressure and station height (gpm)	1281	1290	1293	1298	1303	14	58
1000–700 mb thickness (gpm)	2751	2773	2789	2803	2823	20	100
1000–500 mb thickness (gpm)	5180	5238	5258	5292	5334	19	114

The extent to which the second, and less important, requirement was met was found by introducing a quantity which will be called the uncertainty ratio, defined as the percentage of all occurrences of precipitation for which the probability of snow lay between 25 per cent and 75 per cent, this choice of percentages being arbitrary. The uncertainty ratio of a predictor is an index which measures, for a given set of observations, the rapidity of a change from a high probability to a low probability of either form of precipitation. A low uncertainty ratio is a desirable feature of a predictor, but is by no means essential.

For all predictors, these figures, together with probability levels, are given in Table I.

(i) *Freezing-level as a snow predictor*.—The height of the freezing-level above the ground is the fundamental predictor of the form of precipitation. It is not therefore surprising that it shows the fewest forecasting failures of the six predictors, though by only a small margin. It also has the smallest uncertainty ratio. When the freezing-level fails to predict the right form of precipitation the probable cause is abnormality in the mean temperature of the layer between the ground and the freezing-level.

This predictor has the advantage that a rapid estimate can be made of the snow probability at a high level, since the height of the place (in mb) need only be subtracted from the estimated height of the freezing-level above sea level to give the appropriate value of the predictor. Possible causes of error are mentioned under predictor (iv).

In estimating the magnitude of this predictor allowance should be made for the lowering of the freezing-level caused by precipitation. It should be recognized that this is not a disadvantage of this predictor, but represents a refinement not possessed by the others.

On 3 per cent of occasions a second freezing-level was reported above the one used in the analysis. This appeared to have no significance in relation to the form of precipitation. (Freezing rain or drizzle was reported only once).

(ii) *Screen temperature as a snow predictor*.—Surface air temperature was an essential predictor of snow before regular upper air observations were made. It continues to be used because it is a quantity which is continuously measurable and because it is quite highly correlated with the form of precipitation. However correlation alone does not justify the use of an element as a predictor.

There are several factors which make surface temperature in cold weather very difficult to forecast. It depends, for example, on cloud cover, whether the ground is frozen hard and whether there is a covering of snow. In addition the temperature falls fairly sharply as rain changes to snow, so extrapolated temperatures give little indication of when this is about to take place.

Figure 3 shows the mean relationships found between 1000–850 mb thickness and surface temperature for the three types of precipitation and for all of them together (full line). With a thickness of about 1290 geopotential metres, for example, snow occurs at a surface temperature on the average a little under  $1^{\circ}\text{C}$  and rain when the temperature is about  $2^{\circ}\text{C}$  higher. The form of precipitation could be no more than a consequence of temperature close to the ground but for the fact that the curve for combined precipitation forms is distorted in this region. This implies that it is the change of form which causes the temperature to be low for the thickness. The uneven curve for all precipitation implies that the frequency distributions of the thickness and temperature are dissimilar, temperatures of  $3^{\circ}\text{C}$  (where the curve is steep) being relatively infrequent and temperatures of  $1\text{--}1.5^{\circ}\text{C}$  more common. This corresponds to the surface temperature in Figure 2 falling more quickly from G to J than from J to L during a steady lowering of the freezing-level. Surface temperature must therefore be regarded as a particularly unreliable indicator of an impending change from rain to snow.

(iii) *1000–850 mb thickness as a snow predictor*.—Figure 4 shows the mean relationship found between the 1000–850 mb thickness and the pressure at the

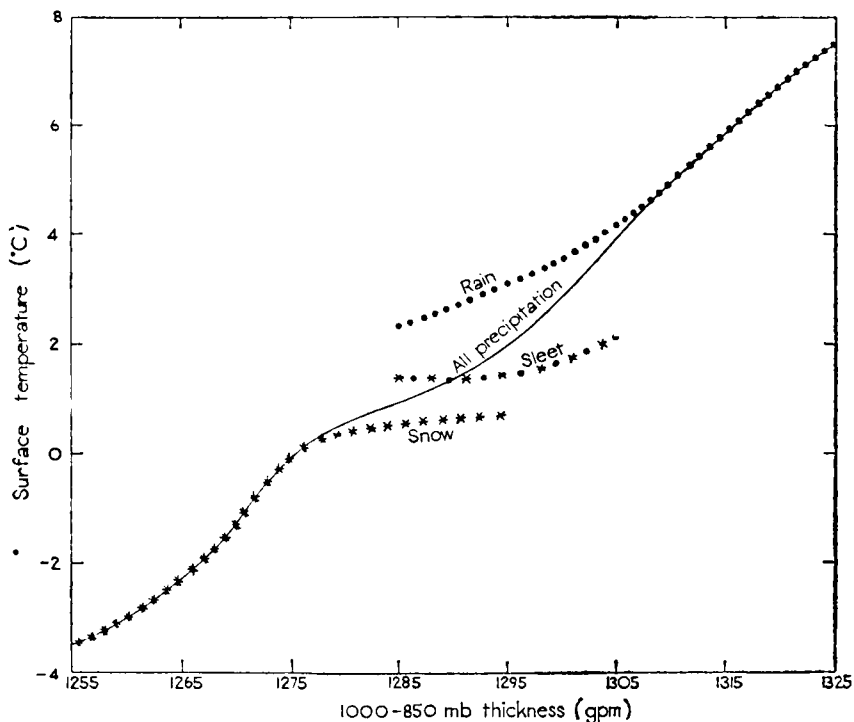


FIGURE 3—THE EFFECT OF THE FORM OF PRECIPITATION ON THE RELATIONSHIP BETWEEN SURFACE TEMPERATURE AND THE 1000-850 MB THICKNESS

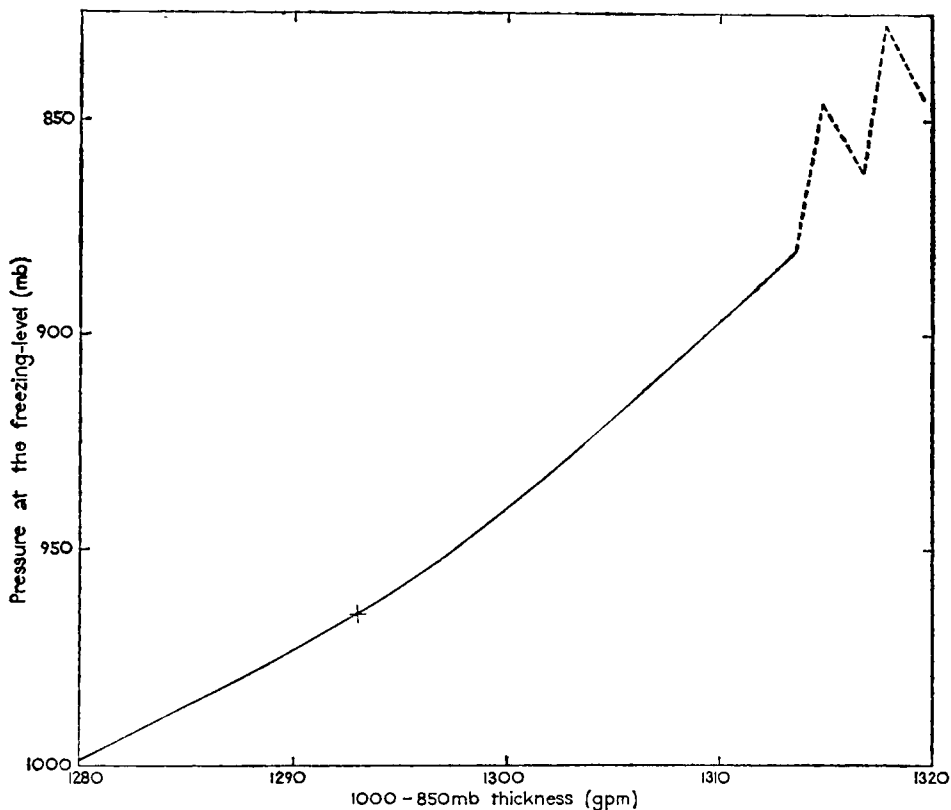


FIGURE 4—RELATIONSHIP BETWEEN THE 1000-850 MB THICKNESS AND THE PRESSURE AT THE FREEZING-LEVEL, BASED ON MEAN VALUES DURING PRECIPITATION

The broken line above 880 mb shows where the relationship becomes indefinite.  
The cross shows where rain, sleet and snow are equally likely at the 1000 mb level.

freezing-level during precipitation. The association was fairly close up to the 880 mb level and was independent of the hour of observation. At 880 mb there was a sudden increase in the scatter of points and the association was a very loose one above this level.

The 1000–850 mb thickness proved to be a much worse predictor than the height of the freezing-level, giving 39 per cent more wrong forecasts of the form of precipitation. Three factors are involved. The first is that the layer of air above the freezing-level contributes to the thickness but is not relevant to the form of precipitation; this is not important on most occasions because this layer is a shallow one. The second, and by far the most important, is that no allowance is made for surface pressure; this is discussed under (iv), below. The third factor is that the 1000–850 mb thickness is rather insensitive to the lowering of the freezing-level caused by melting snow. As was shown earlier, a rainfall rate of 1 mm/h caused a freezing-level around 50 mb above the ground to lower at a rate of up to 7 mb/h. The rate of thickness decrease due to the melting snow is about 0.6 m/h, which Figure 4 shows to correspond to an average lowering of the freezing-level of only a little over 2 mb/h. Thus the change in thickness due to melting snow may have only about one-third the response which is desirable in a predictor of snow.

(iv) *Adjusted 1000–850 mb thickness as a snow predictor, allowance being made for sea-level pressure and height above sea level.*—The form of precipitation depends on the depth and mean temperature of the atmosphere below the freezing-level. The 1000–850 mb thickness is quite well related to temperatures at levels specified in units of pressure, but less well related when the unit is the height above sea level. The thickness alone cannot accurately give the probability of snow at a place which may be 200 m above the 1000 mb surface on one day and 200 m below it on another. This may be allowed for by a simple adjustment to the thickness which is easily applied in forecasting.

At the temperatures involved when snow is a possibility, the depth of the atmosphere at low levels corresponding to a pressure difference of 1 mb can be taken as 8 gpm.

$$\begin{aligned}
 \text{Let } z \text{ in gpm} &= \text{height of the 1000 mb surface above sea level} = z/8 \text{ mb,} \\
 \Delta z &= 1000\text{--}850 \text{ mb thickness,} \\
 h \text{ in gpm} &= \text{height of the ground above sea level} = h/8 \text{ mb,} \\
 p_g &= \text{pressure at the ground in mb,} \\
 p_f &= \text{pressure at the freezing-level in mb,} \\
 \text{then} \quad p_g - p_f &= (1000 + z/8 - h/8) - p_f \quad \dots (3) \\
 &= f(\Delta z) + z/8 - h/8,
 \end{aligned}$$

where the function  $f(\Delta z)$  is given by Figure 4.

In the important region where  $\Delta z$  is a little under 1300 gpm and the atmosphere may therefore be cold enough for snow,  $f(\Delta z)$  may be approximated to 3.7 ( $\Delta z - 1283$ ), from measurement of the slope of the curve of Figure 4. Equation (3) may then be written

$$\frac{p_g - p_f}{3.7} + 1283 \simeq \Delta z + z/30 - h/30. \quad \dots (4)$$

Of the three terms on the right-hand side of equation (4),  $z/30$  is the adjustment to allow for surface pressure and  $h/30$  for the height of the station above sea level.

As is seen from Table I, rain and snow were estimated to be equally likely at sea level when the magnitude of the right-hand side of equation (4) was 1293 gpm. Disregarding the third term, this means that if sea-level pressure is greater than 1000 mb a 50 per cent probability of snow exists with a 1000–850 mb thickness of less than 1293 gpm (by an amount  $z/30$ ), and if the sea-level pressure is less than 1000 mb the reverse will hold. The reduction of 23 per cent in the number of failures as compared with the unadjusted 1000–850 mb thickness scarcely does justice to the importance of the correction on occasions when the sea-level pressure is markedly different from 1000 mb. For example, if the thickness were 1295 gpm and the sea-level pressure 980 mb the probability of snow would exceed 60 per cent. For the same thickness and a pressure of 1010 mb the probability would fall to 30 per cent.

In applying the pressure adjustment over the British Isles it is usually satisfactory to raise the numbering of the 1000–850 mb thickness lines by  $(p_0 - 1000)/4$  gpm, where  $p_0$  mb is the general level of sea-level pressure. Graphical addition of 1000–850 mb thickness lines (at 1-gpm intervals) to 4 mb isobars (1000 mb being subtracted from all pressures) is desirable only when there are very strong gradients in the sea-level pressure field.

The adjustment for height of the ground above sea level can be made by subtracting  $h/30$  from the thickness adjusted for sea-level pressure and estimating the snow probability from Table I. Alternatively, if the 1000–850 mb thickness adjusted for pressure is, say, 1303 gpm, then the height when there is a 50 per cent probability of snow is  $30(1303 - 1293) = 300$  gpm.

It was not possible to verify this relationship because there is no high-level radiosonde station in the British Isles. A possible source of error is the interpolation over high ground between low-level radiosonde stations. There is likely to be a lowering of the freezing-level as air crosses high ground and moreover the mean lapse rate between the freezing-level and the high ground may not be the same as the mean lapse rate below a freezing-level which is at the same height above low ground. From a comparison of the frequency of snow at Eskdalemuir (242 m above sea level) with frequencies at Aldergrove and Shanwell it appeared that these factors were not important, but only a somewhat crude test was possible.

(v) *1000–700 mb thickness as a snow predictor.*—Whereas about three-quarters of the 1000–850 mb layer is above the freezing-level at the time when rain and snow are equally likely, the proportion in the 1000–700 mb layer is about seven-eighths. The deeper layer must therefore be the less precise of the two as a snow predictor.

(vi) *1000–500 mb thickness as a snow predictor.*—This predictor appears to suffer from all the disadvantages of the 1000–700 mb thickness but to a greater degree. Its accuracy is only half that of the two best predictors, namely the height of the freezing-level and the adjusted 1000–850 mb thickness. It was noticed in particular that in southern parts of the British Isles snow occurred with quite high thickness because of the overrunning of warm air at heights far above the melting-level. Unusually warm air aloft gives a thickness which is unrepresentative of the capacity of surface layers to melt falling snow. Moreover, this lack of association means that the thickness at which rain and snow are equally likely depends on the set of observations analysed, and thus mainly accounts for the difference between the 5258 gpm found in this investigation and the 5224 gpm found by Murray.<sup>1</sup>

**The forecasting of sleet.**—As mentioned earlier, no independent method of forecasting sleet was found. It is most likely to occur when rain and snow are equally probable, when because of the variation in the initial sizes of snowflakes some have completely melted and others have not. It was found that at 0000 GMT, when sleet was falling, the surface temperature (in whole degrees Celsius) was  $1^{\circ}\text{C}$  or  $2^{\circ}\text{C}$  on 92 per cent of occasions. At 1200 GMT the temperatures covered a wider range because of surface heating, but 60 per cent were either  $1^{\circ}\text{C}$  or  $2^{\circ}\text{C}$ . The corresponding concentration of freezing-level heights between 30 and 40 mb above the ground has already been noted.

It is obvious that when the value of a predictor is such as to favour either rain or snow, the borderline situation for sleet is likely to occur less frequently. This is borne out by Figure 5, which shows the curve of frequency of sleet to follow quite well the curve of snow or rain, whichever is the less likely form of precipitation at the particular freezing-level height. In a forecast of precipitation form based on the height of the freezing-level the following features of Figure 5 are of interest:

- (i) When rain and snow are equally probable, sleet is as likely as either.
- (ii) If rain is wrongly forecast to be the form of precipitation, the alternatives of snow and sleet are equally likely.
- (iii) If snow is wrongly forecast to be the form of precipitation, sleet is more likely than rain.

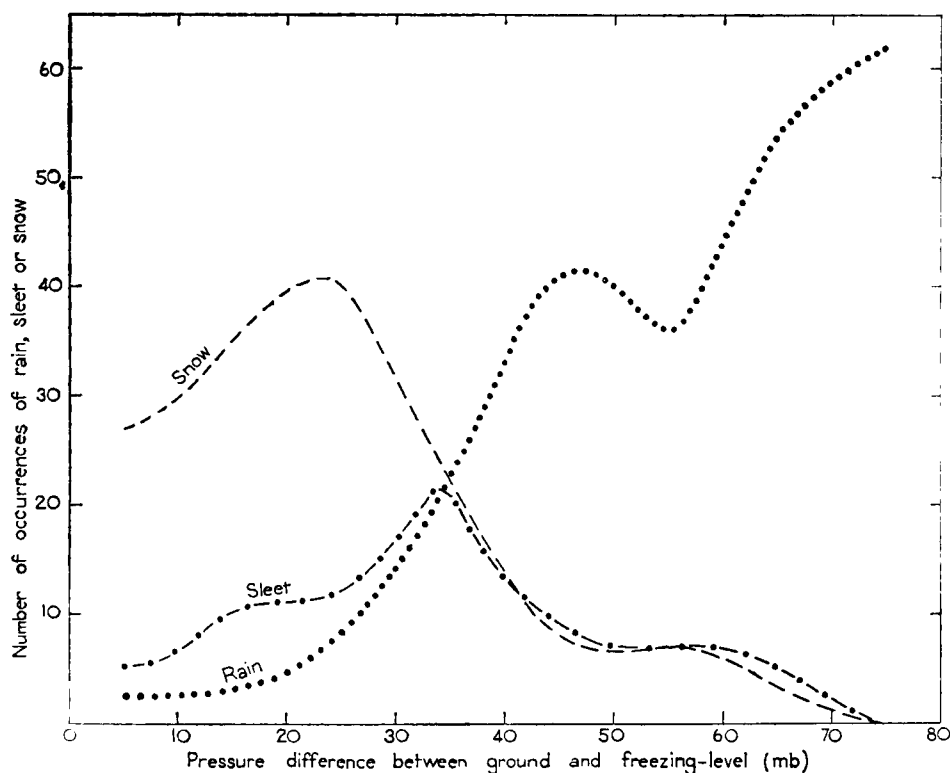


FIGURE 5—THE ASSOCIATION BETWEEN THE FREQUENCIES OF SLEET AND THE LESS LIKELY OF THE OTHER FORMS OF PRECIPITATION

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## STRATOSPHERIC CHANGES OVER THE BRITISH ISLES DURING ANTICYCLOGENESIS

By M. K. MILES

**Introduction.**—With the increase in the amount of data available from the stratosphere it has become evident from the studies of Godson,<sup>1</sup> Boville<sup>2</sup> and others that considerable changes occur from time to time in the winter circulation of the middle stratosphere, i.e. the part between about 50 mb and 10 mb. The changes extend over several days and it is natural to speculate, as Wilson and Godson<sup>3</sup> do, on the “possibility of the reflection of the tropospheric ‘blocking high’ situation in the stratospheric circulation.”

It has been suggested by some American meteorologists that the large-scale features of the stratospheric circulation influence the perturbations of the tropospheric circulation with wavelengths greater than 120° of longitude, but generally, opinion in America and in Britain seems to favour an influence by the troposphere on the stratosphere.

Among Continental meteorologists opinion is much more in favour of a controlling influence by the stratosphere on the troposphere. Baur<sup>4</sup> and Attmannspacher<sup>5</sup> have suggested that changes in the circulation at the level of the ozonosphere (50 mb to about 5 mb) arising from changes in the incident long-wave ultra-violet radiation have important effects on the strength and latitude of the tropospheric west-wind belt. Scherhag<sup>6</sup> goes further and suggests that individual blocking anticyclones sometimes follow within a few days of stratospheric warmings. Wurlitzer<sup>7</sup> has put forward evidence that blocking over western Europe is closely related to the geomagnetic index—a connexion which clearly supposes a control from the high stratosphere, and Berkes,<sup>8</sup> in a study of variations in the latitude of blocking anticyclones during the sunspot cycle invokes the “Duell-Wurlitzer Effect,” as he calls it, to explain what he found.

More recently Mironovitch<sup>9</sup> has presented his studies on blocking anticyclones and the accompanying changes in the stratosphere. He found in a sample of 26 cases that there was an associated “stratospheric perturbation” in 11 cases but in the other 15 cases the stratosphere up to 10 mb was “passive or presented a compensating effect.” So inclined is he to find a stratospheric control that he supposes that in these 15 cases it must be located above 10 mb.

The idea that interruptions of zonal flow in the west-wind belt are induced by changes originating in the stratosphere is perhaps partly due to the failure

to explain them satisfactorily in terms of tropospheric events. Although the arguments for stratospheric control are not always very cogent the idea obviously cannot be dismissed without careful consideration. However at present it is not certain exactly what form or scale the stratospheric influence might have and considerable analytical study is required to gain some idea of this in order to see the problem in correct perspective. It is certainly dangerous to choose one phenomenon that happens occasionally in the stratosphere, be it a warming or a cooling or a change from bipolar to asymmetric flow and relate it to a much more frequent tropospheric occurrence such as anticyclogenesis. It is less dangerous (and it may help to clear the field a little) to study changes in the stratosphere that accompany anticyclogenesis.

This is done in the present paper for all cases of clear-cut anticyclogenesis occurring over or very near the British Isles for the months October to April inclusive from October 1958 to December 1962. Cases in which a pressure rise has occurred over Britain resulting from the extension of a ridge from a continental anticyclone have not been included, and neither have those cases in which an anticyclone centred in the Bay of Biscay has affected southern England for some time before a build of pressure occurring over Scotland has transferred the centre of the anticyclone to the northern North Sea or Scandinavia (a typical case of this sort in February 1962 is discussed but not included in the statistics).

The winter half of the year was selected for study in the expectation that if there is an influence from the stratosphere it will show up best in the season when the middle stratosphere is most active.

**Observational data.—**

(i) *Surface pressure changes.*—The criterion used in selecting the cases of anticyclogenesis was that there must be a substantial rise of pressure over the British Isles taking the general level of pressure from well below average to well above. This was required to happen over a period not longer than about four days and usually resulted in an anticyclone centred north of 50°N latitude, i.e. a blocking anticyclone. The pressures at Kew and Wick give a very good indication of the pressure pattern over Britain, and values for 1200 GMT were extracted for a period of six consecutive days for each case. The six days were chosen so that the anticyclogenesis was complete by day 4 or, at latest, day 5. In almost every case no substantial rise of pressure had set in by day 1. The dates of day 1 for the 17 cases in the statistics and 4 other cases which were looked at are given in an appendix.

Table I gives the average sea-level pressures at 1200 GMT for each of the six days at Kew and Wick as well as the mean of the two pressures: this can be regarded as typifying the sea-level pressure over England during each day of the process.

TABLE I—PRESSURES OVER BRITAIN DURING 17 CASES OF WINTER ANTICYCLOGENESIS

Day	1	2	3	4	5	6
	<i>millibars</i>					
Kew	1008.8	1012.5	1020.4	1029.1	1031.2	1030.1
Wick	996.3	1003.7	1015.4	1025.5	1026.9	1028.0
Average of Kew and Wick	1002.6	1008.1	1017.9	1027.3	1029.0	1029.0



These means indicate that the period of most rapid surface rise of pressure has been centred fairly satisfactorily between days 2 and 4 and the rise is virtually complete by day 5.

(ii) *Contour height changes aloft*.—Representative values of the level of the 200, 100 and 50 mb pressures were obtained for a central point over Britain. This was done by extracting the values obtained at 0000 GMT and 1200 GMT from the radiosonde stations at Aughton and Hemsby and plotting them on a time graph. When observations were missing or appeared obviously anomalous, values from Crawley, Aldergrove or Shanwell radiosonde stations were added to the graph. A smooth curve was then drawn through these points for each of the three levels, and from these curves values for 1200 GMT for each of the six days were read off. The means of these for 17 cases are given in Table II.

TABLE II—HEIGHTS AT VARIOUS PRESSURE LEVELS OVER ENGLAND DURING ANTICYCLOGENESIS

Day	1	2	3	4	5	6
			<i>decametres</i>			
200 mb	1163	1161	1169	1178	1181	1178
100 mb	1602	1601	1605	1611	1613	1613
50 mb	2039	2038	2039	2043	2047	2048

These values and the appropriate sea-level pressures are plotted together in Figure 1.

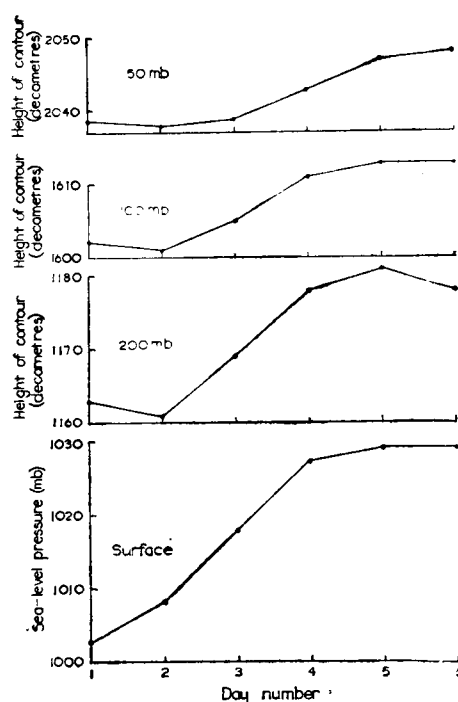


FIGURE 1—MEAN CHANGES IN SEA-LEVEL PRESSURE AND CONTOUR HEIGHT AT 200 MB, 100 MB AND 50 MB DURING ANTICYCLOGENESIS OVER BRITAIN

At 200 mb, which can be considered the top of the troposphere, the course of events closely resembles that at the surface, with the steepest height rise between days 2 and 4.

In the stratosphere the rate of height rise is less and decreases upwards. At 50 mb the period of steepest rise occurs one day later than that at 200 mb.

The slight fall of height at 200 mb between day 1 and 2 is almost certainly real and corresponds to the passage of a thermal trough in the upper troposphere just before the onset of anticyclogenesis in over half of the cases.

The height rise at 50 mb is almost entirely due to two cases—January 1959 and December 1962. In both of these the 50 mb height at day 1 was below the average value for the season based on the monthly means given in appendix 2. Apart from two other cases which however produced rises of only 7 and 10 decametres between day 1 and day 6, the 50 mb height at day 1 was above the seasonal average for day 1. In fact the mean for the 17 cases was +5 decametres, compared with a mean of +2 decametres at 200 mb with equal numbers above and below the average.

The occasion in February 1962 is especially interesting in this connexion. Although the 200 mb height was 16 decametres above normal on day 1 (obviously associated with the warm anticyclone already in existence just to the south-west of the British Isles) the 50 mb height was 25 decametres below normal. By day 6 the 200 mb height had risen only 6 decametres but the 50 mb height was 49 decametres higher than on day 1. Summing up it can be said that while in the majority of cases the 50 mb height rises far less than that at 200 mb there were three cases with a rise greater than 15 decametres (i.e. the mean rise at 200 mb from day 1 to day 4) and in two of them the 50 mb height was untypically below the seasonal average on day 1. The three cases of anticyclogenesis in 1963 (looked at after the statistics had been compiled) do not however fit into this pattern particularly well. The 50 mb heights in the February and March cases were 7 and 4 decametres respectively below the seasonal mean on day 1 and neither showed any rise during the anticyclogenesis. The April case was slightly above the mean on day 1 and rose 11 decametres during the six days.

It would obviously be premature to form any conclusions about the circumstances under which the 50 mb height rises appreciably during anticyclogenesis. All that can be said is that the rise equals that at 200 mb in only a small minority of cases.

(iii) *Wind changes in the stratosphere.*—The 24-hour vector wind changes were computed from the Aughton radar wind observations supplemented where necessary by values from Hemsby. The mean values for each of the five 24-hour intervals for the 17 cases are given in Table III.

TABLE III—24-HOUR VECTOR MEAN CHANGES OF WIND OVER CENTRAL ENGLAND DURING ANTICYCLOGENESIS

	Day 1-2	Day 2-3	Interval Day 3-4 <i>degrees/knots</i>	Day 4-5	Day 5-6
200 mb	020/6	040/25	100/8	140/22	050/13
100 mb	330/2	045/15	080/3	150/9	040/5
50 mb	360/1	025/10	090/6	090/2	165/2

As these means are made up of rather variable components the distribution by quadrants of the individual values is given in Table IV to help in the assessment of their significance.

The marked concentration of these values in the two eastern quadrants implies a reduction in the strength of the prevailing west to north-west wind (average 200 mb wind on day 1 was 274° 46kt). The concentration in the



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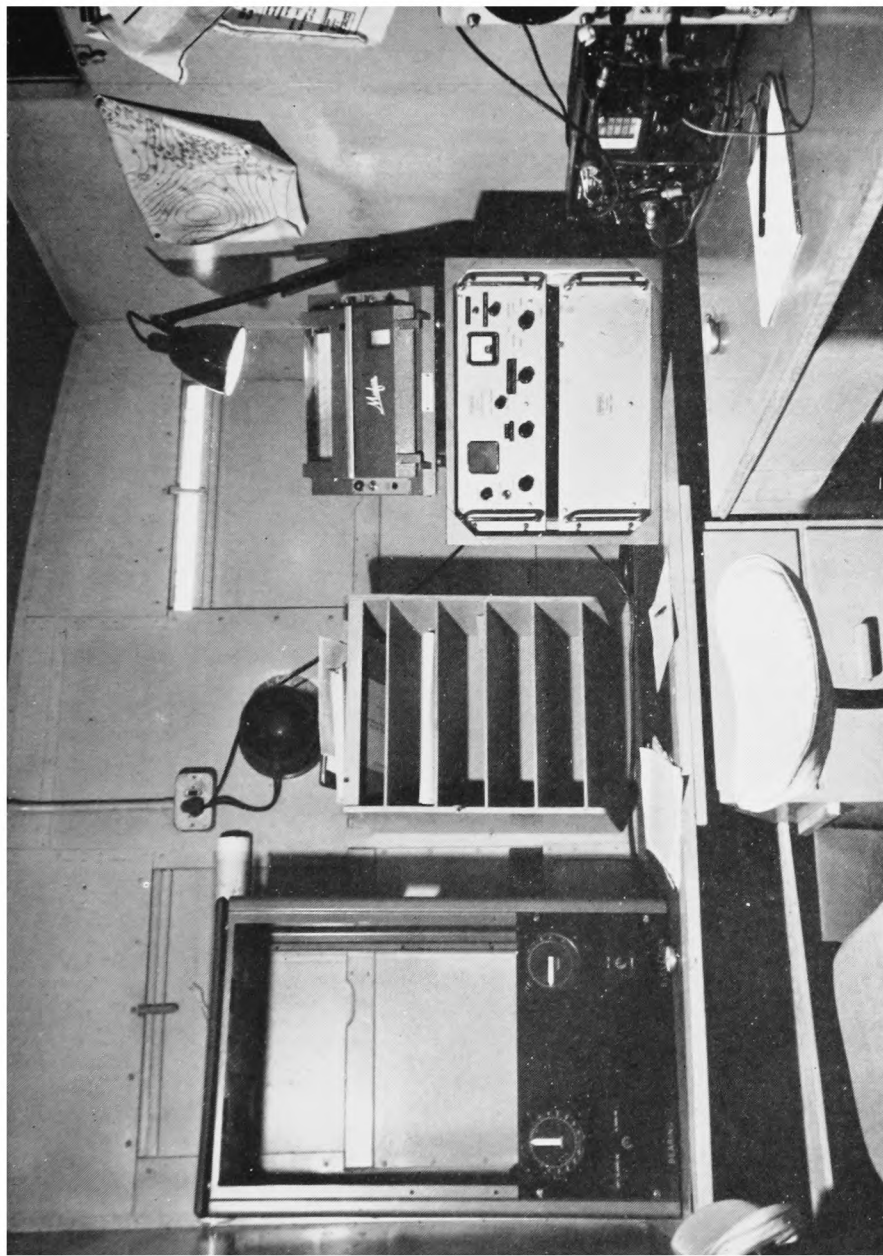
PLATE I—HAAR OVER THE EDEN ESTUARY AT 1145 GMT ON 5 JUNE 1964  
(see p. 379)



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PLATE II—HAIL STONES BLOCKING A STREET IN BURNLEY AFTER THE HEAVY STORMS IN EAST LANCASHIRE ON 18 JULY 1964

During the storm 1.36 inches of rain fell in 15 minutes in Nelson, Lancashire, about 4 miles from Burnley.



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PLATE III—METEOROLOGICAL OFFICE EQUIPMENT FOR RECEIVING AUTOMATIC  
CLOUD PICTURE TRANSMISSIONS FROM THE AMERICAN SATELLITE 'NIMBUS A'

To face p. 369



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PLATE IV—METEOROLOGICAL OFFICE CLOUD PICTURE RECEIVING AERIAL AT THE  
EXPERIMENTAL SITE NEAR BRACKNELL

'NIMBUS A' was launched at midday on 28 August 1964 and continues an experimental series which started with the satellite TIROS VIII. Cloud pictures, as seen from very high levels, will form very valuable additional material for meteorology when regular information covering all parts of the world is available. At this stage, the main interest of the Meteorological Office is to develop economic British-made receiving equipment and to make preliminary assessments of the value of this new form of information, together with the means by which it may be assimilated into routine weather forecasting. Unfortunately 'NIMBUS A' ceased transmitting on 23rd September, but further experimental satellites are planned.

TABLE IV—DISTRIBUTION BY QUADRANTS OF 24-HOUR VECTOR WIND CHANGES  
OVER CENTRAL ENGLAND DURING ANTICYCLOGENESIS

Interval Pressure level mb	Day 1-2			Day 2-3			Day 3-4			Day 4-5			Day 5-6			All days		
	200	100	50	200	100	50	200	100	50	200	100	50	200	100	50	200	100	50
Direction quadrant	<i>number of occasions</i>																	
005-090°	5	4	2	10	8	5	8	7	1	3	2	2	5	5	2	31	26	12
095-180°	5	3	3	1	2	2	4	3	3	7	9	1	5	1	3	22	18	12
185-270°	3	2	1	2	1	0	2	4	1	5	3	2	3	1	3	15	11	7
275-360°	4	4	1	4	2	1	3	0	0	1	0	0	3	1	0	15	7	2
Variable, less than 10 knots	0	4	8	0	4	8	0	3	10	1	3	10	1	9	8	2	23	44

north-east quadrant on day 2-3 and the size of the resultant in Table III indicates a wind veer at this stage in the anticyclogenesis at the three levels. The steady decrease in the magnitude of the resultants and the increase in the proportion of wind changes less than 10 kt from 200 mb to 50 mb indicates a marked damping of the tropospheric wind perturbation upwards into the stratosphere.

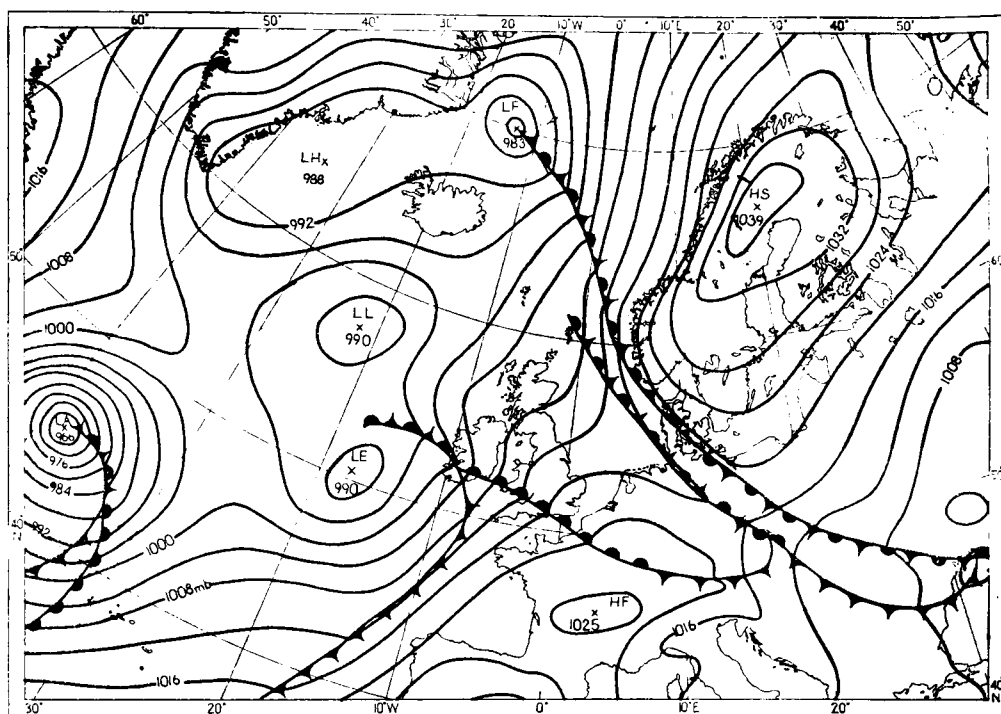
The wind data at 25 and 30 mb are not sufficiently complete to provide mean values which can be compared with the changes at 50 and 100 mb. There is not however quite such a notable concentration in the eastern quadrants on day 2-3, but rather more on day 3-4. This may tentatively be regarded as further evidence of a lag of one day in events at 50 mb and above compared with the lower levels of the stratosphere.

**Discussion of individual cases.**—The anticyclogenesis of December 1961 has been illustrated by synoptic charts in order to convey an idea of the scale and sequence of the changes. This situation is fairly typical apart from the presence of a strong anticyclone over Scandinavia at the start of the process. This makes the change in the surface situation look rather less than is usually the case, but the maps for 200 mb show that quite a drastic change occurred in the tropospheric westerlies. The maps in Figure 2 show the tropospheric situation at 0000 GMT on 13 December which is midway between days 2 and 3, and those in Figure 3 show the situation 48 hours later when the tropospheric perturbation had almost reached its maximum amplitude. Figures 4 and 5 show the changes at 100 mb and 50 mb during this time interval. The maps show quite clearly that the anticyclogenesis over Britain was accompanied by a great amplification of the ridge at 200 mb, and this amplification decreased with height above the tropopause (which was mostly near 200 mb during the period).

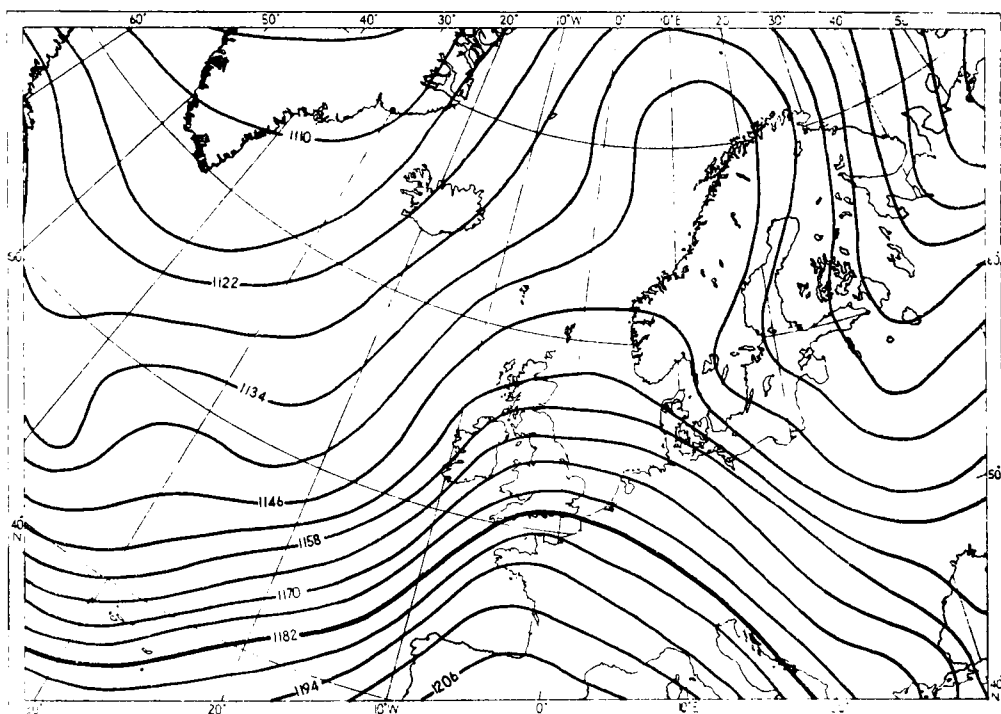
Reference to the 10 mb charts prepared and published by the Institut für Meteorologie und Geophysik der Freien Universität, Berlin, shows that there was probably very little rise of contour height at this level over Britain during the period, but a flat ridge is shown to have developed near the British Isles. This is however no more than a very small feature on the strong, nearly circumpolar vortex.

Study of these charts for 10 and 30 mb for several of the other situations indicated that the ridge amplification decreased with height and was usually insignificant at some level between 30 and 10 mb and occasionally by 30 mb.





(a) Surface chart

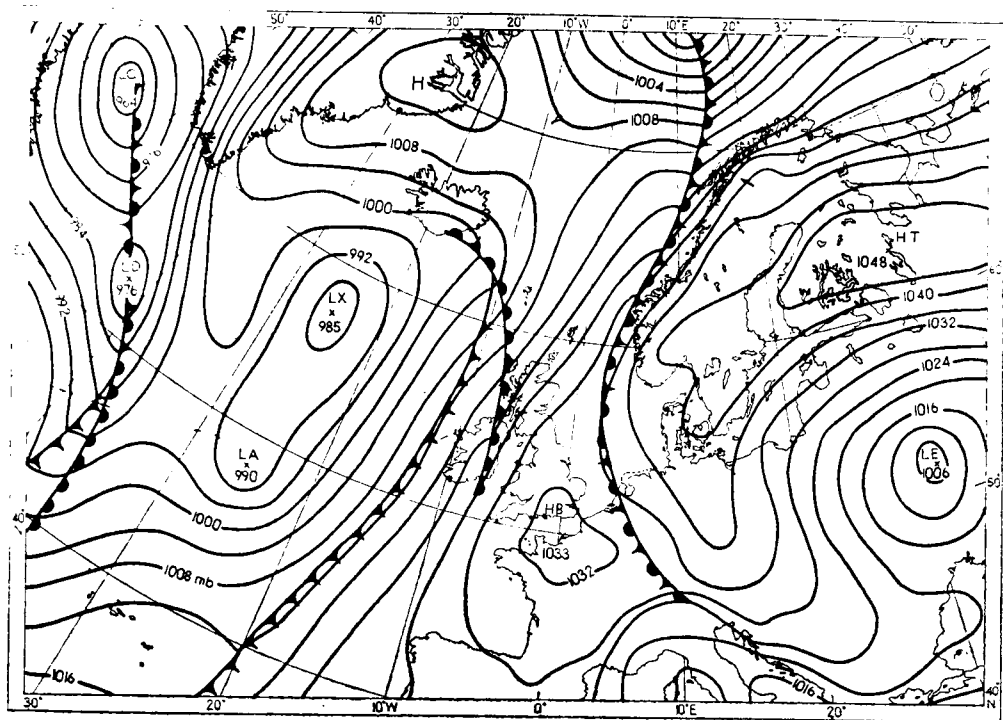


(b) Contours at 200 mb (in decametres)

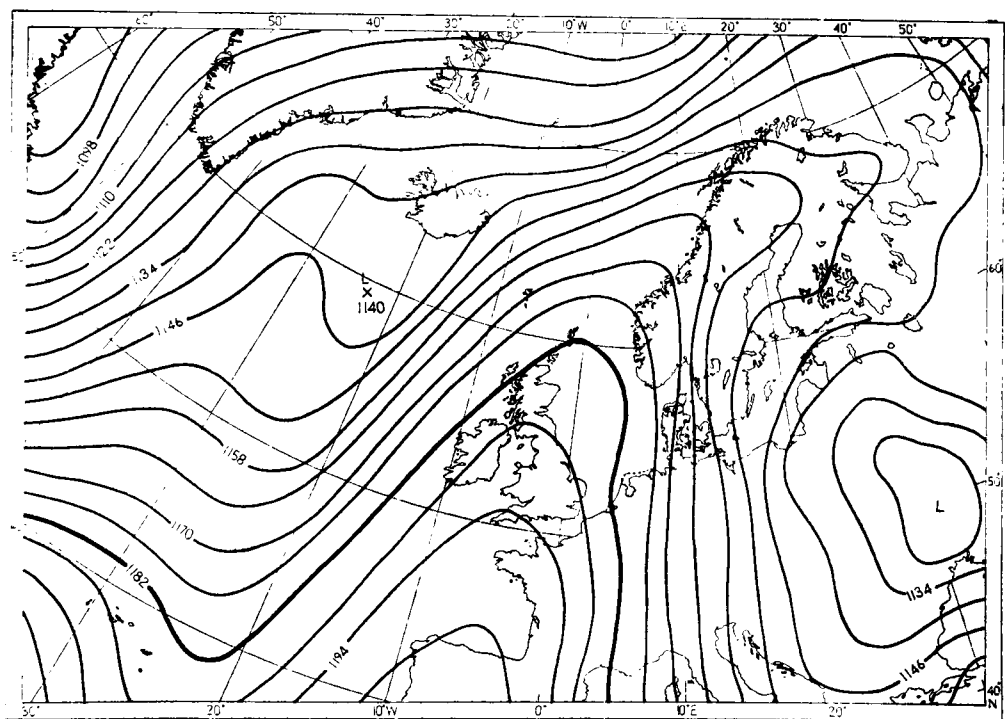
FIGURE 2—0000 GMT ON 13 DECEMBER 1961

In Figures 2–5 one contour in the upper air charts has been made bolder to show the development of the ridge at each level.



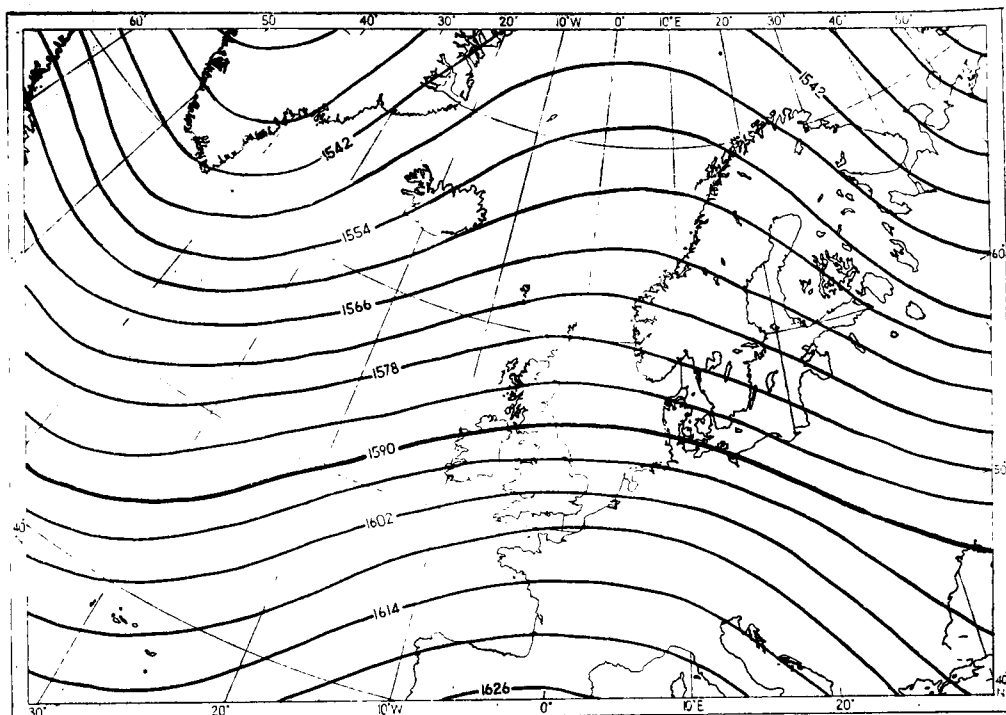


(a) Surface chart

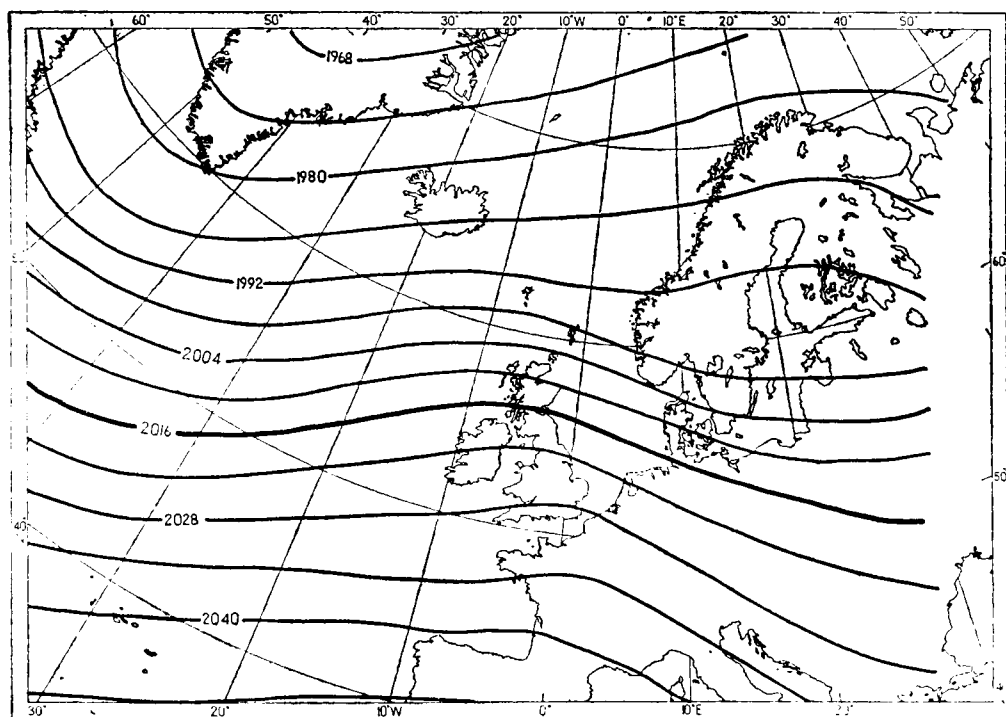


(b) Contours at 200 mb (in decametres)

FIGURE 3—0000 GMT ON 15 DECEMBER 1961

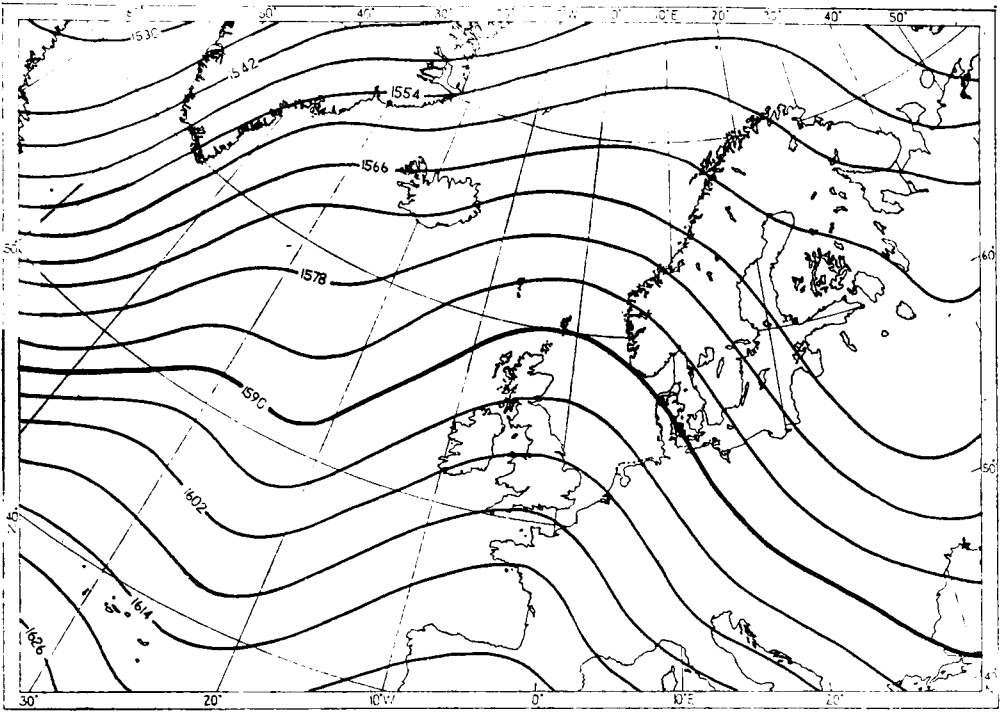


(a) Contours at 100 mb (in decametres)

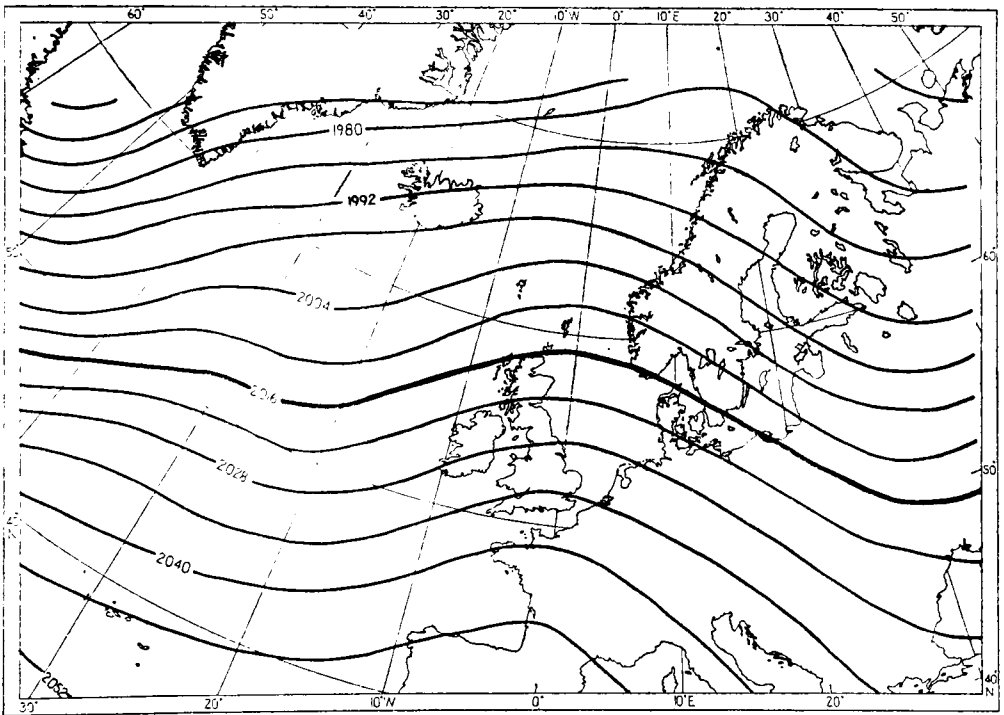


(b) Contours at 50 mb (in decametres)

FIGURE 4—0000 GMT ON 13 DECEMBER 1961



(a) Contours at 100 mb (in decametres)



(b) Contours at 50 mb (in decametres)

FIGURE 5—0000 GMT ON 15 DECEMBER 1961

One such occasion was during the anticyclogenesis of 14–16 November 1958. In fact the contour heights at 10 mb actually fell slightly from 13–16 November as a trough moved south towards England. The situation in the lower stratosphere was also somewhat untypical. On 13 and 14 November there was a strong ridge at 100 mb over the east Atlantic so that the 100 mb winds at Aughton were northerly at the start of anticyclogenesis. As the contour height at 100 mb rose over England the strength of this northerly wind decreased so that the vector changes between days 2 and 3 and days 3 and 4 were  $200^\circ$  11 kt and  $200^\circ$  15 kt respectively, i.e. contrary to the most common direction. At 25 mb however the winds started by being around  $300^\circ$  and backed to  $280^\circ$ —changes symptomatic of those at 10 mb referred to earlier.

With the blocking which was completed on 14 April 1962 there was a clear lag of one day in the ridge formation at 30 mb compared with 100 mb. At 10 mb there was a much flatter ridge by the 14th than at 30 mb.

Similarly with the block set up between 3 and 6 January 1960 although a well-marked ridge had developed at 100 mb just west of the British Isles, at 30 or 10 mb there was no ridge in the west-north-westerly airflow round the cold vortex near Novaja Zemlja.

With the block set up by 17 October 1958 a closed contour high at 50 mb at  $45^\circ\text{N}$   $25^\circ\text{W}$  on the 14th had moved away from the British Isles to a position  $40^\circ\text{N}$   $35^\circ\text{W}$  on 16 October.

A warm stratospheric high centred over the Bay of Biscay was in existence for a week or more before the rather short-lived blocking at the end of January 1962. It neither strengthened nor moved nearer to the British Isles during the period of anticyclogenesis between 26 and 28 January.

### Conclusions.—

(i) Anticyclogenesis over Britain is almost invariably accompanied by the development of a fairly peaked ridge at 200 mb.

(ii) The sharpness of this ridge is reduced as the stratosphere is penetrated. There is usually a flat ridge at 50 mb, but it is usually absent by 10 mb and often by 25 mb.

(iii) The height rise at 50 mb during anticyclogenesis exceeded that at 200 mb only once in the 21 cases examined. In the majority of cases the rise at 50 mb was considerably smaller than that at 200 mb and tended to happen one day later.

(iv) Most of the cases of anticyclogenesis studied involved an amplification of the waves in the tropospheric westerlies with a spacing of no more than  $30^\circ$  longitude between the upwind trough and the ridge associated with the surface anticyclone. This is not on the scale envisaged by Baur and Attmannspacher, but is probably the type of occurrence Scherhag, Berkes, Mironovitch and Wurlitzer have in mind. The results of this study do not seem susceptible of the kind of explanation they favour. On the scale of the tropospheric process the primary effect appears to be in the troposphere, but this does not of course rule out the possibility that some larger-scale change in the stratosphere some days earlier was responsible for the distortion of the tropospheric westerlies.

## Appendix 1

Dates of 'day 1' for 17 cases of anticyclogenesis

15 October 1958	3 January 1960	9 January 1961	1 October 1962
13 November 1958	3 February 1960	9 October 1961	23 November 1962
22 January 1959	1 March 1960	11 December 1961	18 December 1962
5 March 1959	13 April 1960	25 January 1962	
16 April 1959		10 April 1962	

Dates of 'day 1' for other cases mentioned in text

17 February 1962	20 March 1963
19 February 1963	22 April 1963

## Appendix 2

Monthly averages of contour height (mean of Aughton and Hemsby) for 1958-62:

	Oct.	Nov.	Dec.	Jan. decimetres	Feb.	Mar.	Apr.
200 mb	1180	1164	1151	1150	1159	1155	1163
50 mb	2054	2032	2019	2000	2046	2037	2048

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551.5:629.13

## MEETING ON THE METEOROLOGICAL ASPECTS OF SUPERSONIC TRANSPORT OPERATIONS

By A. A. WORTHINGTON, B.Sc.

A meeting on the meteorological aspects of supersonic transport was held on 29 June 1964 in the Lecture Room of the Meteorological Office, Bracknell. It was attended by representatives from the Guild of Air Pilots and Navigators, the British Airline Pilots' Association, the Ministry of Aviation, the Air Registration Board, the Imperial College of Science and Technology and the Meteorological Office.

The Chairman, Mr. P. J. Meade, Deputy Director of the Meteorological Office, in his opening address, stated that the purpose of the meeting was largely informative. Specialist speakers drawn from the Meteorological Office would, he said, discuss various meteorological subjects of importance to the operation of supersonic transport. In doing so, they would outline the work now in progress and the plans for further research. The particular problems of

cosmic radiation and atmospheric electricity would however not be discussed since they were somewhat outside—at least at present—the fields of research covered by the Office.

Some aspects of organization and operational procedures were reviewed by Mr. A. A. Worthington. His main theme was the need for co-ordination in effort in preparing for the advent of supersonic transport in the early 1970's. The International Civil Aviation Organization (ICAO) and the World Meteorological Organization (WMO), he said, were undoubtedly aware of the coming needs. He cited the findings of the recent Joint Session of the Meteorology and Operations Divisions of ICAO and the Commission for Aeronautical Meteorology of WMO and also the recent action taken by the Executive Committee of WMO. It was now, he continued, largely a question of planning in detail. He pointed in particular to the need for development of networks of regular and reliable radiosonde and radiowind ascents to 80,000 feet and said, in this regard, that the time factor involved in translating international agreement into practice had to be borne in mind. After all, 1970 was not very far away.

Wind and turbulence near the ground were discussed by Dr. A. G. Forsdyke. His talk was mainly on meeting the operational requirements for information on these elements, requirements which were as much for present-day jet aircraft as for future supersonic aircraft. There were, he said, the problems of meeting the requirements for actual and forecast information on light surface winds, on gusts and gustiness and on vertical wind shear. There was also the requirement to be considered for the supply of wind information in component form related to the runway in use. He discussed the characteristics of wind structure in the lower layers of the atmosphere. It was his opinion that the operationally desired accuracies were not yet attainable and that much more work would have to be done before any conclusions could be reached as to how far the accuracies could be achieved. In listing the ways in which such work could be undertaken, Dr. Forsdyke referred in particular to the mounting of sensitive anemometers at various heights on masts at strategic sites on airfields. This he thought would probably be found to be the best method for further investigation of the wind structure near the ground. In the discussion which followed it was learnt that a new sensitive anemometer was now under test which could, in addition to being responsive to light winds, provide wind speed data in component form.

Winds and temperatures in the upper air were discussed next. Mr. C. L. Hawson spoke about the layer of the atmosphere bounded by the 100 mb and 50 mb surfaces. He listed points concerning the wind and temperature systems in that layer. The systems tend to be very large, the lower stratosphere acting as a filter so that the shorter wave-length disturbances decay rapidly with increasing altitude. The systems are mostly slow moving. In temperate and northern latitudes the systems, he said, are very dependent on the season. There is marked similarity in the patterns of different summers but, on the other hand, large changes are found in the patterns of different winters. In the late winter and spring extraordinary wind and temperature systems occasionally develop and Mr. Hawson referred to 'explosive warming' in which an area of warm air developed rather quickly. Such development he considered was associated with vertical motions originating, in some cases, in levels much

above the 10 mb surface. In the tropical belt, Mr. Hawson said, the seasonal variation is very different from that in higher latitudes and shows a fluctuation in zonal wind component with a period of about 26 months. Mr. Hawson commented on the difficulties of high-level analysis: difficulties which arose mainly from the fact that errors associated with geopotential height determination of a radiosonde observation are cumulative with altitude, that the effect of errors induced by solar radiation increases with decreasing density and that the number of upper air observations decreases with altitude. Current analyses used as forecasts for intervals up to at least 24 hours ahead, Mr. Hawson thought, would be perhaps more accurate than forecasts utilizing techniques applicable to the troposphere. However, he pointed out that using current analyses would not hold in the case of 'explosive warming'; forecasting the change in respect of this phenomenon would be necessary. Mr. Hawson also pointed out that one further consequence of the tendency for persistence was that if, for some reason, a stratospheric disturbance interfered with a particular operation then it could be a week or more before a change in the situation could be expected. In discussion it was noted that the operation of supersonic aircraft could well be limited by temperature. It was said that 'explosive warming' had posed some questions yet to be answered. However, the impression was that the general effects of temperature on aircraft performance were known.

Mr. J. Briggs followed with a discussion on turbulence in clear air and in cloud. He concentrated on those features of the high troposphere and of the stratosphere which may be expected to produce turbulence for supersonic aircraft. The problem, he said, is complicated by the fact that atmospheric turbulence may not necessarily cause aircraft 'bumps' owing to the selective response of the aircraft to input at different frequencies. On the other hand, laminar airflow would not necessarily mean smooth flight since the high speed of traverse across successive up and down flows of the air pattern may create an impulse cycle close to one of the natural frequencies of the aircraft structure. In general, the frequency range of interest, he said, is from 0.1 to 10 cycles/second. Conventional aircraft have mainly responded to disturbances or eddies of the order in size of 50 feet to 6000 feet, but the important size for the supersonic aircraft may well be 20,000 feet or more. On convective turbulence Mr. Briggs said the most serious cases are likely to occur in or near cumulonimbus cloud. The size of a cumulus cloud is a rough guide to the strength of the vertical currents, and so of turbulence in or near the cloud. Cumulonimbus, he said, is characterized not only by its size and vigour but by its persistence and the presence of strong down draughts. Further, it seems likely that the strongest currents will occur in the middle and upper parts of the cloud, which may extend to the tropopause or beyond. The presence close together of intense up and down draughts may not in itself contribute to severe bumpiness during a traverse but at supersonic speeds, even allowing for the appreciable horizontal dimensions, the strong shear at the edges of these draughts is likely to create extra turbulence and the gust speeds, as distinct from draught speeds, may be very large. Severe convective turbulence has been experienced, he said, at heights up to 65,000 feet. Mr. Briggs turned next to non-convective turbulence; an expression, he said, which covered several mechanisms of which knowledge is still very limited. Some bumpiness will occur in the crossing of temperature discontinuities, some from resonance effects in crossing laminar flow, such as

mountain-induced waves, and some will be due to true atmospheric turbulence. Analyses of reported non-convective turbulence in relation to synoptic situations have shown that some 70 per cent of occurrences are associated with jet streams. Examinations of links with smaller-scale features have not been very successful but it does seem, he said, that vertical shear of wind and the static stability of the air are the most significant. Mr. Briggs stressed that even for traverses of jet streams the frequency of turbulence, of intensity greater than slight, is low. He went on to say that the most severe cases of clear-air turbulence have usually been found associated with mountain waves and the effect of such waves could extend well up into the stratosphere. Mr. Briggs suggested that the forecasting of turbulence in other than very general terms seemed a long way off and perhaps unrealizable. In discussion it was felt that perhaps the most hopeful solution lay in the forward detection of turbulence by an aircraft and in this connexion it was noted that with supersonic aircraft it may be necessary to make a decision regarding diversion as much as 200 miles away from an area of turbulence.

Mr. R. F. Jones outlined the present position regarding information on cloud, precipitation and ozone. He dealt at some length with hail. The thunderstorm, he said, with its associated hail and turbulence represented perhaps the greatest meteorological hazard to aviation, supersonic or otherwise. However, the hazard must be considered in proportion. For many routes and for certain times of the year the problem was non-existent as regards the cruise phase of supersonic operations. Within any thunderstorm and within many a cumulonimbus cloud at some stage of its existence, it is highly probable that there is a core containing hail but, judging from evidence available, the horizontal extent of the hail core compared with the total extent of the cloud is almost certainly small. On a particular flight the low probability of being within a cumulonimbus cloud multiplied by the low probability of being within that part of the cloud with hail and the low probability that the hail will be above a significant size, indicates that the chances of a hazardous hail encounter are very small indeed. Putting figures to the chances, he said, was however not easy. As regards forecasting storms, Mr. Jones doubted whether a forecaster will ever be in a position to forecast for more than perhaps an hour or so ahead (and this assumes an accurate and up-to-date knowledge of actual conditions) that a storm will or will not be in a certain precise place at a certain time. However, if there is a storm somewhere the forecaster may be able to give some guidance on the likelihood of it containing large hail. Also the forecaster should be able to say whether conditions are favourable for the development of storms or not. It follows, Mr. Jones said, that if it is critically necessary for the aircraft to avoid storms either in cruising flight or, more likely, in the transonic phase, then precise up-to-the-minute information of the presence and position of storms will be required together with the means of informing the pilot. He suggested that perhaps the best answer to the problem of hail was the avoidance of all active cloud and in this, no doubt, airborne radar would be essential. Mr. Jones went on to discuss icing and ozone. Icing caused by the interception of supercooled cloud droplets seems, he said, likely to occur mostly in the subsonic phase of flight and so will present the same problems as for present-day aircraft accentuated perhaps by the smaller radii of curvature of leading edges and perhaps by a greater susceptibility to any modification of airflow caused by icing. As regards ozone, there appeared to



be adequate information. Mr. Jones also referred to sonic boom. He said that until the precise nature and accuracy of the meteorological data which may be required in sonic boom accountability are known it would not be possible to say whether or not present radiosonde networks would be adequate.

A general discussion followed which ranged over quite a number of points including the incidence of cumulonimbus cloud tops above 55,000 feet, thermal gusts, erosion aspects of precipitation, the maximum concentration of ozone which could be encountered and methods of obtaining further meteorological data for the supersonic operating levels.

The Chairman, in closing, expressed his appreciation of the presentations by the speakers of the various subjects discussed. He felt that a lot of good had been derived from meeting together and discussing the meteorological problems relating to the operation of supersonic transport.

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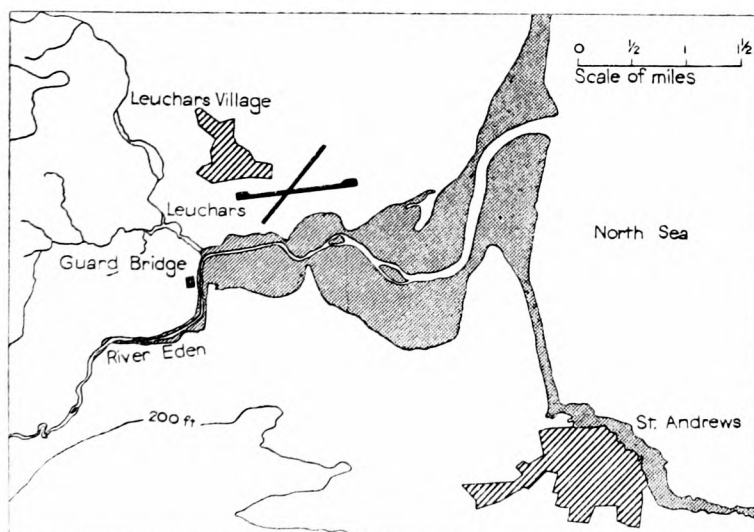
## **TIDAL EFFECTS ON THE DISSIPATION OF HAAR**

By L. L. ALEXANDER

The Eden estuary forms the southern boundary of Leuchars airfield and joins the open sea about  $1\frac{1}{2}$  miles east-south-east of Leuchars. At this point, it is about 1 mile wide at high tide and funnels to about  $\frac{1}{2}$  mile wide in the 3 miles of tidal water which ends at Guard Bridge (1 mile south-west of the airfield). At low tide, extensive areas of sand and mud are rapidly uncovered, so that the estuary is effectively a land surface. West of Guard Bridge, the Eden is only a small and insignificant stream (Figure 1).

The photograph (Plate I) illustrates the effect of the tidal waters of the Eden estuary on the clearance of haar at Leuchars. The photograph was taken at 1145 GMT on 5 June 1964, and is looking south-east. High tide was at 0950 GMT. The sea temperature measured at Bell Rock was 9°C.

A spell of haar had started at 0800 GMT on 4 June and there had been 8/8 continuous low stratus, the base varying between the surface and 800 feet.



**FIGURE 1—MAP OF THE LEUCHARS AREA SHOWING THE LARGE TIDAL AREA**

The stratus described in the observations in Table I was confined to the tidal water and the western edge of it receded eastwards with the ebbing tide.

The stratus could be seen to be moving from the east with the wind and disappearing as it reached the edge of the water surface.

TABLE 1—OBSERVATIONS AT LEUCHARS, 5 JUNE 1964

Time GMT	Surface wind		Visibility	Cloud	Temperature °C	
	Direction	Speed			Dry-bulb	Dew-point
0848	140°	4 kt	500 yd	5/8 at surface 8/8 at 300 ft	11.5	11.5
0948	090°	6 kt	3000 yd	1/8 at surface 2/8 at 300 ft 2/8 at 2000 ft	12.7	12.3
1035	120°	9 kt	1600 yd from E to SW 2-3 n.miles elsewhere	2/8 at surface 2/8 at 2500 ft	—	—
1050	110°	10 kt	500 yd	5/8 at surface 2/8 at 2500 ft	13.2	11.9
1148	070°	7 kt	2000 yd to SE 16 n.miles elsewhere	1/8 at surface 2/8 at 3000 ft	14.4	12.4

It is well known locally that the tidal waters of the Eden have an effect on the formation and dissipation of haar on the airfield. The reverse of the process described above has often been seen with incoming tides. Similar effects have been described by Lawrence<sup>1</sup> and Watts.<sup>2</sup>

The increase in low stratus between 1035 and 1050 GMT illustrates the speed with which stratus can move onto the airfield (probably because of a change in wind direction, though this cannot be confirmed because of the distance of the anemograph from the stratus at the critical time).

By 1227 GMT the stratus had cleared from the vicinity of the airfield. Bell Rock was in fog (visibility less than 220 yards) from 0300 to 1500 on 5 June.

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**Additional observation by A. S. Russell.**—In confirmation of Mr. Alexander's note, the visibility was 300 yards and the cloud base below 100 feet at 0700 GMT on 5 June at St. Andrews, 4 n.miles south-east of Leuchars. By 0800 GMT the fog and cloud had completely dispersed and visibility was  $1\frac{1}{2}$  to 3 n.miles. At about 1100 GMT I drove along the St. Andrews-Guard Bridge-Cupar road which runs along the south side of the Eden estuary at a distance varying between one-quarter and three-quarters of a mile from the estuary edge. The road and the area to the south were completely clear of fog and cloud but haar completely filled the estuary (which at the time was still covered by tidal water) to a depth of 150 feet. The haar bank narrowed westwards with the estuary until, less than a quarter of a mile west of Guard Bridge, where the river Eden is no more than 15 to 20 yards wide, there was complete clearance.

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#### CONFERENCE ON SATELLITE METEOROLOGY, LONDON 1964

By T. H. KIRK

A lecture series on satellite meteorology was held in London from 23 to 26 June 1964, following a corresponding series in Oslo from 16 to 20 June 1964, both being promoted by the Advisory Group for Aeronautical Research and Development (AGARD) of the North Atlantic Treaty Organization. The lectures in London were given in the Imperial College of Science and Technology, all necessary arrangements being made by the staff of the Department of Meteorology.

The lecturers were Dr. S. Fred Singer, Dean of the School of Environmental and Planetary Sciences, University of Miami, and the specialists: Dr. Philip M. Diamond, Meteorological Satellite Study, Aerospace Corporation; Mr. David W. Holmes, Deputy Director, Operations, National Weather Satellite Center, Weather Bureau; Mr. Lester F. Hubert, Synoptic Meteorology Branch, National Weather Satellite Center; and Professor Verner E. Suomi of the University of Wisconsin. Representatives of many European countries and organizations attended the lectures; those from the United Kingdom included staff of the Meteorological Office and of industrial concerns.

After a welcoming speech by Professor P. A. Sheppard, C.B.E., F.R.S., Head of the Department of Meteorology, Imperial College, Dr. Singer opened the series with a comprehensive review of the subject, dealing first with the general principles of design of a national operational meteorological satellite system; in particular, the considerations governing the choice of orbits, what can be observed and the sensors that are now available to make the observations, how to use the data once obtained and finally the factors relevant to the important aspect of minimizing the overall cost.

The satellite views the atmosphere by both emitted and scattered radiation which ranges from the ultra-violet through the visible part of the spectrum to the infra-red and microwave bands. From the ultra-violet and visible parts of the spectrum the data usage can be listed under the general headings, meteorological, non-meteorological and economic. The meteorological data relate to ozone, airglow, emissions from atmospheric constituents, cloud patterns, fronts, cyclones, storms, and jet streams. Non-meteorological data include those of ice, snow, soil properties, insect clouds, sea state, while on the economic side there are geological features, crops and vegetation, droughts and floods, large-scale constructions, terrain features, coast lines and mineral resources. The infra-red sensors provide meteorological information on surface temperature, water vapour distribution, cloud heights and atmospheric structure, and non-meteorological information such as forest fires and other conflagrations, volcanoes and ocean currents. In the microwave band, information can be provided on atmospheric structure, water vapour distribution, precipitation, spheres, and the properties of soil, snow and ice surfaces. In short, the satellite provides a wide variety of information, both meteorological and non-meteorological, of great potential use.

Dr. Philip M. Diamond dealt with the following engineering aspects: Attitude Control for Meteorological Satellites; Electric Power Systems; Miscellaneous Sub-systems; and, finally Systems Cost Analysis. His detailed analysis gave a considerable insight into the many problems and difficulties which had to be surmounted before the satellite project achieved its success.

Mr. D. W. Holmes was concerned with two main topics, Television Sensors and Cameras and secondly, Operational Data Transmission, Processing and Utilization. The scope was admirably outlined in his introduction: "It is no exaggeration to state that nature uses clouds to draw its own weather map; satellites permit us to both see and use this map. The function of the camera is to optically collect an image of the sunlit earth cloud-cover and correct the image to electrical signals which can be processed and transmitted to the users." Then followed details of the TIROS Vidicon Camera System, the Advanced Vidicon Camera Sub-System, the Automatic Picture Transmission (APT) Camera System and future cameras.

It is the APT which provides a means for local read-out of cloud cover from weather satellites, given suitable reception facilities of relatively modest cost. This sub-system was installed first in TIROS VIII and is incorporated in the NIMBUS satellite. Pictures already received from both these satellites have confirmed the possibilities of APT as a forecasting tool. In his second lecture Mr. Holmes gave details of the projected operational TIROS system whereby satellites in polar orbits will provide complete global coverage.

Those with the necessary research background must have derived great benefit and inspiration from Professor Suomi's lucid treatment of infra-red and microwave radiometers and their applications. Synoptic meteorologists were however more naturally interested in the lectures of Mr. L. F. Hubert who first dealt with the effectiveness of meteorological satellites in the coverage problem. Then followed "Cloud Picture Interpretation" and "Utilization of Cloud Pictures for Synoptic Analysis."

The television pictures provide a bewildering amount of meteorological information at middle scales, i.e., scales less than synoptic but larger than those visible from a near-earth observation point. Little is known of atmospheric behaviour at these scales and the satellite provides a new mode of observation. Illustrations were given of sub-synoptic scale organization together with interpretations. There are two aspects to the problem of utilizing cloud pictures in synoptic analysis; first, the interpretation of meteorological information from pictures, an identification of scale being of significance and second, the devising of techniques for incorporating the data derived in this way into the analysis.

In a closing lecture Dr. Singer examined the feasibility of utilizing satellites to provide world-wide collection and dissemination of meteorological data. This was a stimulating climax to a most comprehensive series of lectures painstakingly and enthusiastically presented. Confronted with this enthusiasm and obvious achievement, one's initial doubts regarding the future of satellite meteorology seemed somewhat unworthy and ungenerous.

Hitherto, in the United Kingdom (and indeed elsewhere outside of the U.S.A.) satellite information has been available for application in day-to-day forecasting only in the form of "nephanalyses" i.e., facsimile pictures of cloud systems resulting from the interpretation of the original television photographs. These have proved of only limited value for two reasons; first, they were available only for limited areas of the earth's surface, according to the programmed orbits and no continuity was possible; second the nephanalyses were some nine hours old when received. The APT sub-system, first installed in TIROS VIII made possible the local interception of satellite data for orbits passing sufficiently close to the British Isles. With the NIMBUS satellite one more restriction is removed because this satellite maintains a polar orbit and thus affords complete global coverage. We thus have the present capability for picture coverage over a local area surrounding the British Isles, without undue delay, and for subsequent nephanalyses over extensive areas. The layman would expect satellite pictures to improve the daily forecasts and in due course an improvement will undoubtedly be made. For the present, however, the importance of the satellite to forecasting is that it provides a vast amount of data in a new way. The emphasis on cloud and circulation systems must engender new techniques from which we can ultimately look for further advances.

## OBITUARY

We regret to announce the death of Mr. J. A. Van Duijnen Montijn, President of the Commission for Maritime Meteorology, at De Bilt on 29 August 1964.

Jan Adriaan Van Duijnen Montijn was born at Oudewater (near Gouda) in January 1899. After training at the Royal Naval College at Den Helder he served from 1921 to 1930 in the Royal Netherlands Navy attaining the rank of Lieutenant Commander. In 1930 he came ashore and was working at the Ministry of Marine at The Hague until 1935. In October 1935 he was appointed an Assistant Director at the Royal Netherlands Meteorological Institute at De Bilt and in January 1956 was promoted to the post of Director of the Division of Oceanography and Marine Meteorology at that Institute.

In August 1960 at the conclusion of the Third Session of the Commission for Maritime Meteorology at Utrecht, Mr. Montijn was elected President of that Commission.

During the 29 years that he was working at De Bilt, his activities included the preparation of oceanographic and meteorological atlases, for which the Netherlands are rightly famous. The preparation and editing of four atlases was mainly his responsibility; 'Sea Areas around Australia' (1949), the 'Red Sea and Gulf of Aden' (1949), the 'Indian Ocean' (1955) and the 'Mediterranean' (1957).

Mr. Montijn had been an active and energetic member of the Commission for Maritime Meteorology since 1952. He showed much energy and enthusiasm as President and was in the midst of the preparations for holding the Fourth Session of that Commission, which is being held at Geneva in December this year, when he died.

Jan Montijn was an efficient and hard worker, a good organizer and was international in his outlook; he was a pleasant companion and had a very good sense of humour. He is survived by a widow and two sons to whom we extend our sympathy.

C.E.N.F.

## NOTES AND NEWS

### **Meteorological Magazine: increase in price**

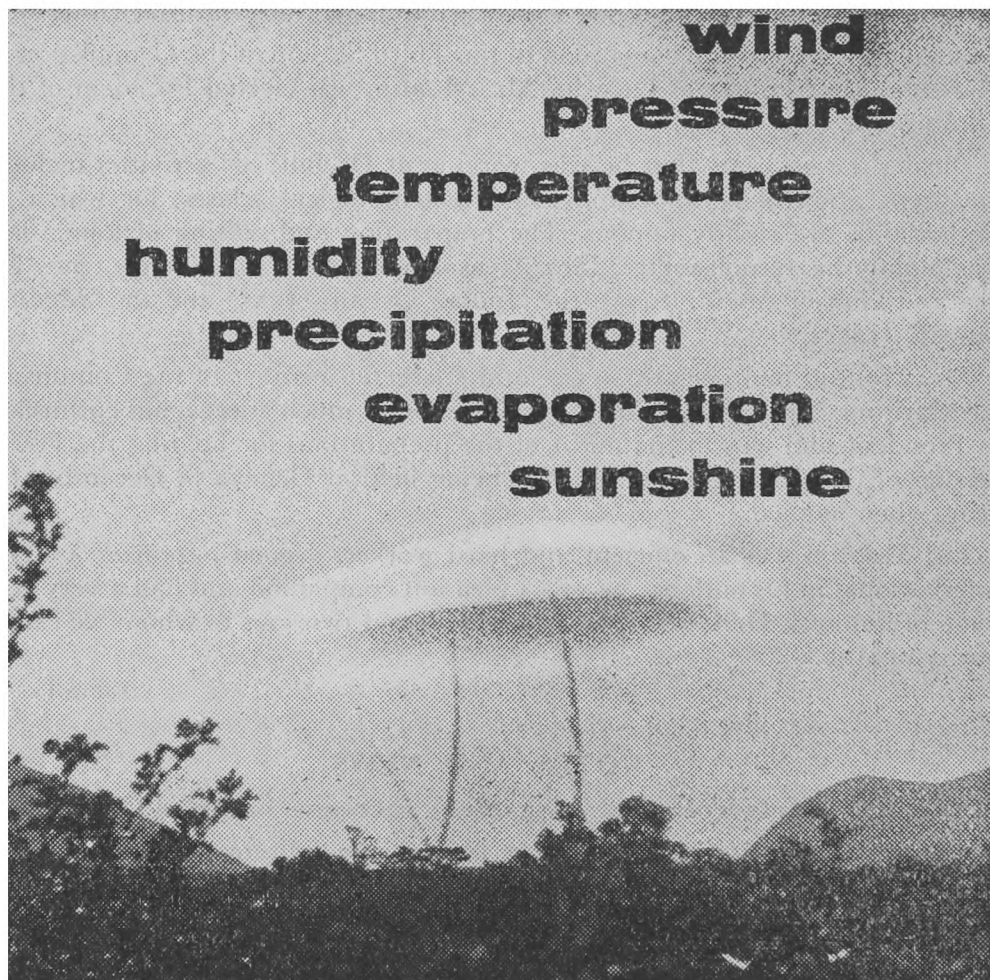
We regret that owing to the need to recover the full cost of postage it will be necessary to increase the price of the *Meteorological Magazine* beginning with the January 1965 issue. The net annual subscription will become £2 including postage, but individual copies will continue to be 3s. od. each.

## CORRIGENDUM

*Meteorological Magazine*, October 1964, p. 290, line 38: after "shallow soil" add "as the trees sway in the wind."

# **METEOROLOGICAL INSTRUMENTS**

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