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LARGE-SCALE DISTURBANCE OF THE EQUATORIAL ATMOSPHERE*

By J. S. SAWYER

Summary. Cloud distributions in the equatorial atmosphere as observed by satellites confirm the existence of long-period large-scale disturbances which can be linked with the occurrence of wet and dry spells in individual equatorial areas, e.g. East Africa and Gan, and with wind fluctuations observed in the upper atmosphere. These disturbances are also of importance in studies of the influence of one hemisphere upon the other.

Some speculations on the nature of the disturbances are put forward. In the vorticity equation, the twisting terms and the frictional terms (arising primarily from the vertical exchange of momentum by small-scale motions) may play an important part in the dynamics of large-scale motions because they provide a mechanism whereby the sign of the absolute vorticity of an airstream may change in passing from one hemisphere to the other. Further studies of large-scale motion in the equatorial belt and extending over at least 60 degrees of longitude should be undertaken as well as the effort concentrated on mesoscale and microscale observing.

Introduction. Meteorology as a science has developed principally in countries outside the tropics and important new developments, such as frontal analysis, development of aerological networks or application of numerical dynamics, have first been applied to the atmospheric problems of middle latitudes. Meteorologists, recognizing the success of these ideas in middle latitudes, have naturally tried to export them to low latitudes, but it might be argued that the development of tropical meteorology has suffered almost as much as it has gained by this. Certainly in the 1930s and 1940s there was a significant diversion of effort to the search for fronts in the equatorial belt and for a frontal theory of tropical cyclones.

It is also noteworthy that the nature of depressions, fronts and other disturbances of middle latitudes makes weather forecasting for 12 to 36 hours ahead a practical and rewarding task. This is not true of many areas of the equatorial belt. Over land masses the diurnal cycle may be so dominant that it hardly requires a meteorologist to describe it each day, and in most areas the differences from one day to the next are not generally such as to be of major importance to the weather-sensitive industries which have supported the development of weather forecasting services elsewhere — aviation, shipping, etc. The development and movement of tropical cyclones is, of course, an exception to this generalization, and provides an important justification for the maintenance of day-to-day forecasting services in the

*Paper presented at the Symposium on the Global Atmospheric Research Programme at Princeton, New Jersey, January 1969.

areas liable to their effects. However, the severe thunderstorms, etc. which are also of importance to aviation are of a local nature and are best treated on an hour-to-hour basis with radar as the main forecasting tool.

Relatively little attention has been given to disturbances of the equatorial atmosphere which have a time-scale of two or three weeks and a space-scale comparable with the major planetary waves of middle latitudes. The purpose of this article is to draw attention to the fact that such disturbances exist and to some of the dynamical problems posed by them. Since they are linked with the occurrence of wet and dry spells in many equatorial areas, they are of interest for the problems of agriculture, and the possibilities of forecasting them must have considerable economic importance. An understanding of disturbances of the tropical atmosphere on long time-scales must also be of importance in regard to extended forecasting in middle latitudes, if the influence of the opposite hemisphere is to be taken into account.

It therefore seems important that both the planned Global Atmospheric Research Programme (GARP) and any tropical observing experiments leading up to it, should make provision for the study of long-period and large-scale variations of the equatorial atmosphere.

Some illustrations of large-scale disturbances of the equatorial atmosphere. The existence of large-scale disturbances in the equatorial atmosphere has been particularly well illustrated by the cloud distributions observed by satellites, initially by the observations from the TIROS and ESSA series, but more particularly from the remarkable observations of ATS-1 and ATS-3.

Figure 1 shows an analysis of the cloud distribution over the Indian Ocean and surrounding areas from the observations of ESSA-3. This is one of a series made at Bracknell by D. H. Johnson, D. W. Dent and B. H. Preedy from the microfilm supplied by the National Weather Records Center, Asheville, U.S.A. The feature of particular interest is the belt of cloud which extends across the Indian Ocean in low latitudes. This is associated with the feature which has been known for many years as the intertropical convergence zone (ITCZ), and it is immediately apparent from these analyses that it is a very real and important feature of the equatorial atmosphere.

The analysis of the cloud systems in Figure 1 has been carried out using a slight variation of the conventional scheme which has proved particularly convenient for the purpose. Areas most heavily shaded represent systems of thick cloud which in the opinion of the analyst are associated with active weather systems. They correspond more or less with the areas of synoptic importance in the routine ESSA analyses. 'Mainly covered' areas which contain a substantial proportion of cumulonimbus clusters are cross-hatched.

The belt of cloud following the ITCZ is obvious on the satellite pictures almost every day, whatever form of analysis is adopted. However, the fact to which I wish to draw particular attention is that the ITCZ as seen from the ESSA satellite pictures is not merely a persistent climatological feature, but that it has considerable variations both in position and intensity, and that these extend over periods measured in weeks rather than days. Indeed the changes are best recognized in cloud distributions some 5 or 10 days apart rather than in the differences from day to day. Figure 2 shows the distribution

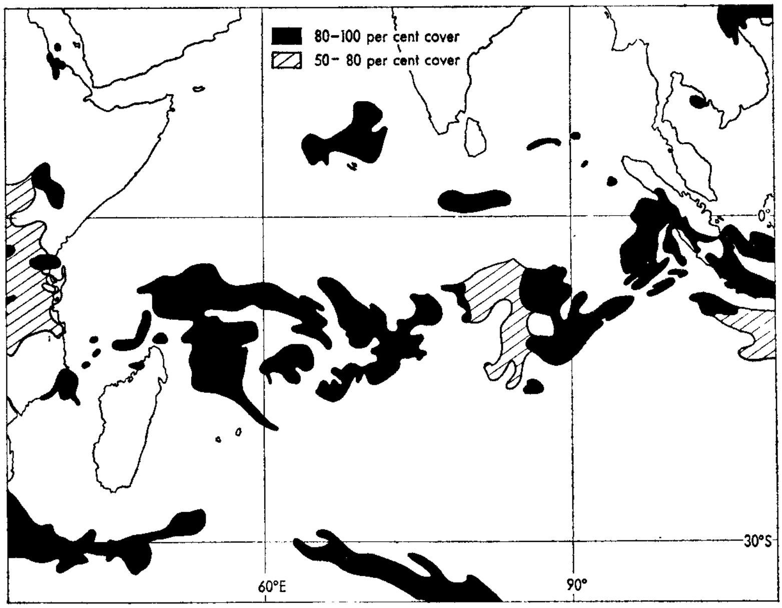

FIGURE 1—CLOUD ASSOCIATED WITH ACTIVE WEATHER SYSTEMS, INDIAN OCEAN, 8 FEBRUARY 1967

Note : Clouds not associated with active weather systems are omitted from the analysis.

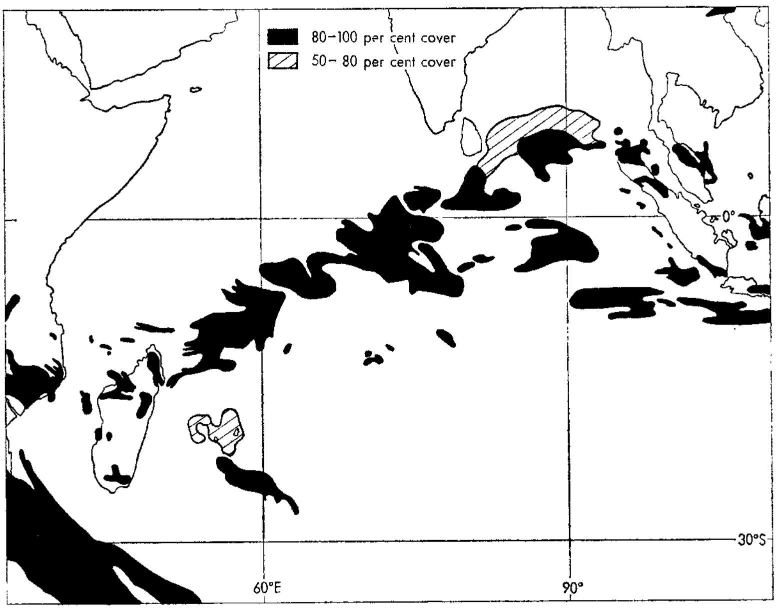

FIGURE 2—CLOUD ASSOCIATED WITH ACTIVE WEATHER SYSTEMS, INDIAN OCEAN, 19 FEBRUARY 1967

Note : Clouds not associated with active weather systems are omitted from the analysis.

of clouds as analysed fror the Indian Ocean some 11 days later than Figure 1. The change in the position of the ITCZ is apparent and also its change in orientation from an east–west line to one tilted from north-east to south-west.

The extent of the movement of the ITCZ is illustrated by Figure 3 on which lines have been drawn representing the position at 5-day intervals of the axis of the cloud belt as shown in the ESSA cloud pictures.

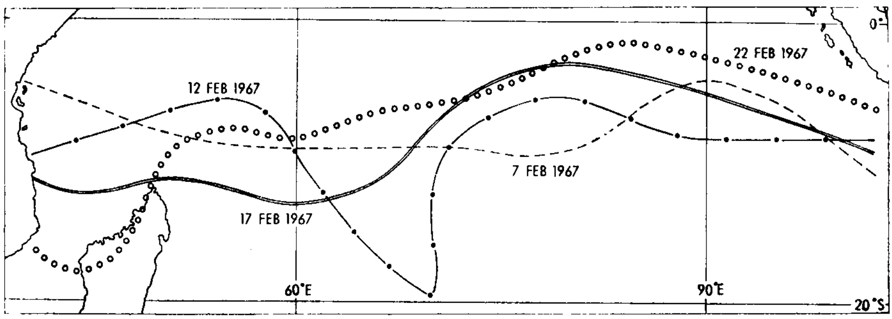

FIGURE 3—AXIS OF MAIN BELT OF CLOUD ACROSS THE TROPICAL INDIAN OCEAN AT 5-DAY INTERVALS, AS REVEALED BY ESSA-3 CLOUD PHOTOGRAPHS, 5–22 FEBRUARY 1967

The existence of disturbances of the equatorial atmosphere on the time-scale of weeks is also apparent in the upper wind observations of equatorial stations. Figure 4 shows the eastward and northward components of the wind at 200 mb day by day at the island of Gan. The existence of fluctuations with a time-scale extending beyond a few days is undeniable; these are particularly well developed in the upper troposphere.

D. H. Johnson[1] in analysing the rainfall patterns over East Africa has demonstrated clearly that relatively wet and dry periods occur at intervals of two to four weeks superimposed upon the climatological cycle of seasonal rainfall. These variations are best brought out when the rainfall of a region is considered as a whole and Johnson uses the proportion of stations experiencing rain each day as an index.

The behaviour of the satellite-observed areas of extensive cloud is certainly linked with the occurrence of relatively wet and dry periods in individual areas, and is probably also linked with the observed variation of wind on the same time-scale. This is illustrated by a comparison which Johnson and Dent have made for the island of Gan (Figure 4) while testing the significance and relevance of their analyses. The upper line of the diagram shows the percentage of a 5-degree square around Gan which is cloud-covered in the satellite pictures. The groups of a few days on which cloud amounts are large clearly coincide with rainy periods as shown by the second line of the diagram.

Some speculations on the nature of long-period equatorial disturbances. So little is known about the three-dimensional structure and physical behaviour of disturbances of the tropical atmosphere that it might be regarded as inappropriate to speculate about their dynamical mechanism and causes. However, the choice of the programmes by which we investigate them is to a great extent governed by the preliminary ideas we may have as to their nature and so, at a time when observational programmes for the tropics are being prepared, some discussion of the subject is not out of place.

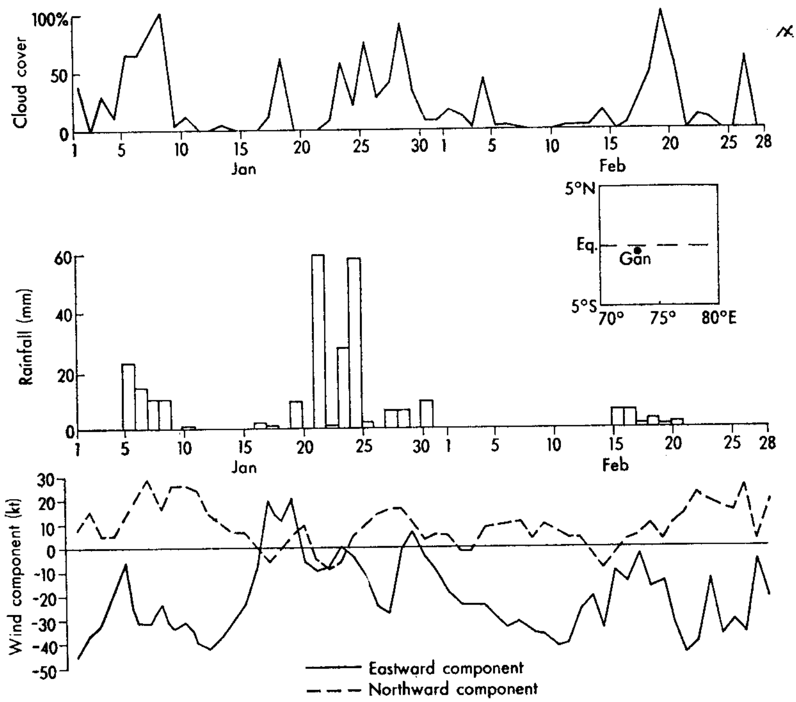

FIGURE 4—CLOUD COVER, RAINFALL AND WIND COMPONENTS AT GAN, JANUARY AND FEBRUARY 1967

Cloud cover relates to a 5° square 70–75°E by 5°S – equator.

One basic difference between the equatorial atmosphere and that of middle latitudes lies in the way in which the two regions play their part in the latitudinal transports of heat and momentum which are essential to the general circulation of the atmosphere. Transport of both heat and momentum through middle latitudes has been demonstrated to be largely dependent on disturbances of the mean circulation, the long waves, depressions, etc. Without such disturbances the transports would be quite different, and the mean state of the atmosphere could not be maintained. We must expect that disturbances should arise spontaneously in the real atmosphere and in any realistic model of it. They form an essential part of the mechanism.

The same is not true of the equatorial atmosphere. Although this is the seat of the main heating of the atmosphere, the transport of heat from equatorial to middle latitudes and the latitudinal movements of momentum can be largely explained in terms of the mean meridional circulation and the 'standing eddies'. The transient eddies play a secondary part only. In consequence there is no reason to think that the transient eddies must arise spontaneously as part of the general circulation of the atmosphere. Rather, the remarkable consistency of the major air currents in the equatorial belt and the 'reliability' of the seasonal cycle of weather in most areas leads one to think of the tropical atmosphere as a stable dynamical system responding to external influences of which the most important is the seasonal change in the declination of the sun.

Charney[2] has recently drawn attention to a type of instability — his 'conditional instability of the second kind' — which arises when latent heat is released in low latitudes in broad areas of convergence of the surface air layers. The convergence increases the vorticity, and the greater the vorticity in the Ekman layer the greater the convergence which occurs. When the convergence is linked to the energy release by latent heat an unstable development is possible. Such a mechanism must be an essential feature of the intensification of tropical cyclones. However, these are a special problem which already receives much attention, and their existence should not discourage us from looking at the remainder of the equatorial atmosphere as an essentially stable system.

Charney has also shown that the same interrelation of Ekman-layer convergence, vorticity and latent-heat release leads to the concentration of convergence along a relatively narrow band 200–300 km wide at the ITCZ. However, observations of the equatorial atmosphere are not suggestive of any unstable disturbances on a large scale, although the mechanism of Ekman-layer convergence may impose its own time-scale on the response of the equatorial atmosphere to external influences.

If one is to look for the cause of the fluctuations in the tropical atmosphere with a period of weeks, it is natural to look to the extratropical atmosphere where fluctuations on a similar time-scale undoubtedly exist as a result of the dynamical instability of the large-scale circulation. The 'index cycle' studied by Rossby and others around 1950 has this time-scale and the fluctuations also show up in the life of 'blocking systems'. A recent theoretical paper by Mak[3] has shown by numerical integration that disturbances imposed on the tropical atmosphere at latitudes 30°N and 30°S with a structure similar to those occurring in nature should result in disturbances in the equatorial belt with time-scales from 5 to 40 days rather similar to those observed.

The existence of important links between the equatorial and middle latitude atmosphere is made very clear by the analysis of winds in the upper troposphere across the equatorial belt. This can be seen clearly in some transequatorial analyses for 200 mb in a paper by Johnson.[4] Air from the easterlies near the equator enters the anticyclonic ridges on the equatorial side of the subtropical jet stream, and the dynamics of the equatorial current cannot fail to be influenced by the disturbances of the subtropical jet, itself materially affected by disturbances of middle latitude. This linkage has been dramatically illustrated recently by rapidly moving filaments of cirrus observed from the geostationary satellites as entering the subtropical jet stream from regions well within the equatorial atmosphere.

I conclude from this, that a very useful approach to the dynamics of the equatorial atmosphere might prove to be through the investigation of the disturbance initiated in the equatorial belt by distortions of the subtropical jet stream and other changes of the circulation around latitudes 25 to 30 degrees from the equator. This might well prove more rewarding than a study of disturbances arising spontaneously in the equatorial atmosphere which generally do not appear to possess the scale in time and space which is likely to be of most interest to the development of the synoptic meteorology of the equatorial belt.

Vorticity near the equator. The behaviour of the vertical component of vorticity near the equator is a specific problem of some interest which is important to the understanding of the behaviour of large-scale disturbances of the equatorial atmosphere. The problem is relevant to certain seasonal monsoon currents as well as to the behaviour of large-scale fluctuations in the seasonal currents.

It is generally recognized that in large-scale air motions of middle and high latitudes the vertical component of the absolute vorticity has the same sign as the component of the earth's rotation about the vertical. With the usual convention of sign the absolute vorticity is positive in the northern hemisphere and negative in the southern hemisphere. It is very doubtful whether quasi-geostrophic motion would be possible with absolute vorticity of the opposite sign and certainly a circular vortex or straight shearing flow and, presumably, other kinematic systems, would be dynamically unstable. There is, presumably, a region near the equator where absolute vorticity appropriate to both hemispheres can be found and Kruger[5] has endeavoured to identify areas with vorticity appropriate to the opposite hemisphere. However, this region cannot extend much beyond 10 to 15 degrees of latitude from the equator because of the observed quasi-geostrophic nature of the flow in higher latitudes. The way in which the absolute vorticity of an air-stream may be changed from the sign appropriate to one hemisphere to that appropriate to the other thus needs to be studied, particularly in regard to well-defined transequatorial currents.

That some substantial transequatorial currents exist is clearly demonstrated by Findlater[6,7] who analysed the structure of the low-level jet stream which exists over East Africa during the period of the Indian monsoon. A well-defined régime of mainly southerly winds exists from at least 10°S to near 10°N with maximum velocities of 40 kt or more at around 5000 ft. A return flow from the northern hemisphere to the southern must exist, probably in the upper troposphere, as a northerly component over a broader longitude band.

The vorticity equation (in pressure co-ordinates) expresses the rate of change of the absolute vorticity, η, as follows:

$$\underset{\text{(A)}}{\frac{\mathrm{D}\eta}{\mathrm{D}t}} + \underset{\text{(B)}}{\eta \,\mathrm{div}_{\mathrm{H}}\, \mathbf{V}} + \underset{\text{(C)}}{\left\{ \frac{\partial\omega}{\partial x}\frac{\partial v}{\partial p} - \frac{\partial\omega}{\partial y}\left(\frac{\partial u}{\partial p} - \frac{2\,\Omega\cos\varphi}{g\,\rho}\right)\right\}} = \underset{\text{(D)}}{\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}}, \ldots (1)$$

where $\omega \equiv \mathrm{D}p/\mathrm{D}t$, $\mathrm{D}/\mathrm{D}t$ represents differentiation following motion, Ω is the angular velocity of the earth, and F_x and F_y represent the stresses due to friction and eddy viscosity. (A term due to the latitudinal variation of the horizontal component of the Coriolis parameter has been omitted because it is small and particularly so near the equator.)

The second term (B) in equation (1) provides the principal control on vorticity in middle and high latitudes through the action of horizontal convergence and divergence, but it cannot be responsible for a change in the sign of η because it vanishes when η is zero.

Thus in order to seek a mechanism which can change the sign of the absolute vorticity of air as it moves from one hemisphere to the other we must look either to the 'twisting terms' (C) or to the frictional terms (D) in equation (1) for the generation of appropriate absolute vorticity in air which crosses the equator and enters the quasi-geostrophic régime of the opposite hemisphere.

The possible magnitude of the 'twisting terms' (C) depends on the horizontal gradients of ω and is clearly greater for smaller-scale features (i.e. a narrower current). Examination of the possible magnitude of the terms in the light of the winds observed near the equator shows that only with relatively narrow currents of, say, 1000-km width or less could these terms produce a vorticity change comparable with the Coriolis parameter in latitude 10 degrees, and then only in particularly well-suited distributions of wind and vertical velocity.

It is interesting to note that some positive vorticity could be generated in a northward-moving current in which wind decreases with height if there were descent to the left (west) of the current and ascent to the right (east). The very dry and subsided nature of air over Somalia and parts of Kenya when the low-level East African jet is present in July–August suggests that appropriate vertical movements may be present. A careful evaluation of the magnitude of the twisting terms from synoptic charts of the area would be needed to assess the possible significance of the effect.

Whatever the role of the twisting terms in the rather special East African current, they cannot be large enough to play the primary role in vorticity changes in the broader currents which are more characteristic of trans-equatorial air movements at least in the upper troposphere.

We are therefore led to look at the 'frictional terms' (D) the effect of which arises primarily from the vertical exchange of momentum by small-scale motions.

Charnock, Francis and Sheppard[8] measured the surface wind stress in the Caribbean and the average value which they observed, 0·041 N/m^2 (0·41 dynes/cm^2), would have removed half the momentum of the atmosphere up to 800 mb in about 3 days. A similar time-scale would arise in the exchange of momentum between the upper and lower troposphere if the eddy viscosity K were about 50 m^2/s (5×10^5 cm^2/s), a value comparable with that given by Riehl *et alii*[9] and about half of that deduced by Tucker[10] when including the effect of vertical motions on all horizontal scales.

The time-scale for the exchange of vorticity will, of course, be similar to that for the exchange of momentum, and it appears probable that the vertical transfer of momentum by vertical motions in relatively small-scale systems may play an important part in the dynamics of the large-scale motions of the equatorial atmosphere. The vertical motions in convective cloud systems, by their magnitude and vertical penetration, are likely to be the most effective factors.

It may be significant in this connection that when the mean air motion across the equator is analysed (Tucker,[11] Wright and Ebdon[12]) it is usually found that a current with a southerly component in the upper troposphere overlies a current with a northerly component in the lower troposphere and vice versa. Such a distribution of currents gives an opportunity for the vorticity of transequatorial currents in the upper troposphere to be brought to an appropriate sign for the hemisphere into which they move by the vertical eddy transport of momentum. A recent paper by Fujita *et alii*[13] has demonstrated that vertical momentum transfer mainly to the ground is effective in changing the sign of absolute vorticity in transequatorial currents in the lower troposphere.

Desirable characteristics of tropical observing experiments. The aim of the present note is to bring out some of the significance of large-scale air motions in the equatorial belt and of fluctuations in them. It is desirable that tropical research programmes should put some emphasis on these features, and that special observing programmes mounted as sub-programmes of GARP, or otherwise, should be designed so that the large-scale motions can be studied.

It is true, as I have indicated, that small-scale convective systems play an important part in the dynamics of the larger systems by the transfer of momentum, heat and water vapour which they bring about. Such convective systems deserve our study, but I think that we should be unduly optimistic and perhaps misguided, if we were to assume that the quantitative aspects of the transfer processes can be inferred from studies of mesoscale and microscale systems alone. The motions in the large-scale systems are themselves likely to prove an important control on the fluxes, particularly on that of momentum, and realistic assessment of the fluxes may, in fact, only prove possible through the study of the dynamics of large-scale systems.

I therefore regard it as particularly important that the tropical observing experiments should endeavour to document the large-scale air motion over the whole equatorial belt from one hemisphere to the other and extending over at least 60 degrees of longitude. Effort should not be solely concentrated on mesoscale and microscale observing which is, perhaps, somewhat easier to organize, and which, perhaps, provides objectives more readily achieved with the resources of an individual experimenter or a small group.

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SOME FACTORS AFFECTING THE CATCH OF RAIN-GAUGES

By M. J. GREEN

Water Research Association*

Summary. Meteorological Office Mk 2 gauges were installed at various heights above ground and their catch compared with that of a 9-hole gauge mounted close to the ground. An experiment was devised to examine the effect of rim height on catch and also the effect of the size of an anti-splash grid surround. Various values of wind speed and rain inclination were considered.

Introduction. It is desirable to design and site a rain-gauge so that the funnel collects the same amount of precipitation as that which would have fallen on the ground surface had the gauge not been present. If the gauge has the rim of its collecting funnel above ground level it deflects the local airflow so as to cause a wind eddy effect and a consequent loss of catch, whilst if the rim is installed flush with the ground surface the funnel becomes subject to in-splash from the surrounding ground. A critical review of precipitation measurements compiled by Kurtyka[1] describes these errors. The present paper describes the performance of a 9-hole gauge mounted close to ground level with an anti-splash surround and compares its catch with that of different rain-gauge installations for various values of wind speed and rain inclinations. The effect of rim height on catch is examined and also the effect of the size of an anti-splash grid surround.

Location. The site at Turville Hill, in the Chiltern Hills, was selected for its relatively level hilltop site and its open aspect to the south and south-west winds. As the hill is used solely for sheep grazing, a 1-metre high wire sheep-netting fence with a 5-cm hexagonal mesh was erected to enclose an area of 8×15 metres. Figures 1 and 2 show the plan of the site and the position of each gauge within the enclosure before and after 1 October 1966. Plate I is a photograph of the earlier enclosure.

Instrumentation. Within the enclosure was sited the 9-hole gauge described by Bleasdale,[2] which comprised a 3×3 group of square funnels mounted close to ground level each with a collecting area of 250 cm^2 and each with its own collecting bottle. To prevent in-splash the gauge was surrounded by an aluminium frame into which were slotted, at angles of 45°, green-painted aluminium venetian-blind slats, 5 cm in width (Plate II). The complete frame with slatting, measuring $228\cdot5 \times 228\cdot5$ cm, was laid on the grass so that the top edges of the slats were level with the gauge rim at a height of 4 cm above ground. The slatting was angled in the frame in such a way that raindrops which could have splashed into the funnels were deflected away from the gauge. This arrangement also served to prevent in-splashing from the ground surface.

Gauges A and B were 5-inch Mk 2 gauges, installed without any shielding, with their rims at 30·5 cm above ground level. Gauge C, also a 5-inch Mk 2 gauge with its rim at 30·5 cm, was shielded by a 'turf wall' which had been constructed from a framework of eight sections with tongued and grooved

*Ferry Lane, Medmenham, Marlow, Bucks.

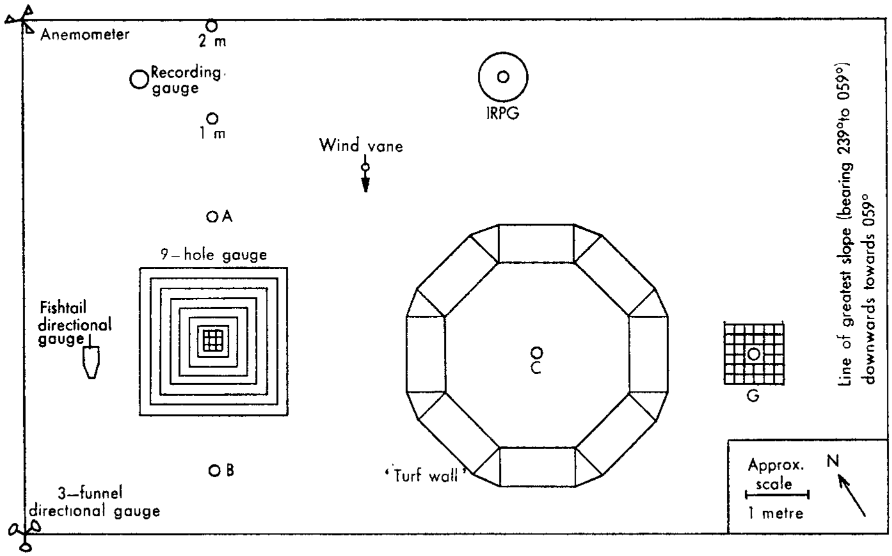

FIGURE 1—PLAN OF HILLTOP ENCLOSURE, BEFORE 1 OCTOBER 1966

A and B	Mk 2, 5-inch gauges (rim at 30·5 cm above ground)
C	Mk 2, 5-inch gauge (rim at 30.5 cm above ground) with 'turf wall'
1 m	Mk 2, 5-inch funnel with rim at 1 m above ground
2 m	Mk 2, 5-inch funnel with rim at 2 m above ground
IRPG	Mk 2, 5-inch funnel with an Alter shield and rim at 1 m above ground
9-hole gauge	3×3 group of square funnels each with collecting area of 250 cm^2 and mounted with rim 4 cm above ground
G	5-inch gauge with rim at ground level and flush with a 90×90 cm polystyrene grid.

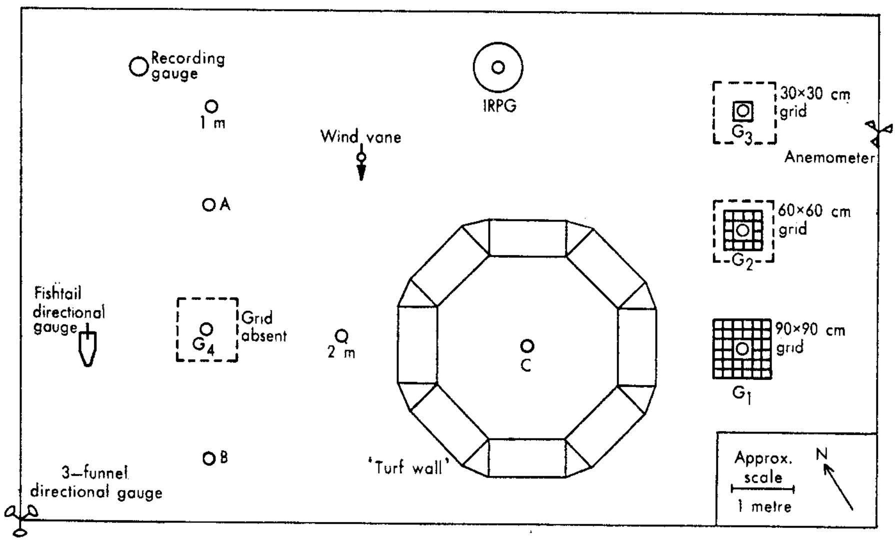

FIGURE 2—PLAN OF HILLTOP ENCLOSURE, AFTER 1 OCTOBER 1966

G_1 to G_4 5-inch gauges with polystyrene grid surrounds of different areas but flush with the ground; rim heights above ground were varied from 0 to 22 cm

Details of the Turville gauges are given beneath Figure 1.

board for the inside retaining walls. Initially, fine chicken-wire was stretched over the frame to represent the sloping outside walls, but this was replaced later by an earth slope.

The elevated gauges included an interim reference precipitation gauge (IRPG) (Mk 2 funnel mounted at 1 metre with an Alter shield), and two 5-inch Mk 2 funnels without any shielding, one mounted at 2 metres and the other at 1 metre.

Gauge G was pit-mounted with its rim set at ground level and flush with a 90 × 90 cm polystyrene grid composed of cells 5 cm square by 4·5 cm deep (Plate III). Other gauges included a recording rain-gauge designed by Barsby,[3] which, with the records from a recording anemometer and wind vane, made it possible to determine wind speed and direction during rainfall. Two directional gauges furnished data on rain inclination and wind direction during rain. One was the stationary '3-funnel type' similar to that described by Rose and Farbrother[4] and the other, called the 'Fishtail' gauge, was one that can rotate with the wind through 360° and in which rainfall can be deposited in 8 bottles representing 45° sectors of wind direction during rain.

The 9-hole gauge. The area of each compartment of the 9-hole gauge was checked by planimetry and linear measurement and the difference between compartments was found to be less than 1 per cent. A check on splash from the slatting surround was made by pasting the slats with a viscous solution of gum arabic and sodium chloride. The catch within each funnel was analysed after each rain event, but no increase in sodium chloride was detected.

The coefficient of variation (the ratio of standard deviation to mean) in catch was examined for 1962 and found to be 0·026; this was thought to be the result of wind eddies within the square funnels, and for the following years each compartment was subdivided by diagonal inserts which were 12·5 cm deep. The effect was to reduce the coefficient of variation to 0·009, 0·011, 0·012 and 0·011 respectively for the individual years 1963 to 1966. For the 1963–66 period the ratios, where available, of the catch of other gauges within the enclosure to the mean of the 9-hole gauge did not vary appreciably (see Table II). All results exclude snow.

Bleasdale[2] states that under windy conditions it is preferable to analyse the compartments in groups of three, at right angles to the rain direction. The results for rain from the south-west are given in Table I. The variance between groups was not significant at the 1 per cent level with the inserts.

TABLE I—ANALYSIS OF COMPARTMENTS IN GROUPS OF THREE AT RIGHT ANGLES TO RAIN FROM THE SOUTH-WEST

Reference number of compartments	Catch ratio with reference to (i) Overall mean of the 9 compartments	(ii) Mean of the 3 centre compartments
(a) Without inserts (1962)		
1 2 3	0·986	0·961
4 5 6	1·026	1·000
7 8 9	0·988	0·963
(b) With inserts (1963–66)		
1 2 3	0·992	0·987
4 5 6	1·005	1·000
7 8 9	1·003	0·998

Note : The compartment rows 1 4 7, 2 5 8, 3 6 9 are aligned 239° to 059°.

From these results the 9-hole gauge appears to be a suitable standard of reference when the diagonal inserts are installed.

Annual catch of gauges compared with that of the 9-hole gauge. A preliminary experiment was carried out to test the homogeneity of rainfall over a rectangular area of 120×45 metres, which included the enclosure. The results showed that over the 120-metre distance the range of catch at a given rim height was within ±6 per cent of the mean, while the 45-metre distance gave a ±3 per cent range. It was therefore assumed that the catch across the enclosure area of 8×15 metres was adequately homogeneous and that the gauges within the enclosure were directly comparable. Gauge B is excluded for reason of its proximity to the perimeter mesh fence.

The annual results are shown in Table II. The catch of each gauge is compared with the mean of the 9-hole gauge with inserts, and expressed as a catch ratio. The overall result shows that gauges A and B had catch deficiencies of 3 per cent and 7·5 per cent respectively; gauge C (turf wall) was within 1 per cent of the ground-level gauge; gauges IRPG, 1 metre and 2 metres had deficiencies of 4 per cent, 6 per cent and 10 per cent respectively, and gauge G had an excess of 2·5 per cent. At a less exposed site Rodda[5] found that during a 5-year period a ground-level gauge caught 6·6 per cent more rain than a standard gauge at 30·5 cm (occasions of snow were disregarded).

TABLE II—CATCH OF GAUGES REFERRED TO MEAN CATCH OF 9-HOLE GAUGE FOR THE YEARS 1962–66

Gauge	1962		1963		1964		1965		1966		1962–66	
	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.
9-hole (mean)	1·000	18	1·000	37	1·000	34	1·000	50	1.000	26	1·000	165
A	0·975	18	0·971	37	0·966	34	0·967	50	0·966	26	0·968	165
B					0·919	24	0·928	50	0·923	26	0.925	100
C					0·989	19	1.005	50	0·987	26	0·997	95
IRPG			0·957	17	0·952	33	0·973	50	0·959	26	0·962	126
G							1·023	45	1·029	15	1·025	60
2 m							0·868	8	0·910	26	0·900	34
1 m							0·911	7	0·952	18	0·941	25

N.R. = number of readings.
For positions and descriptions of gauges see Figures 1 and 2.

In Figure 3 the mean catch ratio has been plotted against rim height together with data from de Zeeuw,[6] Symons (after Kurtyka[1]) and Law (Fylde Water Board — private communication). It must be pointed out that the reference gauge height for Symons was 5 cm, for de Zeeuw and Turville it was 4 cm, and for Law 0 cm. All gauges except IRPG and C are unshielded. The results for gauge A indicate that it may be somewhat sheltered at this site.

Dependence of catch ratio on wind speed and on rain inclination and direction. According to Poncelet[7] and Reynolds[8] the long-term catch ratios may be misleading, and they suggest classifying data into climatic seasons. The Turville results go further in that they have been classified by wind speed during rain, by rain direction and by rain inclination, for periods of up to 2 weeks.

When the catch ratios were plotted against wind speed recorded at a height of 2 metres during rain, the relationships exhibited a large amount of scatter. Rain amounts, inclinations measured from the horizontal, and directions were calculated from the 3-funnel gauge[4] at a height of 2 metres, but when such data were introduced into the plot of wind speed against catch ratio there was no visible improvement in the relationship.

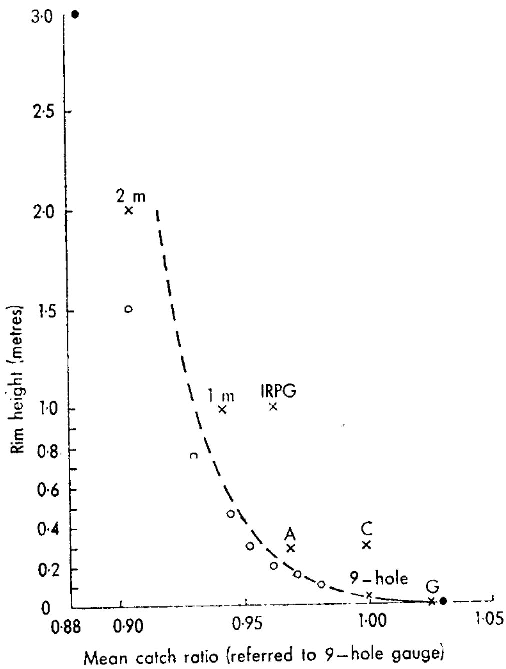

FIGURE 3—COMPARISON OF CATCH AT TURVILLE HILLTOP GAUGES WITH OTHER DATA FOR UNSHIELDED GAUGES

x Turville o Symons after Kurtyka[1] . Law

— — — — De Zeeuw[6] regression

Details of the Turville gauges are given beneath Figure 1. Reference gauge was the 9-hole at Turville. All gauges were unshielded except IRPG and C.

Another approach is seen in Table III where rain inclination is grouped into four classes for a given rain direction. The predominant south-west

TABLE III—CATCH RATIOS* FOR VARIOUS GAUGES ACCORDING TO SPECIFIED RAIN INCLINATION GROUPS

Gauge	Rain inclination to horizontal							
	<50°		50° – 60°		60° – 70°		>70°	
	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.
9-hole								
1	0·994	49	0·974	17	1·000	10	0·980	19
2	0·994	49	1·000	17	0·990	10	1·000	19
3	0·985	49	0·988	17	0·991	10	1·002	19
4	0·992	49	1·002	17	1·011	10	1·001	19
5	1·010	49	1·027	17	1·007	10	1·021	19
6	1·023	49	1·024	17	1·015	10	1·010	19
7	0·997	49	0·989	17	0·989	10	0·993	19
8	1·014	49	1·008	17	1·009	10	1·001	19
9	0·990	49	0·987	17	0·987	10	0·992	19
Mean	1·000	49	1·000	17	1·000	10	1·000	19
A	0·962	49	0·974	17	0·977	10	0·985	19
C	0·987	30	1·009	8	1·013	6	1·010	12
IRPG	0·960	31	0·974	11	0·987	8	0·992	18
G	1·029	18	1·027	5	1·009	4	1·040	10
2 m	0·888	17	0·906	4	0·943	2	—	—
1 m	0·924	12	0·935	4	0·962	3	—	—

N.R. = number of readings.

*Catch ratios obtained for gauges in hilltop enclosure for rain direction from the south-west (between 194° and 284°) and referred to the mean catch of the 9-hole gauge.

For positions and descriptions of gauges see Figures 1 and 2.

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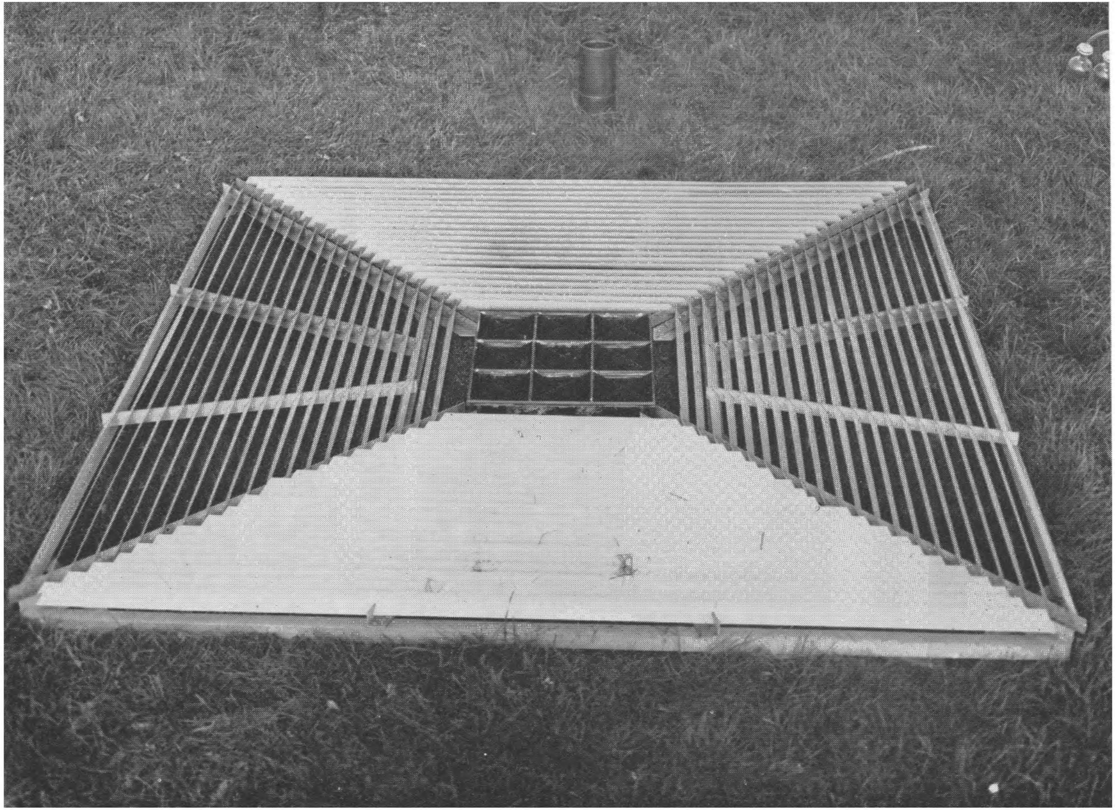
PLATE I—VIEW OF HILLTOP ENCLOSURE, LOOKING NORTH, BEFORE 1 OCTOBER 1966



By courtesy of Water Research Association

PLATE II—9-HOLE GAUGE WITH INSERTS AND SLATTING SURROUND

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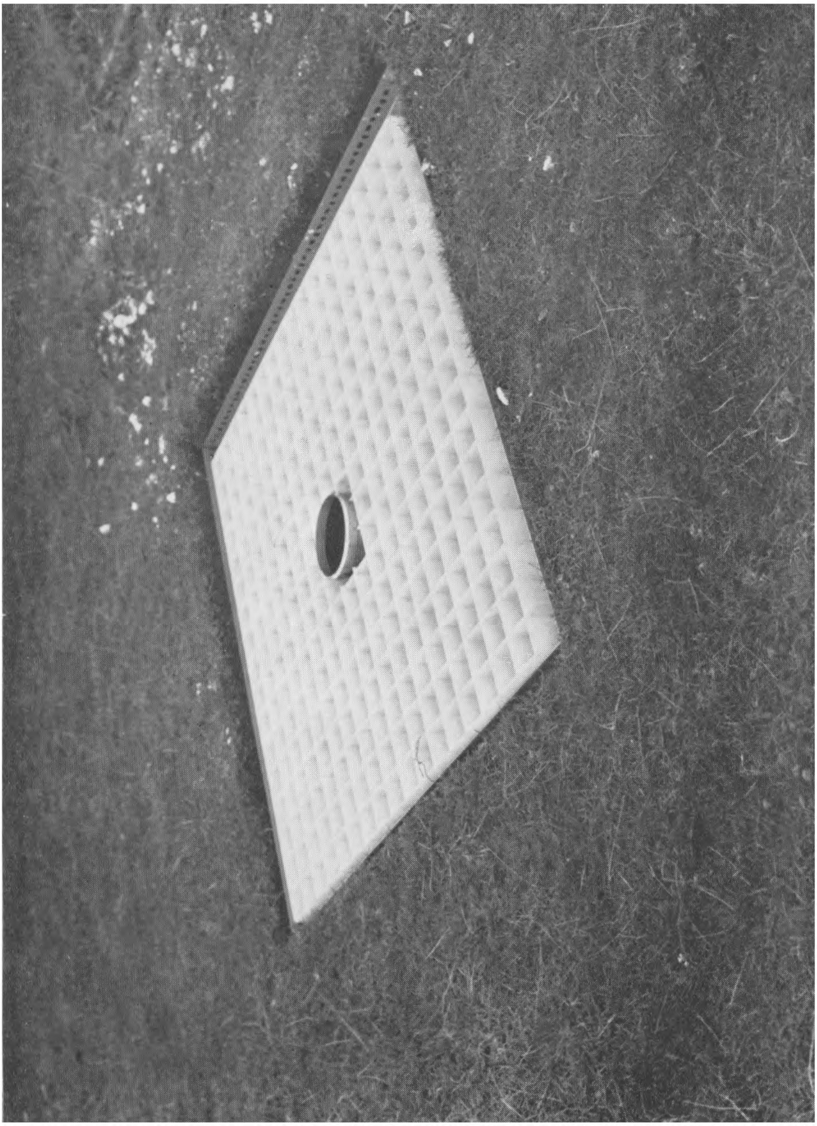

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PLATE III—PIT GAUGE WITH POLYSTYRENE GRID SURROUND direction was examined. The groups were selected according to the limitations of the 3-funnel gauge which was only able to measure rain inclination from 45° to 90° from 1962 to 13 September 1965 and from 35° to 90° after a modification to the funnels on the 13th. From examination of Table III it is seen that, excepting gauge G and individual compartments of the 9-hole gauge, catch ratios decrease with decreasing rain inclination to the horizontal.

A better estimation of catch ratio is given when wind speed at gauge height is combined with rain inclination. Initially wind speed at gauge height had to be correlated with wind speed at 2 metres, and five surveys were carried out with sensitive cup anemometers installed adjacent to and at the rim height of each gauge. Each survey comprised a 25-minute wind run for a given wind direction. From these results the wind speed at gauge heights was normalized with respect to that at 2 metres. This was undertaken by calculating a linear regression of wind speed at gauge heights with that at 2 metres. The regression coefficients have been incorporated in Figure 4 which shows the relationship between catch ratio, wind speed and rain inclination. The wind speed at the 9-hole gauge (height 4 cm) was extrapolated from a relationship of wind speed with height.

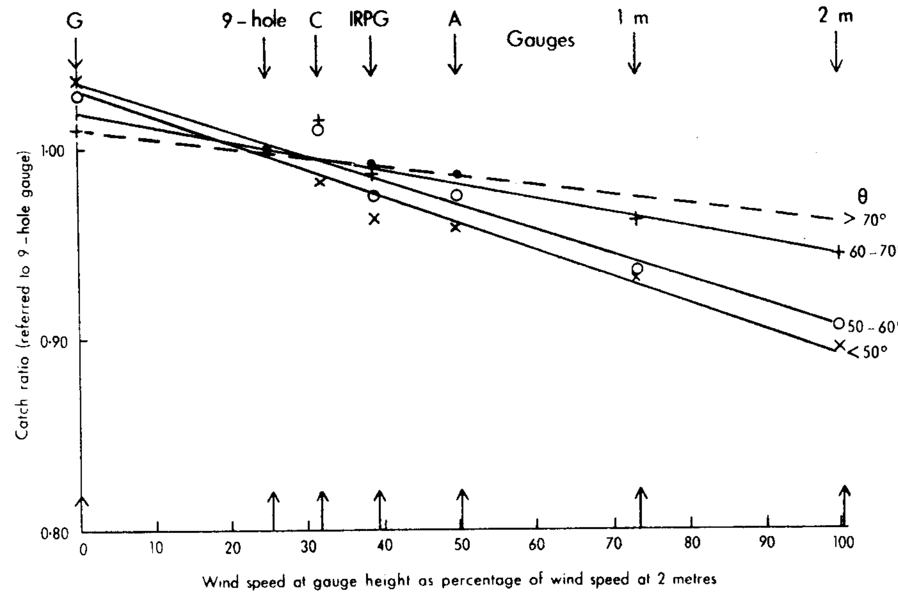

FIGURE 4—RELATIONSHIP BETWEEN CATCH RATIO, WIND SPEED AND RAIN INCLINATION

θ = rain inclination from the horizontal.
. Catch ratio for θ > 70° + Catch ratio for θ 60–70°
o Catch ratio for θ 50–60° x Catch ratio for θ < 50°
The pecked line was estimated because data for θ > 70° were limited.

For three groups of rain inclination, linear regressions were calculated as seen in Table IV.

TABLE IV—REGRESSION DATA FOR RANGES OF RAIN INCLINATION

Rain inclination, θ	Regression	Correlation coefficient	Standard error of y
$\theta<50°$	$y = 1{\cdot}029 - 0{\cdot}14x$	0·85	0·03
$50°<\theta<60°$	$y = 1{\cdot}032 - 0{\cdot}13x$	0·96	0·01
$60°<\theta<70°$	$y = 1{\cdot}017 - 0{\cdot}07x$	0·86	0·01

y is catch ratio,
x is wind speed at gauge rim height expressed as per cent of that at 2 m.

The limited data available for rain inclination (θ) greater than 70° did not warrant a regression and the dashed line in Figure 4 represents an estimate. Gauge B results were omitted from the analysis because of the proximity of this gauge to the fence (Figure 1).

From Figure 4 it is seen that the regressions tend to converge to a point where the catch ratio is 1·00, and for catch ratios between 1·01 and 0·99 the regressions give wind speeds of between 20 per cent and 30 per cent of that at 2 metres. The maximum wind speed experienced during the wind surveys was 13·6 m/s at 2 metres which, if the wind at the lower rim height is assumed to be 25 per cent of that at 2 metres, gives 3·4 m/s. This satisfies the requirements of Gold[9] who recommended that the wind speed at rim height should not exceed 10–15 miles/h (4·4 to 6·7 m/s).

Effect of area of grid and rim height on the catch of a gauge.

Chemical tests of in-splash. Although appreciable amounts of splash had never been detected in the early trials of the 9-hole gauge, a further investigation was undertaken with gauge G. To provide evidence of in-splash a semicircular metal tray with three annular compartments of width 30·5 cm and depth 1·5 cm was placed on the ground surface on the south-west of the gauge with its diameter passing through the rain-gauge (Figure 5). The central semicircular portion was cut away and the nearest tray was 50 cm from the centre of the gauge. The 90 × 90 cm grid surround occupied the space between

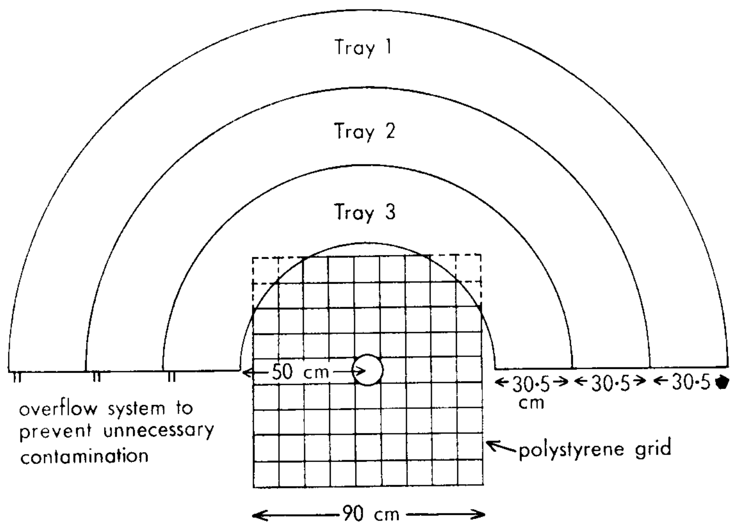

FIGURE 5—SKETCH PLAN OF SEMICIRCULAR TRAY ARRANGEMENT
A 5-inch rain-gauge is at the centre of the grid.

the tray and the gauge. Each tray was filled to a depth of 0·5 cm with a chemical solution; sodium chloride in the tray furthest from the gauge (No. 1), ammonium sulphate in the middle tray (No. 2) and potassium chloride in the nearest (No. 3).

The aim was to detect the chemicals in the rain catch. The mean catch ratio of gauge G with the trays was 1·079 against the long-term mean without trays of 1·029. Probably more splash was generated from the wet metal surface than would have been the case with grass.

The mean concentration in each tray was determined and it was assumed that rainfall causes a proportionate dilution of the chemical solutions. For each rain event the in-splash from the tray zone was found from the analyses of the catch in the gauge. The results are set out in Table V.

TABLE V—ANALYSIS OF CATCH SHOWING IN-SPLASH FROM TRAYS OF CHEMICAL SOLUTIONS

Apparent proportion of catch ratio derived from in-splash from trays				Catch ratio of G to the mean of 9-hole gauge	Corrected catch ratio	θ
Tray 1	Tray 2	Tray 3	All trays 1+2+3			
0·033	0·004	0·020	0·057	1·127	1·070	36°
0·020	0·028	0·030	0·078	1·120	1·042	52°
0·007	0·023	0·025	0·055	1·067	1·012	40°
0·004	0·004	0·007	0·015	1·020	1·005	47°
0·008	0·015	0·013	0·036	1·059	1·023	<35°
				Mean 1·079	Mean 1·030	

θ = rain inclination to horizontal.

From these results the catch ratios, less the apparent proportion due to splash from the trays, were greater than unity on each occasion, varying from 1·005 to 1·070 with a mean value of 1·030. This latter figure is essentially identical with the long-term catch ratio of 1·029 for gauge G without chemical trays (see Table III), when compared to the mean of the 9-hole gauge for rain inclinations of less than 50° to the horizontal. The subtraction of chemical in-splash from the tray zone is equivalent to inserting a splash-free zone there. Consequently the near equality of these figures, 1·030 and 1·029, implies that the grass beyond the 90×90 cm grid of gauge G contributes negligible in-splash.

Variation of grid area and rim height. Following the chemical in-splash investigation a more detailed study was undertaken at four sites within the enclosure. The size of grid surround and rim height of gauge above the surround were varied. The positions of the gauges are seen in Figure 2 (G_1 to G_4).

The polystyrene grid surrounds, installed flush with the ground surface, were 90×90 cm, 60×60 cm and 30×30 cm and the fourth site was left without a grid. The rim heights above the ground were 0 cm, 7·5 cm, 15 cm and 22·5 cm. When the rim height was flush with the ground surface and the grid surround was absent, an annular space of 1 cm was left between the gauge wall and the soil. The levelled rim of the gauge was left slightly above the ground surface to prevent any surface run-off entering the funnel. Table VI sets out the mean of four catch ratios, and rain inclinations and directions for each grid area and rim height. As the 9-hole gauge was not available all catch ratios are with reference to gauge C (rim 30·5 cm above ground, set within a turf wall).

TABLE VI—CATCH RATIOS,* AND RAIN INCLINATION (θ) AND DIRECTION WITH DIFFERENT RIM HEIGHTS AND GRID SIZES

	Gauge G_1 (Grid 90×90 cm)			Gauge G_2 (Grid 60×60 cm)			Gauge G_3 (Grid 30×30 cm)			Gauge G_4 Grid absent			
Rim height	Catch ratio	θ	Rain direction E of N	Catch ratio	θ	Rain direction E of N	Catch ratio	θ	Rain direction E of N	Catch ratio	θ	Rain direction E of N	Mean catch ratio
cm													
0	1·054	34°	159°	1·041	47°	194°	1·054	37°	148°	1·127	41°	167°	1·050 (excluding 1·127 result)
7·5	1·027	41°	167°	1·036	34°	159°	1·012	47°	194°	1·033	37°	148°	1·027
15·0	0·951	37°	148°	1·010	41°	167°	1·006	34°	159°	0·993	47°	194°	0·990
22·5	0·987	47°	194°	0·948	37°	148°	0·969	41°	167°	0·979	34°	159°	0·971

*Mean of 4 readings compared with gauge C (rim at 30·5 cm).
θ = rain inclination to horizontal.

The effect of grid area was not critical except when rim heights were 0 and 7·5 cm. The ranges of mean ratios for these rim heights, excluding occasions when the grid was absent, were 1·041 to 1·054 and 1·012 to 1·036 respectively. Anomalies did occur; for example, the mean catch ratio with the 60×60 cm grid was less than that with the 90×90 cm grid at a rim height 0 cm, and with the 30×30 cm grid the mean ratio was less than that with the 60×60 cm or the 90×90 cm grid at a rim height of 7·5 cm.

At rim heights 15 and 22·5 cm the mean catch ratio ranges were 0·951 to 1·010 and 0·948 to 0·987 respectively, while the ratio of gauge A (30·5 cm) to that of gauge C for the corresponding period was 0·971. Analysis of variance shows that the effect of grid area on catch ratio is not statistically significant at the 1 per cent level using an *F*-test.

The effect of rim height is seen in Table VI and the analysis of variance shows that the effect is highly significant at the 1 per cent level using an *F*-test. The decrease in catch ratio with rim height is seen in Figure 6. The solid curve represents the catch ratio when in-splash is avoided and the dashed curve the ratio when the grid surround is absent and when splash is probable. The area between these curves estimates the amount of in-splash, which at a height of 7·5 cm and above is less than 1 per cent. Gold[10] gives the theoretical maximum height reached by splash in still air of raindrops 2 mm in diameter or over as 0·73 to 0·43 metres, depending on the number of splash droplets produced. The spectrum of raindrop size as given by Meinzer,[11] indicates that raindrops are usually smaller than 2 mm diameter.

Conclusions. There was no evidence to suggest in-splash into the 9-hole gauge from the angled venetian-blind slatting, whereas the inter-compartment variation was attributed to wind eddying within the square compartments. Diagonal inserts within each funnel diminished the wind eddying and the variation.

For the 5 years of record a Mk 2 gauge with rim at 30·5 cm caught 3·2 per cent less than the mean catch of the 9-hole gauge, and when a Mk 2 with rim at 30·5 cm was surrounded by a turf wall the catch was within 1 per cent of the mean catch of the 9-hole gauge. An IRPG and Mk 2 funnels at 1 metre and 2 metres caught 4, 6 and 10 per cent, respectively, less than the mean catch of a 9-hole gauge. A 5-inch gauge set in a pit with its rim flush with the ground surface and surrounded by a 90×90 cm polystyrene grid caught 2·5 per cent more than the mean catch of the 9-hole gauge.

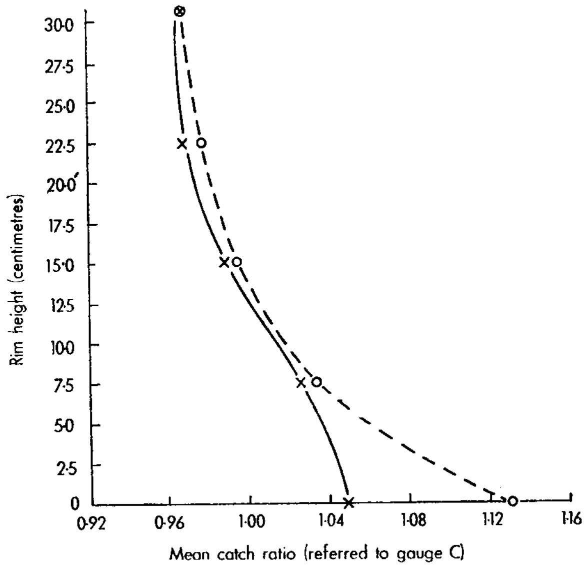

FIGURE 6—RELATIONSHIP BETWEEN CATCH RATIO (REFERRED TO GAUGE C) AND RIM HEIGHT

x Mean catch ratio for each rim height with gauges in positions G_1 to G_4 as shown in Figure 2 (rim heights of 0 and 7·5 cm with grid absent are excluded)
o Mean catch ratio for each rim height with grid absent
Catch ratio for gauge A shown at 30·5 cm.

When the area of the grid was varied between 30×30 cm and 90×90 cm around a pit gauge the range in catch ratios was from 1·041 to 1·054. From measurements of induced chemical in-splash it was found that the grass area beyond the 90×90 cm grid was producing negligible in-splash.

The effect of rim height on loss of catch was highly significant but in-splash was not significant above a rim height of 7·5 cm.

It was shown that a gauge would catch within 1 per cent of the mean of the 9-hole gauge if the wind speed at rim height was between 20 to 30 per cent of that at 2 metres.

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WINTER PRECIPITATION OVER EAST ANGLIA

By M. F. SMITH

Summary. Occasions of snow in East Anglia during a period of five winters were found to be associated with 1000–850-mb thickness of 1310 gpm or less. Nearly all occasions of sleet occurred in this thickness range also, and there were many occasions of rain. A scatter diagram was prepared in which the 850-mb temperature and the height of the freezing-level above sea level were used as axes and the type of precipitation (snow, sleet or rain) appeared in the diagram in symbolic form. The diagram was then divided, by eye, into sectors containing the main concentrations of snow, sleet or rain. The percentage of each type in each sector was calculated and used to represent the probability of the type within that sector. The occasions were then classified further, mainly into 10-gpm bands of 1000–850-mb thickness, and again scatter diagrams were drawn.

The diagrams were used as prediction diagrams over a set of independent data for winter 1967/68 and tables are given showing the success obtained at Mildenhall and Marham. Comparison is made with the success obtained with the two predictors recommended by Boyden for a snow probability of 50 per cent and above.

Introduction. Murray[1] investigated the use of 1000–700-mb and 1000–500-mb thickness and height of freezing-level as predictors of winter precipitation. Mineeva,[2] following the work of Popova, used the surface temperature and 1000–850-mb thickness with the air temperature at 850 mb in certain cases over Russia. Boyden[3] compared several predictors, though the air temperature at 850 mb was not among them. He came to the conclusion that surface temperature is an unreliable predictor and he decided that, of those he examined, the height of the freezing-level and the 1000–850-mb thickness with some allowance for sea-level pressure and station height, were the two best predictors of winter precipitation over the British Isles.

In the present paper it is assumed (as it was in the other investigations mentioned above) that some entirely different techniques have been used to decide that precipitation is going to fall, and once this has been decided, the question which then has to be answered is what kind of precipitation will fall. The method presented in this paper combines the 1000–850-mb thickness and the height of the freezing-level with a third predictor, the 850-mb temperature. It also distinguishes between rain and snow mixed, and snow or rain separately. An attempt is also made to give the probability of a forecast being correct.

Data used. The upper air ascents for Hemsby, Crawley and Aughton reported daily in the *Daily Aerological Record* for the months November to April for the five winters 1962/63 to 1966/67 were examined and an estimate was made of the following items appropriate to East Anglia for 0000 and 1200 GMT each day :

(i) 1000–850-mb thickness in geopotential metres.
(ii) 850-mb temperature in degrees Celsius.
(iii) Height of freezing-level expressed in millibars above sea level. The lowest value was taken, surface inversions being excluded.

The surface observations as given in the *Daily Weather Report* for Wittering (66 m above MSL), West Raynham (76 m), Gorleston (2 m), Cardington (28 m), Mildenhall (5 m) and Wattisham (89 m) were examined for the same months and years. All cases of snow and of sleet* were recorded. There were 370 cases with the 1000–850-mb thickness ≤ 1310 gpm and only 9 extra cases of sleet occurred with the thickness value in the range 1311–1320 gpm. The observations were then re-examined and 224 cases of rain and/or drizzle which occurred with the 1000–850-mb thickness value of ≤ 1310 gpm were also recorded and classified as rain. For precipitation in the period 0000–1200 GMT, upper air data were taken from the 00 GMT ascents and for the period 1200–0000 GMT from the 12 GMT ascents.

A total of 594 cases with thickness ≤ 1310 gpm were recorded, classified as snow, sleet or rain. If more than one type of precipitation was reported by the stations in the same 12-hour period, the type was classified as snow if snow was reported at any of the stations, otherwise it was classified as sleet.

At Mildenhall only, the dew-point at the time of commencement of the precipitation was noted by reference to the register of observations.

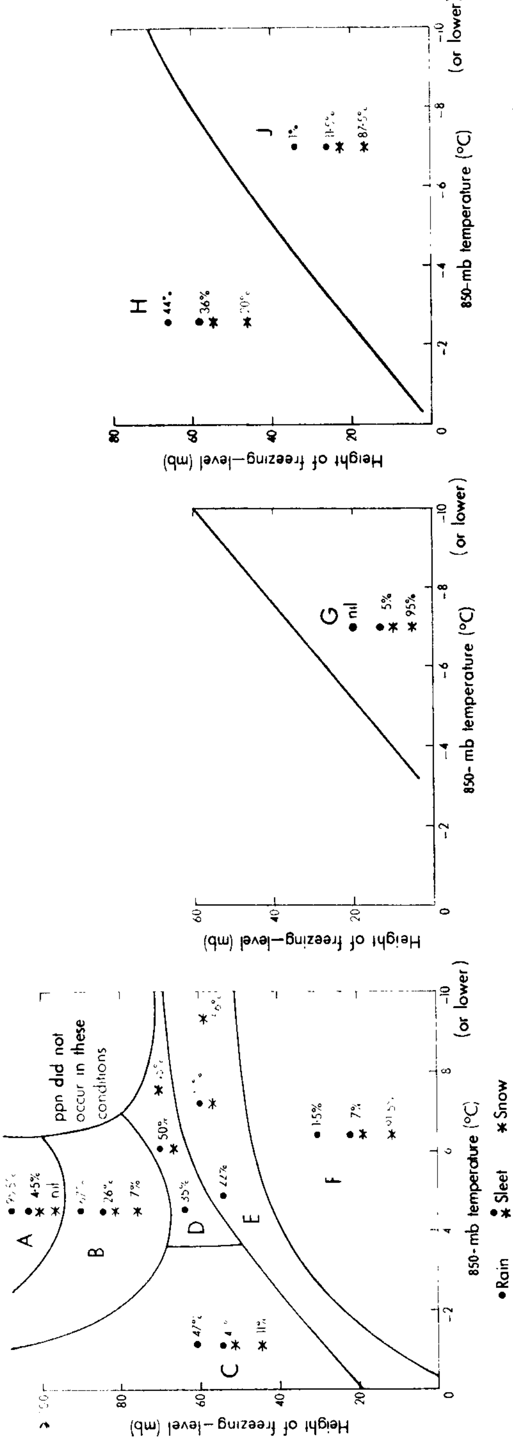
Preparation of the prediction diagram. A scatter diagram of 850-mb temperature against height of freezing-level was plotted for the 594 cases with geopotential thickness ≤ 1310 gpm, and the 9 cases of sleet with thickness 1311–1320 gpm were included. Different symbols were used for snow, sleet and rain. The diagram was divided into sectors containing significantly different proportions of snow, sleet or rain by drawing lines to avoid as many rogue plots as possible. The percentage of each type of precipitation in each sector was calculated by counting the number of plots of each type of precipitation, multiplying by 100 and dividing by the total number of plots in that sector. The boundary lines are given in Figure 1(*a*) and each sector is identified by a letter. The number of observations and percentage frequencies are given in Table I.

TABLE I—NUMBER OF OBSERVATIONS AND PERCENTAGES IN THE SECTORS IN FIGURES 1(*a*) – (*f*)

Figure	Sector	Number of observations				Percentages		
		Rain	Sleet	Snow	Total	Rain	Sleet	Snow
(*a*)	A	64	3	Nil	67	95·5	4·5	Nil
	B	84	32	9	125	67	26	7
	C	29	26	7	62	47	42	11
	D	14	20	6	40	35	50	15
	E	11	11	28	50	22	22	56
	F	4	18	237	259	1·5	7	91·5
	A to F				603†			
(*b*)	G	Nil	4	72	76	Nil	5	95
(*c*)	H	11	9	5	25	44	36	20
	J	1	11	84	96	1	11·5	87·5
(*d*)	K	27	5	1	33	82	15	3
	L	9	21	4	34	26	62	12
	M	9	10	56	75	12	13	75
(*e*)	N	66	4	Nil	70	94	6	Nil
	P	52	24	7	83	63	29	8
	Q	15	13	9	37	40	35	25
(*f*)	R	16	2	Nil	18	89	11	Nil
	S	6	9	Nil	15	40	60	Nil

†Including the 41 cases of snow with thickness < 1270 gpm.

*Sleet is here defined as snow and rain (or drizzle) together or snow melting as it falls.

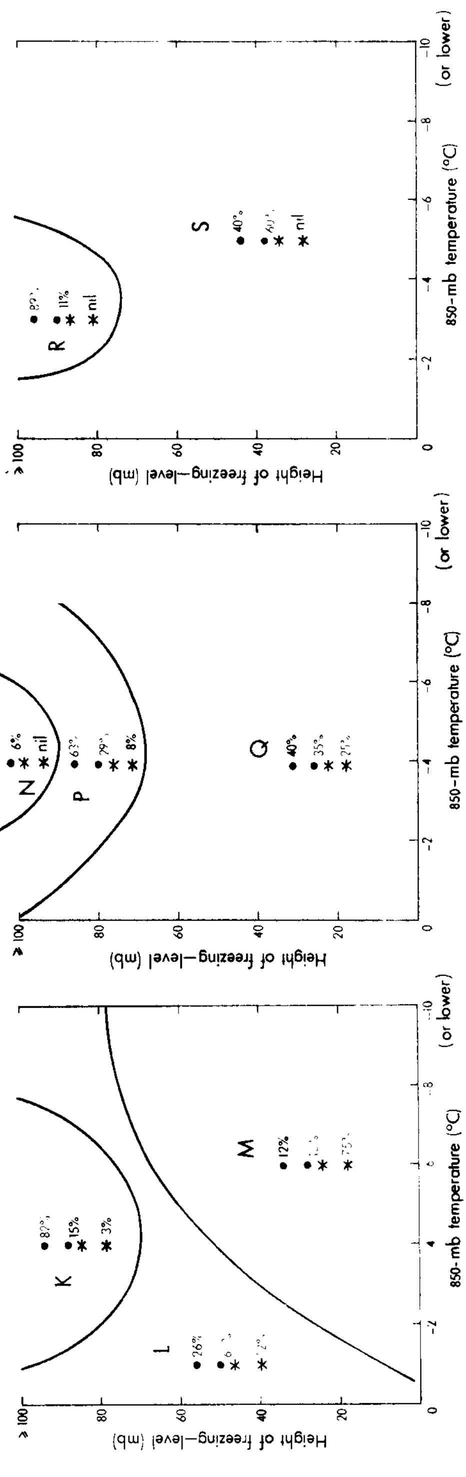


(*a*) With 1000–850-mb thickness ≤1310 gpm, including 9 occurrences of sleet with thickness 1311–1320 gpm.

(*b*) With 1000–850-mb thickness 1270–1279 gpm.

(*c*) With 1000–850-mb thickness 1280–1289 gpm.

FIGURE 1—PERCENTAGE PROBABILITY OF OCCURRENCE OF WINTRY PRECIPITATION



(*d*) With 1000–850-mb thickness 1290–1299 gpm.

(*e*) With 1000–850-mb thickness 1300–1309 gpm.

(*f*) With 1000–850-mb thickness 1310 gpm, including 9 occurrences of sleet with thickness 1311–1320 gpm.

FIGURE 1—PERCENTAGE PROBABILITY OF OCCURRENCE OF WINTRY PRECIPITATION —*continued*

Secondly, all cases were grouped according to the 1000–850-mb thickness in the ranges *(a)* <1270 gpm, *(b)* 1270–1279 gpm, *(c)* 1280–1289 gpm, *(d)* 1290–1299 gpm, *(e)* 1300–1309 gpm, and *(f)* 1310 gpm (which included the 9 extra cases of sleet with thickness 1311–1320 gpm), and scatter diagrams were also prepared of 850-mb temperature against freezing-level for the groups *(b)* to *(f)* separately. Figures 1*(b)*–*(f)* show the boundary lines and lettered sectors for these groups and Table I gives the number of observations and percentage frequencies. All 41 cases of precipitation in group *(a)* — thickness <1270 gpm — were of snow, and these are included in Figure 1*(a)* only.

No physical explanation is offered for the shapes of the sectors in the various diagrams. They were derived empirically and their usefulness depends on how well they behave in practice. This is discussed later in the paper.

Use of diagrams. A forecast of the type of precipitation for the periods 0000–1200 GMT and 1200–0000 GMT can be made using the diagrams and the appropriate ascent, if it is assumed that the diagrams are representative. Figure 1*(a)* contains all cases with thickness ⩽ 1310 gpm and therefore by use of this figure an answer can be obtained quickly from a single diagram. Note that the boundary limit for snow is of probability 56 per cent, i.e. higher than that used by Boyden, and in most sectors the relevant probability is much more than 50 per cent. Figures 1*(b)* – *(f)* classify the cases according to thickness and therefore selection of a diagram from amongst these figures, by taking in an extra predictor, should increase the reliability of the result.

From the latest available upper air ascents at Hemsby, Crawley or Aughton, estimate the values of the 1000–850-mb thickness, the 850-mb temperature and the height of the freezing-level for the forecast area (East Anglia). Plot the point given by these estimates in Figure 1*(a)* or one of the Figures 1*(b)* – *(f)*. Forecast snow, sleet or rain according to the type of precipitation with maximum percentage probability. For example, if Figure 1*(a)* were used and the values of the 850-mb temperature and the height of the freezing-level were −3°C and 40 mb respectively, the forecast would be snow with a probability of 56 per cent (say 60 per cent).

However, if the forecaster thought that the advection of colder air either near the surface or at 850 mb would cause the freezing-level, the 850-mb temperature and/or the 1000–850-mb thickness to fall so that the plot would fall in area F, then the probability of snow could be raised to 91 per cent.

Test of the method. The method was tested on independent data at Mildenhall and Marham during the winter months November 1967 to April 1968 inclusive. As the primary purpose of this method is to help the forecaster to decide in doubtful cases what kind of wintry precipitation will occur, the diagrams were used only on those occasions when the 1000–850-mb thickness was ⩽ 1310 gpm. It was found from the preliminary examination of the data that no precipitation other than rain occurred with the 1000–850-mb thickness in excess of 1320 gpm, and only 9 cases of sleet (less than 3 per cent of 370) occurred in the range 1311–1320 gpm; therefore the results of the test are not weighted with a large number of successful forecasts of rain on occasions when a forecaster would not even have considered any other possibility. On the other hand, no occasion of sleet or snow has been omitted from the analysis. Occasions when no precipitation occurred have been ignored.

TABLE II—NUMBER OF FORECASTS OF SNOW, SLEET AND RAIN AT MILDENHALL AND MARHAM COMPARED WITH THE TYPE OF PRECIPITATION THAT ACTUALLY OCCURRED DURING THE PERIOD NOVEMBER 1967–APRIL 1968 WITH 1000–850-mb THICKNESS $\leqslant$ 1310 gpm

Forecast of:	MILDENHALL Snow occurred	Sleet occurred	Rain occurred	Total	MARHAM Snow occurred	Sleet occurred	Rain occurred	Total
Snow	20	4	3	27	12	1	0	13
Sleet	2	7	4	13	1	1	2	4
Rain	0	0	11	11	1	0	6	7
Total	22	11	18	51	14	2	8	24

Table II gives the 3×3 contingency tables of the results of the method at Mildenhall and Marham. There were fewer cases at Marham as observations there are made only from 0000 GMT on Mondays to about 1800 GMT on Fridays.

The chi-square test showed that the results were significant at the 0·1 per cent level for Mildenhall but there were too few cases at Marham for the test to be properly applied.

At Mildenhall, on the three occasions when snow was forecast from the diagrams but rain occurred, the percentage probability of occurrence of snow was over 80 per cent; in each case only slight rain fell. On the two occasions when snow occurred and on the four occasions when rain occurred, after a sleet forecast, the figures gave a probability of sleet of about 30 per cent.

Comparison with other methods.

(i) Murray's criterion[1] for snow is that the 1000–500-mb thickness is <5224 gpm. In the test only 4 out of 22 cases of snow at Mildenhall occurred with the 1000–500-mb thickness <5224 gpm, so that 18 out of 22 did not satisfy Murray's criterion.

(ii) Boyden[3] found that a 1000–500-mb thickness of 5258 gpm gave a 50 per cent probability of snow occurring. In the test winter at Mildenhall only 4 cases out of 22 cases of snow occurred with the 1000–500-mb thickness <5258 gpm.

(iii) Boyden[3] found that the two most suitable snow predictors over the British Isles during four winters were *(a)* the height of the freezing-level above ground and *(b)* the 1000–850-mb thickness adjusted for sea-level pressure and for height above sea level. He found that the 50 per cent probability of snow occurred when the freezing-level was 35 mb above ground or when the adjusted 1000–850-mb thickness was 1293 gpm. Boyden forecast two categories only, snow or rain, and used the 50 per cent probability of snow as the boundary limit. If sleet actually occurred the forecast was counted half right and half wrong. For this comparison, occurrences of sleet were counted for the present method in the same way and, in addition, forecasts of sleet were counted as half snow forecasts and half rain forecasts. A comparison with the present method is given in Table III.

Table III gives the 2×2 contingency tables comparing forecasts of rain or snow with the actual occurrences of rain or snow for the present (reduced) method and for Boyden's two recommended predictors for probabilities of

TABLE III—NUMBER OF FORECASTS OF SNOW OR RAIN AT MILDENHALL AND MARHAM COMPARED WITH THE TYPE OF PRECIPITATION THAT ACTUALLY OCCURRED, USING THREE METHODS OF FORECASTING

Method	Forecast of:	MILDENHALL Snow occurred	MILDENHALL Rain occurred	MILDENHALL Total	χ^2	MARHAM Snow occurred	MARHAM Rain occurred	MARHAM Total
a	Snow	24¾	8¾	33½	13·4	13¼	1¾	15
	Rain	2¾	14¾	17½		1¾	7¼	9
b	Snow	18½	4½	23	10·0	11	4	15
	Rain	9	19	28		4	5	9
c	Snow	16	3	19	8·6	9½	½	10
	Rain	11½	20½	32		5½	8½	14

Method *a* As described in this paper
b Boyden, 1000–850-mb thickness
c Boyden, freezing-level height

Note : the fractions ¼ and ¾ occur when the 3×3 contingency table is reduced to a 2×2 table.

snow of 50 per cent and above. The chi-square value (with Yates's corrections) is also given. The 0·1 per cent significance value is 6·63. However, the value of the present method is considerably reduced by the counting of sleet forecasts as half snow forecasts and half rain forecasts.

The 13 forecasts of sleet at Mildenhall (see Table II) occurred with 1000–850-mb thickness 1290–1309 gpm and were re-examined and re-forecast as either rain or snow with the help of Figures 1*(d)* and *(e)*. Table IV gives the 2×2 contingency table including the sleet forecasts reassessed either as a rain forecast or as a snow forecast. The value of chi-square for the table is 19·8.

TABLE IV—NUMBER OF FORECASTS OF SNOW OR RAIN AT MILDENHALL COMPARED WITH THE TYPE OF PRECIPITATION THAT ACTUALLY OCCURRED, USING PRESENT REDUCED METHOD

Forecast of:	Snow occurred	Rain occurred	Total
Snow	24½	5½	30
Rain	3	18	21
Total	27½	23½	51

From Tables III and IV it is shown that the present reduced method gave 24½ correct snow forecasts out of 30 snow forecasts, and only 3 occasions of snow occurred after a rain forecast, whereas Boyden's freezing-level method gave 16 correct snow forecasts out of 19 but 11½ occasions of snow occurred after a rain forecast. Boyden's adjusted 1000–850-mb thickness method gave 18½ correct snow forecasts out of 23 snow forecasts and 9 occasions of snow occurred after a rain forecast. In Table II a point of interest is the fact that the present method did not give a rain forecast for any occasion on which snow or sleet occurred at Mildenhall.

Dew-point at time of commencement of precipitation. At Mildenhall the dew-point at the time of commencement of the precipitation was noted. Out of the 139 cases of snow, 134 occurred with a dew-point of 0·0°C or below, 4 occurred with a dew-point of + 0·1 to + 0·5°C and only one occurred with the dew-point above 0·5°C. Out of seven cases of rain occurring with a negative dew-point, five were pre-warm-frontal, and in fact the dew-point soon increased to zero or above. For sleet, dew-points were in most cases less than + 1·0°C. If a definite increase or decrease of the surface dew-point through advection could be foreseen, some modification of the probabilities for snow or rain given by the diagrams could be made.

Conclusions. This paper provides the forecaster who is dealing with winter precipitation with a method of deciding in doubtful cases whether to forecast rain, sleet or snow.

During the period of the test, as Table II shows, no snow or sleet occurred after a forecast of rain at Mildenhall and the only forecast which failed to satisfy this criterion at Marham was ahead of a warm front. This method is therefore recommended when the forecasting problem is to ensure that no occasion when snow occurs is forecast as rain. Alternatively, the predictors for 90 per cent probability of snow suggested by Boyden may be used.

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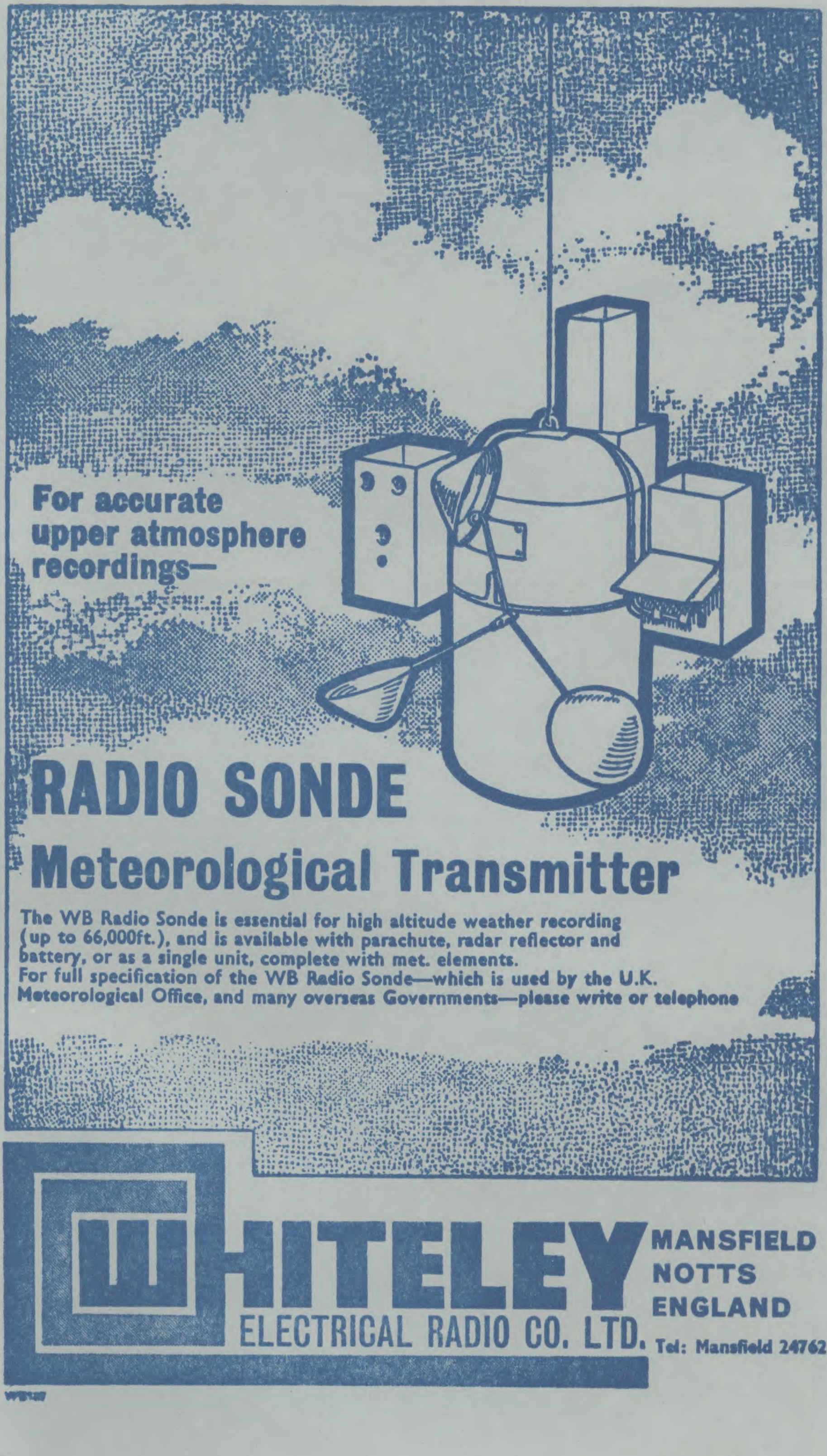
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THE CLIMATE OF INTERIOR OMAN

By D. E. PEDGLEY
Anti-Locust Research Centre, London

Summary. Using fragmentary data, it is possible to deduce schematic patterns of low-level winds for each month over interior Oman. The southerly monsoon from July to September is little more than one kilometre deep on average, and is best developed in July. It spreads across the interior but is deflected to south-easterly by the Hajar Mountains. Its higher humidity contrasts with the dry north-westerlies dominating most of the region for the rest of the year. There is indication of an Oman convergence zone, where these north-westerlies meet either easterlies (November to January) or southerlies (February to June, and October). This zone becomes the intertropical convergence zone from July to September, when the north-westerlies meet southerlies from the southern hemisphere. Rainfalls are largely confined to the *seif* season (March to May); *kharif* (July to September) rains are very light, except over some mountainous areas. Average annual totals probably exceed 150 mm over the Hajar Mountains, but decrease to 30 mm or less over most of the interior.

Introduction. Our understanding of the climate of interior Oman, and of the Empty Quarter of Arabia in general, has been qualitative (e.g. Brice[1]), being based on fragmentary observations,[2] on travellers' accounts (e.g. Thesiger[3]), and on an extrapolation from neighbouring areas. By contrast, the climate of the Arabian Sea, Gulf of Oman and Persian Gulf has been mapped and described in some detail.[4,5] In recent years, as a result of the activities of oil companies and of the establishment of experimental farms, several series of records have accumulated which can be used to construct a more detailed account of the climate of interior Arabia. Dodd[6] made some estimates of temperature and rainfall, partly based on records kept by the Arabian American Oil Company. The following note discusses some further records available from interior Oman.

Records from Fahud. Petroleum Development (Oman) Ltd have kept an almost continuous daily record of temperature, humidity, wind and rainfall, either at their base camp, Fahud (22°15′N 56°30′E, altitude about 250 m), or at drilling sites nearby (Figure 1). By combining observations from these places, sequences covering periods of three to five years can be obtained. Table I gives a summary.

Monthly means of daily maximum temperature show an expected seasonal trend. January was coolest but June, not July, was hottest. The three months July to September were each a little cooler than might be expected from the trend shown by other months. Correspondingly, the 1000 h (0600 GMT)

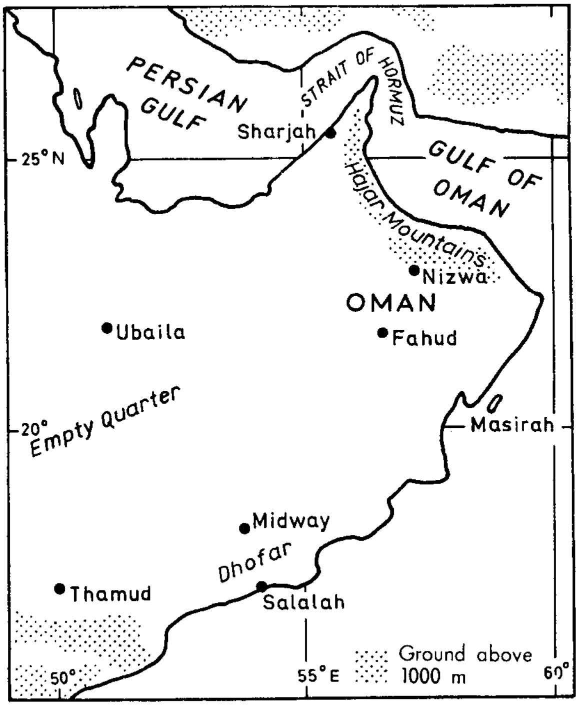

FIGURE I—MAP SHOWING PLACES MENTIONED IN THE TEXT

TABLE I—CLIMATOLOGICAL DATA FOR FAHUD AND NIZWA

FAHUD. 22°15′N 56°30′E. Altitude about 250 m.
Period : 1963–67, with additional rainfall 1956–57.

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
*Temperature**														
Monthly mean of daily max. (°C)		25	28	34	36	41	45	44	43	40	37	32	26	36
Relative humidity														
Monthly mean of readings at 1000 h (per cent)		55	55	37	34	31	23	36	39	39	33	42	51	40
Rainfall														
Monthly means														
(a) Total (mm)		1	tr	9	9	8	tr	tr†	3	0	0	0	tr	30
(b) Rain days		<1	<1	1	3	1	<1	2	1	0	0	0	<1	10
Surface wind														
	N	5	14	6	15	6	8	2	1	0	2	1	7	5
Percentage	NE	11	0	2	3	1	1	0	3	7	11	13	0	4
frequency	E	11	4	7	5	13	7	8	15	18	9	4	2	9
of occurrence	SE	23	22	26	26	27	29	50	50	42	28	26	15	32
of different	S	6	14	10	18	11	6	6	10	13	13	9	17	11
directions	SW	0	0	0	5	3	2	3	1	4	4	2	0	2
at 1000 h	W	6	0	4	5	9	5	2	3	0	6	4	0	4
	NW	22	24	21	12	16	27	15	10	0	6	1	7	14
	Calm	16	22	24	11	14	15	14	7	16	20	39	51	19
No. of observations		112	93	101	117	120	110	155	144	83	93	84	58	1270

NIZWA. 22°55′N 57°30′E. Altitude about 450 m.
Period : 1963–67.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Rainfall													
Monthly means													
(a) Total (mm)	15	8	5	28	50	1	30	5	5	6	7	2	161
(b) Rain days	1	1	1	2	2	<1	2	1	<1	<1	1	<1	11

* Including observations at nearby drilling sites. Readings corrected to altitude of Fahud using a lapse rate of 10°C/km assuming that the potential temperature does not vary horizontally within the area of the drilling sites. This is probably true since the sites differ in height by 200 m at most, whereas the convective layer probably extends to 3–5 km above the ground.
† But 75 mm fell in July 1967.

relative humidity was higher for the same months. Thus, although maximum relative humidities occurred on average in January and February, there were minima in both June and October, separated by a secondary maximum in August/September. Closely similar trends were recorded in individual years.

It is natural to associate the cooler and moister months of July to September with the monsoon, blowing from the Arabian Sea. Monthly means of the percentage frequency of occurrence of wind directions observed daily at 1000 h (Table I) show south-easterlies were dominant in those three months. Such a direction may be considered to be a local distortion by the Hajar Mountains of the south to south-west monsoon. Indeed, throughout the year a local deflexion of the wind is suggested by a strong preference for directions from south-east and north-west. South-easterlies were usually dominant, but the two directions were about equally frequent from January to March, and in June. There were remarkably few south-west winds, at least at this time of day, whilst north-easterlies became important only in October, November and January.

Rainfall was also measured during 1956 and 1957, but the 7-year period of records is too short to yield any reliable averages, although a few general remarks can be made. The annual total appears to be about 30 mm, falling on about 10 days each year. Most of this total fell during the *seif* season (March to May), and the *kharif* rains (July to September) were very scanty. However, a phenomenal 75 mm fell in July 1967, mostly associated with an unusual disturbance that moved westwards from the Arabian Sea.

Five years' rainfall records are also available from the experimental farm at Nizwa (22°55′N 57°30′E, altitude about 450 m) on the southern slopes of the Hajar Mountains, and for much the same period as the observations at Fahud. The annual total at Nizwa was about five times that at Fahud. Again most of the rains fell during the *seif* season, but *kharif* rains accounted for about a quarter of the annual total. By contrast with Fahud, *kharif* rains fell each year at Nizwa.

Records from Midway, Dhofar. Three years' daily observations were taken by Dhofar Cities Service Petroleum Corporation from 1956 to 1958 at Midway (18°02′N 53°55′E, altitude about 450 m) in Dhofar province of Oman. Table II gives a summary. Monthly means of daily maximum temperature show a trend closely similar to that at Fahud. Again the period

TABLE II—CLIMATOLOGICAL DATA FOR MIDWAY, DHOFAR

MIDWAY. 18°02′N 53°55′E. Altitude about 450 m.
Period : 1956–58.

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temperature														
Monthly mean of daily max. (°C)		25	28	32	35	39	41	37	38	38	34	30	27	34
Relative humidity														
Monthly mean of readings at 1000 h (per cent)		53	40	39	38	28	25	53	45	38	35	41	54	41
Surface wind														
	N	14	21	11	8	14	10	0	0	4	11	22	30	12
Percentage	NE	2	1	3	1	1	0	0	0	0	16	9	2	3
frequency	E	7	7	5	5	1	3	0	0	4	19	13	16	7
of occurrence	SE	2	4	1	1	0	0	0	0	1	5	3	0	2
of different	S	28	35	52	45	32	40	85	82	68	30	21	25	45
directions	SW	1	0	0	4	2	2	2	3	0	2	6	3	2
at 1000 h	W	7	7	0	3	17	7	8	2	1	6	8	9	6
	NW	16	6	1	11	8	8	0	0	1	2	8	1	5
	Calm	22	19	27	12	25	30	5	13	21	9	10	14	18
No. of observations		93	83	92	75	91	60	62	93	89	89	90	89	1006

July to September was relatively cool and moist. The monthly means of percentage frequency of occurrence of wind directions observed daily at 1000 h show that during these three months southerly winds blew, to the almost complete exclusion of other directions, reflecting the steadiness of the monsoon. Southerlies were common in most other months; from November to January they were about as frequent as north and north-west winds but from February to June they were dominant, being most frequent in March. There were remarkably few west or south-west winds. Easterlies or north-easterlies were significant only from October to December, but they became dominant in October, paralleling their increased frequency at Fahud at the same time of year.

Wind field, July to September. Tables I and II suggest that during the months July to September the monsoon spreads inland to reach at least as far north as Fahud, where it is deflected to a south-easterly, and where it is only occasionally interrupted by north-westerlies. These north-westerlies can be taken as a southward extension of the dominant north-westerlies over the Persian Gulf. The junction between the two streams is the inter-tropical convergence zone (ITCZ) if that is defined to include a region where trade and monsoon meet.

Some indication of the average northward extent of the southerlies can be found in the winds observed at Sharjah. There is a strong diurnal variation of surface wind at that place[7] associated with the sea-breeze, but at an altitude of 1000 m the wind as measured by pilot balloons at 0900–1000 h probably indicates a broader-scale flow. Table III shows monthly means of percentage frequency of occurrence of wind directions at 1000 m observed almost daily

TABLE III—MONTHLY MEANS OF PERCENTAGE FREQUENCY OF WIND DIRECTIONS AT SHARJAH AND MASIRAH

(a) SHARJAH. Winds at 1000 m at about 1000 h. Period 1961–65

Direction ranges *degrees*	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
350–010	1	2	1	5	5	2	0	2	1	7	1	1	2
020–040	4	1	3	3	1	1	1	2	4	5	7	4	3
050–070	3	0	2	4	2	1	2	3	5	7	6	7	4
080–100	8	6	1	1	4	3	4	4	7	6	7	9	5
110–130	4	3	2	0	2	3	6	7	11	3	10	4	5
140–160	4	1	1	3	2	3	4	9	7	6	5	5	4
170–190	5	9	11	8	4	6	17	12	7	3	5	4	8
200–220	7	11	8	7	9	6	9	9	2	3	4	5	7
230–250	5	6	11	11	5	11	12	6	5	1	1	7	7
260–280	16	14	13	8	12	11	7	6	5	6	7	7	9
290–310	20	19	27	27	15	20	9	9	11	10	15	13	16
320–340	7	5	4	9	17	12	5	1	7	10	5	7	7
Calm or <5 kt	16	23	16	14	22	21	24	30	28	33	27	27	23
No. of observations	153	140	152	149	119	147	153	155	149	155	150	155	1777
Missing observations	2	1	3	1	5	3	2	0	1	0	0	0	18

(b) MASIRAH. Winds at 500 m at about 1000 h. Period 1961–65

Direction ranges *degrees*	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
350–010	1	1	1	1	0	1	0	0	0	4	3	3	1
020–040	5	4	2	1	1	0	0	0	0	4	8	14	3
050–070	22	16	4	1	1	1	3	2	0	9	27	37	10
080–100	13	9	5	2	1	1	2	0	0	3	10	8	5
110–130	7	4	3	0	2	0	0	3	1	1	2	2	2
140–160	5	5	5	2	3	0	1	0	3	0	0	1	2
170–190	2	3	7	9	9	3	6	8	6	3	1	0	5
200–220	3	4	9	20	13	24	17	22	22	4	3	1	12
230–250	2	7	14	24	35	32	29	33	30	16	3	1	19
260–280	3	5	11	9	18	19	21	11	7	9	3	1	10
290–310	7	9	1	9	5	6	7	6	0	5	3	5	6
320–340	3	3	4	2	1	1	4	0	0	1	3	4	2
Calm or <5 kt	27	31	24	20	11	12	10	15	31	41	34	23	23
No. of observations	113	109	148	148	148	139	107	90	94	115	119	147	1477
Missing observations	11	3	7	2	7	11	17	34	36	9	1	8	137

from 1961 to 1965. From July to September, south-west to south-east winds were dominant, but north-westerlies were more frequent than as Fahud. These southerlies were not deep, however, for at 2000 m north-westerlies were strongly dominant.

Thus, on many days the monsoon reaches at least as far north as Sharjah, as a current between one and two kilometres deep. At the surface, night-time winds at Sharjah usually blow from between east and south,[7] directions to be expected with a monsoon modified by a land-breeze.

Some indication of the depth of the monsoon along the south-east coast of Oman can be found from pilot-balloon winds at Salalah and Masirah. Frequent low cloud at Salalah leads to few observations at 1000 m, so the calculated frequencies are unlikely to be representative of the true flow at that altitude. However, the very presence of clouds is indicative of lifting of the moist monsoon current. This low cloud is confined to coastal waters and the adjacent hills that rise to a general altitude of 1000 m, but it is deep enough to give drizzly rain.[5] Spillage of the monsoon over these hills probably leads to the remarkably persistent southerlies at Midway. The evidence suggests the monsoon is between one and two kilometres deep over Salalah, and this depth agrees well with that measured[8,9] over the adjacent sea during the International Indian Ocean Expedition. At Masirah, although there is less low cloud, frequencies of 1000 m winds are still likely to be biased towards days with fair weather, particularly those with little cloud and light winds. However, at 500 m there are considerably fewer missing observations, and these winds (Table III) probably indicate the broad-scale flow largely undisturbed by sea-breezes. From July to September, south-westerlies are strongly dominant, with an almost complete exclusion of directions other than those between south and west, again demonstrating the steadiness of the monsoon.

Above the monsoon, winds are mostly north or north-west. In the interior, day-time convective mixing might therefore be expected to transfer northerly momentum downwards to the surface. At Midway, winds measured at 1600 h show a small increase in the frequency of northerlies compared with 1000 h, more so in September than in August, suggesting not only that a vertical exchange of momentum does occur but also that the monsoon becomes more shallow as the season progresses. This further implies, by analogy with the Sudan and West Africa, where the depth of the monsoon decreases northwards,[10,11] that the ITCZ is furthest north in July. No afternoon observations were available from Fahud, but data for July and August 1964 from Thamud (17°20′N 49°55′E, altitude about 600 m) confirm an increase in the frequency of northerlies during the afternoon (1700 h) compared with the morning (0900 h). In both months, afternoon north to north-east winds were about as frequent as south to south-easterlies, suggesting that on average the ITCZ lay close to Thamud in the afternoon and therefore, again by analogy with Sudan and West Africa, about 200 km to the north-west in the morning.

Combining these fragmentary observations it is possible to obtain a coherent pattern of the average, low-level (up to an altitude of 1000 m) monsoon flow over Oman. For July, this is shown schematically in Figure 2*(a)*. Southerlies are deep enough to cross the coastal hills east of about 50°E, subsequently flowing across the relatively flat interior, but being deflected by the Hajar Mountains. After crossing the coast of Trucial Oman, these southerlies will be warmer than, and should therefore ride above, north-westerlies flowing in contact with the relatively cool sea surface of the Persian Gulf. Approaching the mountains of Iran, it is likely that the flow is deflected to the east. Over the Gulf of Oman, westerlies prevail[5] except for a thin surface film of easterlies that meet winds from the Persian Gulf in the Strait of Hormuz.

The position of the ITCZ as shown in Figure 2*(a)*, although further north than is commonly believed, agrees closely with one suggested by Flohn.[12] Further support comes from observations at Ubaila (22°00′N 50°55′E), in the northern Empty Quarter, which Dodd[6] considers to be near the northern limit of the monsoon.

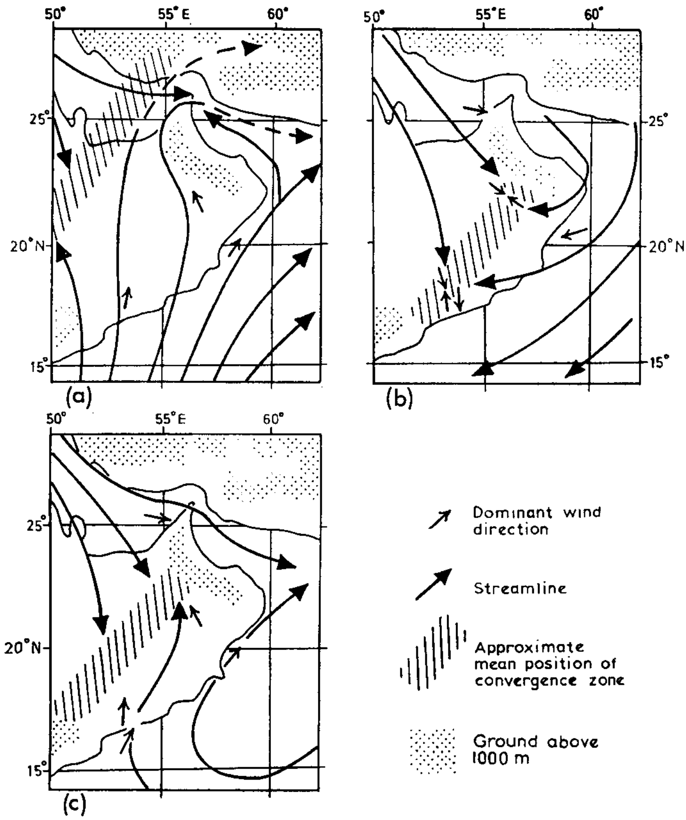

FIGURE 2—SCHEMATIC PATTERNS OF WIND FLOW AT 1000 HOURS IN THE LOWEST KILOMETRE OF THE ATMOSPHERE OVER OMAN

(a) July *(b)* January *(c)* April

The flow patterns are based on observations at various heights (see Tables I–III), and it is assumed that wind direction does not change with height through the layer. Streamlines are broken where winds from the land flow above a thin surface film of air moving from a different direction.

The shallowness of the monsoon, with a consequently restricted source of low-level moisture, is probably responsible for the rarity of rain over Oman from July to September. Possibly the only two exceptions are the Hajar mountains and the hills behind Salalah. About 50 mm probably fall on favoured places in the former mountains, and somewhat more on the latter.

However, heavy rains have occurred elsewhere — for example 12 mm at Sharjah[13] on 26 July 1956, and 30 mm at Masirah in July 1967, the latter in association with the 75 mm fall at Fahud. Such rains are probably related to unusual travelling disturbances accompanied by a deepening of the monsoon and a northward surge of the ITCZ.

Above the monsoon, the north-westerlies probably acquire their warmth and low relative humidity partly as a result of subsidence, particularly that associated with the right-exit region of the so-called 'tropical easterly jet' with its axis in the high troposphere[14] near 15°N, and partly because of intense insolation under clear skies over the Near East and Iran.

Wind field, November to January. During this season, the south-west monsoon over the Arabian Sea has been replaced by the north-east trades. Considering 1000 h winds, at 500 m over Masirah (Table III), the dominant direction is east-north-east with a weak secondary maximum from the north-west, but at 1000 m over Sharjah north-westerlies dominate with east-north-easterlies forming a secondary maximum. North-west winds develop in the rear of disturbances moving across the area, and their leading edge is often marked by a cold front ahead of which winds usually blow from between south and east. The presence of north-westerlies at Masirah suggests that some of these fronts can cross the south-east coast of Oman, buton most occasions the north-westerlies fail to reach the coast so that a semi-permanent zone of convergence probably exists in this season over interior Oman, separating north-westerlies from the trade wind. This can be called the Oman convergence zone (OCZ). Some indication of its position can be found in the observations at Fahud, where in January north-west winds are about as frequent as south-easterlies. This is consistent with the OCZ lying, on average, close to that place in January. In November and December, dominant south-easterlies at Fahud and north-westerlies at Sharjah place the OCZ further to the north-west. Some indication of its orientation can be found in the Midway observations. With northerlies about as frequent as southerlies there from November to January, the OCZ would be approximately as shown in Figure 2*(b)*, i.e. with an orientation similar to that of the ITCZ in July. The OCZ has some characteristics of a lee convergence zone, where north-westerlies from the Near East meet north-easterlies from West Pakistan in the lee of the Iran mountains.

Wind field, February to June, and October. At Masirah during February, 500-m south-westerlies increase in frequency at the expense of east-north-easterlies of previous months, and by March they are dominant. Throughout the season, southerlies are dominant at Midway, forming part of a broad-scale flow from the Arabian Sea before the monsoon sets in, usually some time during June. This change from east or north-east winds to south or south-west is probably a response to the increasing difference between air temperatures over land and sea as the year advances. A similar change occurs along the east coast of India. In both areas, anticyclonic cells appear over the ocean in March and April, leading to south-westerlies along eastward-facing coasts, but the cells fade as the monsoon develops. Similar weak cells appear fleetingly in October. Thus, the south-westerlies can be looked upon as local distortions of the trade flow. Nevertheless, they are continuous in time with the monsoon south-westerlies flowing from the southern hemisphere during the period June to September.

Although southerlies are dominant from February onwards at Midway, south-easterlies at Fahud only slowly become more frequent than north-westerlies, suggesting a slow seasonal displacement of the OCZ north-westwards (Figure 2*(c)*). Indeed, in June the OCZ seems to return temporarily to near Fahud. Throughout this season the OCZ is less like a lee convergence zone; it shows more the character of the trade front *(front alizé)* of north-west Africa. Thus, there appear to be progressive seasonal changes in the OCZ, not only of its position but also of its character, for by July it has evolved into the ITCZ with the south-westerlies coming from the southern hemisphere. During October, when trades replace the south-westerlies, the OCZ is re-established over interior Oman as a lee convergence zone.

A synoptic pattern associated with rainy days, particularly during the *seif* season but also more generally from November to May, is the presence in the upper tropospheric westerlies of a cold trough extending southwards to 20°N or even lower latitudes. Divergent flow is to be expected in the south-westerlies ahead of such a trough, leading to widespread ascent and sometimes to the formation of extensive cloud sheets in mid-troposphere. Local outbreaks of rain can then occur, especially if potential instability is released. If, at the same time, there is advection of moisture from the Indian Ocean by lower tropospheric winds ahead of the accompanying cold front, together with day-time heating over land, then such a pattern would favour the development of deep convection clouds and heavy rain. Deep convection can also be expected on infrequent occasions in the rear of a cold front particularly during the coldest months. This would occur near the axis of the associated upper cold trough,[15] where winds are west to north-west throughout much of the troposphere, and where heat and moisture have been added from the Persian Gulf or the Gulf of Oman.

Tropical cyclones can also lead to heavy and extensive rains. However, these disturbances are uncommon — one approaches the Arabian coast about once in three years[16] — and they are largely confined to the transition months preceding and following the monsoon, May–June and October–November. Even so, tropical cyclones contribute a quarter of the annual rainfall at Salalah, but only about five per cent at Masirah. Over interior Oman, their contribution is probably less, although occasional heavy falls with flooding do occur, for example[17] in October 1948. Heavy rains sometimes fall in each of several successive rainy seasons. As an example we may note the cyclonic rains of November 1966, the *seif* rains of March–April 1967, the monsoon rains of July 1967 and the rains of January–February 1968.

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551.515.43:551.577.2(53)

RAINFALL AT BURAIMI OASIS IN JULY 1969

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Summary. A description is given of a storm in July 1969 at Buraimi Oasis, on the border of Abu Dhabi territory with Muscat, during which 6·4 mm of rain fell. Some data for dewfall in the area in July 1969 are also given, as well as monthly rainfall data for the Oasis for the period November 1965 to July 1969.

The oases in the Buraimi group are at a height of 280 m above sea level and are situated at the northern end of Jebel Hafit (Figure 1). They lie partly in Abu Dhabi territory and partly in Muscat territory and are about 120 km from the Persian Gulf. The Hajar Mountains are about 20 km to the east and separate Buraimi from the Gulf of Oman.

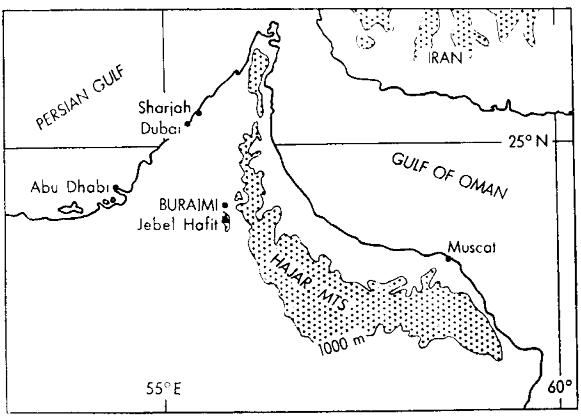

FIGURE 1—MAP OF THE BURAIMI OASIS AREA

The usual meteorological instrumentation is lacking at Buraimi apart from a single rain-gauge at Jahili Fort (Trucial Oman Scouts), which was established in autumn 1965. Dew-gauge readings are also available for a period in July 1969. Rainfall data are given in Table I and it is clear that scattered showers are not unusual during the summer months. However, July 1969 was considered abnormal by the local inhabitants on account of the frequency of humid days, whilst there was a heavy rainstorm on 7 July.

TABLE I—RAINFALL AT BURAIMI OASIS

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual total
						millimetres							
1965				Gauge not installed							Nil	Nil	
1966	Nil	37·5	Nil	Nil	Nil	1·0	1·0	Nil	Nil	Nil	Nil	Nil	39·5
1967	Nil	Nil	6·4	5·9	Tr	Nil	2·5	Nil	Nil	Nil	Nil	Nil	14·8
1968	5·0	69·8	Nil	2·5	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Tr	77·3
1969	33·5	1·3	Nil	4·3	Nil	Nil	6·4						46·7 (Jan.–July)

During the summer months, the climate of the oasis area is mainly influenced by the low-pressure area centred over southern and central Iran. June and July are the months of the 'shamal', a persistent north-west wind, whilst the monsoonal circulation does not generally reach as far north as Buraimi. During July 1969, the effects of the monsoon were felt further north than is usual.

The shift in the monsoonal pattern was probably reflected at Buraimi by the frequency of humid days which were invariably followed by a dewfall (Table II). The dew-gauge was sited at ground level on a grass plot (*Cynodon dactylon*) in a walled garden. The most humid days were 7, 10, 13, 19, 24, and 30 July and on three of these days (7th, 24th and 30th) rain fell at Buraimi. On the other days, and also on the 16th and 27th, towering cumulonimbus were observed over the Hajar Mountains in the afternoon and it seems likely that there was some rainfall.

TABLE II—QUANTITATIVE EQUIVALENTS OF DUVDEVANI DEW-SCALE NUMBERS AT BURAIMI, JULY 1969

		Dewfall *mm*			Dewfall *mm*			Dewfall *mm*
July	6	nil	July	15	nil	July	24	(Rain)
	7	0·15		16	Tr		25	0·075
	8	0·15		17	nil		26	nil
	9	nil		18	0·02		27	Tr
	10	0·02		19	0·075		28	nil
	11	nil		20	nil		29	0·02
	12	nil		21	nil		30	0·15
	13	0·02		22	nil		31	0·15
	14	nil		23	0·045			

The storm on 7 July 1969 was regarded by the local inhabitants at Buraimi as the worst summer storm in living memory. At 1630 h local time, an isolated thunderstorm with visible lightning passed about 8 km north of Buraimi, moving in a westerly direction. By 1720 h the persistent light wind, west-north-west, the local equivalent of the 'shamal', which had blown throughout the day had strengthened and commenced to veer. This was accompanied by a duststorm which, at its most intense phase, reduced visibility to about 50 m, the wind blowing from the north. Rain started to fall at 1750 h and it rapidly became heavy with the peak intensity being reached about 10 minutes later when hailstones up to 6 mm in diameter fell. During this time the wind had strengthened to gale force (estimated speed 100 km/h) and was blowing from the north-east quarter. The heavy rains and wind ceased at 1820 h, though a light drizzle continued for a further 20 minutes. During the storm 6·4 mm of rain were recorded, though this is probably an underestimate since much of the rain and hail was driven almost horizontally by the high winds, and there was enough rain to cause some of the wadis to flow for a short time. Considerable damage was caused to the new low-cost houses, walls were pitted by the hailstones, almost all the 'barasti' huts were blown down, and numbers of palm trees were uprooted. The storm was succeeded by a very humid and calm evening whilst a thick fog, with visibility down to 50 m in places, occurred on the following morning, not dispersing until about 0800 h.

Rainfall on 24 July was much lighter and the amount that fell was not measurable in the gauge at Jahili Fort. The rain was brought about by the movement north-eastwards of the intertropical convergence zone (ITCZ) which was almost directly over Buraimi, whilst the seasonal low pressure over southern Iran had extended southwards. In contrast to the other two days on which rain fell, precipitation did not occur until 2300 h.

At the end of July, the main centre of low pressure over central Iran was reinforced and induced a strong 'shamal'. The light rain that fell was possibly the result of a convection storm developing over the mountains. Although only a few drops of rain fell on 30 July at Buraimi, heavy falls were recorded in neighbouring parts of Muscat territory. Although no temperature records are available, the 30th, like the other days on which rain fell, appeared to be hotter than average. The incidence of a strong 'shamal' and the increased heating of the rocks would provide additional uplift over the Hajar Mountains to the moister air from the Arabian Sea monsoon, resulting in the development of a convection storm.

It is considered that a number of factors contribute to summer rainfall in the Buraimi area. These include :

(i) *The presence of moist unstable air.* Tephigrams showed that on the days that rain fell at Buraimi there was moist unstable air over both the Persian Gulf and the Arabian Sea.

(ii) *Rainfall from middle-level ITCZ cloud.* Such rainfall is usually light and brought about by strong advection.

I should like to acknowledge the information and help provided by Mr K. W. J. Wood, Meteorological Officer, R.A.F. Sharjah, and by Mr J. P. Dixon, R.A.F. Muharraq, as well as the helpful advice of Dr K. Smith.

551.509.324.2:551.509.542

MAPPING SPATIALLY SMOOTHED RAINFALL

By D. J. HOLLAND and JENNIFER M. NOAD

Summary. In the course of verifying numerical forecasts of rainfall, the details of rainfall within a square of side about 100 km have to undergo spatial averaging in order to obtain a grid-point value representing the rainfall over the square. Rainfall for 24 h starting at 0900 GMT are available for a close network of stations over Britain and a set of values can be estimated (subjectively or by computer) at points on a subgrid of grid length 10 km. These estimates can then be averaged over the larger squares of an 'interpretation grid' of grid length 100 km. The average of each square is then allocated to the central grid point.

In practice there is a requirement for mapping rainfall for, say, 24 h starting at 0000 GMT (i.e. 'civil day' rainfall). Measurements are available from autographic records for such 24-h totals but only from a sparse network of stations. However, the ratio *(CD/RD)* of 'civil day' rainfall to 'rainfall day' rainfall, for instance, has a fairly smooth pattern which can be interpolated despite the sparse network. Each measurement of *RD* can then be converted to a *CD* measurement by multiplying by the interpolated *CD/RD* ratio, and a detailed map can be produced for 'civil day' rainfall.

The causes of some discrepancies are discussed.

Introduction. In the course of interpreting numerical predictions of weather in general, and of rainfall in particular, it is necessary to think in terms of values for grid points or grid squares, bearing in mind that the computations implicitly treat the numbers as if they behaved like grid-square averages.

When dealing with patterns of pressure it is usual to gloss this over, because even on a plotted chart of 'actual' sea-level pressure the 'noise', i.e. the ups and downs on subgrid scales, is filtered out by the conventional free-hand drawing of isobars. Much the same is true of isobaric contour heights, layer thicknesses and temperatures, whether drawn by hand or objectively analysed by machine.

Rainfall, however, has hitherto tended to be viewed differently, its fluctuations on the subgrid scale being too big and too interesting either to be dismissed as mere 'noise' or to be filtered out in practice by free-hand drawing. Here the grid-square discipline is new and unfamiliar. A numerical forecast of rainfall, nominally for a grid point, is really telling us something about the spatial mean over quite a big area around, and in the course of relating this to the actual events we must get to know both how the spatial mean rainfalls organize themselves on synoptic scales and how they tie up with the subgrid details. In particular, in the course of research and development in this context, subgrid details of actual 24-hour accumulations of rainfall in the region of the British Isles have had to undergo accurate spatial averaging over unit squares of a grid with a grid length of about 100 km. Although future work of this kind may become computerized, it has been pioneered by hand with procedures whose achievement in quality control is probably unique. These procedures are the subject of this article.

Some particular requirements. A particular project will now be described in order to make clear what is entailed in dealing with spatially smoothed rainfall. The grid framework was already laid down and the manner in which it lay obliquely across the country is clear from, for example, Figure 2. Rainfall figures were required for as many of the squares as would be compatible both with a high standard of quality control of the rain data and with ready access to a quality-controlled version of the data in a form handy for mapping. Moreover, the squares chosen were to suffice for several 24-hour periods, most of which happened to be 'civil days', i.e. starting at 0000 GMT, whilst two started at 1200 GMT. Figures for the corresponding 'rainfall days', starting at 0900 GMT, might serve as intermediaries but were not called for as end products.

In respect not only of quality control and of spatial profusion but also of ready access, the rain-gauging network of the United Kingdom ousted all others from practical consideration. Since its processing by computer is adequately described by Bleasdale and Farrar,[1] no elaboration is required, apart from emphasizing that the taped data are nearly all 'rainfall day' totals, as there are as yet comparatively few tapes with rain data in other time steps. Even when only 24-hour totals are required, autographic records are needed whenever the starting time differs substantially from 0900 GMT. Quality-controlled tabulations from autographic records are readily available but only from a sprinkling of stations, a sparse network by U.K. standards. Because of the starting time of 0000 GMT or 1200 GMT for the selected occasions, recourse would at some stage have to be made to this sparse network; and, in the absence of a full set of tapes, even for this network it would be necessary to some extent to work direct from hand-written tabulations.

The sparseness of this network presented a problem because much of the subgrid detail, particularly in the uplands, slips through such a network unnoticed. Only the 'rainfall day' network picks up this kind of detail and so a procedure had to be designed that would exploit the resolving power of the main network whilst geared in time to the sparse one.

The link that was used was simply to compare, at each station of the sparse autographic network, the recorded rainfall for the 24 hours from 0000 GMT (or, on two of the occasions, from 1200 GMT) with that for the 24 hours from 0900 GMT. It was anticipated that this 'civil day' to 'rainfall day', or *CD/RD*, ratio would not in general be very sensitive to the orography or to the subgrid-scale structure of the rainfall but would reflect rather broadly the time sequence of the rainfall's development, and that on a map this would give the ratio a fairly smooth pattern that could be interpolated despite the sparseness of the network. In particular, of course, if the rain all fell within the 15-hour overlap period, the ratio would be exactly 1, while on the noon-to-noon occasions the ratio would duly be 1 wherever the rain all fell in the 21 hours from noon. Corresponding interpolation on the *RD* or main-network map would, meanwhile, be quite good because of the network's profusion and so the sparsely-gauged *CD* map could be filled in by multiplying the *RD* value for the required position by the *CD/RD* ratio interpolated for that position. This multiplication, strictly speaking, ought to precede the spatial averagings and provision was made for operating in this way now and then, as for example in the Devon area on the specific occasion discussed later. In general, however, it was considered acceptable to do the spatial averagings before the multiplying.

In the absence of rain-gauging at sea, the only eligible grid squares would be those lying largely or wholly inland. In interpreting the word 'largely' no formal pass level was set because the reliability of offshore extrapolation would naturally vary with synoptic situation and with how much of the inland rainfall pattern was effectively orographic, e.g. being better in westerlies over the Thames estuary than over the Bristol Channel and Irish Sea. The 19 fully outlined grid squares that are shown on the maps represented the most that could qualify in general on this understanding, the south-easternmost being acceptable on most occasions despite going quite far out to sea. A few squares that extended comparably far out to sea in the west were to be taken into consideration later but were rated lower in reliability because even if offshore extrapolations across them could sometimes be good, there would often be situations in which they could not. These squares are shown in Figure 2 with pecked lines defining their western edges.

A specific occasion. One of the occasions dealt with, i.e. the 24-hour period from 0000 GMT on 8 September 1965, will now be used to illustrate the procedures which were evolved for obtaining the rainfall in the required form.

The original purpose of the work was to verify precipitation forecasts for grid points of the polar-stereographic grid of the 10-level atmospheric model described by Bushby and Timpson.[2] It was decided that each grid point should be made the centre of a square in a new grid called the 'interpretation grid' (see, for example, Figure 2) which is therefore virtually the same as the polar-stereographic grid except that it is displaced by half a grid length in each direction.

Each interpretation-grid square was subdivided into about 100 cells by subgrid points, 10 km apart, of the National Grid of the Ordnance Survey or of the Irish Grid in the case of Northern Ireland. Owing to differences between the two grids the number of National Grid points in an interpretation-grid square varies from 100 in Scotland to 93 in southern England.

The unsmoothed *RD* rainfall data were plotted on 1 : 625000 Ordnance Survey 'Ten Mile' maps of Great Britain. A similar map was plotted for Northern Ireland. To facilitate plotting, the data were printed out by computer complete with the National Grid References of the stations. Key maps of 'computer areas' were used as a check on the position of each station.

The plotted maps having been drawn up (Figure 1), an estimate was made for each subgrid point in every interpretation-grid square. These estimates were averaged in interpretation-grid square blocks, each such block average being the spatially smoothed rainfall for the square (see Figure 2). This value refers to the 'rainfall day'. As 'civil day' rainfall totals were required, a conversion was necessary, as indicated on page 41. To facilitate this, autographic data were used. Rainfall totals for the 'rainfall day' and 'civil day' were extracted from data of 78 autographic stations in the United Kingdom. The *CD*/*RD* ratio was computed for each station and plotted (Figure 3). The mean value of the *CD*/*RD* ratio was then estimated for each interpretation-grid square. In general, this was multiplied by the spatially smoothed *RD* rainfall for the square (Figure 2) to yield the spatially smoothed *CD* rainfall (Figure 4). A rough guide was provided by an auxiliary map of the *CD* rainfall for the 78 autographic stations. Big discrepancies occasionally occurred, however, for which there were two main causes :

(i) The autographic stations are usually found on relatively low ground, so that the amount of rainfall over a grid square containing mountains is often underestimated by the auxiliary map.

(ii) If there are places where the rainfall on the 'civil day' does not dominate that on the 'rainfall day', e.g. because heavier falls occur between 0000 GMT and 0900 GMT, the product of the averages of *RD* rainfall and *CD*/*RD* ratio can be misleading. The auxiliary map can help, though care is needed in judging the part played by (i). On 8 September 1965 the usual procedure markedly overestimated the *CD* rainfall over the Devon grid square. On this, and on other similar occasions, the grid square was subdivided and each subdivision was

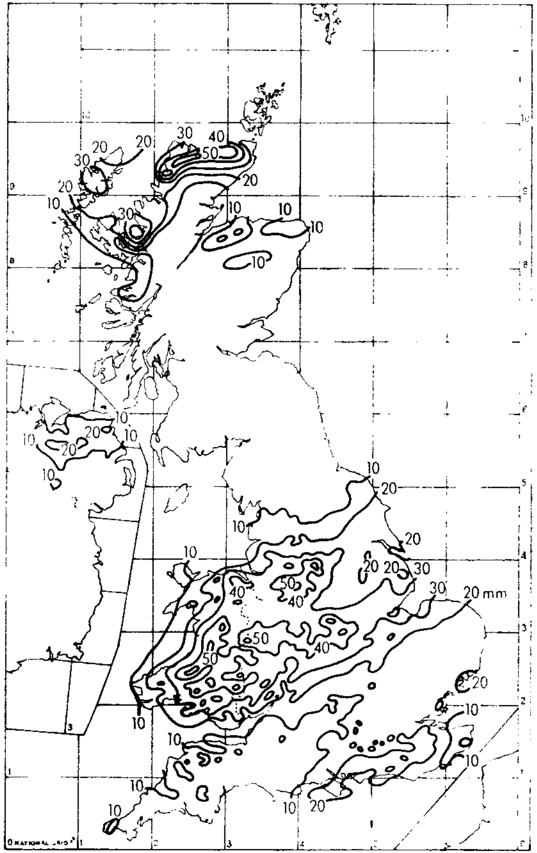

FIGURE 1—ISOHYETS OF THE UNSMOOTHED RAINFALL FOR 24 HOURS FROM 0900 GMT ON 8 SEPTEMBER 1965

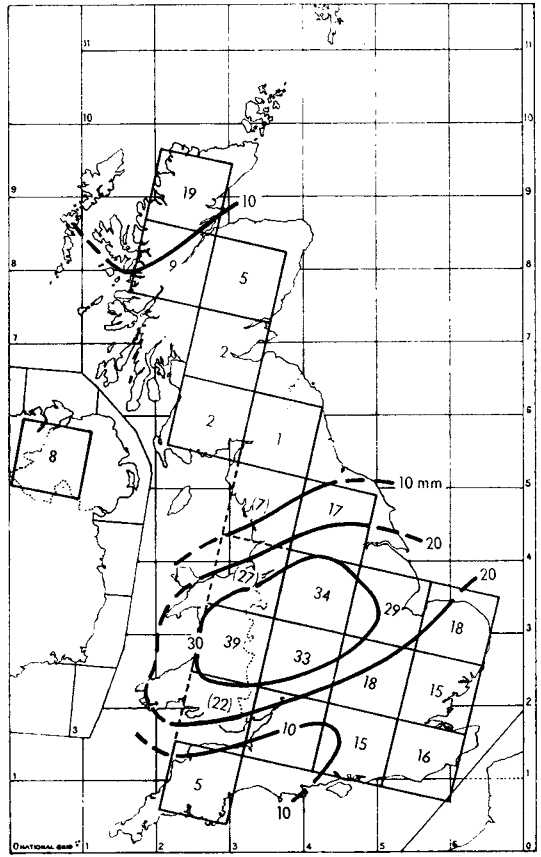

FIGURE 2—RAINFALL FOR 24 HOURS FROM 0900 GMT ('RAINFALL DAY') ON 8 SEPTEMBER 1965 AVERAGED SPATIALLY OVER INTERPRETATION-GRID SQUARES

Isohyets are of spatially smoothed 'rainfall day' rainfall. Values in squares are in millimetres.

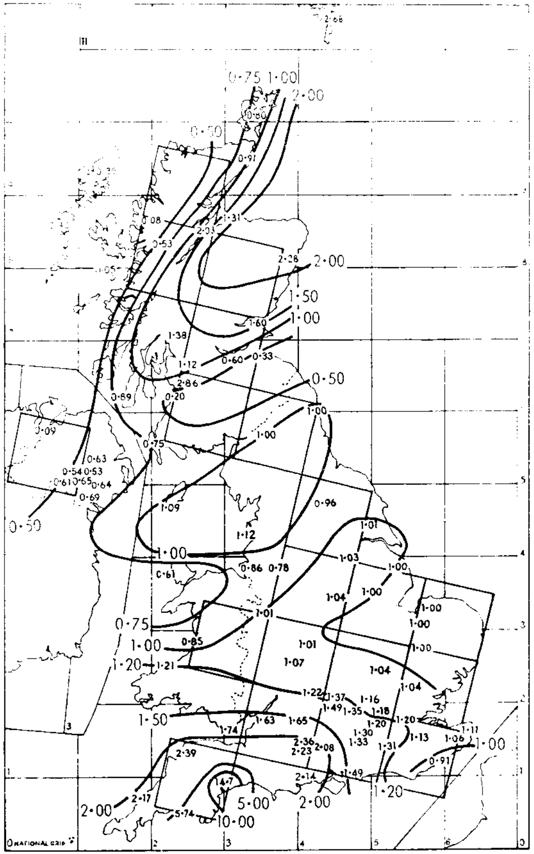

FIGURE 3—RATIO OF 'CIVIL DAY' RAINFALL TO 'RAINFALL DAY' RAINFALL ON 8 SEPTEMBER 1965

'Civil day' rainfall is for 24 hours from 0000 GMT on 8th and 'rainfall day' rainfall is for 24 hours from 0900 on the 8th.

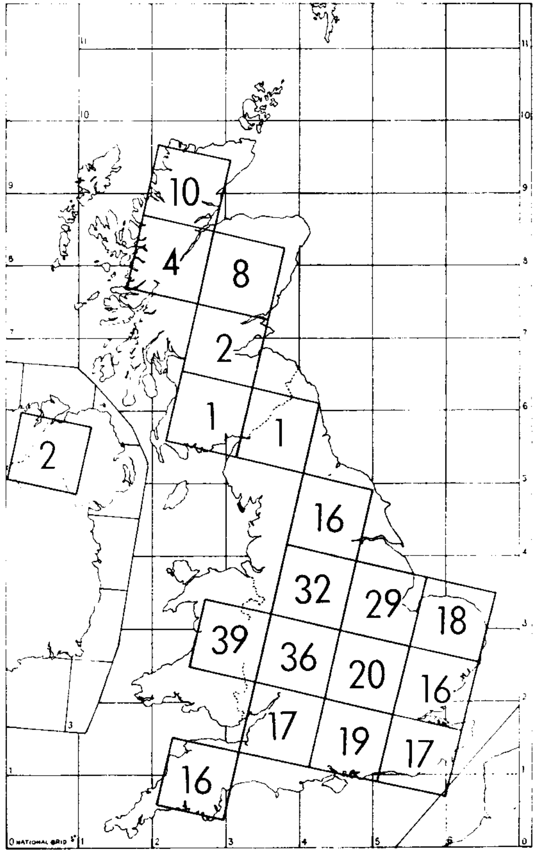

FIGURE 4—APPROXIMATE RAINFALL FOR 24 HOURS FROM 0000 GMT ('CIVIL DAY') ON 8 SEPTEMBER 1965 AVERAGED SPATIALLY OVER INTERPRETATION-GRID SQUARES

Values in squares are in millimetres.

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PLATE I—MAJOR AND MRS K. J. GROVES WITH WINNERS OF THE 1969 L. G. GROVES AWARDS

SAC Rogers and Squadron Leader H. E. B. Mayes are to the left and Dr K. A. Browning and Mr B. R. Kerley are to the right of Major and Mrs Groves (see page 57).

Photograph by R. K. Pilsbury

PLATE II—CIRRUS AND ALTOCUMULUS LENTICULARIS

Eight of these cirrus bands were formed to the north-west of Bracknell, Berks., on 25 April 1969 and they persisted from 1815 to 1900 GMT. Below six of the bands, small pieces of altocumulus lenticularis formed. The northern end of the bands was obscured by cirrocumulus which exhibited a billows structure at right angles to the bands.

Photograph by R. K. Pilsbury

PLATE III—WAVE IN CONDENSATION TRAIL

This trail, taken with the camera facing towards north-west from Bracknell, Berks., at 1800 GMT on 4 April 1967, was moving southwards and long thin streaks of cirrus formed behind it to the north. In this cirrus can be seen an extensive wave structure parallel to the trail.

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Photograph by R. K. Pilsbury

PLATE IV—WAVE CLOUDS

This display, to the west of Bracknell, Berks., was part of a very extensive wave system to the south and west of the area. It began to form around 1100 GMT, 20 August 1968, and persisted for at least an hour. There were fairly rapid changes in cloud shape to the west but to the south several complete waves similar to a sine curve persisted for some time.

assessed separately. If the technique is to be applied on a computer, or otherwise objectively, some method of picking out such areas will be required.

Comment. Not only does this system serve in checking numerical forecasts but it introduces a new form of rain-map interpretation which may be of interest to hydrologists, particularly as interpolation of rainfall to grid points is likely to be used increasingly in computer handling of rainfall data.

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551.588.6

THE EFFECT OF A SMALL UPLAND PLANTATION ON AIR AND SOIL TEMPERATURES

By K. SMITH
University of Durham

Summary. Some data were obtained to assess the moderating influence of forest cover on local temperatures. By using resistance thermometers continuous measurements of air temperatures at screen level (1·2 m) and of soil temperatures (at depth of 10 cm) were made during 1968 at a plantation site and at a neighbouring open site in County Durham.

Mean air temperatures (averages of the mean daily maximum and minimum) over the year or month showed little difference between the sites. The range of air temperature from mean monthly maximum to mean monthly minimum was less under forest cover than in the open. Soil temperatures at 10 cm at 0900 GMT under forest cover were higher in winter than those at the open site, and lower in summer. The mean diurnal range of soil temperatures was small but was less under forest cover than at the open site.

Introduction. One of the most important changes in rural land use during the present century has been the spread of upland afforestation in Britain, and there is now almost as much land under forest as there is land in the built-up areas.[1] It is frequently admitted that both afforestation and urbanization necessarily modify the local climatic conditions, and Chandler,[2] for example, has summarized the largely inadvertent consequences of the continuing expansion of Greater London. On the other hand, much less is known about the modification of rural topoclimates[3] by the spread of a forest cover. Some attention is now being devoted to the nature of the forest water budget, but the thermal implications of afforestation continue to attract relatively little interest.

Although some of the pioneer work in Europe on the climate of small areas was concerned with the broad temperature influence of forests,[4] this theme was never really taken up in Britain. Recent investigations, such as those of Hurst,[5] have dwelt on the air temperature stratifications developed below screen level in lowland plantations. Somewhat divergent views appear to be held about the overall thermal effect of mid-latitude forests as indicated by standard instrumentation. Thus, whilst it is generally accepted that afforestation reduces the range of air temperatures, some workers[6] claim that the mean monthly and annual values are also depressed relative to comparable sites in the open, and attention has been drawn[7] to conflicting evidence presented by experiments in the U.S.A. and Switzerland on the effect of afforestation on the range of variation of maximum and minimum temperatures.

There are few published studies available for Britain, and the work of Coutts[8] in upland Aberdeenshire, for example, is typically concerned solely with the forest environment rather than with local differences observed in relation to standard sites. In view of these deficiencies, it was decided to make some preliminary observations of air and soil temperatures under a small plantation in the northern Pennines.

Site and records. Continuous measurements of air and soil temperatures were made during 1968 at two adjacent sites located on a south-facing slope at an altitude of some 450 m above MSL in upper Weardale, County Durham. Site A was established near the centre of a small but compact plantation of Scots Pine *(Pinus sylvestris)* which covers an area of 0·03 km^2. During the period of the measurements the trees were mature, but the canopy had been thinned in places by wind-blow. Site B was set up some 80 m away with a fairly open aspect and 25 m distant from the southern edge of the plantation.

At both sites air temperature was measured in a standard screen 1·2 m above ground, whilst soil temperatures were recorded at a depth of 10 cm. The data were obtained as a chart trace using resistance thermometers and a Cambridge multi-point recorder, which was installed in September 1967. The thermometers were calibrated against a NPL (National Physical Laboratory) certificated thermometer, and the calibration was checked regularly during the period of observation since only small temperature differences were expected between the two sites.

Air temperature. Mean air temperatures (calculated as the averages of the mean daily maximum and minimum temperatures) were identical at 6·6°C for both sites during 1968. This reflects a similar coincidence for the individual monthly means, and it was only during October that the monthly values differed by as much as 0·5 degC. For four months of the year the plantation was colder than site B but, as shown in Table I, there were also equivalent periods of time when it was warmer than or at the same mean temperature as site B, and there was thus no evidence to suggest that forest values are consistently lower than those obtained from standard sites.

TABLE I—MEAN MONTHLY SCREEN TEMPERATURES

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
							degrees Celsius						
Site A													
Maxima	3·8	1·2	5·6	8·9	9·8	15·9	14·6	15·4	13·6	12·1	5·5	2·6	9·1
Minima	−0·4	−2·9	1·2	2·1	3·4	8·2	8·9	9·5	8·7	8·3	2·6	−0·6	4·1
Mean	1·7	−0·8	3·4	5·5	6·6	12·1	11·8	12·4	11·1	10·2	4·0	1·0	6·6
Site B													
Maxima	4·1	2·2	6·3	9·8	10·3	16·5	15·3	16·0	13·9	12·0	5·4	2·5	9·5
Minima	−0·7	−3·1	1·0	1·7	2·8	7·7	8·3	9·1	7·8	7·5	2·1	−1·1	3·6
Mean	1·7	−0·4	3·6	5·7	6·6	12·1	11·8	12·5	10·8	9·7	3·7	0·7	6·6

When mean monthly maxima and minima are considered, however, it is clear that the tree canopy does suppress the temperature range at site A. From Table I it can be seen that minima were higher at the plantation site in all months, and maxima were lower except for the last three months of the year. As might be expected, the largest differences in maxima and minima between the two sites occurred during the summer half-year, but there was no direct relation with the warmest months since these differences took place in April and September. The difference between minimum temperatures at the two sites averaged 0·5 degC through the year, and was slightly more marked and persistent than the discrepancy in maximum values. Nevertheless, this resulted in only minor variations in the incidence of screen frost as indicated in Table II.

TABLE II—NUMBER OF DAYS WITH AIR FROST

	Jan.	Feb.	Mar.	Apr.	May	June–Oct.	Nov.	Dec.	Year
Site A	16	28	11	10	4	0	3	15	87
Site B	16	29	11	10	4	0	5	18	93

Soil temperature. A comparison of soil temperatures at 10 cm depth revealed quite different characteristics since, for much of the year, there was relatively little diurnal variation at either site; the diurnal range was smaller in the plantation. The cumulative influence of altitude, low evaporation and frequent precipitation, which totals some 1650 mm per year, often produced waterlogging in the soil irrespective of vegetative cover. Under these conditions a surface water gley has developed at both sites, and it is likely that the thermal régime of this soil is as conservative as that of upland peat soils.[9] Consequently, it was considered more meaningful to compare 0900 GMT values of soil temperature rather than daily maxima and minima.

As with air temperatures, the annual averages were identical, but a clear seasonal difference emerged when mean monthly data were compared as in Table III. This shows that the plantation was warmer than the standard

TABLE III—MEAN MONTHLY SOIL TEMPERATURES

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						degrees Celsius							
Site A	2·6	1·7	2·9	4·4	5·8	10·1	10·8	11·8	10·5	9·6	5·2	3·0	6·5
Site B	2·6	1·4	3·2	5·4	6·9	11·5	11·2	11·9	9·8	8·3	3·8	1·5	6·5

site in winter and cooler in summer, with the largest differences occurring in December (1·5 degC) and June and November (1·4 degC). This seasonal variation resulted in a distinction in the phasing of the growing season at the two sites, with an earlier start at site B which was compensated by the prolongation of growing temperatures into November in the plantation as shown in Table IV.

TABLE IV—NUMBER OF DAYS WITH MEAN SOIL TEMPERATURES GREATER THAN 6°C

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Site A	0	0	0	11	10	30	31	31	30	31	4	0	178
Site B	0	0	1	14	19	30	31	31	30	26	0	0	182

In periods of settled weather the discrepancy between mean soil temperatures at the two sites commonly reached between 3 degC and 4 degC on individual days, and it was during dry spells in summer that the largest diurnal fluctuations also took place. This can be illustrated by the mean hourly values of soil temperature for the anticyclonic week from 13 to 19 June, which have been plotted in Figure 1 together with the corresponding air temperatures at site B. Apart from the greater diurnal range of the air temperature and the overall relative warmth of the soil at site B, where afternoon temperatures were almost 6 degC higher than in the plantation, the most striking feature of Figure 1 is the difference in amplitude between the soil temperature curves. Thus, the mean diurnal range of soil temperature at site A was less than half the 4·6 degC recorded at the standard site, whilst, somewhat surprisingly, the daily temperature cycle at site A appears to be phased about one hour earlier than at site B.

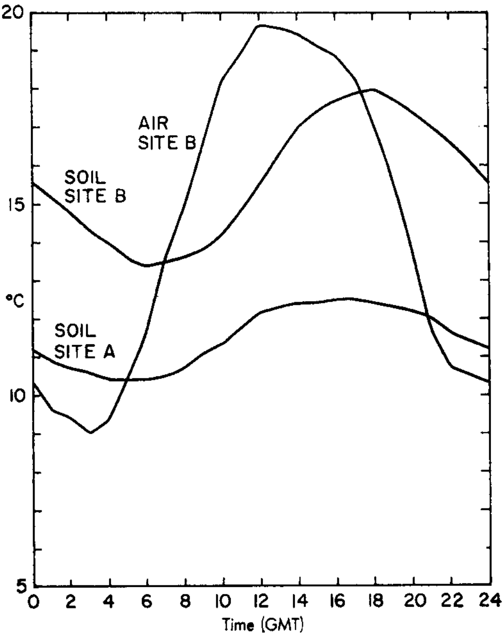

FIGURE 1—MEAN HOURLY SOIL TEMPERATURES AT SITES A AND B AND AIR TEMPERATURE AT SITE B FOR 13–19 JUNE 1968

Discussion. The evidence from this limited investigation suggests that despite the undoubted influence of a woodland cover in reducing the diurnal range of air temperature the suppression of soil temperature fluctuation is much more important and operates on a seasonal as well as a daily scale. This assumption was confirmed by employing the Kolmogorov-Smirnov test on the 366 daily values. It was found that, whilst no statistical significance could be attached to the differences in either maximum or minimum air temperatures between the two sites, the difference in mean daily soil temperatures reached the 0·99 level of significance.

In view of the growing interest in the land-use potential of the British uplands, it is becoming more and more necessary to have quantitative climatic data on which future policies may be based. This is especially so in the case of afforestation where more investigations are required, not only to determine the environmental limits for successful planting but also to assess the moderating influence which the forest cover exerts on the local climate.

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551.509.323:551.509.331

OCTOBER DAILY PRESSURES AND PRESSURE PATTERNS NEAR ICELAND RELATED TO TEMPERATURE QUINTILES OF THE FOLLOWING WINTER IN CENTRAL ENGLAND

By R. F. M. HAY

Summary. Daily data for October (1873–1962) suggest that mean pressures near Iceland over the period 11 to 15 October are significantly higher in that locality before extremely cold winters in central England than they are before extremely mild winters. Through the whole period for which daily records are available (going back to 1779, though with some gaps in the record), cold winters in central England have tended to be preceded by high pressure in Iceland during 11 to 15 October.

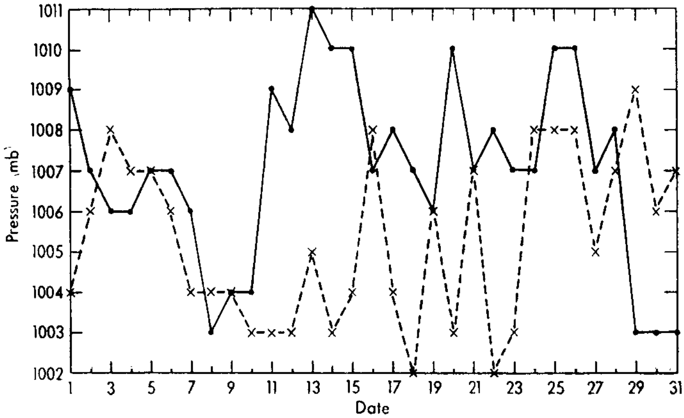
Cold winters in central England are also significantly associated with those preceding Octobers (1873–1962) in which anticyclone centres were formed on at least three days in a defined area near Iceland. A study of the day-to-day movements of anticyclonic patterns in October indicates an association between westward-moving patterns and very cold winters.

Introduction. In a previous paper[1] a relation between the occurrence of high monthly mean pressure near Iceland in October and very cold (T_1*) winters following in central England, was found for the period of blocked circulation which prevailed during 1873–95 and 1941–63. This note describes some results obtained by using daily sequences of pressure (instead of monthly mean pressures) near Iceland mainly for the Octobers between 1873 and 1962. The intention was to find whether the differences already found between mean October pressures before cold and mild winters in central England could be reasonably attributed to the incidence of one or more 'singularities' of the type described by Brooks[2] and others. It was considered possible that such a singularity might be disclosed by a tendency for it to recur at about the same period in October in a majority of the autumns preceding cold winters; whereas its absence or reversal at such time might be an indicator of a mild winter to follow.

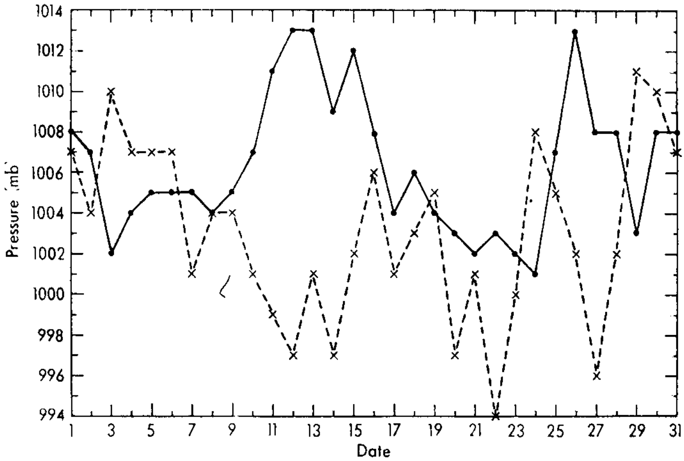
Daily mean pressures in October near Iceland. Daily pressures for the position 65°N 20°W were extracted from *Daily Weather Reports* for each day of October in the years 1873 to 1962 inclusive. From these data, mean values of pressure for each day of October were obtained separately for the groups of years associated with each quintile of winter temperature in central England. The same procedure was applied to the very coldest and very mildest winters, defined here as winters in the lowest (D_1) and highest (D_{10}) temperature decile, respectively.

Figures 1*(a)* and 1*(b)* show the variation of mean daily pressures in Octobers preceding T_1 and T_5, and D_1 and D_{10} winters respectively. The difference between the mean pressures for 11 to 15 October in the two groups of years

* The symbols T_1, T_2, etc., refer to quintiles 1, 2, etc., of winter temperature ranging from T_1 (very cold) to T_5 (very mild). Similarly D_1 and D_{10} refer to deciles of winter temperatures where D_1 is the low temperature decile and D_{10} is the high temperature decile.



(a) In Octobers preceding winters with temperatures in quintiles 1 and 5.
•———• Q_1 (17 years) x - - x Q_5 (19 years)



(b) In Octobers preceding winters with temperatures in deciles 1 and 10.
•———• D_1 (9 years) x - - x D_{10} (9 years)

FIGURE 1—MEAN DAILY PRESSURE AT 65°N 20°W IN OCTOBERS PRECEDING SPECIFIED WINTERS IN CENTRAL ENGLAND

associated with T_1 and T_5 winters in central England is not significant at the 5 per cent level using Student's t-test. However, a similar test using the two (smaller) groups of years associated with the extreme winters (D_1 and D_{10}) of the period just reaches significance at the 5 per cent level.*

The daily standard deviations (σ) were determined for 1, 16, and 31 October. The standard deviation of the difference of two means each formed from N independent values is $\sigma\sqrt{(2/N)}$. The standard deviations of differences of these means for the case where $N = 18$ (corresponding to 18 years in a quintile) were found for the same dates in October; the procedure was repeated making $N = 9$ (corresponding to 9 years in a decile).

* For 5 per cent level with 16 degrees of freedom, t should equal or exceed a value of 2·05.

Figure 2 shows the daily values of the differences between the means of daily mean pressure for years in D_1 and D_{10} (refer to Figure 1*(b)*). Dotted lines show the limits for values exceeding twice the standard deviation of differences of means, which by definition might be expected to occur by chance on 5 per cent of occasions, that is on about $1\frac{1}{2}$ occasions in a month. It was found that daily values of differences between T_1 and T_5 winters did not reach the relevant limits; Figure 2, however, shows that for a difference between D_1 and D_{10} winters the limit is closely approached on at least four consecutive days, and exceeded on one of the days in this series.

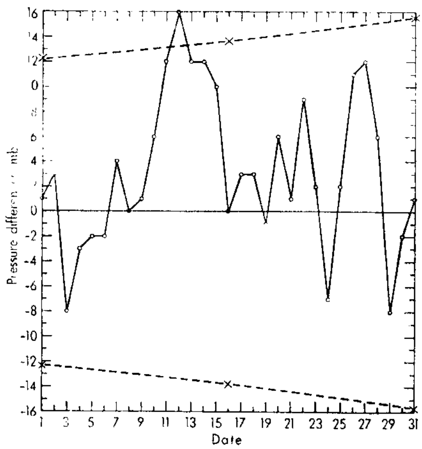


FIGURE 2—DIFFERENCES BETWEEN OCTOBER DAILY PRESSURES AT 65°N 20°W MEANED FOR OCTOBERS PRECEDING UNUSUALLY COLD WINTERS (D_1) IN CENTRAL ENGLAND AND THOSE MEANED FOR OCTOBERS PRECEDING UNUSUALLY MILD WINTERS (D_{10})

X Value of twice the standard deviation of differences of pressure means on 1 October (12·32 mb), 16th (13·73 mb) and 31st (15·69 mb).

Test on independent data. The results just described, supported by a further scrutiny of the data for the Octobers from 1873 to 1962, suggest the existence of a simple relation such that when mean pressure for 11 to 15 October is in the quintile P_5 of high pressure relative to the whole series† of these means for 1873–1962, then a very cold winter (T_1) is likely to follow in central England. Since independent data in the form of daily pressures for Iceland[4] are available for the periods 1779–84 and 1823–36, it was possible to compare these with temperatures for central England in the winters following, and so to test the validity of the relation described above. Freeman's method,[3] currently used in long-range forecasting at the Meteorological Office, Bracknell, was used for this purpose. For the long period 1873–1962 his methods yielded a score of +0·5, while for the two earlier short periods combined a

† The relevant quintile boundaries for this series are : $P_5 \geqslant 1015$ mb, P_4 1006–1014 mb, P_3 1000–1005 mb, P_2 995–999 mb, and $P_1 \leqslant 994$ mb.

score of +0·8 was obtained.* Both these scores rate as 'moderate agreement' between forecast and actual winter temperatures. Moderate agreement covers a range of scores from +1·4 to 0·0.

Although these results inevitably depend upon rather small samples (nine cases in the long period and five in the combined early short periods) they deserve to go on record because they imply that the relation just described, i.e. P_5 in Iceland for 11 to 15 October is likely to be followed by T_1 winter in central England, may well have been a stable one for at least the past 180 years.

The remaining period of independent data from 1963 to 1967 included no occasion when mean pressure at 65°N 20°W for 11 to 15 October was P_5. Hence it was not possible to test the validity of the relation during this short period.

Movements of centres of anticyclones near Iceland. The incidence and daily movement of anticyclones near Iceland during October were investigated in relation to the winters following in central England for the period 1874 to 1963. The procedure adopted was to note the daily positions and intensities of all anticyclone centres and ridges with pressure 1016 mb or more which lay within an area (Figure 3) defined by latitudes 60° and 70°N and longitudes 5° and 35°W. This information was then used to determine the day-to-day directions of movement of anticyclone centres and of ridges for all these cases. The incidence of directions of movement, related to winter temperatures following in central England, is shown in Figure 4*(a)* and *(b)*.

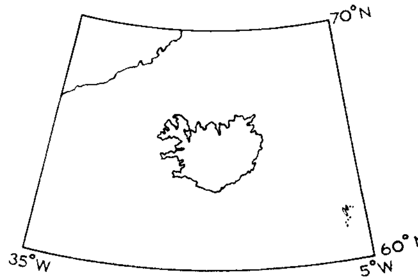


FIGURE 3—AREA NEAR ICELAND USED FOR MOVEMENTS OF ANTICYCLONES AND RIDGES

The bold numbers in Figure 4*(b)* indicate that the occurrence of anticyclone centres in the vicinity of Iceland in October is much more frequent

* In these early periods the number of forecasts of T_1 winters in the various categories of success was :

Category	Forecasts of T_1
A (no serious discrepancy)	2
B (good agreement)	1
C (moderate agreement)	0
D (little agreement)	2
E (no real resemblance)	0

The two winters with forecasts T_1 in category *A* were both extremely cold *(D_1)*, one being the only T_1 winter (also D_1) during the period 1823–36.

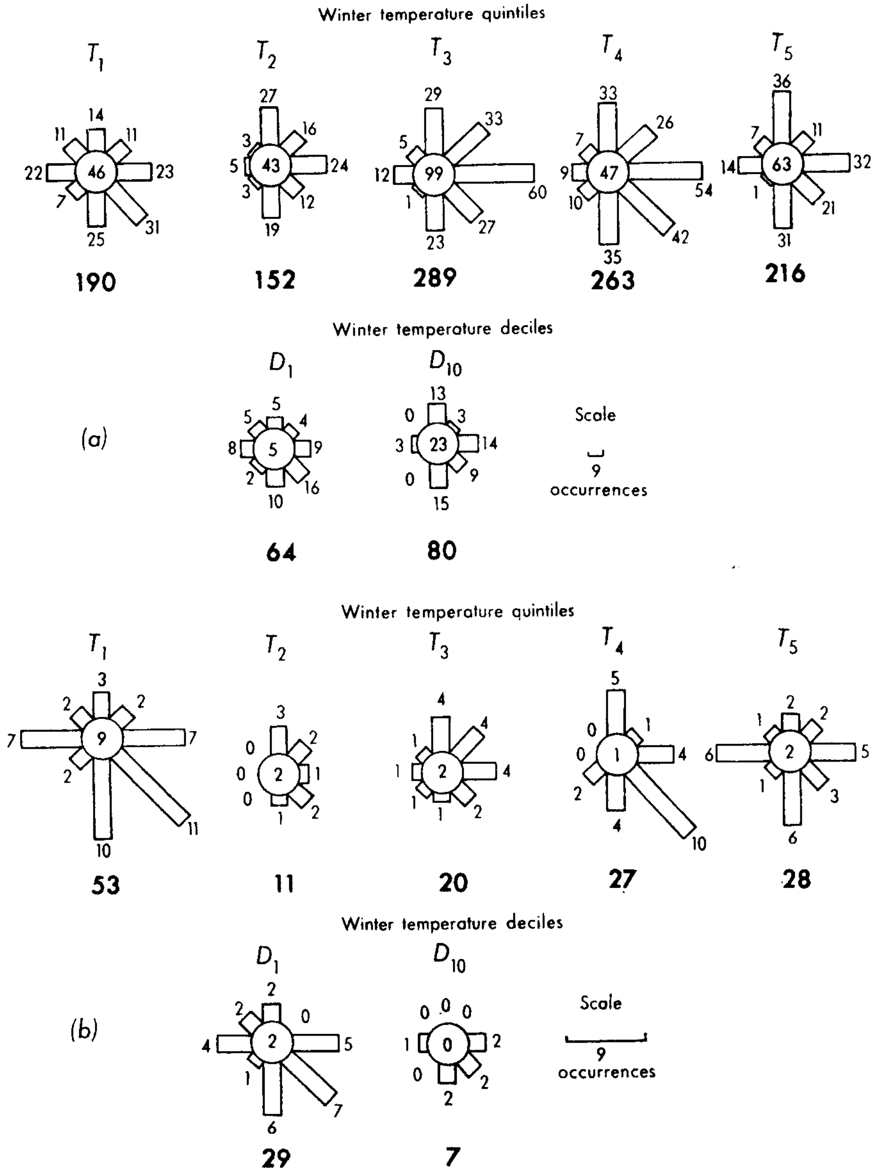


FIGURE 4—THE NUMBER OF DAYS OF OCCURRENCE OF MOVEMENTS OF ANTICYCLONIC PATTERNS NEAR ICELAND IN OCTOBER CLASSIFIED ACCORDING TO TEMPERATURE QUINTILES AND DECILES IN THE WINTER FOLLOWING IN CENTRAL ENGLAND

(a) Centres and ridges (top 2 rows) *(b)* Centres (bottom 2 rows)

The roses show the number of day-to-day movements in October of the anticyclonic patterns towards each direction. The central figures show the number of days when the patterns were stationary and the bold figures refer to the total number in each category.

before T_1 winters than before T_2, T_3, T_4 and T_5 winters. The contrast between D_1 and D_{10} winters is still greater in this respect.

The directions of movement of anticyclone centres and ridges can next be considered by extracting actual frequencies of day-to-day westward movements (i.e. towards south-west, west and north-west) and of day-to-day movements of all anticylonic patterns in all other directions, and relating them to the five temperature quintiles of the following winters as shown in Table I. A chi-square test applied to this 5×2 contingency table shows significance at the 0·1 per cent level, although this level is probably fictitiously high because of correlation between successive days of anticyclonic patterns in the Iceland area. Nevertheless this relation, implying a strong bias towards westward-moving anticyclonic patterns before T_1 winters, has a definite predictive value; it is not, however, easy to apply in practice because of the variation in the actual number of days of westward-moving anticyclonic patterns in October. The number can vary between 0 and 9 in Octobers before T_1 winters for example, with an average number of days of only 2·5. Other quintiles of winter temperature have even lower mean numbers of days with westward-moving anticyclonic patterns (2·5, 0·6, 0·9, 1·4 and 1·2 days in T_1, T_2, T_3, T_4 and T_5 winters respectively).

TABLE I—NUMBER OF DAYS IN OCTOBER WHEN ANTICYCLONIC PATTERNS MOVE TOWARDS SPECIFIED DIRECTIONS AND ARE FOLLOWED BY WINTER TEMPERATURES IN A GIVEN QUINTILE, 1873–1962

Direction of day-to-day movement of anticyclonic patterns*	Winter temperature (quintiles) 1	2	3	4	5	Totals
Towards SW, W and NW	40	11	18	26	22	117
All other directions	150	141	271	237	194	993
Total	190	152	289	263	216	1110

* Anticyclonic patterns include anticyclone centres together with ridges.
$\chi^2 = 29{\cdot}95$, which is significant at better than the 0·1 per cent level.

Also, from Figure 4*(a)* it can be seen that the main contrast between frequencies of day-to-day westward movements (i.e. towards south-west, west and north-west) of anticyclones and ridges near Iceland in October lies between Octobers preceding T_1 and T_2 winters in central England. Since contrasts between similar frequencies before T_1 and T_5 winters, and before T_1 and T_4 are less than the contrast between T_1 and T_2 winters, the T_1–T_2 contrast is of limited value as a forecasting tool. For frequencies of anticyclone centres only, Figure 4*(b)* shows broadly similar results.

There is some value in grouping stationary anticyclones along with those which showed day-to-day movements towards south-west, west, north-west, north and south, because such anticyclones are broadly associated with the incidence of the majority of large-scale blocking patterns in the northern Atlantic. Figure 4*(b)* readily shows that anticyclonic movements of this type occurred on 33, 6, 10, 12 and 18 days respectively before T_1, T_2, T_3, T_4 and T_5 winters, and on 17 and 3 days respectively before D_1 and D_{10} winters.

Table II shows the number of winters (central England) in each temperature quintile when anticyclone centres were found near Iceland during the previous October on at least 3 days, on 2, on 1 and on 0 days in the previous October.

TABLE II—NUMBER OF WINTERS IN EACH TEMPERATURE QUINTILE RELATED TO SPECIFIED NUMBERS OF DAYS OF OCCURRENCE OF ANTICYCLONE CENTRES NEAR ICELAND IN THE PRECEDING OCTOBER, 1873–1962

Winter temperature	Number of days with anticyclone centres in October					
quintile	$\geqslant 3$	$\leqslant 2$	2	1	0	Totals
5	4	15	1	9	5	19
4	5	13	1	1	11	18
3	2	17	2	6	9	19
2	2	15	1	3	11	17
1	11	5	1	1	3	16
Totals	24	65	6	20	39	89

A chi-square test shows that when Octobers having at least 3 days with anticyclone centres near Iceland (4, 5, 2, 2 and 11 cases in T_5, T_4, T_3, T_2 and T_1 respectively) are compared with Octobers having 2 or fewer days (15, 13, 17, 15 and 5 cases in T_5, T_4, T_3, T_2 and T_1 respectively), that is in the form of a 5×2 contingency table, the differences in the frequencies are significant at the better than 0·5 per cent level. Thus, Octobers with 3 days or more with anticyclone centres are strongly associated with T_1 winters to follow in central England.

Conclusions.

(i) Statistical tests made upon daily mean pressure values near Iceland for Octobers preceding anomalous winters during the period 1873–1962 (i.e. those having temperatures in the highest and lowest quintiles and deciles) show that daily pressure values in the period 11 to 15 October before extremely cold (D_1) winters in central England are significantly higher than those daily values found for the same period before extremely mild (D_{10}) winters. This result is also probably true for daily pressure values found for 11 to 15 October before T_1 and T_5 winters, but the available evidence is less conclusive.

(ii) Examination of daily data for Iceland from early years (1779–85 and 1823–36) suggests that high pressure (P_5) over Iceland during 11 to 15 October can be expected to be followed by a T_1 winter and that this relationship may have been stable during at least the past 180 years.

(iii) Anticyclone centres occur in the vicinity of Iceland on individual days in October much more frequently before T_1 winters than before T_2, T_3, T_4 and T_5 winters. The contrast between D_1 and D_{10} winters is still greater in this respect.

(iv) While day-to-day movements of anticyclonic patterns occurred towards all directions in October, westward movements were frequently followed by T_1 winters.

(v) Octobers having at least three days with anticyclone centres near Iceland are significantly associated with T_1 winters.

Acknowledgement. The writer wishes to thank Mr R. Blair for his assistance with processing the data.

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551.501.8:551.511.6:061.3

COLLOQUIUM ON THE SPECTRA OF METEOROLOGICAL VARIABLES

By C. J. READINGS

About 50 scientists from various disciplines attended a colloquium arranged by the Inter-Union Commission on Radio Meteorology and dealing with the spectra of meteorological variables. It was held in June 1969 just on the outskirts of Stockholm in a residential castle called Hässelby Slott. All the local arrangements were supervised by the Swedish National Committee of the International Union of Radio Science and the Committee must be complimented on the efficient manner in which both the conference and the social functions were organized. The latter included a boat trip round the Archipelago of Stockholm and an evening at the Drottningholm Court Theatre — quite apart from a cocktail party and a banquet.

As the participants were drawn from several disciplines (principally fluid dynamics, meteorology and wave-propagation) the first part of the conference was devoted to a series of reviews given by leading authorities in their fields and scientific sessions in which current work was described. During this part of the conference about 50 papers were presented. The topics considered were as follows :

(i) Experimental studies of atmospheric structure and spectra (both near the ground and higher up in the atmosphere).
(ii) Fine-scale structure deduced from wave-propagation experiments using radio, lidar, radar as well as acoustic and optical techniques.
(iii) Experimental and theoretical fluid dynamical aspects of turbulence and waves.

Most of the papers (and the reports of the working parties referred to later) will appear in the December 1969 issue of *Radio Science* (published in Washington D.C.).

A scientific visit to 'Kvarnberget' (a field station run by the Swedish National Research Institute to investigate radio propagation by tropospheric scatter) took place towards the end of this part of the conference. Amongst several interesting exhibits were some laser equipment for accurate survey work and an acoustic anemometer.

As the result of the discussions that took place between the delegates the following list of 'topics of interest' was drawn up :

(i) Intermittency of small-scale structure.
(ii) The spectral gap.
(iii) Fossilized turbulence.
(iv) The anisotropy of the fine structure.
(v) The boundary between laminar and turbulent flow.
(vi) Waves versus turbulence.
(vii) Heat, moisture and momentum fluxes in the boundary layer.
(viii) The budgets of kinetic energy and mean-square temperature fluctuations.

Each of these was allocated to a working group which continued the discussion during the next few days, and finally drafted a report summarizing findings and possible avenues of research. The final part of the conference was devoted to a detailed consideration of these reports by the whole assembly.

Attendance at this conference was a most rewarding experience for all the participants, as not only was a great deal of very interesting material presented but there was much invaluable discussion between scientists of different disciplines. However, it would perhaps have helped if the review sessions had been a little more introductory in nature.

AWARDS

L. G. Groves Memorial Prizes and Awards

The L. G. Groves Memorial Prizes and Awards for 1969 were presented at the Ministry of Defence, Whitehall, on 21 November 1969. Air Marshall Sir Peter Fletcher presided and the presentations were made by Major K. J. Groves, who was accompanied by Mrs Groves. (See Plate I.)

The Aircraft Safety Prize was won by Senior Aircraftman B. Rogers of Royal Air Force, Wildenrath. The citation reads :

> 'SAC Rogers has designed a standard personal survival pack which could replace the greater proportion of the twenty-odd different types of survival pack in current use. In addition, it would eliminate many of the unsatisfactory features which are present in existing equipment.
>
> SAC Rogers' design, the result of three years of research, will need careful evaluation under realistic service conditions and further development may be required. Nevertheless, the principle has been accepted and could well lead to much-needed standardization and greater simplicity in the servicing and training uses of future survival equipment for aircrew.'

The Meteorology Prize was awarded to Dr K. A. Browning, Principal Scientific Officer, Meteorological Office, with the following citation :

> 'In recognition of his work in determining the structure of the cloud and wind systems accompanying meteorological fronts and other rain and thunderstorms. By his effective use of a wide range of radar techniques and other systems for sounding the atmosphere, Dr Browning has been able to establish, for the first time, a comprehensive self-consistent description of the air motion in rain-producing clouds, and to relate this to the observed distribution of rain and hail. From the insight so obtained he has derived models of meteorological systems which will form the starting point for a comprehensive understanding of atmosphere disturbances with dimensions 10 to 100 km and thus form important benefits to aviation meteorology and forecasting.'

The Meteorological Observers' Award was given to Mr B. R. Kerley, Scientific Assistant, Meteorological Office, with the following citation :

> 'In recognition of the very high standard of observing which he has maintained during the flights by the Meteorological Research Flight which have often been arduous. Mr Kerley has been an observer with the Meteorological Research Flight for over four years and has flown over 350 hours on meteorological observer duties. In particular, Mr Kerley was observer on two flights conducted during project Scillonia in March 1968 and January 1969 when flying conditions were extremely bad, but

despite the physical difficulties Mr Kerley completed a set of observations which were required for the success of this unique project for the study of cloud systems.'

The Second Memorial Award went to Squadron Leader H. E. B. Mayes of Royal Air Force, Luqa, the citation reading :

'Since its introduction into service in 1960, the Canberra PR9 has been subject to frequent fuel pump failures which could lead to hazardous situations on long flights. Squadron Leader Mayes has applied himself with great diligence and perseverance to the problem. As a result of his investigations he recommended three modifications to improve the reliability of the fuel system and to remove the hazardous aspects. In directing his energies towards solving the problem, and by providing evidence in support of his proposals sufficient to prove their validity, Squadron Leader Mayes has made a direct and valuable contribution to flight safety.'

REVIEW

Aerology of the polar regions by S. S. Gaigerov. 247 mm × 177 mm, pp. viii + 280, *illus.* (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), Oldbourne Press, 1–5 Portpool Lane, London EC1, 1967. Price: 92*s.* 6*d.*

This important addition to the meteorological literature of the polar regions is one of the early fruits of the International Geophysical Year (IGY). The book is large in scope and deals in detail with most aspects of the polar circulations. Each chapter has separate sections dealing with the Arctic, then the Antarctic, followed by a brief comparison and summary.

Starting with a chapter on the development of aerological research in the polar regions there is a slight but natural bias towards Russian developments which shows an early and continuously active record in the Arctic during the 1930s when North American commitment was very limited. A balanced account of international development in the Antarctic concludes this section. The next section on the special features of investigation of the free atmosphere is a very interesting account of radiosondes, rockets and techniques used by the Soviet Union, which should be read by anyone involved in polar operations. The launching tower developed at Mirnyi is well worth investigation if, as is claimed, successful launches have been made on occasions when surface wind speeds were in excess of 35 m/s. Problems of hydrogen generation and balloon performance are also sensibly discussed.

From this point on, discussion of the polar circulation is developed. First comes a chapter on synoptic processes in the troposphere which begins with an account of investigations to 1962 and then goes on to discuss general physical, climatic and orographic influences and ends with a summary of seasonal processes. A full chapter is devoted to the vertical structure of depressions, anticyclones and fronts and it is interesting to note that the Fifth Soviet Antarctic Expedition (1960) deliberately organized chains of temporary stations to examine certain frontal features. A useful discussion on the contrasting thermal and wind regions of the Arctic and Antarctic follows.

The final extensive chapter deals with the stratosphere and includes a summary of the possible causes of the ozone distribution in polar regions and of the theories of radiational balance of the stratosphere and mesosphere. The inclusion of a limited amount of rocket data to 48 km for Kheysa (Hayes) Island in Franz Josef Land is most welcome. Analysis of IGY and post-IGY data leads to the conclusion that the lower Arctic stratosphere is strongly influenced by the troposphere with radiation control being restricted to the stratosphere above 30 km. Consequently the asymmetry of the Arctic troposphere extends well into the stratosphere in comparison with the Antarctic where radiation control is dominant and leads to a more symmetrical stratospheric circulation.

There is an extensive and wide-ranging bibliography of 418 references, the first 248 of which are to Russian publications. Four appendices of Russian Antarctic upper air statistics complete the volume. The translation is fairly good with a few lapses into quaintness which lead to obscurity of meaning, e.g. 'from up downward' (from above downward), 'from down upward' (from below upward), 'temperature course' (the variation of temperature), 'lowland snowstorms' (drifting snow*). The print is clear but the illustrations leave much to be desired, especially the photographs which are very poor. Frequently longitude and latitude markings are omitted from diagrams and the vertical cross-sections tend to be confusing.

The fairly comprehensive contents list heading the book is useful but it is a pity that there is no alphabetical index. This and the other shortcomings are minor blemishes in such a useful and comprehensive survey which should prove to be a standard reference for several years to come.

D. W. S. LIMBERT

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* See : World Meteorological Organization, International meteorological vocabulary, WMO No. 182, TP 91, Geneva, 1966.

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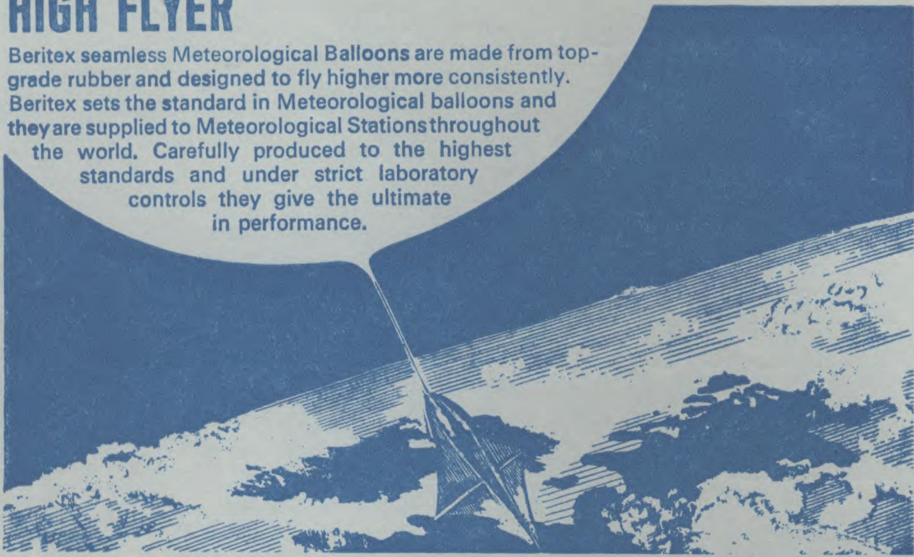

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A METHOD OF ADJUSTING SUNSHINE AVERAGES AT AN OBSTRUCTED SITE TAKING INTO ACCOUNT OBSTRUCTIONS AND DIURNAL VARIATION OF SUNSHINE

By D. F. FURMAGE

Summary. A method is given of adjusting the sunshine averages at a station where there is some obstruction of sunshine by obstacles, in order to obtain an estimate of what the averages would be at an unobstructed site in the vicinity. The method takes into account the diurnal variation of sunshine as well as the percentage of the sun's path which is obstructed.

Introduction. A considerable number of stations record the duration of bright sunshine by using a Campbell-Stokes or Universal Recorder. Summaries of their records are published in the *Monthly Weather Report,** and averages have been published for stations with a sufficiently long record.[1,2] Maps have also been prepared from these averages.[3] Several of these published records are annotated 'S' for some months, especially the winter ones. This annotation means that at the site of the recorder the direct sunshine is obstructed by some object which obscures more than 5 per cent of the sun's path above 3° elevation during the month but the published figures are not corrected for obstruction. (It is accepted as a general working rule that the sun will not cause a burn on the card in the recorder until it has risen more than 3° above the horizon.)

Ideally, the sun recorder should be placed so that buildings, trees, etc., never obstruct the sun when it has an elevation of more than 3°. In some cases this can be done by careful siting; sometimes the best site is on the roof of a building, but the card in the recorder must be changed daily and this restricts the choice of site. Unobstructed sites may be available in the vicinity but it may not be possible to provide adequate protection for the instrument and a partially obstructed site may have to be accepted. If there are permanent obstructions, usually in the form of trees or neighbouring buildings, the average durations of bright sunshine obtained from the recorder are not truly representative of the sunshine régime at an unobstructed site in the area. The following paragraphs suggest a method of making estimates of the corrections to be applied to the durations recorded at an obstructed site to make them representative of an open site in the vicinity. The starting point is the 'obstruction diagram' which is prepared for each obstructed site.

* London, Meteorological Office. *Monthly Weather Report.*

This gives the azimuth and elevation of all obstructions above 3° elevation, as seen from the sun recorder, between north-east and north-west through south. From this diagram and a knowledge of the apparent path of the sun at various times of the year it is possible to calculate the percentage of the daily duration during which the sun's rays cannot reach the instrument because of an obstruction. These percentages are calculated for all obstructed sites, by months, and they form the basis of the 'S' annotations in publications. However, these percentages, obtained by considering local obstructions, cannot be used directly to correct the recorded durations. Obstructions are normally relatively low in the sky and, as can be seen from Figure 1, less sunshine occurs per hour, at the unobstructed site at Eskdalemuir for example, during the early and late hours than during the intermediate hours. This means that less sunshine is lost than the percentage loss by obstruction would suggest, and if the percentages were applied to the recorded durations to obtain an estimate of the unobstructed durations, the result would be a considerable overestimate.

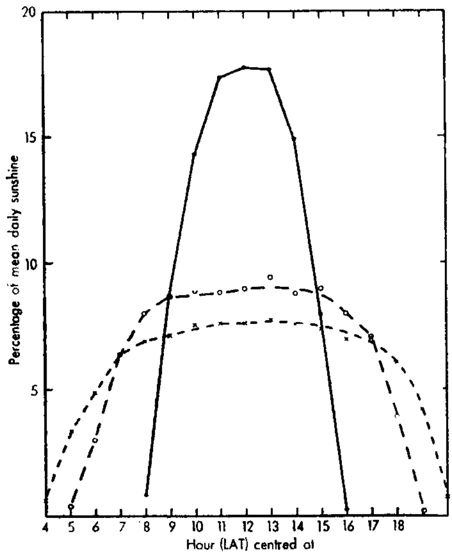

FIGURE 1—DIURNAL VARIATION OF SUNSHINE AT ESKDALEMUIR FOR THE PERIOD 1911–20

·———· January o—o—o April x– –x– –x June

The site at Eskdalemuir was unobstructed during the period 1911–20.

Method. To illustrate the method, the sun recorder site at Marchmont has been chosen (55°44′N 02°25′W, 498 feet above MSL). Marchmont, on the southern slopes of the Lammermuir Hills, has obstructions in every month of the year (see Col. 4 of Table I and Figure 2). The loss by obstruction at Marchmont, expressed as a percentage, is abnormally large, but until recently it was the only sun recorder in the lower Tweed valley and was presumably installed originally (1914) to fill a very large gap in the network. Until the end of 1966 it was used as a District Value Station in the *Monthly Weather Report* and the published monthly departures of sunshine duration from average probably had some real significance. However, the absolute values could not be regarded as representative of the open countryside around.

TABLE I—MARCHMONT SUNSHINE AVERAGES ADJUSTED FOR OBSTRUCTION AND DIURNAL VARIATION OF SUNSHINE AT ESKDALEMUIR

Month	Possible daily sunshine	Actual daily average	Actual monthly average	Loss by obstruc-tion	Loss adjusted for diurnal variation	Adjusted average sunshine Daily	Monthly
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
		hours			*per cent*		*hours*
Jan.	6·7	1·42	44	21·9	15·5	1·68	52
Feb.	8·7	2·16	61	29·9	20·2	2·71	77
Mar.	10·9	3·13	97	17·2	7·8	3·39	105
Apr.	13·2	4·74	142	5·9	3·0	4·89	147
May	15·0	5·55	172	6·5	2·9	5·72	177
June	16·1	6·00	180	6·3	1·2	6·07	182
July	15·6	5·00	155	5·9	1·4	5·07	157
Aug.	14·0	4·58	142	6·2	1·5	4·65	144
Sept.	11·9	3·91	117	10·3	3·2	4·04	121
Oct.	9·5	2·46	76	27·1	17·3	2·97	92
Nov.	7·1	1·57	47	26·1	19·9	1·96	59
Dec.	5·7	1·16	36	27·2	21·7	1·48	46
Yearly average		3·48		13·1	7·2	3·72	
Yearly total			1269				1359

The obstructions, as can be seen from the diagram in Figure 2 are in almost every direction. Though the elevations of the obstructions vary, a study of the obstruction diagram suggests that the sunshine lost by obstruction during any month may be roughly divided equally between the morning and the evening when the sun is at a low angle.

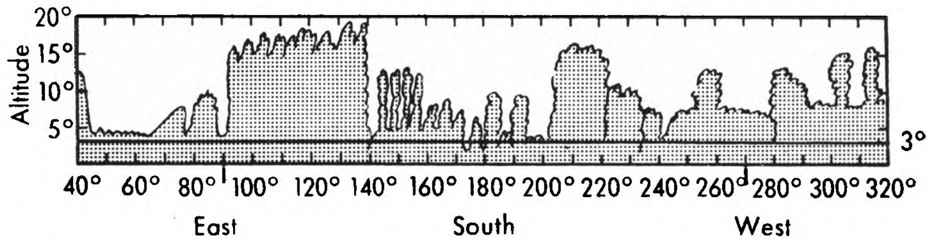

FIGURE 2—OBSTRUCTION DIAGRAM FOR MARCHMONT
Directions are true.

The first problem is to obtain a measure of the diurnal variation of sunshine in the area. Unfortunately very few stations with unobstructed sites measure hourly values of sunshine, and the nearest inland station to Marchmont for which hourly values of sunshine are available is Eskdalemuir (55°19′N 3°12′W, 794 feet above MSL). For some years the shelter belt of trees complicated the horizon of the sun recorder at Eskdalemuir, but there was no obstruction between the years 1911 and 1920 and it was considered that the data for these years would suffice to establish the general diurnal pattern. The mean hourly sunshine was expressed as a percentage of the mean daily sunshine and the values are given in Table II. The hours in the table are Local Apparent Time (LAT) and the percentage values refer to periods of 60 minutes centred at these hours. It might be thought that Eskdalemuir is rather remote fom Marchmont, but stations measuring hourly sunshine are so few that this is likely to be the situation in general and as is shown later the hourly percentage values are not too critical.

The procedure from this point is best illustrated by an example. From astronomical tables the mean daily number of hours of possible sunshine (sun

TABLE II—MEAN HOURLY SUNSHINE AT ESKDALEMUIR (1911–20) AS PERCENTAGE OF THE MEAN DAILY SUNSHINE

Month	Hour (LAT) centred at:																
	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
									per cent								
Jan.					0·8	8·8	14·4	17·4	17·8	17·7	14·8	8·0	0·3				
Feb.				0·3	5·4	10·7	13·1	14·6	13·7	14·2	13·0	9·7	5·1	0·2			
Mar.			0·1	4·1	8·1	10·0	11·1	12·0	11·5	11·5	10·6	9·8	7·6	3·4	0·2		
Apr.		0·4	3·0	6·4	8·0	8·6	8·9	8·8	9·0	9·5	8·8	9·1	8·0	7·1	3·9	0·5	
May	0·3	2·2	4·8	6·0	7·0	8·2	8·2	8·5	8·3	8·0	7·6	7·5	7·2	6·7	6·1	3·2	0·2
June	0·6	3·4	4·9	6·3	6·9	7·2	7·6	7·6	7·6	7·8	7·6	7·4	7·0	7·1	6·1	4·2	0·7
July	0·2	2·5	4·9	6·2	6·4	7·2	7·6	7·8	8·0	8·0	8·4	8·6	8·0	6·9	5·7	3·2	0·4
Aug.		0·8	3·1	5·5	7·5	8·1	8·3	9·4	9·7	9·2	9·1	8·6	8·5	7·2	4·1	0·9	
Sept.			0·5	4·1	7·5	9·5	10·1	10·3	10·4	10·5	10·8	10·2	8·9	6·0	1·2		
Oct.				1·5	7·8	11·6	12·2	12·0	12·8	12·7	11·5	9·9	7·0	1·0			
Nov.					2·0	10·5	14·8	15·9	16·0	15·1	14·2	10·0	1·5				
Dec.					0·1	6·2	15·2	18·5	20·1	18·8	15·3	5·8					
Year	0·2	1·2	2·7	4·6	6·6	8·6	9·6	10·2	10·2	10·2	9·7	8·7	7·0	5·3	3·4	1·6	0·2

above 3°) can be calculated for given latitudes. Column 1 of Table I gives the possible sunshine (above 3°) for 55°N.

The mean daily number of hours of possible sunshine in April is 13·2 hours; of these, the period 0530 LAT to 1830 LAT accounts for 13 hours, the remaining 0·2 hours occurring in the two hours centred at 0500 LAT and 1900 LAT. From Column 4 of Table I the percentage loss by obstruction of possible sunshine at Marchmont in April is 5·9 per cent; the number of hours in which obstruction is effective is 5·9 per cent of 13·2 hours = 0·8 hours.

From Table II, if the diurnal variation of mean hourly sunshine at Marchmont is the same as that at Eskdalemuir, the hourly percentages of actual mean daily sunshine are :

Hour (LAT)	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
Percentages	0·4	3·0	6·4	8·0	8·6	8·9	8·8	9·0	9·5	8·8	9·1	8·0	7·1	3·9	0·5

Therefore, if it is assumed that there is equal obstruction in morning and evening, the 0·2 hours possible in the hours centred at 0500 LAT and 1900 LAT correspond to 0·4+0·5=0·9 per cent of the mean daily sunshine and are assumed to be completely sunless. The 0·6 hours required to make up a total of 0·8 hours per day in which the obstruction is effective must come from the hours centred at 0600 and 1800 LAT. Assuming that in each of these periods centred at 0600 and 1800 LAT there is equal obstruction, then

$$0{\cdot}3 \times 3{\cdot}0 = 0{\cdot}9 \text{ per cent}$$

is the percentage loss in the hour centred at 0600 LAT and

$$0{\cdot}3 \times 3{\cdot}9 = 1{\cdot}17 \text{ per cent, or } 1{\cdot}2 \text{ per cent approximately,}$$

is the percentage loss in the hour centred at 1800 LAT.

Thus 0·2 hours correspond to 0·9 per cent loss
0·6 hours correspond to 2·1 (i.e. 0·9 + 1·2) per cent loss,
and therefore 0·8 hours correspond to 3·0 per cent loss.

The 5·9 per cent loss by obstruction is thus seen to correspond with a 3·0 per cent loss of actual sunshine.

In April the daily average recorded sunshine is 4·74 hours (from Table I). From the foregoing discussion it can be seen that this corresponds to only 97 per cent of the actual sunshine on average. Therefore the total sunshine for an unobstructed site at Marchmont is (4·74 × 100)/97 = 4·89 hours. If the loss of actual sunshine is assumed to be 5·9 per cent, the total sunshine would be (4·74 × 100)/94·1 hours, which is probably much too high.

The procedure was followed for each month of the year. The adjusted percentage losses of sunshine and the adjusted averages are given in Table I. If these adjusted percentages are used to correct the recorded durations at Marchmont for individual months before using the figures in preparing the monthly sunshine maps which are drawn as a routine for internal use in Meteorological Office, Edinburgh, some of the difficulties in drawing the maps disappear, especially in winter months when the loss by obstruction is large, and the Marchmont figures accord much better with neighbouring stations.

This affords some confirmation of the validity of the method, but as a further check Marchmont's actual and adjusted sunshine durations were compared with those recorded at Lauder over the period 1961 to 1966. The results are given in Table III. Lauder is an inland station fairly near Marchmont and with a similar situation (55°44′N 02°25′W, 550 feet above MSL). The site is unobstructed except in midsummer when a cottage cuts off a negligible amount of the evening sunshine. It will be seen from Table III that the adjusted Marchmont sunshine fits the pattern of Lauder's sunshine better than the recorded sunshine. Marchmont's actual sunshine in the least obstructed months is usually higher than that at Lauder, so it is to be expected that the adjusted annual total for Marchmont should be higher than that for Lauder.

TABLE III—COMPARISON OF THE ACTUAL AND ADJUSTED SUNSHINE AT MARCHMONT WITH THE SUNSHINE AT LAUDER, 1961–66

	MARCHMONT				LAUDER	
	Actual mean sunshine		Adjusted mean sunshine		Actual mean sunshine	
Month	Daily	Monthly	Daily	Monthly	Daily	Monthly
	hours		*hours*		*hours*	
Jan.	1·53	47·4	1·81	56·1	1·83	56·7
Feb.	1·89	53·2	2·37	66·7	2·37	66·7
Mar.	3·01	93·3	3·26	101·1	3·33	103·2
Apr.	4·33	129·9	4·46	133·8	4·37	131·1
May	5·95	184·4	6·13	190·0	5·93	183·8
June	5·58	167·4	5·65	169·5	5·15	154·5
July	4·77	147·9	4·84	150·0	4·81	149·1
Aug.	4·63	143·5	4·70	145·7	4·52	140·1
Sept.	3·73	111·9	3·85	115·5	3·80	114·0
Oct.	2·37	73·5	2·87	89·0	3·10	96·1
Nov.	1·73	51·9	2·16	64·8	2·30	69·0
Dec.	1·63	50·5	2·08	64·4	1·79	55·5
Yearly total	1254·8		1346·6		1319·4	

At some stations obstruction may occur only in the morning or only in the evening. The method can easily be adapted to meet this case. For the case of Marchmont in April, if it is assumed that all the 5·9 per cent obstruction occurs in the evening only, the calculation would proceed as follows :

number of hours of possible sunshine lost = 0·8 hours
0·1 hours now correspond to 0·5 per cent,
0·7 hours now correspond to $0·7 \times 3·9 = 2·73$ per cent,
i.e. 0·8 hours now correspond to 3·2 per cent,
and the adjusted daily average would then be 4·90 hours.

If there is an isolated obstruction in one direction only, the actual loss of sunshine has to be calculated in the same way using the obstruction diagram and the solar diagram giving the apparent path of the sun.

Pattern of diurnal variation of sunshine. Table IV gives the percentage hourly sunshine for Aberdeen, 1881–1910, when the only obstruction was a very thin flag pole. The table shows a marked similarity to Table II but the difference in the length of day makes a noticeable difference, especially in winter. Table V gives the adjusted actual monthly percentage losses based on obstruction losses of 5, 10, 15, 20, 25 and 30 per cent, when adjustment is

TABLE IV—MEAN HOURLY SUNSHINE AT ABERDEEN (1881–1910) AS PERCENTAGE OF THE MEAN DAILY SUNSHINE

Month	Hour (LAT) centred at :																
	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
									per cent								
Jan.						3·8	14·1	19·9	20·5	19·9	16·0	5·8					
Feb.					2·3	9·7	13·6	15·2	15·2	14·8	14·0	10·9	4·3				
Mar.			0·3	3·0	8·0	10·2	11·6	11·8	11·6	11·0	10·7	9·6	8·0	3·9	0·3		
Apr.		0·4	3·0	6·0	7·7	8·7	9·1	9·3	9·5	9·5	9·1	8·9	8·1	6·7	3·4	0·6	
May	0·2	2·9	5·3	6·2	6·9	7·4	7·7	7·7	8·1	7·9	8·1	7·9	7·5	6·7	5·8	3·4	0·3
June	1·2	3·9	5·2	5·9	6·4	6·9	7·1	7·4	7·6	7·6	7·7	7·4	7·1	6·7	6·1	4·5	1·3
July	0·8	4·0	5·4	6·4	7·1	7·3	7·3	7·6	7·8	7·6	7·6	7·3	7·0	6·2	5·6	4·0	1·0
Aug.		1·3	4·6	6·3	7·8	8·2	8·6	8·8	9·1	9·1	8·8	8·2	7·6	6·1	4·2	1·3	
Sept.			0·9	5·0	8·2	9·7	10·5	10·2	10·5	10·5	10·0	9·5	8·5	5·7	0·8		
Oct.				0·7	5·3	10·9	13·0	13·0	13·3	13·3	12·6	10·6	6·3	1·0			
Nov.					0·6	6·3	14·9	16·5	18·3	18·8	16·0	8·0	0·6				
Dec.						0·9	12·7	21·8	23·7	22·7	15·5	2·7					
Year	0·3	1·6	3·0	4·3	6·2	8·1	9·8	10·3	10·8	10·6	10·0	8·4	6·5	4·9	3·3	1·6	0·3

TABLE V—ADJUSTED MONTHLY PERCENTAGE SUNSHINE LOSSES FOR SPECIFIED PERCENTAGE LOSSES BY OBSTRUCTION

(a) Using the mean hourly sunshine at Aberdeen (1881–1910) and the solar diagram for Aberdeen

Month	Loss by obstruction (per cent)*					
	5	10	15	20	25	30
			per cent			
Jan.	2	5	7	10	15	20
Feb.	2	4	6	9	13	17
Mar.	2	4	7	10	14	19
Apr.	2	4	6	10	14	18
May	2	4	7	11	15	20
June	1	3	7	11	15	19
July	2	5	8	11	16	20
Aug.	2	4	7	10	14	18
Sept.	1	3	6	10	13	17
Oct.	2	5	8	10	13	18
Nov.	3	6	8	12	14	18
Dec.	3	6	9	13	17	21

(b) Using the mean hourly sunshine at Eskdalemuir (1911–20) and the solar diagram for Eskdalemuir

Month	Loss by obstruction (per cent)*					
	5	10	15	20	25	30
			per cent			
Jan.	3	7	11	14	18	23
Feb.	3	6	8	11	16	20
Mar.	2	5	7	10	14	18
Apr.	2	5	7	11	16	21
May	2	4	7	11	15	19
June	1	3	6	9	14	18
July	1	3	6	9	13	17
Aug.	1	3	6	8	12	17
Sept.	1	3	6	9	13	18
Oct.	2	5	9	12	16	20
Nov.	4	8	12	15	19	23
Dec.	4	7	11	15	20	24

* Samples of percentage losses by obstruction such as might occur at neighbouring obstructed sites.

made for diurnal variation of sunshine by using the hourly percentage figures for Eskdalemuir and Aberdeen and by assuming that the obstructions are at a low angle and are equally divided between morning and evening. The adjusted values for Aberdeen are more uniform throughout the year than are those for Eskdalemuir and the Aberdeen values tend to be lower than the Eskdalemuir values in the winter half of the year. At certain seasons in Britain an inland station such as Eskdalemuir will normally have clearer mornings and evenings than will a coastal station, with more cloud developing during the middle of the day. Therefore there is a tendency for the adjusted percentage loss to approach the loss by obstruction more closely at an inland station than at a coastal station.

The number of stations measuring hourly sunshine in Scotland is unfortunately limited and most of them are coastal or semi-coastal. The actual percentage losses for various percentage losses by obstruction in March were calculated for Benbecula (1957–67), Kinloss (1954–67), Stornoway (1954–67), Tiree (1954–67), Renfrew+Abbotsinch (1936–56) and Turnhouse (1951–66). In the calculations allowance was made for the fact that, since 1921, hourly values are measured for the 60 minutes ending at the exact hour LAT. March was chosen to avoid the complication of varying day length as the duration of possible sunshine above 3° elevation is 10·8 hours at all these stations in March. The results are given in Table VI. Considering the first five stations, which are all coastal, there is a variation of approximately 1 per cent from the mean figures 2, 4, 8, 10, 16 and 18 per cent. Tiree has the highest mean March sunshine of 116 hours (3·75 hours per day). An error of 1 per cent in an adjustment at such a station would amount to about 0·04 hours per day, which is well within the error normally expected in daily sunshine records, or a little over one hour in the monthly total.

TABLE VI—ADJUSTED MONTHLY PERCENTAGE SUNSHINE LOSSES FOR SPECIFIED PERCENTAGE LOSSES BY OBSTRUCTION IN MARCH, FOR VARIOUS STATIONS

Station	Period	Loss by obstruction (per cent)*					
		5	10	15	20	25	30
				per cent			
Aberdeen	1881–1910	2	4	7	10	14	19
Benbecula	1957–67	2	4	9	11	17	19
Kinloss	1954–67	2	4	8	11	16	18
Stornoway	1954–67	1	3	7	10	14	17
Tiree	1954–67	1	4	8	10	16	17
Eskdalemuir	1911–20	2	5	7	10	14	18
Renfrew+ Abbotsinch	1936–56	1	3	6	9	12	16
Turnhouse	1951–66	1	3	6	8	11	15

* Samples of percentage losses by obstruction such as might occur at neighbouring obstructed sites.

The figures for Renfrew+Abbotsinch and Turnhouse suggest that in the more industrial areas the pattern resembles that of a coastal station rather than that of a rural inland station.

General comment. If sunshine duration figures are required for an open site and it is known that the site of the nearest or most appropriate sun recorder is subject to some reduction of sunshine by local obstructions, an attempt must be made on an *ad hoc* basis to adjust the record from the sun recorder. Within its limitations, it is considered that the method described above will provide a better estimate of the true values than either the unadjusted values from the recorder or the values obtained by applying a percentage correction based on the percentage lost by obstruction. If a diurnal variation pattern appropriate to the area is chosen, the estimates should be a close approximation to the true values within the range of obstruction elevations normally encountered in practice. When the obstruction is caused by a major natural feature, e.g. a range of mountains, the same method could be applied to calculate the sunshine at a hypothetical open site, but it would not normally be appropriate to do so since the natural feature is relevant to the climate of the area.

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A RECORDING RESISTANCE PSYCHROMETER

By H. E. PAINTER

Summary. A continuously recording aspirated psychrometer is described which uses resistance elements as sensors. It records dry-bulb and wet-bulb temperatures to an accuracy of $\pm 0 \cdot 2$ degC.

History. During 1867 a photothermograph[1] was installed at Kew Observatory to record the dry-bulb and wet-bulb temperatures in a wooden louvered screen attached to the north wall of the Observatory. Until the end of 1968 a continuous record was obtained with this thermograph, and the dry-bulb and wet-bulb temperatures published for Kew over this period are the temperatures as recorded by this photothermograph. Two mercury-in-glass thermometers are used in the thermograph, one to measure the dry-bulb temperature and the other to measure the wet-bulb temperature. In each of the mercury columns of the thermometers is a small air bubble, and light from small lamps is projected, by means of a simple optical system, through the air bubbles and brought to a focus on to a sheet of photographic paper round a drum. The drum revolves around a vertical axis and is driven by clockwork; it makes one revolution in just over two days. A third light spot is also projected on to the photographic paper to produce a straight datum line when the chart is developed. The projection of the spots of light is so arranged that the resultant traces do not overlap. A shutter operated by the clock every two hours, intercepts the three light beams to give time marks on each trace. Each of the thermometers has a long stem bent twice at right angles to enable the bulb to be exposed outside the building in a screen whilst the vertical stem is inside the building within a light-tight room. Two large graduated thermometers having bulbs similar to those of the thermograph are mounted side by side and close to the thermograph bulbs. Control readings are taken six times daily from these thermometers for comparison with the corresponding thermograph readings. These control thermometers are periodically calibrated at the National Physical Laboratory.

Temperatures are measured from the photographic record with the aid of engraved glass scales appropriate to each recording thermometer. These scales are graduated so as to read temperatures vertically and time horizontally. The scales are set by the datum line on the thermograms, and after hourly readings have been obtained for the whole record comparisons are made with the readings from the control thermometers in the screen. The residual corrections so determined are applied to the tabulation. These corrections are necessary to take account of any expansion or contraction of the photographic paper.

This briefly describes the method employed for recording temperatures at Kew for the past century. The great disadvantage of the method is, of course, the poor and non-standard exposure of the thermometer bulbs. These are about 40 cm from an outside wall of a large building and about 3 m above a stone slab on the artificial mound on which the Observatory is built. The screen has only single louvers and there is no forced ventilation. The non-standard exposure of the north-wall screen has long been appreciated and comparisons have been made (by Whipple[2] for the years 1879–81, by Stagg[3] for 1923–26, by Drummond[4] for 1914–43 and by Chandler[5] for 1958–60) between temperatures from the north-wall screen and temperatures from other screens at Kew with better exposures; Craddock[6] has given a brief summary of such comparisons.

Requirements for a recording psychrometer. The replacement for the photothermograph was designed to satisfy the following requirements :

(i) The instrument should record the dry-bulb and wet-bulb temperatures of the air at the standard height of 1·25 m above a grass surface at an unobstructed site.

(ii) The thermometer bulbs should be aspirated.

(iii) The recording thermometers should be resistance elements recording on a self-balancing resistance bridge.

(iv) Reference mercury-in-glass thermometers should be used in conjunction with the resistance thermometers.

An unobstructed site at Kew was readily selected in the lawn area; underground cables from this site to the main Observatory building about 100 m away were used to connect the sensors to a self-balancing bridge recorder which measures the resistance of the temperature elements and plots the temperatures on a strip-chart.

There are two main reasons for associating mercury-in-glass thermometers with the resistance elements. Firstly, it was desired to use commercially available resistance elements and a commercially available recorder. The manufacturer's tolerance (that is, the allowable departure from the assumed resistance – temperature specification) for the resistance element is equivalent to a temperature difference of $\pm$ 0·6 degC. In addition, errors of up to 0·7 degC have been found in the scale of a recorder in use, and so it is possible at a particular point on the recorder that the true temperature of the element may differ from the indicated chart temperature by more than $\pm$ 1·0 degC. It is thus necessary to determine these differences and to supply corrections. The easiest way to do this is to have a reference thermometer in intimate thermal contact with the resistance element. Secondly, although these combined corrections (which will, of course, in general vary with the temperature) should remain constant with time, periodic readings of the mercury-in-glass thermometers enable any faults in the electrical system to be detected quickly.

Design of the thermometer bulb. To ensure that the resistance element and the reference mercury-in-glass thermometer are measuring the temperature of the same sample of air a special bulb has been designed and made at Kew in which the resistance element and the bulb of the reference mercury-in-glass thermometer are immersed one above the other in a mass of mercury contained in a stainless-steel tube closed at the lower end. By this means the two temperature sensors are in good thermal contact with each other and with the stainless steel, so that any temperature differences between the two thermometers must be very small and transient. The design of the complete bulb was influenced greatly by the need to make it suitable for use as a wet-bulb element in which it is important to ensure that the conduction of heat down the thermometer stem does not lead to unacceptable errors. To this end the open end of the steel bulb is screwed on to an extension tube, made of poorly conducting material. The stem of the reference thermometer is inserted into this tube which fits tightly enough to hold the reference thermometer bulb in the required position inside the steel bulb. The wet-bulb sleeving covers the whole of the steel bulb and a large part of the extension tube.

One of the bulbs of the psychrometer is shown in section in Figure 1. It is 12·7 cm long and 1·3 cm in diameter. The resistance element is made to British Standard Specification (B.S.S.) 2G148, with a nominal resistance of 130 ohms at 0°C and a change of approximately 0·5 ohms/degC. The leads of the resistance element are embedded in the walls of the extension tube so that this tube and the resistance element form a unit. The standard three-lead system[7] is used to connect the resistance element to the recorder, thus making the recording independent of the resistance of the connecting cable. Two leads are taken from the resistance element and enter the lower end of the extension tube. These two leads are embedded in small grooves in the tube and then emerge from the top. A third lead is also embedded in the tube and this lead is soldered to one of the resistance leads near the lower end of the tube to form the third compensating lead; this lead also emerges from the top of the extension tube. The resistance element and its leads are of course electrically isolated from the remainder of the bulb.

The mercury-in-glass reference thermometer is approximately 40 cm long with a maximum diameter of 6·5 mm, graduated from −10°C to 40°C in steps of 0·1 degC. The bulb of the reference thermometer and about 9 cm of its stem are inserted within the combined stainless-steel bulb and its extension tube. In the assembly of the complete bulb a small quantity of mercury is put into the stainless-steel bulb which is then screwed on to its extension tube. Care has to be taken that the level of the mercury is not above the top of the stainless-steel tube after the reference thermometer has been fitted otherwise the conduction of heat down the stem of the wet-bulb thermometer may be significantly increased to cause an error in the wet-bulb temperature.

Assembly of the psychrometer. The assembly of the various components of the psychrometer is shown in Plate I. There is a closed box from the lower

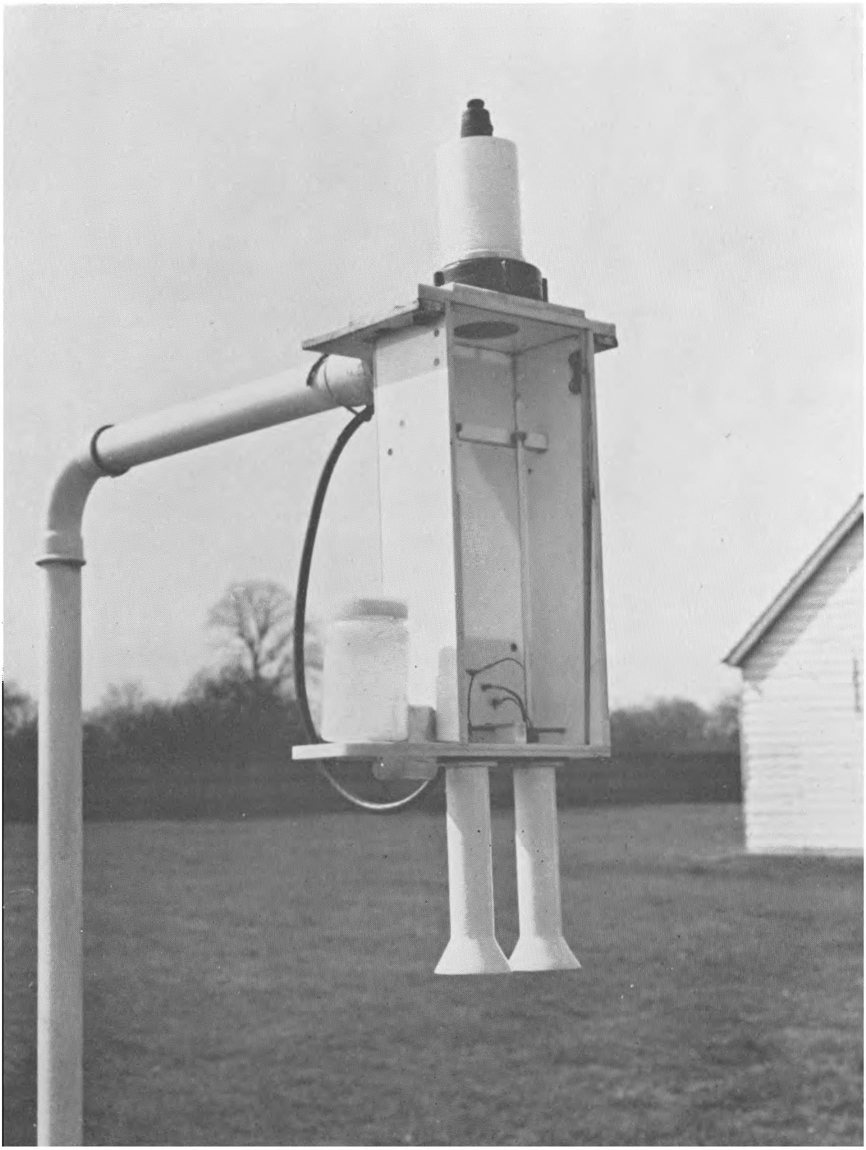

PLATE I—GENERAL VIEW OF THE RECORDING RESISTANCE PSYCHROMETER AT KEW OBSERVATORY

See page 70.

To face page 71

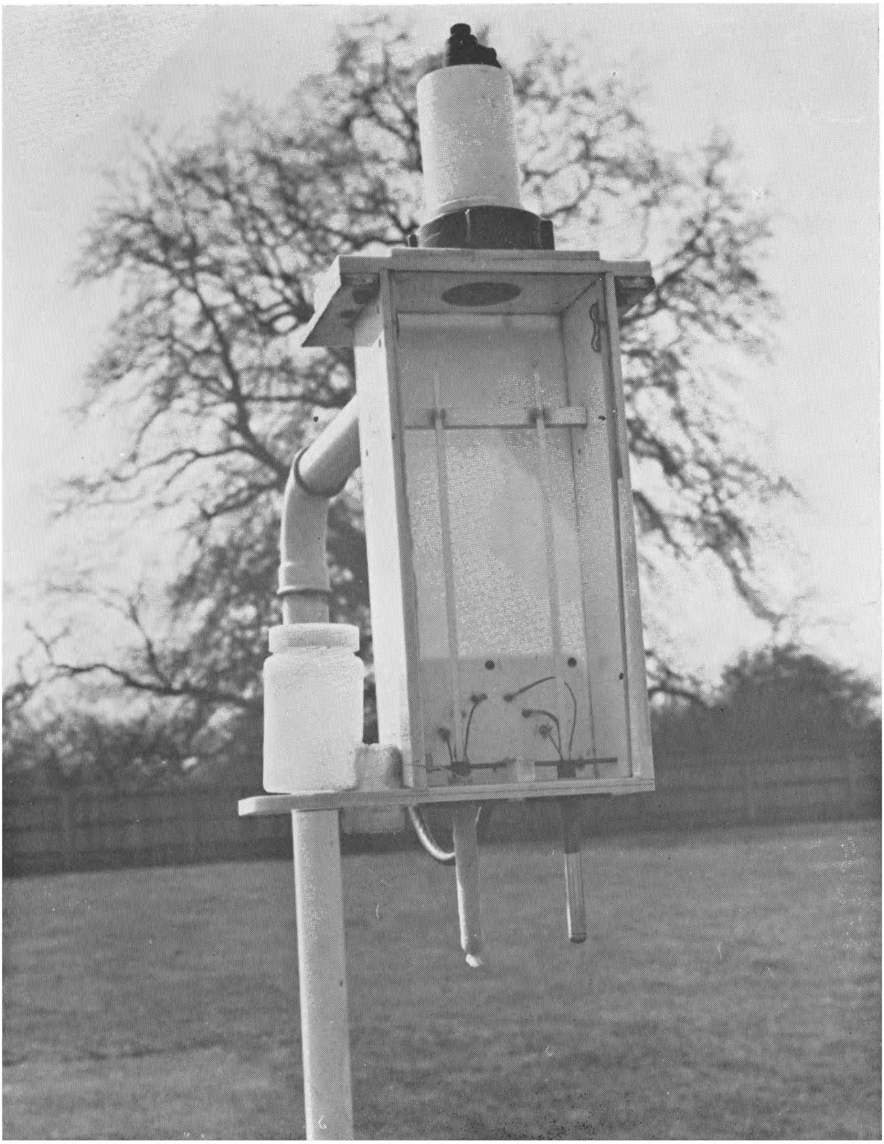

PLATE II—CLOSE-UP VIEW OF DRY-BULB AND WET-BULB THERMOMETERS WITH RADIATION SHIELDS REMOVED

See page 71.

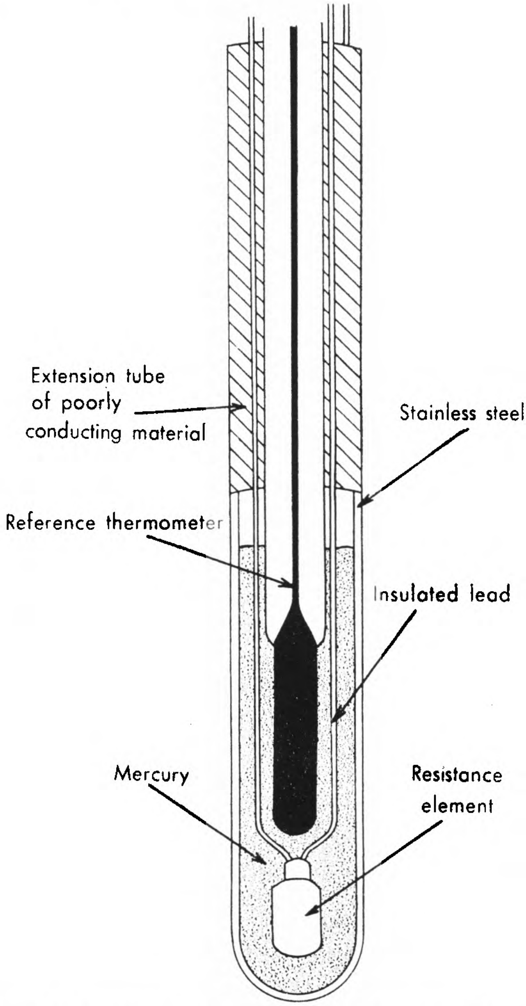

FIGURE 1—SCHEMATIC SECTION OF THERMOMETER BULB

end of which the two thermometer bulbs of the psychrometer project. Connected to the top of the box is a ventilation fan to provide the aspiration. The box is made of white opal material throughout except for the front panel which is clear so that the reference thermometers can be read. Access to the inside can readily be gained by sliding the front panel upwards.

Surrounding the thermometer bulbs are double-walled copper radiation shields through which air is drawn past the bulbs by the ventilation fan. The shields can be unscrewed from the base of the box. (See Plate II.) The lower end of each outer shield is flared outward in order to prevent the entry of rain with the aspirated air. The outside surface of the outer shields together with the inside surface of the flares are painted with white enamel; all the other surfaces of these double-walled shields are painted black. The position of each bulb relative to its radiation shield is of some importance since it is necessary to minimize the amount of reflected radiation from the ground that can directly reach the base of the bulb. The base of each radiation shield is 7·5 cm lower than the base of the associated bulb and experiments showed that at this distance the increase in the temperature of the bulb on a bright sunny day, due to reflected radiation from the ground, was less than 0·1 degC. Further tests showed that differences in the temperature reading due to variations in the long-wave radiation from the ground were undetectable.

To one side of the box is a platform on which stands the container for the distilled water. This container consists of two polyethylene bottles welded together so that water can flow freely from one to the other through a small connecting aperture; the larger bottle acts as a reservoir to maintain a constant water-level in the smaller one which is near the base of the large one. An outlet tube from the lower bottle extends to near the top of the bulb of the wet-bulb thermometer. This arrangement has the advantage that it is possible to fill the reservoir while it is still in position by temporarily inserting a small bung in the outlet tube and removing the screwed cap of the reservoir. The cap is fitted with a gasket so that when it is screwed to the reservoir a perfect air seal is obtained and hence atmospheric pressure acts to prevent an excessive flow of water to the smaller bottle. The covering for the wet bulb is a woven cotton sleeve cut to an appropriate length so that the bulb is covered to within 2 cm of its top. Threaded through the woven sleeve are three cotton strands which pass into the constant-level water container. It has been found that variations in the weave of the sleeving require changes in the number of strands threaded through it in order to maintain an adequate water supply to the wet-bulb. The best results are obtained with a sleeve with a tight weave. Plate II gives a close-up view of the psychrometer with the radiation shields removed from the bulbs. The wet-bulb sleeve and the distilled-water container can be seen.

The box containing the thermometers is mounted on a tubular iron stand, in the shape of an inverted L, so that the reference thermometers can be viewed from the north. This stand is painted white. The bases of the radiation shields are 1·25 m above a grass surface on an unobstructed site. The leads from the resistance elements are connected through the back panel of the box on to a cable which runs through the iron stand and then underground to the recorder in the main Observatory building. A second cable goes to the motor (30 volts a.c.) of the ventilation fan.

Care is needed regarding the general electrical insulation because an error of 0·1 degC will be introduced if a resistance of 350 000 ohms is placed across the resistance element. Such a resistance could easily be produced by water across any pair of uninsulated leads of the resistance element.

Characteristics of the psychrometer. Tests on the variations of wet-bulb depression with changes of voltages applied to the motor of the ventilation fan and hence changes of aspiration, showed that at 10-degC depression there was no change in the depression when the voltage was increased beyond 28 volts. The air speeds over the bulbs were determined by the hot-bulb method.[7] With 30 volts a.c. applied to the motor of the ventilation fan, the air speed past the thermometer bulbs was 13 m/s. The lag coefficients at this speed were 130 and 85 seconds respectively for the dry bulb and the wet bulb.

The aspiration at 1·25 m does not draw air from an appreciably lower level; smoke tests have shown that 6 cm is the greatest depth below the radiation shields from which air is drawn.

It was also shown that the temperatures obtained by the aspirated psychrometer were representative of temperatures at 1·25 m by comparing its temperature with those of a similar psychrometer placed horizontally with its air intake facing north at a height of 1.25 m; no detectable difference could be found between the minimum or other simultaneous temperatures measured by the two aspirated psychrometers.

The recorder. The resistances of the resistance elements are measured and recorded on a standard commercial multi-channel self-balancing resistance bridge which prints a reading from each channel every two minutes on a chart calibrated in temperature. The range of the chart is −30°C to +50°C and the speed used is one inch an hour. Time marks are made every hour by an auxiliary pen on the side of the chart which is controlled by a master clock in the Observatory. Three channels are used for recording, one each for dry-bulb and wet-bulb temperatures and a third channel to register the reading from a fixed reference resistor, corresponding to 30°C, of high stability with respect to both time and temperature. The trace from this reference resistor registers changes of expansion in the paper chart since the chart is positively located at the −30°C reading and is free to expand or contract at the +50°C reading. From the reading produced by the fixed resistor a proportional correction is found for any position on the chart.

To obtain temperatures from the recorder chart to an accuracy of 0·1 degC it is necessary to have a detailed calibration of the recorder obtained by applying resistances corresponding to temperatures at degree intervals. Such calibrations made on two recorders have shown that, after making the reading at 30°C coincident with the chart for that temperature, corrections of up to 0·7 degC were needed to the scale of the recorder chart at other points. These corrections moreover were very variable over the scale and in a 5-degC interval their value could change by 0·5 degC. Either by selecting recorders or by changing slide-wires it is possible to minimize the absolute values of the correction and also the rate of change of correction with temperature, but it is still necessary to know in detail the calibration of the recorder. With careful measurements a single determination of a correction at a particular point of the recorder scale can be made with a standard deviation of 0·05 degC.

Temperature control readings. In addition to corrections to the recorder there are also small corrections necessary because there are manufacturing tolerances on the thermometer resistance elements. To obtain the overall correction arising from both of these sources simultaneous readings are taken from the reference mercury-in-glass thermometers and the recorder. It has been found desirable to make consecutive readings (usually six) at two-minute intervals and from these the mean difference between the reference thermometer and the chart reading is evaluated. One person with a stopwatch can do this by first reading the reference thermometers at two-minute intervals and then returning to the recorder to obtain the corresponding chart readings. The reference thermometers are read to 0·02 degC and the recorder to 0·1 degC. The corrections thus obtained have to be combined with any chart corrections as shown by the record of the fixed resistor.

In a set of observations obtained in the manner just described an individual observation very rarely differs by more than $\pm 0{\cdot}2$ degC from the mean value of the set of six observations. The overall correction to a chart reading can be as much as $\pm 1{\cdot}0$ degC depending upon the resistance element in use. These corrections, of course, apply only for the particular time and temperature at which they are taken. With sufficient observations over an adequate temperature range, mean correction curves are obtained for the recordings of the dry bulb and wet bulb. These correction curves are similar in shape to (but with a constant displacement from) the correction curve obtained for the recorder by applying known resistances. Generally the overall chart correction is evaluated once a day by the method described above of taking the mean of six consecutive readings on the chart and simultaneous readings of the mercury-in-glass reference thermometer, so that any systematic difference from the correction curves can readily be discovered.

Over a period of several months the random error of the daily corrections from the mean correction curve was found to be approximately $\pm 0{\cdot}2$ degC. On 70 per cent of occasions however, the random error was within 0·1 degC. The random error is caused by the instability of the various components and by random errors in the eye readings of the thermometers and the chart.

The specification (B.S.S.) of the resistance elements requires that when they are cooled from 0°C to −80°C for 15 minutes and then restored to 0°C they shall return to their initial resistance to within the equivalent of 0·13 degC. Under the much less severe conditions in which the elements are used in the present psychrometer the stability is probably within $\pm 0{\cdot}05$ degC.

The accuracy of the reference mercury-in-glass thermometer is given on the NPL certificate as $\pm 0{\cdot}05$ degC, and there will be a small random error in the eye reading.

The random error contributed by the recorder amounts to about $\pm 0{\cdot}1$ degC and this is the major portion of the total.

Discussion. The resistance psychrometer has a greatly improved exposure compared with the photothermograph, and its record is immediately available instead of there being a delay of up to two days before a photographic chart is developed. The limitation of the resistance psychrometer lies in the accuracy and stability of the electronic recorder, and for the accurate recording of temperatures there is still the need to have reference mercury-in-glass thermometers, particularly as any slight adjustment to the electronic recorder may alter the corrections to the chart readings. The design of the complete bulb containing the resistance element and the bulb of the reference thermometer ensures that both types of thermometer are at the same temperature. The simplicity and durability of the recorder of the photothermograph is striking in comparison with the complexity of the electronic recorder and its requirement for regular calibration and servicing. At Kew a simple pendulum clock has driven the drum of the photothermograph for over a hundred years; it is too much to hope that a modern recorder will run continuously without replacement for a quarter of that time.

This resistance psychrometer in its present form was brought into use at Kew on 1 June 1966, and from 1 January 1969[8] it replaced the north-wall screen photothermograph as the official instrument at Kew for measuring dry-bulb and wet-bulb temperatures. The photothermograph will, however, continue to record for some further time to ensure that an adequate overlap of the two instruments is obtained so that the effect of the changes in instrument, site and exposure can be fully evaluated. To this end, hourly readings of dry-bulb, wet-bulb and the daily maximum and minimum temperatures from both instruments are measured and sent monthly to the Climatological Services Branch of the Meteorological Office for analysis.

The routine measurement of air temperatures for meteorological purposes with a continuously recording aspirated resistance psychrometer is an important change and a significant development from the long established method of temperature measurements in a naturally ventilated screen. This new psychrometer meets the general requirements specified by the World Meteorological Organization.[9] Similar recording resistance psychrometers were installed at Eskdalemuir and Lerwick Observatories in the early part of 1967 and after an overlap period with the screen temperatures it is intended that the new psychrometer will also become the standard instrument for measuring and recording temperatures at these places.

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TEMPERATURES IN HIGH SUMMER, AND HONEY PRODUCTION

By G. W. HURST

Summary. Honey production in Great Britain from 1929 to 1968 is considered in relation to summer temperatures, and close agreement is shown between good annual honey yields and high frequencies of days with temperatures above 20°C or 25°C in July (especially) and August. It is also shown that warm or hot days were more frequent in the two decades 1921–40 than since, or in many years before, and that the same has been true of warm spells at Kew. Brief comparison is made between early records of honey yields at Street, Somerset, and meteorological records for Bath. Finally, high correlation is shown between early stratospheric warming and high honey yields.

Introduction. In previous papers,[1,2] average monthly temperatures in spring and, more especially, in summer were considered in relation to honey production from 1928 onwards, and a strong relationship was established between average temperatures in the months of July and August and honey yields in the same year; naturally, high temperatures and good yields went together. Examination of climatic records indicated that the years 1931–50 represented 20 years with unusually high summer temperatures.

A disadvantage of this analysis is that the particularly warm days when the bee activity may be great are not taken into account; occasionally a month can enjoy above-average temperatures in rather dull weather with few really warm or hot days.

Another approach to the problem was therefore made by considering the number of days in particular months in the period 1928–69 when the maximum temperature exceeded levels of 20°C, 25°C and 30°C for a number of scattered localities in Great Britain and Northern Ireland. As before, the honey data for 1928–68 were those provided for Great Britain by courtesy of the Bee Farmers Association.* For many purposes it has been convenient to consider good and bad honey years. Good years were taken as those with a national average yield of over 62 lb of honey per hive, and bad years with less than 18 lb per hive; the actual years are listed in Table I. It was found in practice that the frequency of summer days with temperatures above 30°C was so low as to be uninformative; interesting results have emerged however from consideration of temperatures above 20°C and above 25°C.

TABLE I—COMPARISON OF FREQUENCIES OF TEMPERATURES ABOVE 20°C AND ABOVE 25°C AT KEW IN YEARS OF HIGH AND OF LOW HONEY YIELDS IN THE PERIOD 1928–68

Year	Honey yield per hive *lb*	Days with temp. above 20°C July	Days with temp. above 20°C Aug.	Days with temp. above 25°C July	Days with temp. above 25°C Aug.
(a) Years of high honey yield (over 62 lb per hive)					
1928	90	24	15	9	1
34	65	30	20	14	1
35	75	27	24	10	9
40	80	11	22	1	3
47	95	21	29	9	14
49	70	27	27	13	7
55	75	25	23	10	8
59	65	25	26	11	9
Average	76·9	23·7	23·3	9·6	6·5
(b) Years of low honey yield (less than 18 lb per hive)					
1930	15	14	15	1	5
36	10	10	19	0	5
48	15	11	9	5	1
53	15	9	22	0	3
54	10	7	7	0	0
58	10	18	12	2	1
63	16	14	9	4	0
65	10	10	18	0	0
Average	12·6	11·6	13·9	1·5	1·9

Frequency of temperatures above 20°C and above 25°C. The pattern of monthly relationships between honey yield and days with temperatures above 20°C and 25°C did not differ greatly amongst the six or seven stations considered in the U.K., and the results for Kew in the south-east and Cockle Park in the north-east of England are shown in Figure 1. The difference

* Sugar for Commercial Bee-keepers. An unpublished report issued by the Bee Farmers Association; sight of this report may be obtained by reference to the Secretary, Mr H. C. Hilder, Brunswick House, Church Laneham, near Retford, Notts.

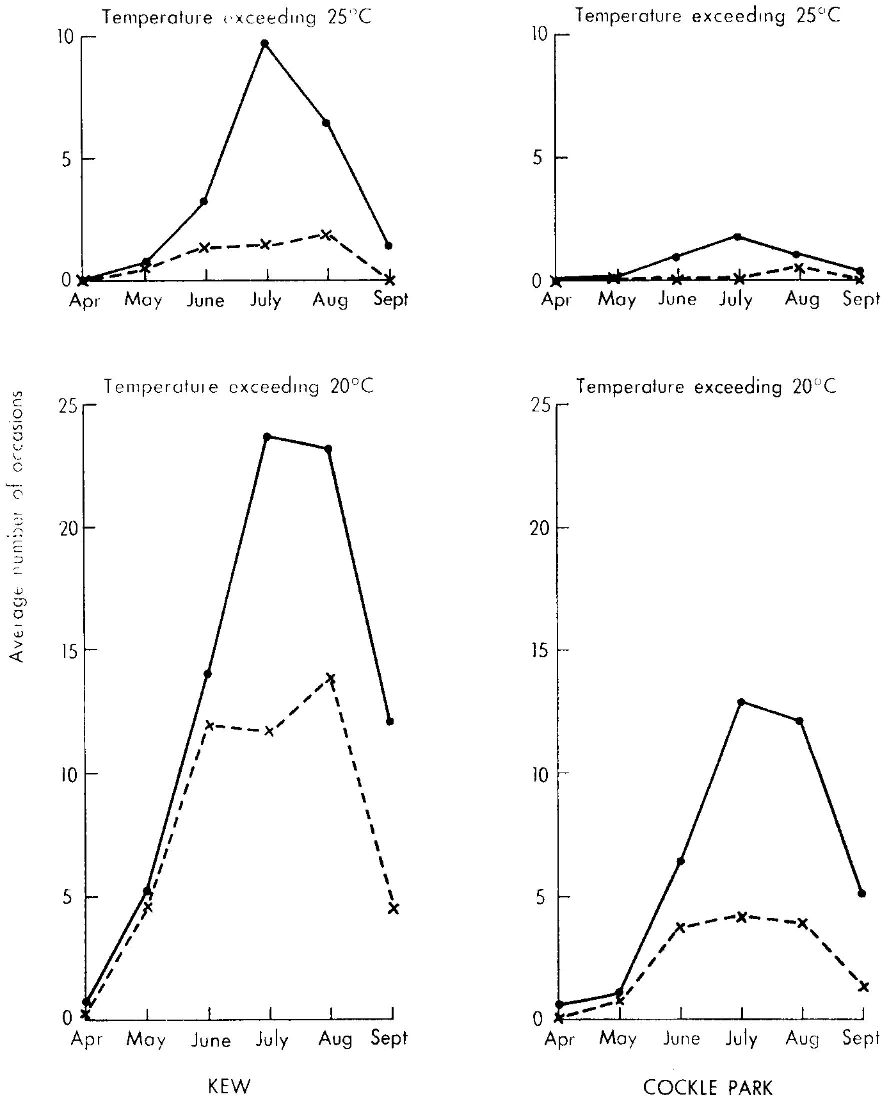

FIGURE 1—FREQUENCY OF DAYS IN GOOD AND BAD HONEY YEARS WITH TEMPERATURES EXCEEDING SPECIFIED LEVELS AT KEW AND COCKLE PARK

•———• Years of well-above average honey yield
x – – x Years of well-below average honey yield
(Years of well-above and well-below average are listed in Table I.)

between average totals of days with temperatures above 20°C in good and bad honey years at Kew is very slight in April and May, is noticeable in June, and is very considerable in July (especially), August and to a lesser extent September. When the 25°C level is considered the differences between good and bad years becomes greater, especially in July. The graphs for Cockle Park are very similar in character but totals of warm days are, of course, much lower. Interestingly, there seems no suggestion that later months (August or possibly September) may be more relevant to nectar collection in the north than in the south. Clearly, in both areas July and August appear to be the key months, and the actual figures for good and bad honey years for Kew are given in Table I.

Apart from 1940 (a good year for honey, with very warm sunny weather in June), no year with a high honey yield had less than 21 days in July when the temperature exceeded 20°C and no year with a low yield had more than 18 such days; and there were never less than 9 days in July with maximum temperature above 25°C in good yield years, or more than 5 days in bad years. August figures are similar in general character but differences between good and bad honey years are not as clear cut.

A further point of interest is that there were eight Julys in which the temperature exceeded 25°C on 10 days or more. These included five of the good honey years (see Table I); the other three Julys were in 1929 (40 lb), 1933 (60 lb) and 1941 (40 lb), in none of which years was the total yield less than the 41-year average of 39·4 lb; the average for these eight years was 61 lb. Similarly, of the eight Julys when temperatures never reached 25°C, four are included in the bad honey years; the other four years were 1931 (25 lb), 1942 (40 lb), 1960 (21 lb) and 1962 (18 lb); the average for these eight years was 19 lb.

Temperatures at Kew above 20°C and above 25°C since 1914. In an endeavour to make a comparison of temperatures over a longer period, similar data for temperatures at Kew above 20°C and 25°C were examined for the period 1914–69; this information is given in Table II.

TABLE II—AVERAGE ANNUAL NUMBER OF WARM AND HOT DAYS IN JULY AND AUGUST AT KEW FROM 1914 TO 1969

Period	JULY Average number of days above 20°C	JULY above 25°C	AUGUST Average number of days above 20°C	AUGUST above 25°C
1914–20	14·7	1·9	17·3	3·3
21–30	19·6	6·7	14·8	2·0
31–40	18·4	4·7	20·7	5·7
41–50	20·9	6·5	16·3	3·9
51–60	16·6	4·7	14·2	2·3
61–69	18·0	3·6	15·1	1·9
Average	18·0	4·7	16·4	3·2

It is obvious in this table that over the two months together the 1930s and 1940s were much more fortunate with warm, and especially hot, days than any other period — in each decade, for example, there is an average of over 10 days in July and August together with temperatures over 25°C.

Warm spells at Kew from 1881. Records have been maintained for Kew of warm spells — periods with day maximum temperatures of 75°F (23·9°C) or more on five consecutive days, but a period in which the maximum temperature only reaches the range 70–74°F (21·1–23·9°C) on one of the days is still deemed to qualify (Brazell[3]). The data are summarized in Table III in decades; included in these figures are any warm spells in the year from as early as May to as late as September. The table also shows the average number and duration of spells in good and bad years for honey yield (as given in Table 1).

PLATE III—LIGHTNING FLASH *Photograph by R. Addie*

The photograph was taken at about 1900 GMT on 14 November 1969 at Bemerton Heath, Salisbury, with the camera looking south-east. The camera, with shutter open, was hand held against a window for about 45 seconds until the flash was observed. Only one flash was visible to the naked eye. The blob on the extreme right was caused by refraction through a raindrop on the window.

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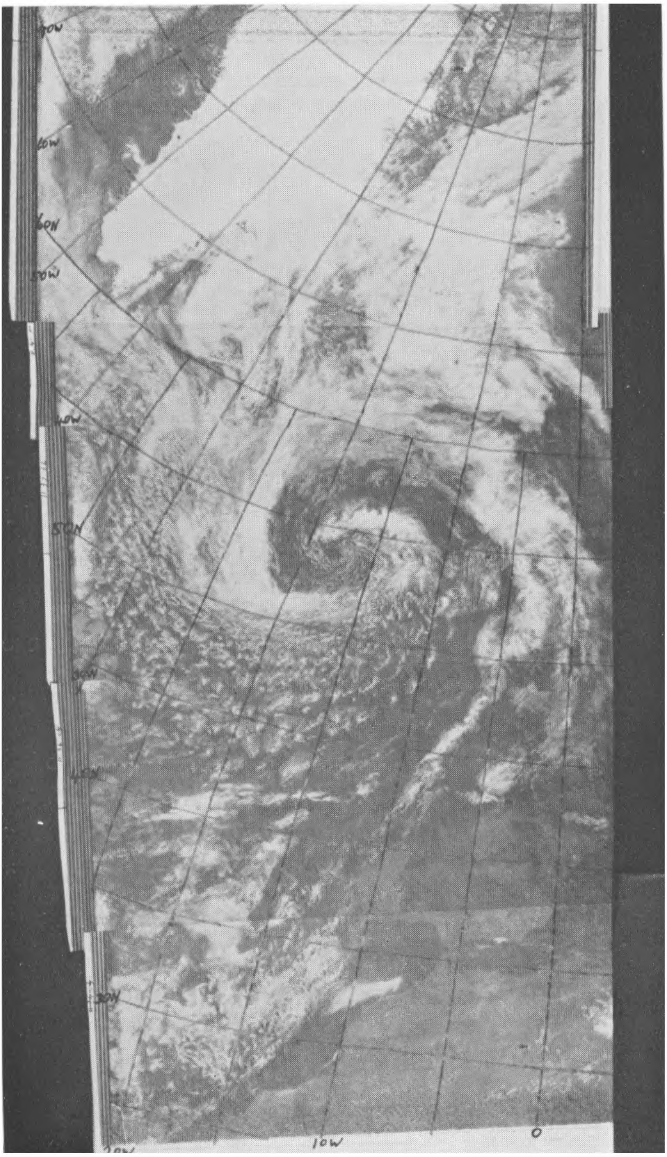

PLATE IV—COMPOSITE CLOUD PHOTOGRAPH FROM NIMBUS SATELLITE, 1134–1144 GMT ON 4 AUGUST 1969

TABLE III—NUMBER OF WARM SPELLS AND TOTAL NUMBER OF DAYS IN WARM-SPELL WEATHER AT KEW DURING THE PERIOD 1881–1969, WITH SIMILAR FIGURES FOR GOOD AND BAD HONEY YEARS IN 1928–68

Decade	Average annual number of spells	Average annual number of days involved
1881–90	1·4	8·5
91–1900	1·9	13·9
1901–10	1·7	11·4
11–20	1·5	12·1
21–30	1·4	14·0
31–40	2·3	15·4
41–50	2·1	15·0
51–60	2·0	11·7
(61–69	1·2	7·7)
Honey yields, 1928–68		
Good years	4·1	31·6
Bad years	1·4	9·1

The average number of warm spells per year was higher in the 1930s and 1940s than at any other time, and so too were the number of days involved.

Honey records at Street compared with meteorological data at Bath. So far, only national honey figures have been compared with records from a small, but it is hoped fairly representative, number of stations. A more exact comparison can be made for a particular locality near Street, Somerset, at which yield figures were carefully maintained from 1918 to 1936, because meteorological data exist for a climatological station at Bath, reasonably nearby. A comparison is made in Table IV between the best five and the worst five honey years at Street and the frequency at Bath of days with temperatures above 20°C and 25°C in June, July and August. It will be noticed that the yields given in this table, for an individual very efficient apiary, are considerably higher than the national averages given in the introduction and used in Table I.

TABLE IV—COMPARISON OF FREQUENCIES OF TEMPERATURES ABOVE 20°C AND ABOVE 25°C AT BATH IN YEARS OF HIGH AND OF LOW HONEY YIELDS AT STREET IN THE PERIOD 1918–36

Year	Honey yield per hive *lb*	Days with temp. above 20°C June	July	Aug.	Days with temp. above 25°C June	July	Aug.
(a) Years of high honey yield							
1919	167	15	15	24	1	0	8
21	170	20	30	16	5	16	2
25	148	21	20	15	5	8	2
33	189	16	24	25	5	9	8
34	163	16	31	18	5	14	1
Average	167·4	17·6	24·0	19·6	4·2	9·4	4·2
(b) Years of low honey yield							
1920	62	9	2	7	0	0	0
24	59	8	12	4	0	2	0
30	63	19	12	10	2	0	5
31	52	11	8	7	0	0	0
36	49	13	7	20	3	0	2
Average	57·0	12·0	8·2	9·6	1·0	0·4	1·4
(c) All 19 years							
Average	105·5	11·9	16·6	15·4	1·9	4·8	2·5

It is clear from this table that there is a very strong link between warm/hot days in July and honey yield; the comparison between 9·4 and 0·4 is very striking. The only year which really does not agree closely with the premise that hot Julys are associated with high honey yield is 1919, when August was quite hot, and so was May and to a lesser extent June.

The lack of sensitivity of June as an indicator is suggested by the closeness between the average number of occasions with temperatures above 20°C in June in all years (11·9) and in the bad honey years (12·0). Another interesting feature in this table is the difference between the average number of warm/hot days in July and in August in years with high honey yields, although the average number of days with temperatures above 20°C for all 19 years *(c)* is not very different between the 2 months.

Honey yields and final stratospheric warming. Mr N. E. Davis has given a correlation between high honey yield and his optimum summer weather index,[4] and has also noticed a close relationship between honey yield and the date of final stratospheric warming. The onset of the warming over the British Isles is often sudden and well marked and can usually be categorized as either early or late (Ebdon[5]); but occasionally the onset is less clear cut and then categorization is more difficult. There is also a well-marked relationship between the date of warming and the July temperatures.

Figure 2 shows the relationship between early and late warming, honey yields and the number of days in July with temperature above 20°C. The agreement is not quite as perfect as the figures suggest because 1960, 1963 and 1967 were by no means clear-cut examples of years with early or late warming. However, the agreement between early warming and high honey yields and the number of warm/hot Julys appears striking.

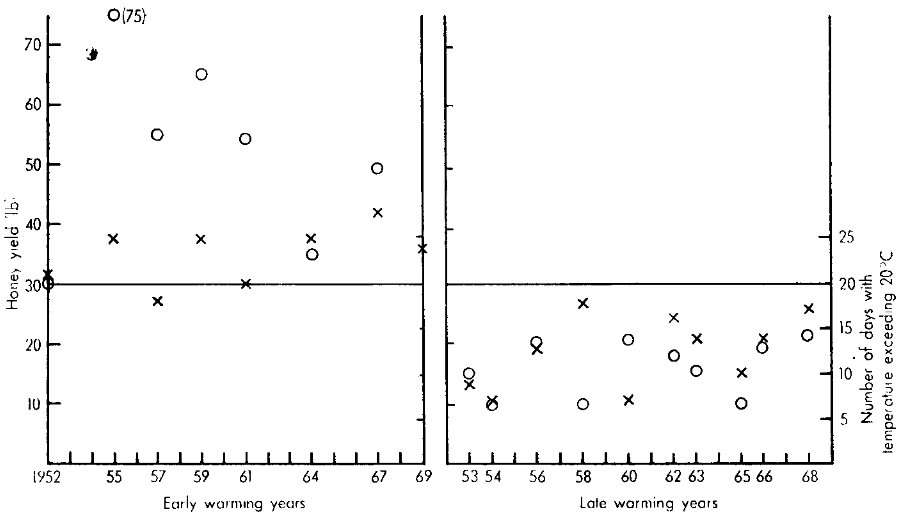

FIGURE 2—HONEY YIELDS FOR GREAT BRITAIN AND JULY TEMPERATURES AT KEW EXCEEDING 20°C RELATED TO EARLY AND LATE STRATOSPHERIC WARMING

o Honey yield x Temperature exceeding 20°C

The future. One cannot do a great deal more about casting into the future than review the past and attempt to draw cautious conclusions. In Hurst,[2] summer average temperatures from 1841 to 1968 were reviewed, and it might be of interest briefly to summarize these data (brought up to date) (Table V).

TABLE V—FREQUENCY DISTRIBUTIONS OF SUMMER TEMPERATURES OVER THREE PERIODS BETWEEN 1841 AND 1969

Period	Summer temperature	Number of occasions in period	Proportion in 10 years
1841–1930	W/VW	10	1·1
1931–50	W/VW	5	2·5
1951–69	W/VW	2	1·1
1841–1930	C/VC	50	5·5
1931–50	C/VC	4	2·0
1951–69	C/VC	8	4·2

VW Very warm } departure from average ⩾2·0 degF
VC Very cold

W Warm } departure from average of 1·0–1·9 degF
C Cold

Out of interest, spring figures are very similar, and details will be found in the same paper. The reason why the number of C/VC years is so much higher than W/VW is of course that the standard period for calculation of the average temperatures is 1931–60, a warm period as we have seen.

Lamb[6] gives a very interesting diagram, partly reproduced as Figure 3, which shows patterns of mean temperature in high summer (July and August) for nearly 300 years as decade averages, based on Manley's data,[7] with a curve showing the 100-year average running means back to the year 1500.

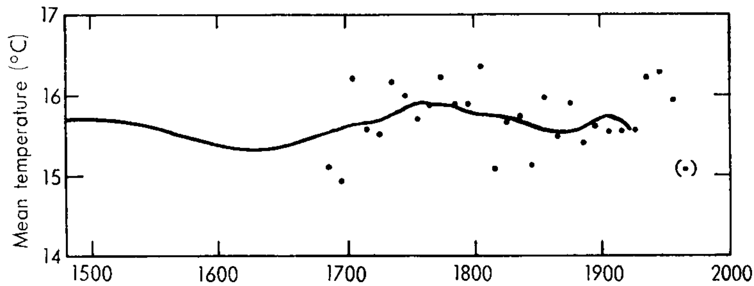

FIGURE 3—MEAN AIR TEMPERATURE IN CENTRAL ENGLAND IN HIGH SUMMER DURING THE PERIOD 1680–1965 (AFTER MANLEY[7]) WITH 100-YEAR RUNNING MEANS BACK TO 1500

• Mean temperature as decade average

Obviously the earlier records must be somewhat less reliable than the more recent, but even with this reservation, it is difficult not to recognize that the 1930s and 40s were amongst the warmest three or four decades during the period, and at no time were there two other consecutive decades with temperatures as much above average. The tentative figures for the 1960s show the decade to be one of the coolest on record. It is impossible to extrapolate with real confidence from this type of information, but one can certainly say there are no obvious grounds for optimism that summer temperatures will be high in the next decade or two.

Conclusions.

(i) A strong relationship has been shown between years with a warm or hot high summer (especially July) and years with high honey yields.

(ii) Records of temperature deviation from average show that the 1930s and 1940s are two of the warmest decades for summer temperatures over the last 300 years. Several different forms of analysis for more detailed meteorological data from 1841 onwards agree with this conclusion.

(iii) A relationship exists between the date of onset of stratospheric warming and honey yield and July temperatures in the following summer.

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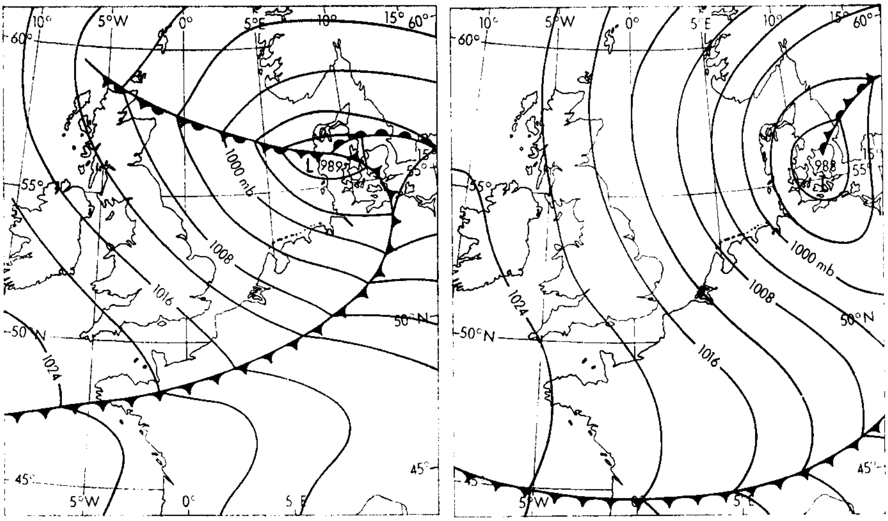
AN UNEXPECTED DETERIORATION IN WEATHER CONDITIONS IN A NORTH-WESTERLY AIRSTREAM AT BRUGGEN, NORTH-WEST GERMANY, ON 28 JUNE 1966

By D. W. SUTTON

Introduction. In a forecast of weather conditions for the area around Bruggen, issued at 0700 GMT on 28 June 1966, the day was expected to be partly cloudy to cloudy with occasional showers but with a belt of rain and low stratus, associated with an occlusion, affecting Bruggen during the evening. In fact a marked deterioration set in soon after 0900 GMT and conditions remained worse than expected almost throughout the day. (Place names are shown on Figure 5*(b)*.)

The synoptic situation. At 00 GMT a depression of 989 mb was centred over Denmark with an associated cold front from the centre to Cologne to Orléans moving quickly east. A strong west-north-westerly gradient (40–50 kt) soon became established over north-west Germany extending back across the North Sea to Scotland. During the day the depression moved slowly east-south-east and the gradient over north-west Germany and the North Sea slowly veered, because there were more rapid pressure rises over Scotland and the northern North Sea than over Germany (see Figures 1*(a)* and *(b)*). The back-bent occlusion from the depression centre to north-east Scotland at 00 GMT was dropped from the 06 GMT and later charts, as the thickness analyses gave no evidence of an occlusion extending as far back across the North Sea as this. In fact a thermal trough extended down the North Sea at 00 GMT and had penetrated well into north-west Germany by 12 GMT (axis Rotterdam to Essen to Berlin). However, there was evidence of a fairly well-marked trough over the North Sea at 00 GMT, up to the 300-mb level, although this had become relatively shallow by 12 GMT.

Basis for forecast weather conditions. The whole forecast hinged on the presence of the back-bent occlusion from the depression centre to north-east Scotland and most of the evidence available did in fact point to the presence of this occlusion. It seemed a good way of explaining the rain which



(a) 00 GMT *(b)* 12 GMT

FIGURE 1—SURFACE SYNOPTIC SITUATION, 28 JUNE 1966

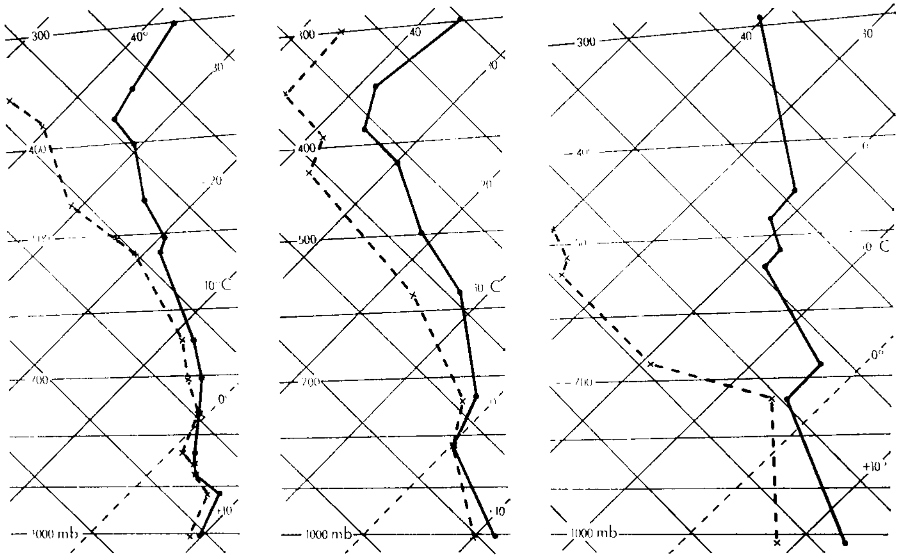
was occurring over east Scotland at 00 GMT and 03 GMT and the Shanwell ascent was quite moist compared with those further south, although no warmer. There was also some historical evidence for the occlusion; the Bracknell analyses of the previous day, and for that matter at 00 GMT as well, had all shown an occlusion extending back from the main depression centre.

Once committed to the presence of the occlusion the rest of the forecast followed quite logically, the upwind ascents at De Bilt, Emden, Uccle, Hemsby, and Aughton were all unstable but reasonably dry, and neither general rain nor any appreciable wind veer could be expected until the passage of the occlusion during the evening.

The actual weather conditions at Bruggen and over north-west Germany. By 03 GMT the cold front had cleared north-west Germany and the weather was mainly dry with variable stratocumulus and cumulus south of 53°N, but with outbreaks of rain and patchy low stratus over the extreme north of Holland and north-west coasts of Germany. However, by 07 GMT outbreaks of rain were showing up along the whole of the Dutch coast and by 10 GMT periods of rain or drizzle were affecting the whole of Holland and all German stations north of 50·5°N.

The rain reached Bruggen at about 0830 GMT and rain or drizzle was almost continuous during the morning becoming intermittent during the afternoon and evening. Stratus, 6/8–8/8, soon formed in the precipitation with base in the range 600 to 1000 feet (confirmed by aircraft reports) during the morning, lifting slightly during the afternoon with the lower cloud becoming more broken and cumuliform. Visibility was reduced to the 1·0 to 3 n.miles range during the morning but improved to 5 to 10 n.miles during the afternoon.

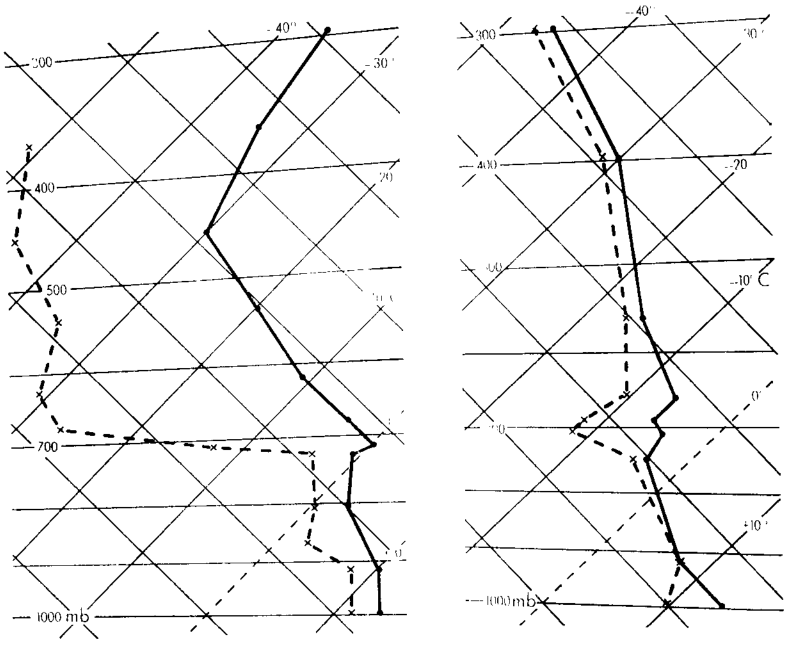
The 12 GMT Essen ascent gives a good representation of the cloud conditions at Bruggen during the late morning period; a change occurred to the 12 GMT De Bilt ascent during the afternoon. The 12 GMT Uccle ascent, just outside the main rain area, seems a good example of the type of air mass originally forecast for the Bruggen area. (See Figure 2.)



(a) Essen *(b)* De Bilt *(c)* Uccle

FIGURE 2—ASCENTS FOR 12 GMT, 28 JUNE 1966

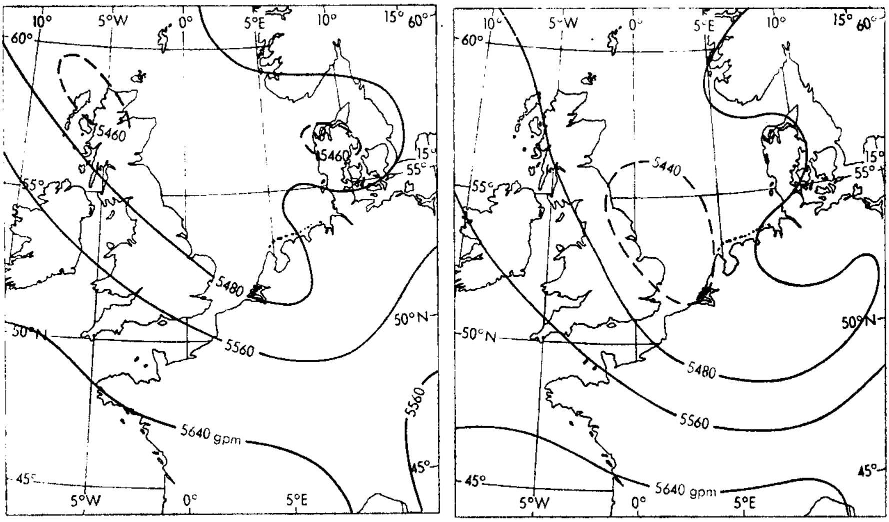
Probable reasons for the deterioration. A study of the 00 GMT and 12 GMT upper air ascents for De Bilt, Essen and Hemsby tends to rule out the possibility of the precipitation being frontal in nature, all the ascents being



(a) 00 GMT *(b)* 12 GMT

FIGURE 3—ASCENTS FOR EMDEN, 28 JUNE 1966

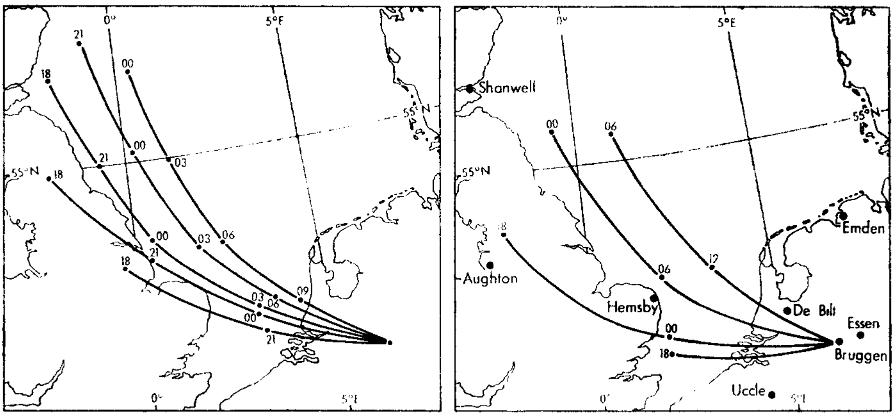
slightly cooler at 12 GMT than at 00 GMT, although all show considerable moistening in the lower layers (up to 600 mb). The Emden ascents (Figures 3*(a)* and *(b)*) however, also show considerable moistening of the upper layers (600 mb to 300 mb) between 00 GMT and 12 GMT, and also some warming at these levels. This can probably best be explained by drawing a short, slow-moving, back-bent occlusion from the depression centre westwards, there being evidence on the Offenbach thickness analysis for 00 GMT (Figure 4*(a)*) of a short tongue of slightly warmer air extending back from the depression centre along the 55°N line of latitude (just north of Emden) moving to near or just south of Emden by 12 GMT (Figure 4*(b)*). The initial



(a) 00 GMT *(b)* 12 GMT

FIGURE 4—OFFENBACH 500–1000-mb THICKNESS ANALYSES, 28 JUNE 1966

dryness of the post-frontal ascents at 00 GMT was probably due to the air having a comparatively short sea track from Britain (see Figures 5*(a)* and



(a) At 2000 ft, of air arriving at Bruggen at 00, 03, 06, 09 and 12 GMT on 28th *(b)* At 700 mb, of air arriving at Bruggen at 00, 06, 12 and 18 GMT on 28th

FIGURE 5—TRAJECTORIES BACKWARDS FROM BRUGGEN ON 28 JUNE 1966

(b)), another possibility being the presence of a zone of drier air immediately behind the cold front. However, there seems little doubt that the moistening of the lower layers was due to the veering gradient producing a long sea track. Figures 5*(a)* and *(b)* seem to confirm this, both the 2000-ft and 700-mb trajectories showing a marked change from short to long sea track between 00 GMT and 12 GMT. The trajectories also show why the precipitation extended only as far south as 50·5°N, at least during the morning.

The fairly well-marked trough previously mentioned over the North Sea at 00 GMT, probably goes some way towards explaining why the air over the North Sea was so moist to such a high level, and although the trough had become quite shallow by 12 GMT, the subsequent 12 GMT ascents and also the 00 GMT Shanwell ascent seem to confirm that there was in fact quite a large area of moist air over the North Sea at 00 GMT, somewhat unstable to sea temperatures.

It is thought that the strength of the gradient was at least partly responsible for the persistence of the rain and low cloud, the temperature inland remaining around 12 to 13°C all day, a degree or so below the coastal temperatures. With a less-strong gradient or less-persistent precipitation it is thought that insolation would have been sufficient to at least have raised the temperature a few degrees and the cloud base to cumulus levels.

Discussion. It is probably true to say that more forecasting errors are made in the Bruggen area with the surface gradient in the north-west quadrant than in any other. These errors are mainly due to some unexpected (i.e. unobserved) phenomena being advected from the North Sea, or insufficient weight being given to local upslope effects. This situation provides a good example of the former. The bulk of the evidence pointed to a partly cloudy to cloudy day with occasional showers, although in retrospect there was probably enough evidence to strike a note of caution in the forecast, e.g. the comparatively large pressure rises over Scotland, showing up as early as 21 GMT on 27 June, implying a slow veer in gradient and lengthening sea track of the air reaching Bruggen.

To sum up, it is thought that all that can be done in these circumstances is to keep a close watch on the Dutch coastal observations and take the appropriate amendment action when it becomes obvious that the original forecast will be wrong. Of course a weather ship in the North Sea would often make the situation easier to handle.

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REPORT ON A SEMINAR ON WEATHER SATELLITE CLOUD PHOTOGRAPHS, HIGH WYCOMBE, OCTOBER 1969

By N. HOLDSWORTH

On 2 October 1969 a seminar on weather satellite cloud photographs was held by the U.S. Air Force at High Wycombe, Bucks. The major part of this was concerned with analysis techniques and the relation between cloud photographs and the synoptic chart. The more noteworthy items have been reproduced in diagram form to accompany this note.

Figure 1 shows the relationship between *(a)* active and *(b)* inactive surface

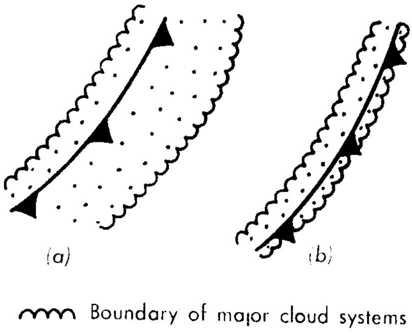


FIGURE 1—SURFACE COLD FRONT RELATED TO COLD-FRONT CLOUD BAND
(a) Active front *(b)* Inactive front

cold fronts and the associated cloud band. This is a generalization of course and not every front will conform, but in most cases the relationship will hold.

Figure 2 shows vorticity in the cold air behind a cold front. A vorticity centre of this kind can induce a wave on the cold front when it is located within about 400 miles of the front. The surface isobars may not reveal the presence of this feature but it is usually well marked on the cloud photograph.

With a mature depression the vortex centre will eventually become divorced from the warm air. Cold air moving round the vortex will be comparatively free from cloud in many cases and will show as a wedge of clear air, the so called 'dry slot', wrapped around the centre. Further deepening of the depression is unlikely after the dry slot has moved to the top side of the vortex as shown in Figure 3.

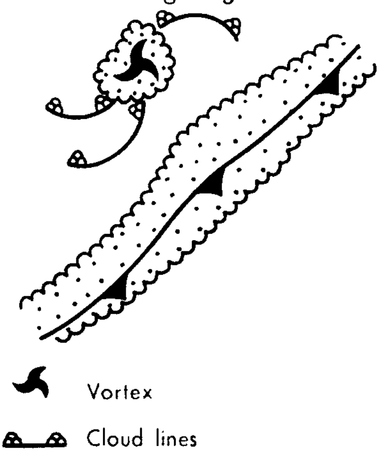


FIGURE 2—VORTICITY CENTRE IN THE COLD AIR WITHIN ABOUT 400 MILES OF THE COLD FRONT MAY INDUCE A FRONTAL WAVE

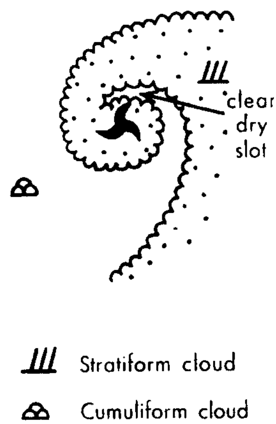


FIGURE 3—FURTHER DEEPENING OF THE VORTEX IS UNLIKELY WHEN THE 'DRY SLOT' OF COLD AIR HAS CIRCULATED TO THE TOP SIDE OF THE VORTEX

The location of the 500-mb trough in relation to cloud features is illustrated in Figures 4 and 5. The comma-shaped cloud shown in Figure 4 is the familiar pattern of cloud associated with positive vorticity advection (pva max). It

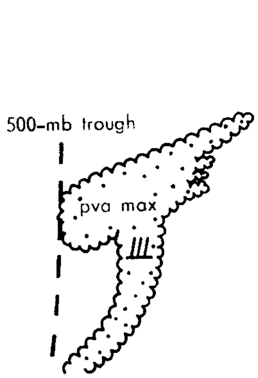


FIGURE 4—500-mb TROUGH LOCATION ASSOCIATED WITH A pva MAXIMUM
pva = positive vorticity advection

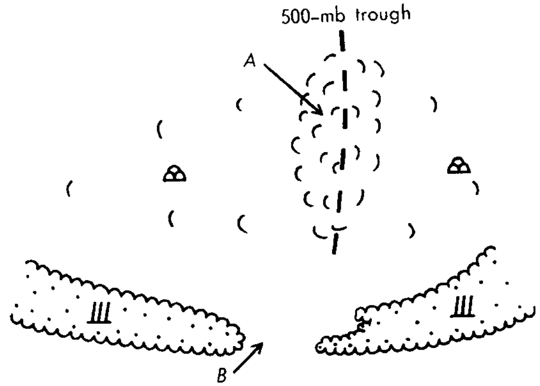


FIGURE 5—500-mb TROUGH MARKED BY ENHANCED CUMULUS DEVELOPMENT, *A*, AND WEAKENED FRONTAL CLOUD, *B*

signifies the intensification of cyclonic motion. The 500-mb trough line can be related to the rear edge of the main cloud mass. Figure 5 shows the 500-mb trough as a zone of increased cumuliform cloud. The frontal link to the south shows a break in frontal cloud on and behind the trough line.

Cirrus clouds associated with high-level troughs and ridges form in extensive bands between the trough and a line just ahead of the preceding ridge — see Figure 6. Cirrus will sometimes spread downwind ahead of the ridge but generally cloud in this area is weak.

In the case of the polar-front jet stream the cirrus cloud is a warm air feature. The strongest winds coincide with the cloud edge as shown in Figure 7. Lateral banding appearing in the jet cirrus is indicative of turbulence in the area.

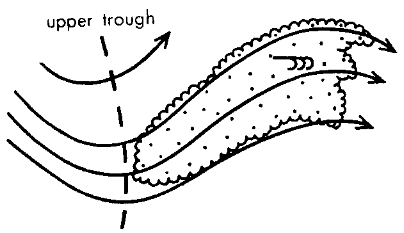


FIGURE 6—LOCATION OF CIRRUS CLOUD ASSOCIATED WITH UPPER RIDGES AND TROUGHS

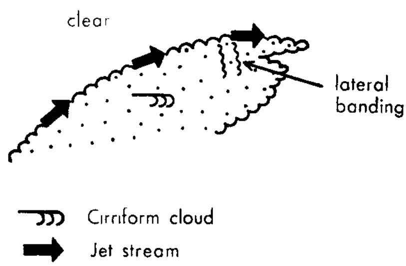


FIGURE 7—LATERAL BANDING IN JET-STREAM CIRRUS SUGGESTS TURBULENCE

Surface ridges can be identified in polar air as cloud type discontinuities, (Figure 8). Southerly flow tends to be stratiform and northerly flow cumuliform. However, these features are often obscured by higher cloud.

The subtropical surface ridge line is more easily seen and Figures 9, 10 and 11 show some methods of location. Cloud type identification is shown in Figure 9 with stratocumulus type cloud to the north of the ridge line and

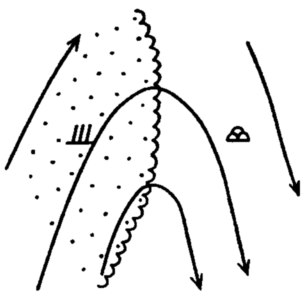


FIGURE 8—SURFACE RIDGE LOCATION IN POLAR AIR BY REFERENCE TO CLOUD TYPE

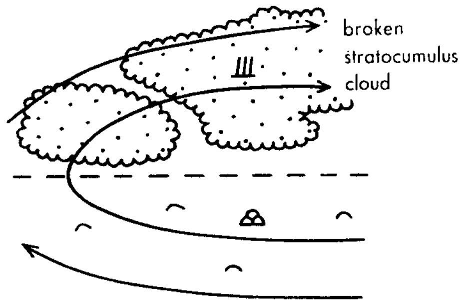


FIGURE 9—SURFACE RIDGE LOCATION IN SUBTROPICAL AIR BY REFERENCE TO CLOUD TYPE

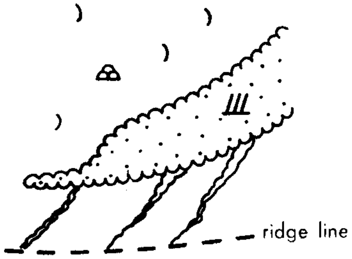


FIGURE 10—SUBTROPICAL SURFACE RIDGE LINE INDICATED BY THE TERMINATION OF CLOUD FINGERS FROM A COLD FRONT

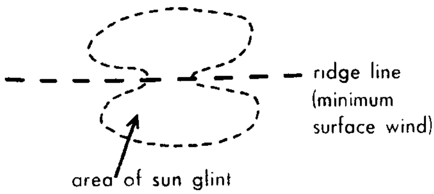


FIGURE 11—SUN GLINT INDICATING THE SUBTROPICAL RIDGE LINE. MINIMUM SUN GLINT AREA CAN BE EQUATED WITH LOW SURFACE WIND SPEEDS

cumulus cloud to the south. A front to the north of the ridge, Figure 10, will sometimes show narrow lines of cloud (cloud fingers) extending towards the high pressure centre and these often terminate on the ridge line. A third method using sun glint can sometimes be employed. The image of the sun reflected by the sea surface is small and intense when the sea is smooth. As the surface becomes rougher the image becomes larger and more diffuse. Figure 11 shows how the diminished area of sun glint can be related to the minimum surface wind associated with the ridge line. This method can only be employed satisfactorily in lower latitudes, i.e. south of the polar front.

A new term 'occluded frontogenesis' was used during the seminar. This is intended to indicate the development of a pseudo-occlusion or trough line connecting a secondary depression or wave to the primary and having the characteristics of an occlusion without having undergone the preliminary occluding process, Figure 12. This term is in common use amongst American meteorologists but as yet has not earned official status.

The climatological aspect of satellite cloud photography was also introduced. In the U.S.A., computers are used to process and store cloud data. This information is then reprinted in various ways to facilitate climatological study. For example, charts of mean cloudiness are produced covering periods of from 5 to 90 days. These charts can be compiled into a time-lapse film and

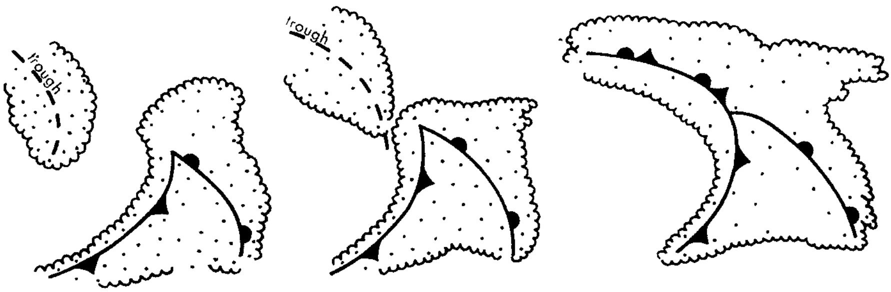


FIGURE 12—THREE STAGES IN THE PROCESS OF OCCLUDED FRONTOGENESIS

when shown in this way illustrate the seasonal fluctuations of semi-permanent synoptic features such as the intertropical convergence zone and the subtropical anticyclones.

Time-lapse film sequences from the stationary satellite ATS I over the Pacific are also prepared. The original photographs are taken every 30 minutes, and even a one-day sequence can be very revealing. It is now current practice in the U.S.A. to prepare such films on a daily basis to assist operational weather forecasting.

Infra-red photographs available from the NIMBUS III satellite provide useful information on the position and intensity of the major cloud systems during the night-time period. The direct read-out facility used by the British Meteorological Office is received in seven shades from black to white representing temperatures from 185 degrees Kelvin to 330 degrees Kelvin (−88°C to +57°C). The main cloud features can be seen on these photographs but small differences of temperature are not apparent. Future developments are expected to include improved direct read-out infra-red data and further work in the field of carbon-dioxide radiation measurements.

The following is a selection of useful references :

POTHECARY, I. J. W. and RATCLIFFE, R. A. S.; Satellite pictures of an old occluded depression and their usefulness in analysis and forecasting. *Met. Mag., London,* **95**, 1966, pp. 332–338.

POTHECARY, I. J. W. and JAMES, D. G.; Some aspects of satellite meteorology. *Met. Mag., London,* **94**, 1965, pp. 193–202.

Geneva, World Meteorological Organization. Reduction and use of data obtained by TIROS meteorological satellites. *Tech. Notes Wld. met. Org., Geneva,* No. 49, 1963.

ANDERSON, R. K., FERGUSON, E. W. and OLIVER, V. J.; The use of satellite pictures in weather analysis and forecasting. *Tech. Notes Wld. met. Org., Geneva,* No. 75, 1966.

CORMIER, R. V. and DOWNEN, D. W.; A digest of the interpretation of meteorological satellite data. *Navy Weather Research Facility Tech. Paper* No. 8–68, Norfolk, Virginia, 1968.

REVIEW

A 700 mb atlas for the northern hemisphere, by E. W. Wahl and J. F. Lahey. 280 mm × 220 mm, pp. 147, *illus.*, University of Wisconsin Press, c/o American Universities Publishers Group, 27–29 Whitfield St, London, W.1. Price: 47*s.*

This is a very nicely produced atlas showing the 5-day mean 700-mb height field over the northern hemisphere for each pentad of the year together with similar charts of standard deviation and of height change from one pentad to the next. It follows a similar atlas of 5-day mean sea-level pressure charts for the northern hemisphere which was published by the University of Wisconsin Press in 1958.

The maps were produced from 15 years of daily data (1951–65) for each of 469 grid points covering the northern hemisphere. Each grid point therefore on the pentad maps was the average of 75 values (except for the pentad containing 29 February which had more). Although daily charts for 00 and 12 GMT were available these mean charts were produced using only the 12 GMT data. The intension here was to avoid diurnal effects and at the same time to use the greatest amount of data.

These charts will form a valuable addition to the armoury of the synoptic climatologist; they are useful in drawing attention to major pentad-to-pentad changes and may lead to better understanding of the hemispherical nature of some of the well-marked singularities.

Although the quality of the reproduction is very good, one would like to have seen, at least faintly, the major latitude and longitude lines on the maps. It is also rather surprising that units throughout are in feet despite the almost universal use of decametres for this type of work since the late 1950s.

One looks forward to the promised production of similar charts for other levels, indeed it is surprising that 500 mb was not the first level to be considered but this was probably because the 700-mb data were more readily available. Altogether this is a very useful atlas and the first of its kind I have seen.

R. A. S. RATCLIFFE

NOTES AND NEWS

International co-operation in weather investigations in November 1969

During the month of November 1969, meteorologists all over the world, with the aid of mariners, pilots and volunteer weather observers from many walks of life, assembled a collection of data about the state of the atmosphere which will be the most extensive yet compiled.

This was done in support of the basic data set project arranged by the Joint Organizing Committee for the Global Atmospheric Research Programme (GARP). GARP is a joint international venture of the World Meteorological Organization and the International Council of Scientific Unions, aimed at the investigation of scientific problems which stand in the way of a fuller understanding of the atmosphere's structure and behaviour. The basic data set project is designed to provide fundamental information for the planning of the global GARP experiment, to take place in the middle seventies.

In addition to the substantial extra contribution by all meteorological services of the world, active support to the project was given by the International Air Transport Association, the International Federation of Airline Pilots' Association and the International Civil Aviation Organization. Thanks to these agencies, pilots of scheduled airlines observed and reported weather conditions on the world air routes. Arrangements were also made for pilots of non-scheduled flights and government aircraft to participate.

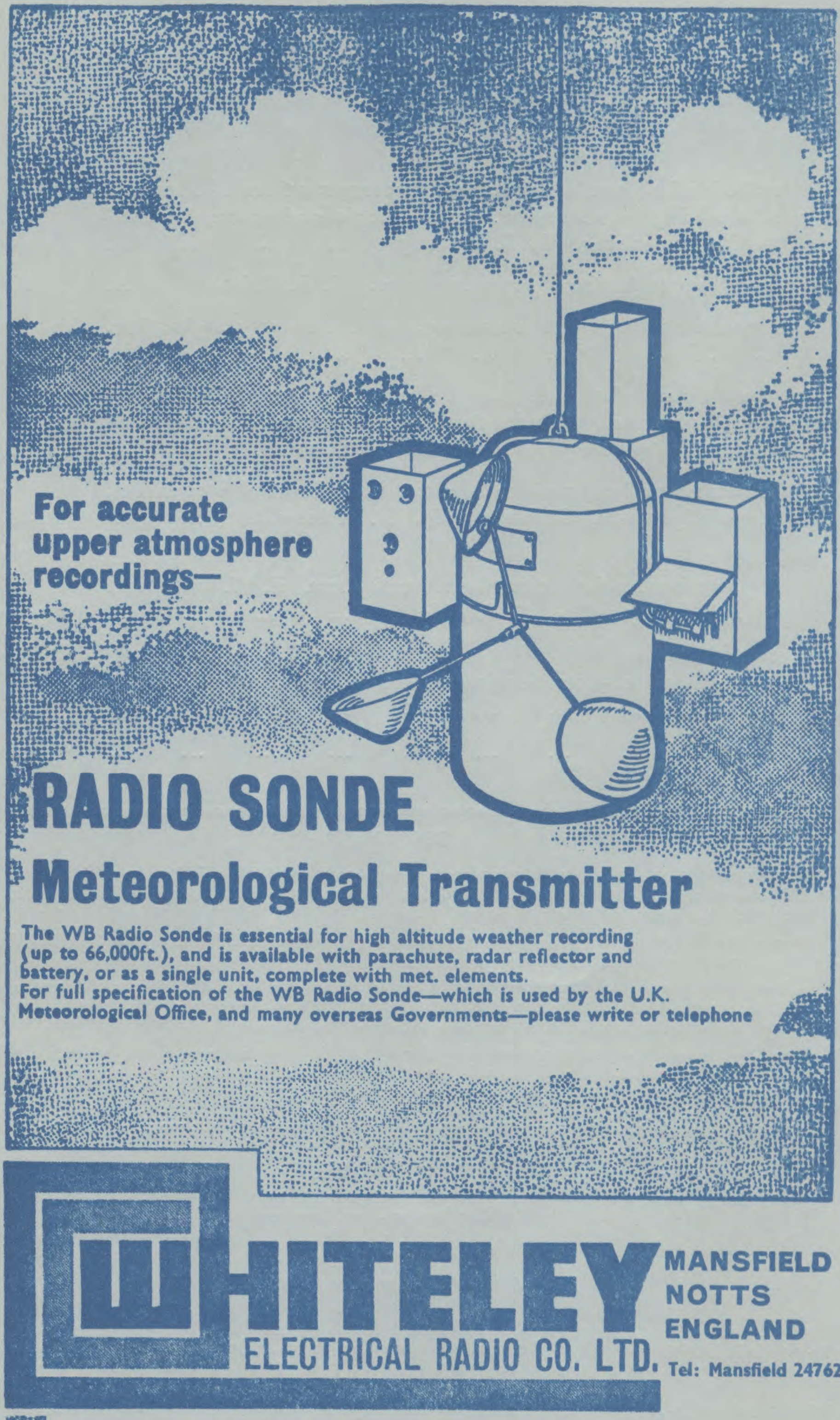
Aims of the project are to gather from every possible source information additional to that provided on a routine basis by the international weather observation network of reporting stations, by satellites, by aircraft, by ships at sea, etc.; these data, some of which will arrive by mail, will then be checked, assembled and analysed at three centres, Washington (U.S.A.) for the northern hemisphere, San José (Costa Rica) for the tropical belt, and Melbourne (Australia) for the southern hemisphere.

The data collected during this period will then be available for workers conducting research, mainly with computers, into the behaviour of the atmosphere.

A repetition of this project is planned for June 1970.

OBITUARY

It is with regret that we have to record the death of Mr M. J. Oliver (Scientific Assistant) on 13 November 1969.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THE METEOROLOGICAL MAGAZINE

VOL. 99 NO. 1172 MARCH 1970

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THE TETHERED RADIOSONDE

By H. E. PAINTER

History. Since June 1942, observations, at specific heights up to 1200 metres (900 metres since March 1967), of dry-bulb and wet-bulb temperatures and wind speed have been made at Cardington, near Bedford, with instruments attached to the steel cable of a captive balloon.

In the Meteorological Office these observations have been referred to by the name BALTHUM, a word abbreviated from 'BALloon Temperature and HUMidity'. These ascents have been made four times daily (three times daily before 1956) whenever weather conditions permitted the balloon to be flown safely. The observations have been sent by teleprinter to Meteorological Office stations for use in forecasting and have also been used for climatological analyses. Some early results were discussed by Shaw.[1]

Until 1964 the instrument for measuring temperatures was basically that described by Swinbank[2] in which copper-constantan thermocouples were used. The dry-bulb temperature was measured relative to a 'cold' junction in an ice bath and the wet-bulb depression was obtained by measuring the difference between the e.m.f.s (electromotive force) generated by the dry-bulb and wet-bulb thermocouples. The e.m.f.s from the thermocouples were measured by a potentiometer at ground level connected to the thermocouples by means of a multicore cable. A cup-contact anemometer was also attached to the balloon cable and was connected to a ground relay counter by the multicore cable. Height could only be determined by measuring the length of balloon cable paid out. This, of course, was not a very accurate method since the height of the balloon was affected by the wind. In practice the telemetering cable was often the cause of trouble when in light winds it became entangled with the balloon cable; in extreme cases it had to be cut to be disentangled.

A new instrument has been designed in which signals are transmitted to the ground by radio and this radiosonde first came into routine use on 9 November 1964; there have been some changes in the design since then and the latest version is described below. In addition to the previous measurement of dry- and wet-bulb temperatures and wind speed, there is a pressure sensor which permits more accurate determinations of heights than hitherto.

The sonde circuit. Suitable circuits had already been designed by the Meteorological Office for its rocketsonde[3] and these circuits have been adapted for the tethered radiosonde. The transmitter consists of an R/F (radio-frequency) oscillator coupled to a $\frac{1}{4}$-wave aerial and operates at a pre-set frequency in the meteorological band 27·5–28·0 MHz. This R/F oscillator is modulated by two A/F (audio-frequency) oscillators. One A/F oscillator is used in conjunction with a cup-contact anemometer and oscillates at about 5 kHz when the contacts of the anemometer are closed, but at a much lower frequency when these contacts are opened. The second A/F oscillator is made to vary in frequency by variations in resistive transducers. A switch is energized every 8 seconds and this switch connects in sequence to the A/F circuit two thermistors measuring dry-bulb and wet-bulb temperatures, a variable resistance controlled by an aneroid capsule and a reference resistor of fixed value. The frequencies in this A/F circuit are between 800 and 2000 Hz, and when received at the ground are filtered by a band pass filter to exclude interference from the wind A/F oscillator. The filtered signals are measured on a frequency counter and from these measurements temperatures and pressures, and hence heights, can be deduced.

Temperature sensors. The temperatures are measured by ordinary commercial thermistors; those used have a nominal resistance of 1000 ohms at 20°C. They have a faster response time than is required and their response time is increased by fitting them into hollow brass cylindrical bulbs 30 mm long and 6·5 mm in diameter. The top of each brass bulb is screwed into a tube of poorly conducting material 32 mm long and 6·5 mm in diameter. The leads of the thermistor pass through the centre of the tube and are sealed with epoxy resin to prevent any short-circuiting of the thermistor by moisture. The tube, since it is a poor thermal conductor, serves a double purpose; it is used as a support for the temperature element and also, by fitting the wet-bulb sleeve over the brass bulb and well up the stem of the poorly conducting tube, errors in wet-bulb readings, due to conduction down the stem, are greatly reduced.

Over the range of temperatures (+40° to −30°C) required for the tethered sonde, the stability of the thermistors has proved to be very satisfactory. Laboratory tests were made on the thermistors by measuring their resistance when placed in baths of liquids of known temperature. Resistance measurements were made by the potentiometric method using a standard 1000-ohm resistor. The current through the thermistor in these measurements was never greater than 0·1 mA; at this current the self-heating is quite negligible (<0·01 degC). When used with the sonde the current through the thermistor is much less than 0·1 mA. It was found that a good calibration of the thermistors could be obtained by taking very accurate resistance measurements at two temperatures only and then evaluating the constants in the standard equation for the relation between the resistance and temperature of a thermistor. This equation can be put into the form

$$\log_{10} R = A + B/T,$$

where R is the resistance in ohms, T the absolute temperature, and A and B are constants.

The two fixed temperatures chosen for these calibrations were 0°C and approximately 20°C, both being very easy to obtain and maintain in the laboratory. Repeated tests over 18 months showed that the thermistor calibrations were reproducible to within the equivalent of 0·05 degC, and that there was no discernible drift.

The two thermometer bulbs are mounted in double-walled radiation shields and are aspirated by a fan which draws air over the thermometer elements. Plate I shows the psychrometer unit attached to the box containing the batteries and circuits of the sonde. Both radiation shields have been removed (and are lying below) to show the thermometer elements projecting below the aspirator housing. The wet-bulb sleeving can be seen on the left-hand element and this sleeving passes through a polythene tube to a water bottle. When the radiation shields are screwed into position they project to the same level as the bottom of the sonde container so that the air that is drawn into the shields has not come into contact with the large box housing the sonde circuits. The fan is 70 mm in diameter and delivers about 0·7 m^3 of air a minute at a water pressure of about 8 mm. The fan is of the axial type and operates from 12 volts d.c.

Wind-tunnel tests show that the ventilation over the dry bulb is about 10 m/s. At this rate of ventilation the lag coefficients of the dry bulb and wet bulb are about 40 and 22 seconds respectively. The wet-bulb thermometer with this aspiration is giving the maximum wet-bulb depression as shown by tests in the laboratory.

Attempts were made to assess errors due to radiation by shining a bright light on the psychrometer. A radiation intensity of 50 mW/cm^2 falling on a vertical plane through the radiation shield caused a rise in temperature of 0·15 degC. A radiation intensity of 90 mW/cm^2 falling on a white surface below the thermometer element (to simulate conditions when the radio-sonde is above an extensive cloud sheet) caused the thermometer element to warm up by 0·2 degC. The extreme upper limit of errors due to radiation is thus thought to be 0·35 degC.

Pressure transducer. An instrument to measure height to the degree of accuracy desired for low-level soundings is not readily available. A special transducer was made consisting of an aneroid capsule mechanism driving a brush round a silver-palladium potentiometer. The operative range of the transducer is 1050 to 800 mb and the resistance then varies between 0 and 2500 ohms, approximately linearly with pressure changes. Tests were made in a pressure chamber to determine the reproducibility of the calibration. For a given pressure the greatest difference detected in resistance was 7 ohms (equivalent to 0·7 mb). In the majority of cases the readings were reproduced to within 0·5 mb. These differences included errors due to hysteresis, which would not affect an actual sounding when readings are taken on the ascent after a reduction in pressure. The maximum change in calibration for a change in temperature from −20°C to +40°C was 2·5 mb. The pressure transducer is situated in the thermally lagged container of the sonde and under normal conditions the change of temperature of the transducer is not more than 10 degC. If for special measurements it was thought necessary, the temperature of the transducer could be measured and telemetered to the ground.

Construction. The transistorized circuits are wired to three small plug-in boards. The R/F oscillator circuit together with the A/F oscillator circuit for the wind measurements, are on one board. A second board has the A/F circuit for the oscillator measuring temperatures and pressures, and the third board has the switch circuit which operates a rotary switch so that the various transducers are connected in turn to the A/F oscillator. A six-way switch is used, although at present only four different elements are connected to the A/F circuit. The switch is energized every eight seconds and switches in turn into the circuit resistances controlled by the dry bulb, wet bulb, pressure, dry bulb, wet bulb, and reference resistor, and so on. The circuits and pressure transducer are contained in the upper portion of the sonde and the necessary batteries in the lower portion. The whole of this container is thermally lagged with 1-inch thick polyurethane foam. There are five 6-volt accumulators all of the unspillable type. Two of these accumulators are of higher capacity and supply 12 volts to the fan motor, the other three supply 18 volts to the sonde circuits.

Calibration of temperature and pressure oscillator. The A/F oscillator plays a vital part in the measurement of temperature and pressure, and hence the stability of its various components must be very high. The oscillator has been designed to keep to a minimum changes in frequency due to small variations in voltage and variations in the temperature of the components. The small changes in frequency arising from the oscillator circuit, apart from the meteorological transducers, are measured by putting a very high-stability wire-wound resistor of 1800 ohms into the circuit instead of the meteorological transducers. Each A/F oscillator has its own reference resistor and the calibration of the oscillator is made with reference to the frequency appropriate to the standard resistor.

Hitherto the frequency of the A/F oscillator has been mentioned in terms of hertz, but in common with current radiosonde practice in this country readings from the tethered radiosonde are made in terms of periodicity, by timing a fixed number of cycles, the unit employed being microseconds (μs). The calibration of the sonde is carried out in two stages; firstly a resistance/temperature or resistance/pressure relationship for the meteorological transducers is determined, and secondly the relationship between resistance and periodicity for the A/F oscillator is determined. This oscillator is accurately calibrated for resistances between 450 and 12 000 ohms. During this calibration the oscillator circuit is placed in a thermally insulated box at 20°C and the voltage accurately maintained at 18·00 volts. Decade resistance boxes are adjusted to give readings for every 5 μs from 750 μs to 1300 μs. At frequent intervals throughout the calibration the reference resistor is switched into the circuit and the corresponding period noted. The overall change throughout the calibration in the periodicity produced by the reference resistor is about 0·5 μs. These changes are mainly due to small variations in the values of certain components of the oscillator arising from small changes in their temperature. The final calibration table of the oscillator is arranged to give the resistance at every 5 μs allowing for variations deduced from the reference resistor measurements. In practice the period for this reference resistor is rounded off to the nearest whole number. Thus, for example, for a particular A/F oscillator the relationship between resistance and periodicity is known

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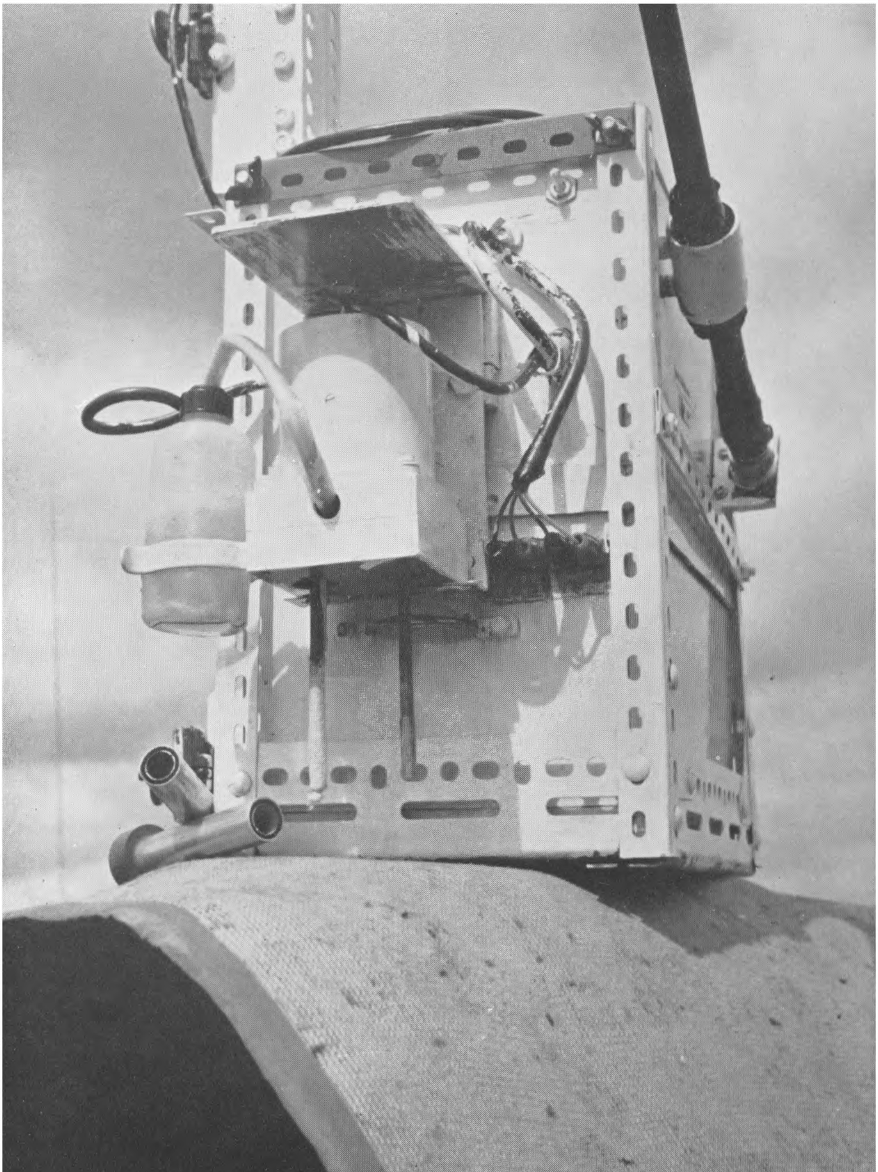

PLATE I—TETHERED RADIOSONDE SHOWING PSYCHROMETER WITH SHIELDS REMOVED FROM TEMPERATURE SENSORS

See page 95.

To face page 97

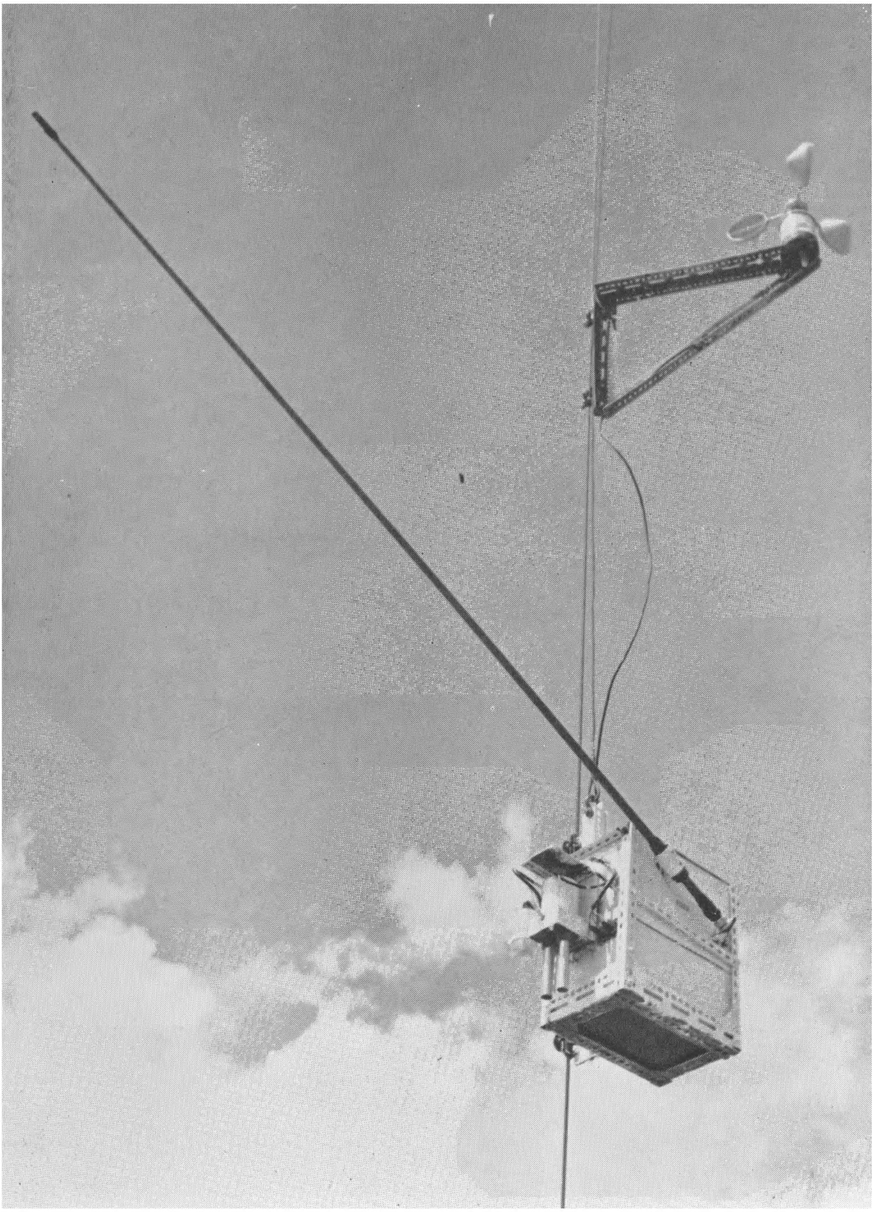

PLATE II—COMPLETE TETHERED RADIOSONDE ATTACHED TO THE BALLOON CABLE

See page 95.

when the period for the reference resistor is, say, 1047 μs. This period must be known and used whenever measurements are being made with the particular A/F oscillator.

From the resistance calibrations of the meteorological transducers and the resistance calibration of the A/F oscillator, calibrations of the meteorological transducers are evaluated in terms of periodicity. This process is done on a computer and tables are produced to give the temperature to 0·1 degC and the pressure to 0·1 mb. The final temperature calibration against periodicity is almost linear, being about 8 μs per degC. This is convenient although fortuitous and occurs because the resistance/temperature calibration of the thermistor and the resistance/periodicity calibration of the oscillator are combined to give a linear relationship between temperature and periodicity. The pressure calibration ranges from 0·3 mb/μs at 800 mb to 1·8 mb/μs at 1050 mb.

In routine use, small changes in the stability of the oscillator are observed by measuring the periodicity corresponding to the reference resistor. The difference between this periodicity and that for which the calibration of the oscillator was evaluated is applied as a displacement correction to all periodicity readings obtained with the meteorological transducers. To estimate errors likely to be introduced by this method, readings were taken with the A/F oscillator under standard conditions and again with the voltage reduced by 0·1 volt and the temperature increased by 10 degC, under which conditions the errors are cumulative. Under these conditions, by assuming a constant periodicity correction as given by the reference resistor, the errors in temperature were found to be no greater than 0·03 degC and the errors in pressure no greater than 0·2 mb. During routine operation of the sonde the stability of the calibration of the thermistors is checked weekly by taking a periodicity reading when the thermistor is in a bath of ice. The pressure sensor is checked at the beginning of each ascent by taking a periodicity reading and comparing this reading with a value from the calibration corresponding to a pressure reading from a standard barometer. Laboratory tests showed that, provided the transducers did not produce a difference of more than 1·5 μs from their original calibrations, a constant periodicity correction could be applied to all readings with a maximum error of 0·04 degC for temperature and 0·2 mb for pressure. In operation, the corrections from all sources are less than 1 μs so that the application of constant periodicity corrections over the whole range of temperature or pressure is well justified.

Wind speed. For the tethered radiosonde no change has been made to the wind speed sensor. For very light winds a sensitive cup-contact anemometer is used and for higher wind speeds a standard Meteorological Office cup-contact anemometer is used. The signals from the wind oscillator are filtered at the ground, the pulses are automatically recorded, and the mean wind speed is obtained for five minutes at each level at which measurements are made.

Ground equipment. The ground equipment is very simple, consisting of a short-wave radio receiver, two filters to discriminate the signals from the two A/F oscillators, a counter to measure the anemometer pulses, and a digital frequency counter which displays the periodicities from the pressure and temperature oscillator. At present the pressure and temperature readings are written down but there are plans for automatic recording.

Soundings. Soundings are made daily when conditions are suitable at the standard times of 00, 06, 12 and 18 hours GMT. Plate II shows the instrument connected to the balloon cable. The cup anemometer is fixed to a bracket on this cable about 2 m above the main sonde to which it is wired; the main sonde contains the pressure sensor, the various circuits and accumulators and the psychrometer, which can be seen projecting from the container. The long rod is the $\frac{1}{4}$-wave aerial which consists of a piece of wire inside a glass-fibre fishing rod. Since the transmitter is for the most part over the receiving station, the best attitude of the aerial has been found to be at about 30° to the horizontal. The main container of the sonde is approximately 50 cm by 22 cm by 38 cm and its weight including accumulators and psychrometer is about 16 kg. Readings of all elements are taken at nominal heights of 2, 36, 75, 150, 300, 450, 600, 750 and 900 metres, these heights being determined by the length of the balloon cable paid out. On the midnight sounding readings are also taken at 225 m. The sonde is held at each height for six minutes. Temperature and pressure readings are taken after five minutes. A continuous count of the wind speed is made from the end of the first minute to the end of the sixth minute and the mean wind speed over five minutes is determined. The reported message for the soundings of the tethered radiosonde consists of a reading of pressure, dry-bulb and dew-point temperatures and wind speed at the nominal heights listed above.

Acknowledgements. Thanks are due to the staff at Kew Observatory, where the laboratory tests, calibration and constructional work were done, and the staff at the Meteorological Office Research Units at Cambridge and Cardington who were concerned with the field trials.

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OBJECTIVE ANALYSIS OF UPPER AIR HEIGHT AND HUMIDITY DATA ON A FINE MESH

By MARGARET J. ATKINS

Summary. This paper describes an objective analysis system which has been developed in the Forecasting Research Branch of the Meteorological Office to produce initial fields of height and relative humidity for the fine grid of the Bushby-Timpson 10-level model. The method of height analysis is based on that of Bushby and Huckle, and Corby, and is similar to the current operational analysis of the Meteorological Office. The humidity analysis has been devised specifically for the 10-level model. The possible use of these and other methods in a future operational system is discussed.

Introduction. The widespread use of numerical models in weather prediction has led to the development of several methods of objective analysis. Numerical models need as initial data certain meteorological variables to be specified at points of a regular grid or mesh. The variable most often required is geopotential height, and methods of objective analysis have been devised to produce values of geopotential height, at a regular grid of points at about 300-km intervals, by using reported height and wind data from radiosonde ascents, aircraft reports and, more recently, satellite data. Among these are Cressman's[1] correction method, Gandin's[2] method of optimal interpolation, and methods of polynomial interpolation such as that of quadric fitting, described by Bushby and Huckle[3] and Corby,[4] which is currently used in the British Meteorological Office. Although mainly used for analysing height fields, some of these methods have been used to analyse other variables such as wind.

With the development of more sophisticated numerical models such as the Bushby-Timpson[5] 10-level model, some thought needs to be given to the most suitable method of objective analysis which should be used with the new models in an operational system. The 10-level model requires initial values of heights, winds and relative humidities; the heights and winds are required at all levels, and the relative humidities at the mid-points of the 7 lowest layers of the model. The heights and relative humidities are obtained from analyses of observed data, and the winds are obtained from the height fields by means of the balance, omega and continuity equations, as described by White.[6] There are two versions of the model. One is on a hemispheric scale and has a grid length of about 300 km in middle latitudes; established methods of objective analysis may be used for the height fields in this case. The other, on a finer scale, has a grid length of about 100 km, and it is this version with which the work described in this paper is concerned.

An experimental analysis system for the fine-scale version of the 10-level model has been developed in the Forecasting Research Branch of the Meteorological Office. This has shown up some problems in the analysis of heights on a fine grid and some improvements and other possible methods of analysis are suggested. It has also necessitated the development of a completely new system to analyse relative humidity.

Contour height. Upper air data are analysed at the seven standard levels 100, 200, 300, 400, 500, 700 and 850 mb. The 1000–500-mb thickness is also analysed and used in conjunction with the 500-mb field to obtain a 1000-mb field. The 900, 800 and 600-mb fields are obtained by vertical linear interpolation using formulae given by White.[6] A more realistic 1000-mb field obtained from surface data is compared with the 1000-mb field obtained from upper air data. The upper levels are adjusted according to the formulae

$$h_n' = h_n + \frac{(n-1)}{9} \cdot \Delta h \qquad \ldots (1)$$

where n is an integer and $1 \leqslant n \leqslant 10$, h_n' is the corrected height at $n \times 100$ mb, h_n is the original height at $n \times 100$ mb and Δh is given by

$$\Delta h = h_s - h_{1000} \qquad \ldots (2)$$

where h_s is the 1000-mb height obtained from surface data and h_{1000} is the 1000-mb height obtained from upper air data. The surface data are currently analysed subjectively, but a computer programme is being developed for the objective analysis of surface data for the fine mesh. The fields are then ready for the initialization procedure.

Analysis methods: quadric fitting, 'single-scan'. In the first experiments the operational objective analysis system used in the Meteorological Office at that time was adapted to the fine grid of the 10-level model, the grid length being one-third of that of the operational model. This method, for all levels except 100 mb is described by Bull[7] and is based on that of Bushby and Huckle[3] and Corby.[4] In the analysis of each grid point on the fine grid, the observations used were the same as if the point were one of a larger grid and the distance weighting factor for each observation remained the same in terms of distance on the surface of the earth (Figure 1). The relative weight of winds to heights and the relative weight of observations to background field also remained the same. The background fields were derived by three-dimensional linear interpolation from the operational

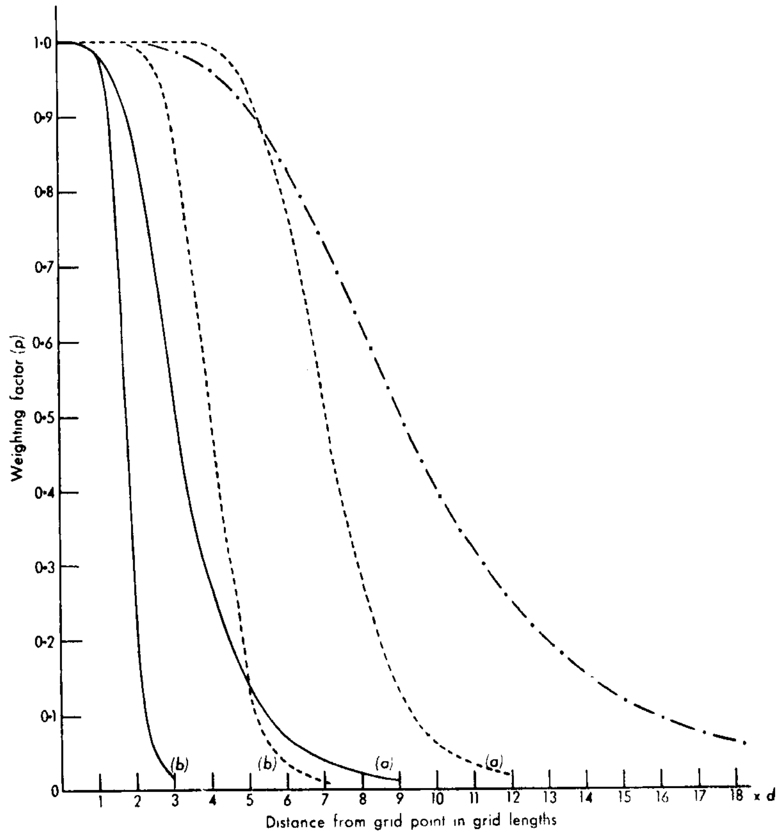

FIGURE 1—DISTANCE WEIGHTING FACTORS

——— Humidity *(a)* 1st scan $\frac{1}{1+0{\cdot}01d^4}$ *(b)* 2nd scan $\frac{1}{1+0{\cdot}01d^8}$

– – – – 2-scan height *(a)* 1st scan $\frac{1}{1+1{\cdot}5\times10^{-7}d^8}$ *(b)* 2nd scan $\frac{1}{1+1{\cdot}5\times10^{-5}d^8}$

— · — 1-scan height $\frac{1}{1+1{\cdot}4371794\times10^{-4}d^4}$

where d = grid length

analyses at 1000, 500, 200 and 100 mb. The nine background points used were as shown in Figure 2.

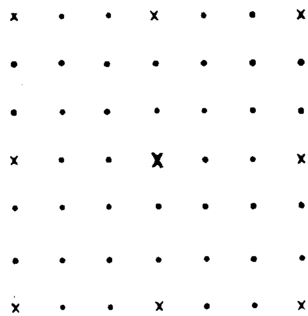

FIGURE 2—BACKGROUND FIELD POINTS USED IN ANALYSIS OF ONE GRID POINT

X Grid point being analysed
x Grid points used
Distance between **x** and **x** is 300 km.

The 100-mb analysis was essentially that devised by Woodroffe,[8] with similar modifications to those described above. The background field was obtained by horizontal interpolation from the operational 100-mb analysis.

The results on the whole tended to be rather rough, particularly at upper levels in regions of strong winds. The data check after the first analysis was found to be unsatisfactory. In the first analysis erroneous heights tended to be fitted in favour of correct winds. During the data check these heights were not rejected but some correct winds were rejected, resulting in an even poorer second analysis.

Since the object of this work was to produce analyses for research purposes rather than operational use, it was decided to leave out the automatic data check at all levels except 100 mb, where it is an essential part of the method, and examine the data subjectively before the analysis was begun. The data were extracted from archival magnetic tapes containing synoptic upper air observations and a facility was put into the programme for rejecting or inserting data. It was found that owing to a lack of data in the Atlantic the insertion of artificial data to produce a more realistic analysis was necessary on some occasions.

This procedure, however, did not remove all roughnesses and further investigation of some of the actual quadric surfaces in one of the worst cases showed that there was some difficulty in fitting winds. Winds at a distance of more than about six grid lengths from the basic grid point were very badly fitted and their exclusion from the data caused the nearer winds to be fitted better. This was because a quadric surface necessarily has a constant rate of change of slope in any direction and the combined height and wind data suggested a surface whose slope first increased and then decreased on crossing the area surrounding the grid point. This suggests that a better analysis could be obtained by only including winds within, say, six grid lengths, or by letting the distance weighting factor for winds fall off more sharply with distance from the grid point.

The roughnesses in the field, therefore, are caused not merely by over-fitting of bad observations with the use of an interpolated analysis as a background field, although this may be a contributory factor, but by the inadequacy of the quadric surface to fit the data. This inadequacy may cause a considerable change in the form of the surface, if there is a change in the data when the analysis passes from one grid point to the next, and on a fine grid these changes show up as roughnesses in the field. However, with the judicious rejection and insertion of data in bad cases, it was thought that the smoothing of the analysis in the initialization process would be sufficient to remove these roughnesses so as not to upset the forecast. Both objective analyses that have so far been used for forecasts, that is those for 12 GMT, 9 July 1968 and 00 GMT, 6 February 1969, have been done in this way.

One objective method of improving the data is to use the differences between the observations and the analysis at 100 mb to correct the data at lower levels (Hawson and Caton[9]). A proportion of these differences, or random errors, is removed from the data at each of the levels from 500 to 200 mb. Although the 100-mb analysis on the 10-level grid is not perfect, it seems good enough to improve the analyses of lower levels by this method.

Analysis methods : quadric fitting, 'double-scan'. About the time that this work was being done, problems concerning the fitting of winds in the operational analysis were noticed. Some work by Spackman, of the Central Forecasting Office of the Meteorological Office, concerning the distance weighting factors has led to an improved scheme, here referred to as the 'double' or '2-scan' method, being introduced into operational use. The main features are :

(i) the first analysis is used as a background field for the second,
(ii) a distance weighting factor which gives less weight to more distant observations is used in the second analysis, and
(iii) the values of T^2, the factor weighting winds relative to heights, is increased in the second analysis.

This has now been adapted to the analysis scheme for the 10-level grid in a similar way to the 'single-scan' system and is summarized in Table I, where p is the distance weighting factor (see Figure 1) for an observation at d grid lengths from the grid point being analysed.

TABLE I—WEIGHTING FACTORS USED IN 2-SCAN METHOD FOR HEIGHT FIELD

Scan No.	p	T	Background field
1	$\dfrac{1}{1+1{\cdot}5\times10^{-7}d^8}$	4	Interpolation from operational analysis
2	$\dfrac{1}{1+1{\cdot}5\times10^{-5}d^8}$	8	Result of 1st scan

The double-scan method has been run a few times only, but results so far indicate a smoother analysis and a closer fit to observations than has been obtained with the single-scan method.

Other possible analysis methods.

(i) *Linear interpolation from a larger grid.* An acceptable analysis might be obtained by direct linear interpolation from a larger grid, as has been used to obtain background fields. However, current evidence suggests that this is unlikely to give as good results as the above scheme, although improvements in the coarse grid analysis would result in corresponding improvements in the interpolated fine-scale analysis.

(ii) *Two-dimensional orthogonal polynomials.* A pilot experiment has been done using Dixon's[10] method of orthogonal polynomials on a small area of the 10-level grid. The results are good but more work needs to be done.

(iii) *Three-dimensional analysis in the orthogonal system.* Experimental work done in the Central Forecasting Office of the Meteorological Office has shown that it may be possible to use Dixon's method in three dimensions and to fit the whole volume of the 10-level model in four or two blocks, or even only one block, thus ensuring both horizontal and vertical consistency.

Relative humidity. In the analysis system which is being developed in the Forecasting Research Branch of the Meteorological Office, objective analyses of relative humidity are used for the layers centred at 850, 750, 650, 550, 450 and 350 mb. It is thought that surface data should be used in the 950-mb analysis and since surface humidity data are only just becoming available in digital form, the 950-mb layer is at present analysed subjectively.

Relative-humidity data are available at standard levels, and the relative humidity at the mid-points of the layers is obtained by vertical interpolation at each observing station.

Method of analysis. Since fields of relative humidity are characterized by sharp gradients and by features on the scale of fronts, it was decided that each observation should influence the analysis over a small area only. As there is no analogue to the wind used in the height analysis, there is only a small amount of information available for analysing the humidity at a particular grid point, and therefore it was decided to use a simple weighted mean of the data.

As there are large areas over the sea with no data, a background field is necessary. In an operational system it might be possible to use a forecast humidity field but for research purposes this is unpractical. Instead a background field based on initial vertical velocities derived from the omega equation as described by White[6] is used. It proved difficult to derive a formula for relative humidity in terms of vertical velocity by statistical methods, probably because of the large areas of slow upward and downward motion. The following empirical formula was devised :

$$R = \begin{cases} 70 - 5\omega & \text{for } -6 \leqslant \omega \leqslant 14, \\ 100 & \text{for } \omega < -6, \\ 0 & \text{for } \omega > 14, \end{cases} \qquad \ldots (3)$$

where R is relative humidity and ω is vertical velocity in millibars per hour. This gives a reasonable range of relative humidity. Equation (3) has been tried on two cases which were very different from each other. The first (12 GMT, 9 July 1968) gave fairly smooth fields, but at upper levels the general value was too high. The second (00 GMT, 6 February 1969) was characterized by strong upward and downward motion and the resulting background field was rather rough. It may be necessary to alter this formula in the light of experience.

The formula used in the analysis for each grid point is of the form

$$R = \frac{\sum_{i=1}^{n} (p_i R_i + b R_b)}{\sum_{i=1}^{n} p_i + (b)} \qquad \ldots (4)$$

where R_i is an observation of relative humidity at a nearby station, R_b is the value of the background field of relative humidity at the grid point concerned, b is the relative weight of the background field to the observations and p_i is a distance weighting factor for observations of the form

$$p_i = \frac{1}{1 + \lambda d_i^{\gamma}} \qquad \ldots (5)$$

where d_i is the distance in grid lengths from the station to the grid point, and λ and γ are parameters which determine the shape of the curve. The summation of (4) is taken over the n nearest stations. In practice n was limited to six. When there are no observations, equation (4) is replaced by the value of the background field.

At first it was decided that only stations within three grid lengths of the grid point should be used; for most grid points this implied fewer than four stations. The distance weighting factor was

$$p = \frac{1}{1 + 0{\cdot}01 d^8}. \qquad \ldots (6)$$

This was found to be unsatisfactory as in places the background field differed markedly from the observations and this resulted in 'pools' around isolated observations.

The system which has been adopted is one which consists of two scans through the field. The first uses the background field derived from vertical velocities, and up to six stations within a distance of nine grid lengths from the grid point. The second scan uses the results of the first scan as background field, and stations up to three grid lengths from the grid point. This second scan is intended to bring out the smaller-scale features.

The system is summarized in the Table II.

TABLE II—WEIGHTING FACTORS FOR 2-SCAN METHOD FOR HUMIDITY FIELD

Scan No.	p	r	Background field	b
1	$\frac{1}{1+0{\cdot}01d^4}$	9	$70 - 5\omega$	0·05
2	$\frac{1}{1+0{\cdot}01d^8}$	3	Result of 1st scan	0·2

where r is the radius of influence in grid lengths. The distance weighting factors are shown in Figure 1. In the first scan the weight of the background field is the same as that of an observation at about six and a half grid lengths, and in the second scan it is the same as that of an observation at about two grid lengths.

Results for an occasion in February 1969. Figures 3 and 4 show

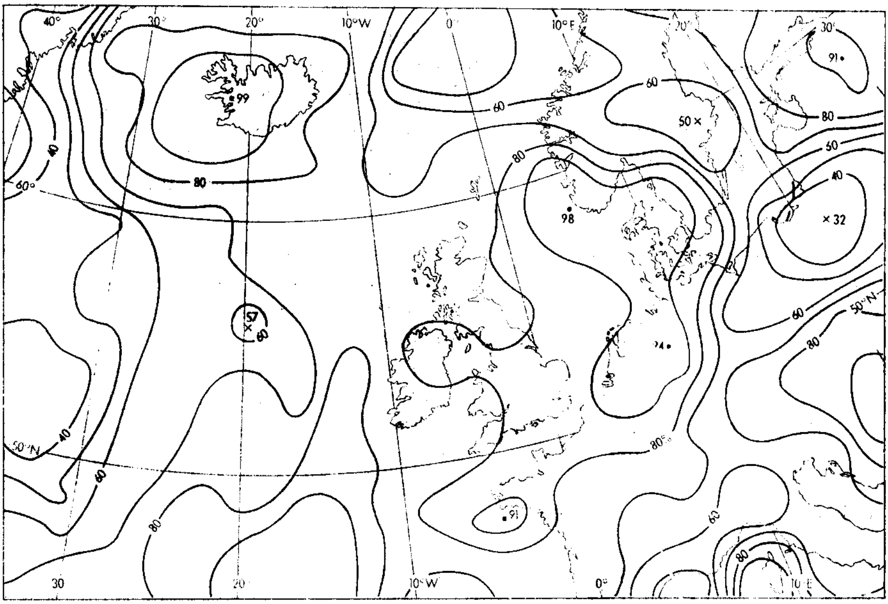

FIGURE 3—OBJECTIVE ANALYSIS OF 850-mb RELATIVE HUMIDITY FIELD, 00 GMT, 6 FEBRUARY 1969

Isopleths at intervals of 10 per cent.

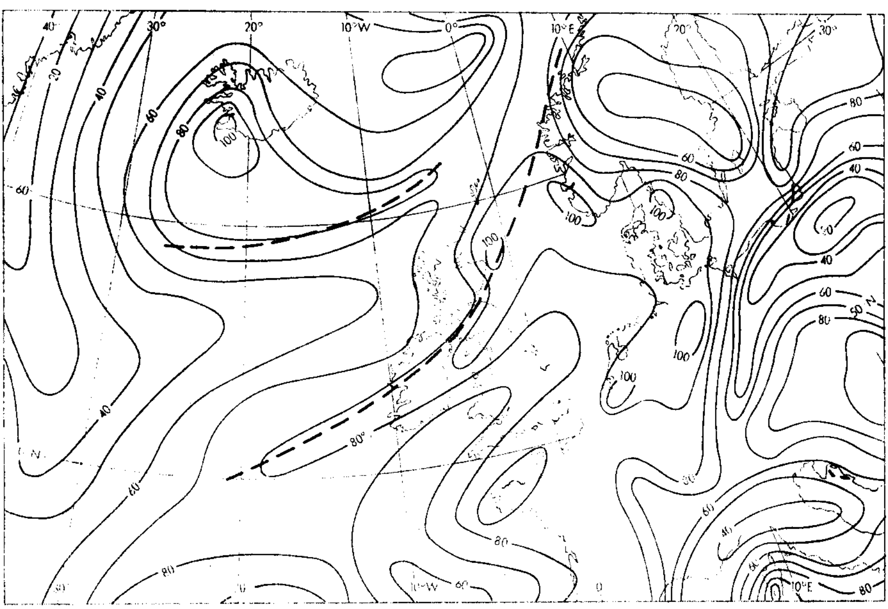

FIGURE 4—SUBJECTIVE ANALYSIS OF 850-mb RELATIVE HUMIDITY FIELD, 00 GMT, 6 FEBRUARY 1969

— — — Surface fronts

Isopleths at intervals of 10 per cent.

objective and subjective analyses of relative humidity at 850 mb for 00 GMT on 6 February 1969. The values at the corresponding grid points are reasonably close to each other, although the shapes of the features are different. The shape is not quite so important here as in a height analysis, because it does not imply anything analogous to a wind. However, in sparse data areas it is difficult to identify such features as fronts. In this case there was a surface front from western Norway, through Shanwell and Long Kesh, to just south of ocean weather station 'J'.

An objective analysis of humidity for this date, for all levels from 850 to 350 mb with a subjective 950-mb analysis, has been successfully used in conjunction with an objective height analysis to produce a 24-hour forecast. Figures 5 and 6 show the actual synoptic situation for 00 GMT on 6 and 7 February 1969 respectively. Figure 7 shows the forecast surface and 500-mb patterns valid for 00 GMT on the 7th. The surface trough has been forecast to move from a position south-east of Iceland across the British Isles into the North Sea, although it has not been deepened sufficiently. The region of high pressure in the Atlantic has been intensified and that over Europe weakened. The 500-mb trough has been moved eastward but it is still 5° of longitude too far west and not sufficiently deep. Figure 8 shows the present weather for 00 GMT on the 7th. There are scattered showers over most of the British Isles except south-east England; they are more frequent on exposed coasts but there are some inland, mostly carried in from the sea by strong winds. Figure 9 shows the forecast precipitation for the same time. The main area of rain has been forecast to the east of the British Isles but in the southern North Sea is west of its actual position; the area indicated in the Atlantic is purely convective. There is an absence of showers over the British

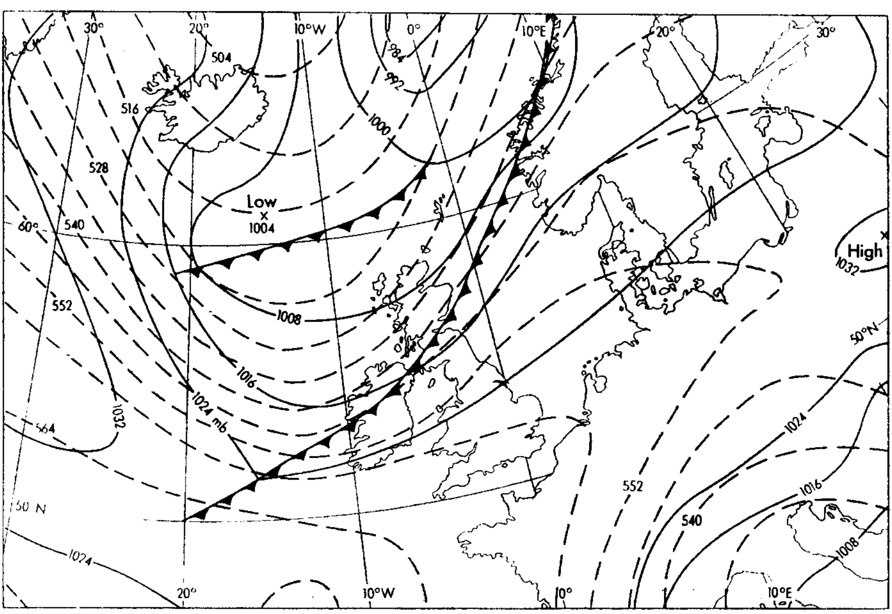

FIGURE 5—ACTUAL SYNOPTIC SITUATION, 00 GMT, 6 FEBRUARY 1969

——— Surface isobars at intervals of 8 mb

— — — 500-mb contours at intervals of 6 geopotential decametres

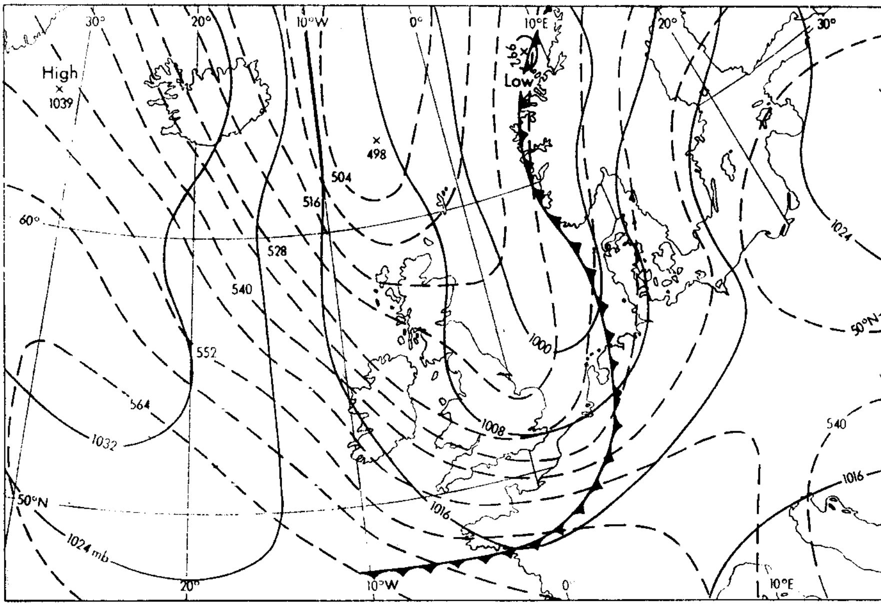

FIGURE 6—ACTUAL SYNOPTIC SITUATION, 00 GMT, 7 FEBRUARY 1969

——— Surface isobars at intervals of 8 mb
— — — 500-mb contours at intervals of 6 geopotential decametres

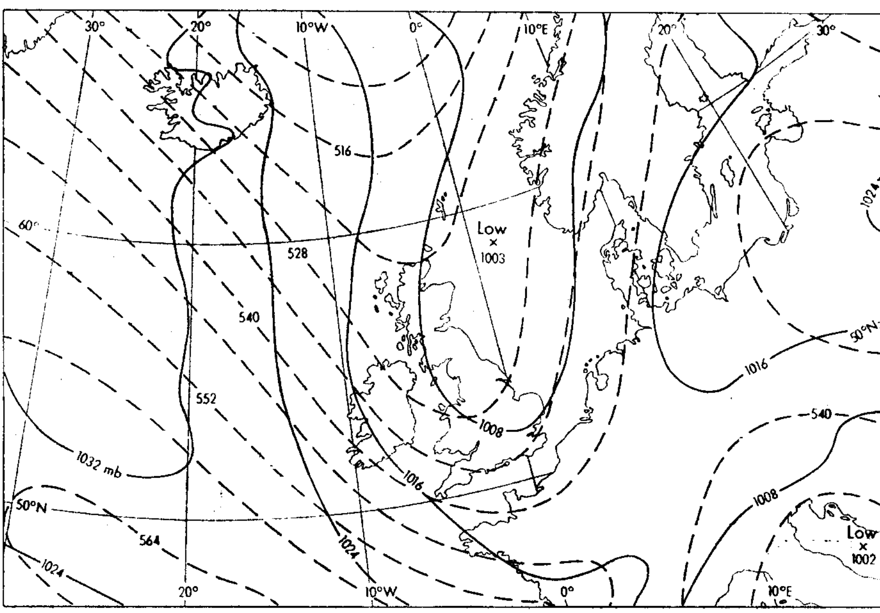

FIGURE 7—24-HOUR FORECAST OF SYNOPTIC SITUATION, 00 GMT, 7 FEBRUARY 1969

——— Surface isobars at intervals of 8 mb
— — — 500-mb contours at intervals of 6 geopotential decametres

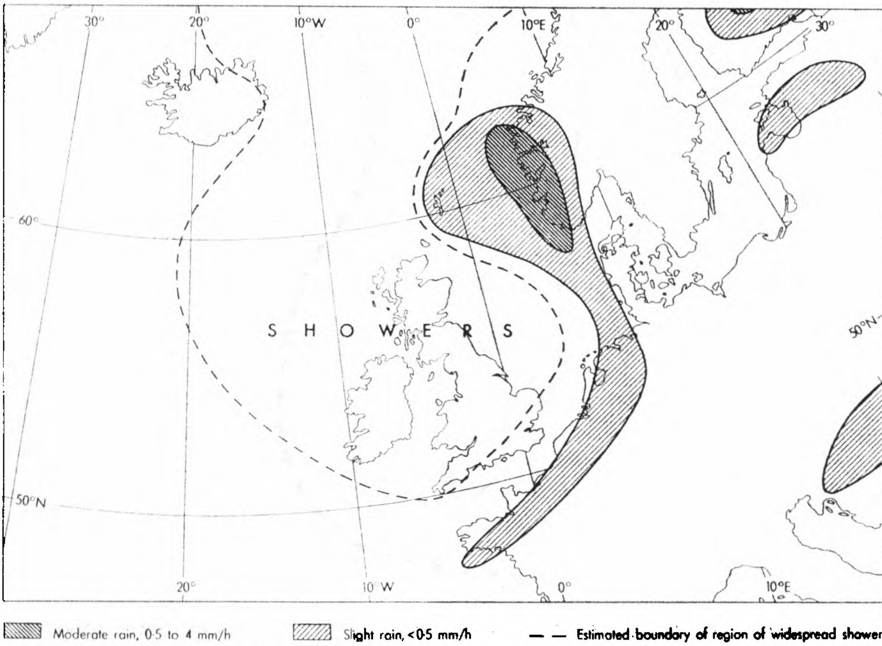

FIGURE 8—PRESENT WEATHER, 00 GMT, 7 FEBRUARY 1969

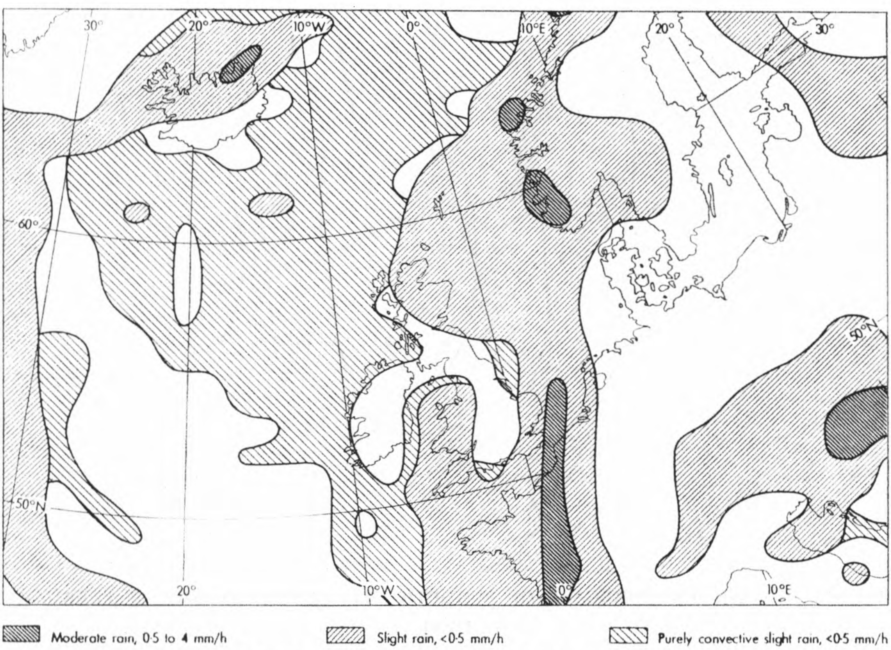

FIGURE 9—24-HOUR FORECAST OF TOTAL RATE OF RAINFALL, 00 GMT, 7 FEBRUARY 1969

Isles in the forecast because the surface heating, which is used in the model for land surfaces in February, is naturally insufficient to induce convection and the model does not allow for showers being advected inland from over the sea.

A 6-hour forecast was also computed using the same objectively analysed heights but subjectively analysed humidities. There are some small differences between the 6-hour forecast in the 1000-mb height and rainfall. However, these are probably the result of the way the 950-mb humidity field was obtained and mask effects due to the difference between subjective and objective analyses at higher levels. In the subjective case, a subjective analysis of surface humidity was used as a 1000-mb humidity field and the 950-mb field was obtained by vertical interpolation. In the objective case this same subjective analysis was used directly as the 950-mb humidity field. This resulted in the 950-mb field being moister in the objective analysis in some areas, and at 6 hours the forecast from objective data appeared better.

Discussion. The system of analysis of heights and humidities described above is adequate for research purposes but would not be suitable for operational use in its present form. Both the height and humidity data are examined subjectively before the analyses commence, and those used in the analyses are assumed correct. At present the 1000-mb height and 950-mb humidity fields are analysed subjectively. It should be relatively easy to develop a 1000-mb height analysis from surface data using established methods, but some research needs to be done on the use of surface humidity data in the analysis of the 950-mb relative humidity field.

A probable method of improving the height analyses is the use of orthogonal polynomials in two dimensions and it may be possible to fit the whole area of the 10-level model with one surface. It is not thought likely that linear interpolation from a larger grid would improve the height analyses very much.

The humidity analysis is good over areas of good data coverage but could be improved over areas of sparse data. Some possible methods are as follows :

- (i) The use of forecast humidity fields as background fields.
- (ii) A better background field obtained by an improved relationship with vertical velocity.
- (iii) The use of surface cloud and present weather data. Chisholm *et alii*[11] and Ball and Veigas[12] have done some work relating dew-point depression at 850, 700, 500 and 400 mb with surface observations.
- (iv) The use of satellite cloud data.
- (v) The use of significant-level data. This could be particularly valuable in analysing the 950-mb layer.

However, the method of objective humidity analysis for upper levels described above compares well with a subjective analysis and it has been used to obtain a reasonable forecast. It should be possible to use it operationally if no better method is meanwhile developed.

Acknowledgements. I wish to thank members of the staff of the objective analysis section of the Central Forecasting Office of the Meteorological Office for the use of some of their programmes and for their general help and advice, and also Mrs V. D. McDougall for her assistance in the programming for this work.

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MOUNTAIN LEE-WAVE INCIDENTS IN SCOTLAND

By M. BAILEY

Summary. Three cases of mountain lee waves are described. In each case the aircrew reports are related to the values of wavelength and maximum vertical velocity determined by the method due to Casswell. It is suggested that this technique can provide a useful guide when assessing the aviation hazards in a particular wave situation.

Introduction. Recent work by Casswell[1] and Foldvik[2] has given forecasters a simple graphical method whereby maximum vertical velocities, wavelength and level of maximum amplitude of mountain lee waves can be assessed using simple quantities obtained from a representative tephigram.

The vertical motions, wind variations and turbulence involved in well-developed wave systems can each present a major hazard for aircraft. When an aircraft in level flight encounters a wave updraught it will tend to rise, but its angle of attack may be reduced by the pilot so the aircraft will enter a shallow dive relative to the rising air and its airspeed will increase. If altitude is maintained in a downdraught, airspeed will decrease unless power is increased. A stall might result from this loss in airspeed.

When an aircraft is climbing through a wave system, for example on take-off, the actual rate of climb will vary, being greater in the updraughts. This variation is not directly related to the strength of the draughts, because the actual rate of climb will depend upon how the aircraft is flown, and its type, since entry into a draught will alter the incidence of air on the wing and hence the lift. This is illustrated in the first case described (Figure 4). Units used are in accordance with the usual aviation units.*

*Conversion factors to Système International (SI) units: 1 kt ≈ 0·5 m/s, 1000 ft/min ≈ 5 m/s 1000 ft ≈ 300 m, and 1 n. mile ≈ 2 km.

29 April 1966. At 0550 GMT on 29 April 1966 a British European Airways Herald aircraft flying from Aberdeen to Edinburgh reported marked standing waves. Writing several days after the event the pilot described the incident.

> 'I recall that the rate of climb was varying between 600–800 ft/min and 1500–1700 ft/min and the airspeed was varying between 160 and 210 kt in sympathy. As I recall there was no noticeable turbulence. In consequence of aircraft weight, altitude and power in use, rate of climb should have been approximately 1000–1200 ft/min and airspeed constant at 204 kt. Airspeed in the updraughts would have been in excess of the 210 kt stated, but power was reduced to keep speed within the aircraft limits.'

The route flown lies on a bearing of 226° (true) from Aberdeen/Dyce to Perth. This airway (shown on Figure 1) crosses the eastern flank of the Grampians where there are several ridges and valleys approximately at right angles to the route.

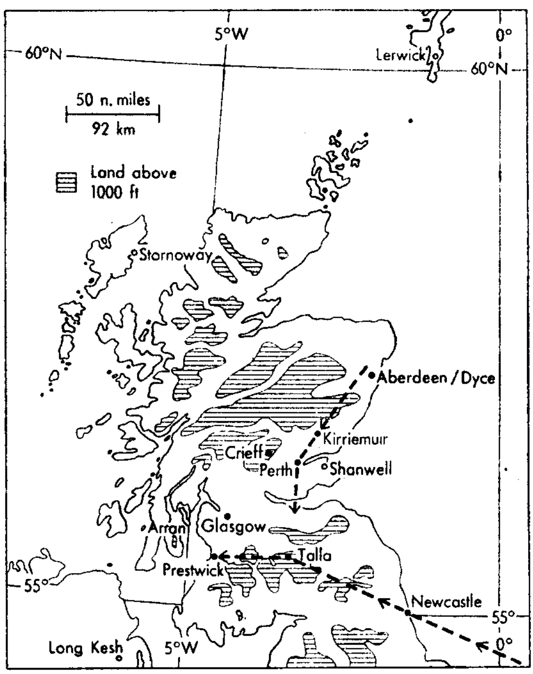


FIGURE 1—ROUTES FLOWN BY AIRCRAFT REPORTING TURBULENCE
o Upper air stations

The 06 GMT surface chart showed a weak warm front to the west of the British Isles and a strong south-westerly gradient over Scotland. Similarly, the 500-mb chart showed a strong south-westerly flow, mainly to the west of Scotland (Figure 2). This strong wind belt moved slowly eastwards during the day. The 00 GMT upper air sounding from Shanwell had a marked inversion at 850 mb, with instability above and below. This inversion was probably due to subsidence but there was evidence of the warm frontal air at 500 mb. At 06 GMT the wind at the inversion level was 42 kt, increasing above the 400-mb level to reach 69 kt at the tropopause. Figure 3 shows

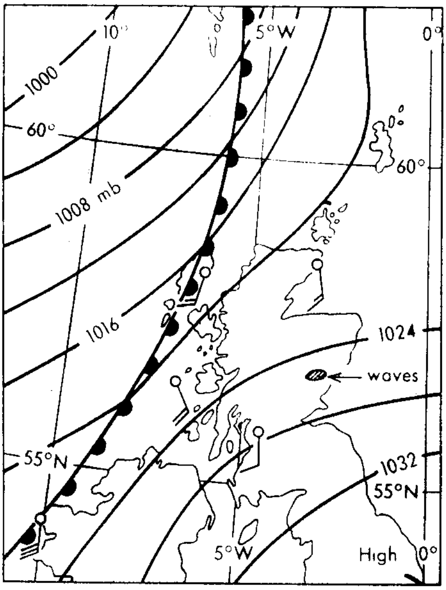


FIGURE 2—SYNOPTIC SITUATION AT 06 GMT ON 29 APRIL 1966, AND SHOWING LOCATION OF WAVES

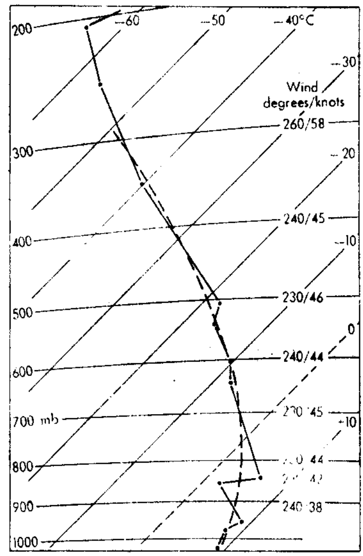


FIGURE 3—UPPER AIR SOUNDING FOR SHANWELL AT 00 GMT ON 29 APRIL 1966, WITH WINDS AT 06 GMT

·——· Temperature
— — — Smoothed curve used in Casswell calculation

the 00 GMT sounding from Shanwell and the 06 GMT winds with the smoothed curve used in the Casswell calculation. The results appear in Table I.

TABLE I—MOUNTAIN LEE WAVES OBSERVED AND PREDICTED, 29 APRIL 1966

Location	Time	Wind at 900 m	Wind components* 850 mb	500 mb	Wavelength (Observed)	Vertical speed (Observed)	Height (Observed)
	GMT	*deg/kt*	*knots*		*n. miles*	*ft/min*	*ft*
Observations							
Banchory	0550					400	6 000
Calculations					(Computed)	(Computed)	(Computed)†
Long Kesh	00	220/29	34	33	5·8	290	8 500
	06	230/38	40	44	7·8	456	11 000
Shanwell	00	230/35	34	33	6·2	420	9 000
	06	240/38	41	45	9·0	494	11 000

*Components at right angles to ridge.
†Level of maximum amplitude from Casswell's graph.

When Casswell's method was used the 06 GMT winds at Shanwell gave a maximum vertical velocity of 494 ft/min with a maximum amplitude at 11 000 ft and a wavelength of 9 n. miles, whereas the aircrew reported changes in the rate of climb equivalent to 400 ft/min at a level 5000 ft below this. Figure 4 shows the aircraft flight path from Aberdeen, based on an estimated ground speed and expected rate of climb. The updraughts and downdraughts were encountered while climbing through the 6000-ft level in the region 15 to 20 n. miles south of Aberdeen. Simplified streamlines have been drawn to show the wave motion downstream of the final lee slopes of the Grampians.

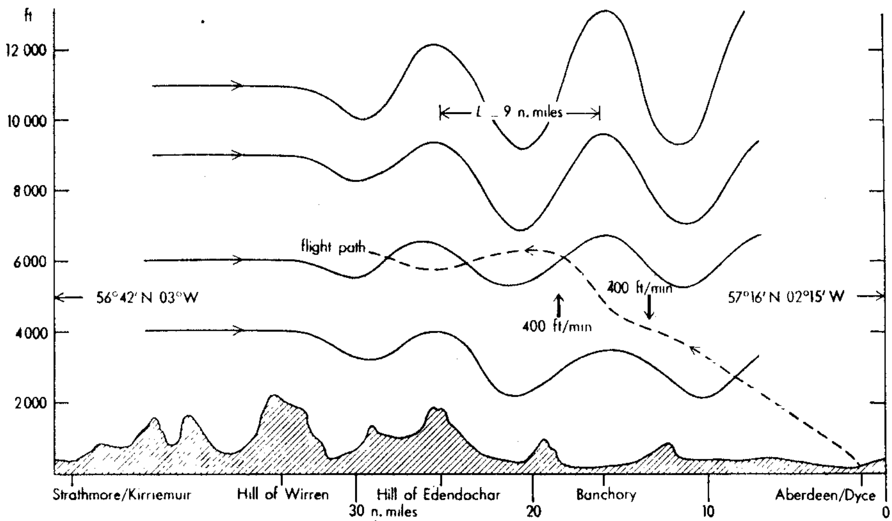


FIGURE 4—SIMPLIFIED CROSS-SECTION FROM ABERDEEN/DYCE TO KIRRIEMUIR, 29 APRIL 1969

L = wavelength

Theory indicates that the first wave-crest will occur three-quarters of a wavelength downstream of the initiating ridge. It is usually accepted that the final lee slope of a mountain system determines the wave form over the downstream lowlands, although Bérenger and Gerbier[3] suggest that consecutive mountain ridges may cause resonance and affect the wave amplitude. The wave amplitude could be increased if ridges are in phase with the wave form and the distance between ridges is close to the wavelength. Examination of the relief profile showed that the Hill of Edendochar was the final marked lee slope below the airway but approximately 7 n. miles upstream a sharp lee slope lies on the north side of the Hill of Wirren. In composing the diagram it was assumed that the latter slope generated the final wave motion with resonance over the Hill of Edendochar, which lies three-quarters of a wavelength downstream. The greatly simplified wave train shown in Figure 4 had a trough about 21 n. miles south of Aberdeen and a crest about 16 n. miles south of Aberdeen. The diagram shows how the aircraft penetrated the up-draughts and downdraughts in this region and the flight path has been adjusted in accordance with the modified rates of climb reported. Rough values for the wave amplitudes were obtained using the formula

$$w_{(\max)} = \frac{2\pi Ua}{L}$$

(where w is the vertical component of wind, U the horizontal component of wind, a the semi-amplitude and L the wavelength) quoted by Corby.[4] In this case there is fair agreement between computed values and those observed.

13 January 1967. On this occasion four reports of mountain lee waves or associated phenomena were received at Prestwick. At 0330 GMT a pilot flying between Amsterdam and Prestwick reported wave activity over the Southern Uplands with vertical velocities of 300 ft/min at 8500 ft. At 0915 GMT severe turbulence was reported between 1000 and 1500 ft near Glasgow Airport, and during the afternoon reports of downdraughts with vertical speeds 1500 ft/min were received. These occurred in the vicinity of Crieff between 4500 and 6000 ft and south of Shanwell at 3000 ft.

At 00 GMT an anticyclone was situated between ocean weather station 'J' and the Brest peninsula. The centre drifted slowly south-east and a strong west to north-west surface flow was maintained throughout the day over Scotland and Northern Ireland (Figure 5). The upper air pattern was similar

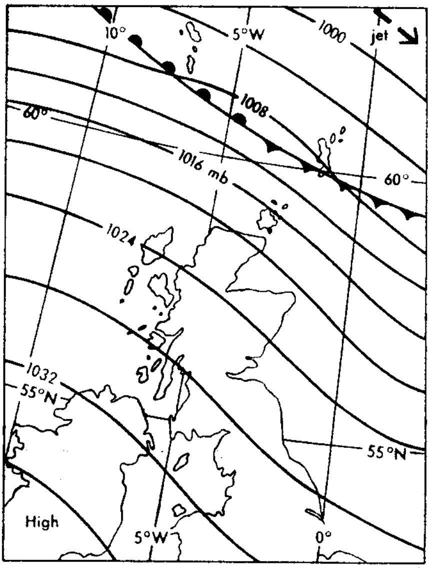
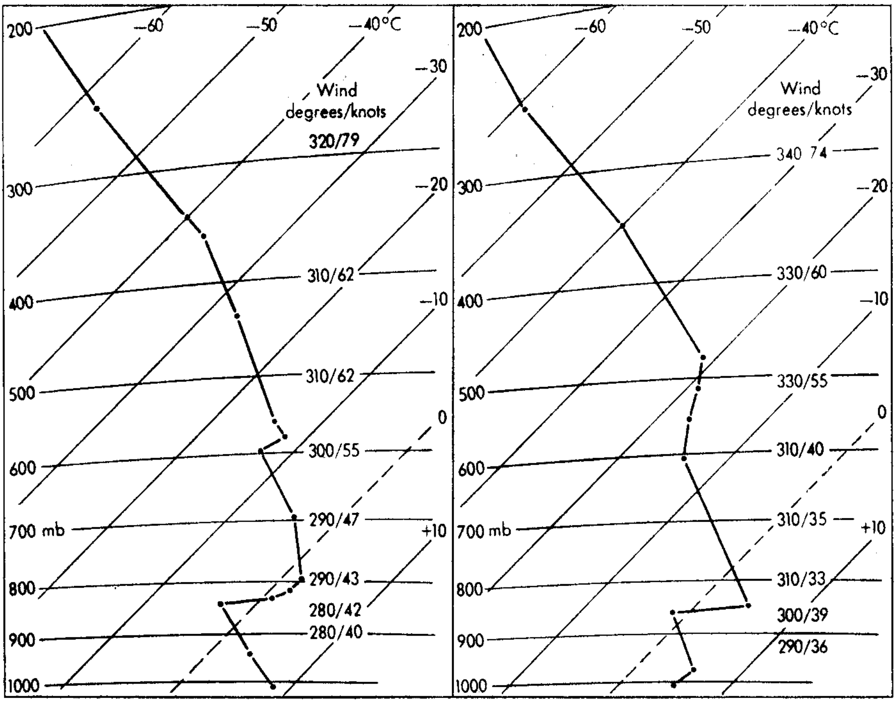


FIGURE 5—SYNOPTIC SITUATION AT 06 GMT ON 13 JANUARY 1967

with a strong flow around the high centre south-west of Ireland. The strongest wind belt lay to the north of the British Isles with a jet stream from Iceland to Oslo. The upper air soundings at Long Kesh, Stornoway and Shanwell (Figure 6) all show typical subsidence inversions close to 850 mb. At Stornoway the steady increase of wind with height was particularly favourable to wave development, but winds at Shanwell and Long Kesh were barely strong enough for well-developed waves.

Calculations based on Casswell's method gave the results in Table II. The wavelengths and vertical speeds increase from the south to north, i.e. towards the strong wind zone. The calculated levels of maximum amplitude were also higher in the north. The highest calculated vertical velocity was 560 ft/min based on the 00 GMT data. At Long Kesh a value of 300 ft/min at 6000 ft was obtained at 00 GMT but the method failed to give results at 06 GMT and 12 GMT.

Examining the four reports one finds fair agreement between the 00 GMT values at Long Kesh or Shanwell and the report from the Southern Uplands. It is probable that these waves were due to the coastal hills of Ayrshire, or possibly the island of Arran. The Glasgow report may be due to a down-draught in the lee of the Kilpatrick Hills but marked wind shear above the Clyde Valley could also be a contributory factor. At 0920 GMT Glasgow



(*a*) Stornoway (*b*) Shanwell

FIGURE 6—UPPER AIR SOUNDING AND WINDS FOR STORNOWAY AND SHANWELL AT 00 GMT ON 13 JANUARY 1967

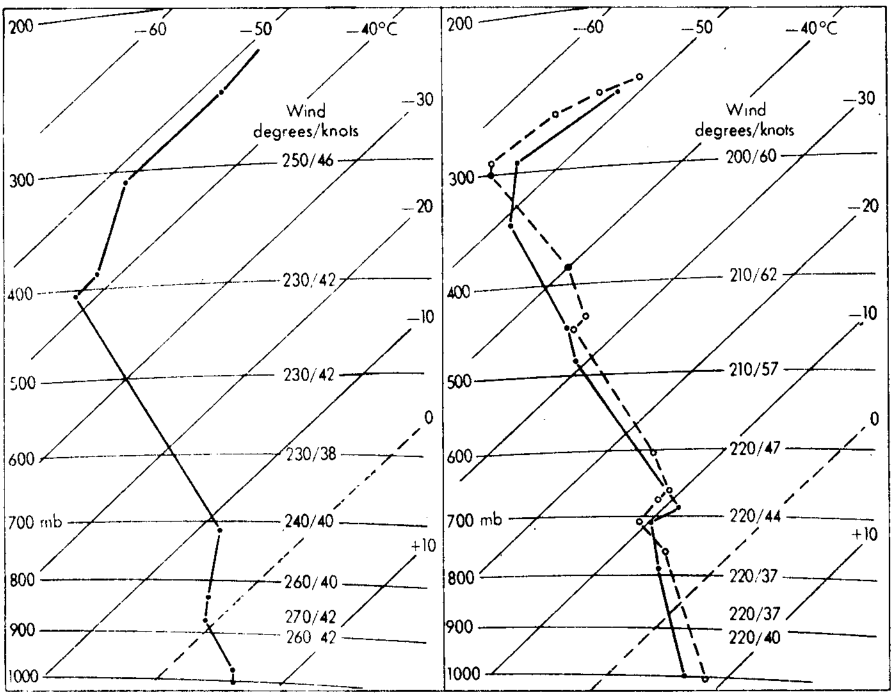
TABLE II—MOUNTAIN LEE WAVES OBSERVED AND PREDICTED, 13 JANUARY 1967

Location	Time	Wind at 900 m	Wind components* 850 mb	Wind components* 500 mb	Wavelength (Observed)	Vertical speed (Observed)	Height (Observed)
	GMT	*deg/kt*	*knots*	*knots*	*n. miles*	*ft/min*	*ft*
Observations							
Southern Uplands	0230					300	8 500
Crieff and Shanwell						1500	3 000 6 500
Calculations					(Computed)	(Computed)	(Computed)†
Long Kesh	00	310/25	27	27	4·0	300	6 500
	06	300/29	37	24	no result	—	—
	12	310/29	39	26	no result	—	—
Shanwell	00	290/36	38	42	7·0	360	10 500
	06	300/43	44	43	7·8	344	11 500
	12	290/39	43	45	8·0	312	12 000
Stornoway	00	280/40	42	53	9·0	560	11 500
	06	280/46	43	42	7·7	414	11 000
	12	290/42	40	49	9·5	504	13 000

*Components at right angles to ridge.
†Level of maximum amplitude from Casswell's graph.

Airport reported surface wind 270° 24 kt, varying between 15 and 37 kt. At 0950 GMT the wind direction was varying between 230 and 290°. Marked vertical wind shear and turbulence are often encountered in this area, particularly when inversions exist near to the surface. Similarly, the Crieff and Shanwell cases might be associated with downdraughts to the lee of major ridges.

18 January 1967. In the third caseconsidered, mountain lee waves were encountered over the Southern Uplands. On this occasion examination of the wind and stability profiles for Long Kesh, Aughton and Shanwell (Figure 7) suggested that waves were unlikely to be a major hazard, although the strong surface winds to the south-east of the depression would produce turbulence in the lower levels. The high level of the inversions, the unstable air at



(a) Long Kesh *(b)* •——• Shanwell o– – –o Aughton

FIGURE 7—UPPER AIR SOUNDING AND WINDS FOR LONG KESH, SHANWELL AND AUGHTON AT 00 GMT ON 18 JANUARY 1967

Long Kesh and the veering winds were the main factors in this decision. The occurrence of significant waves was demonstrated by the following report.

The crew of an aircraft flying from Amsterdam to Prestwick observed mountain waves over the Southern Uplands. The waves were encountered '20 minutes flying time from the east coast', i.e. 40 n. miles out to sea south-eastwards from Newcastle, 'continuing as far as the west coast at Prestwick'. Vertical speeds in the waves were estimated at 300–400 ft/min with the wave-length 'equivalent to 10 minutes flying time'. The flight path was overhead Newcastle to Talla at 8500 ft followed by descent to arrive at Prestwick at 0250 GMT.

At 00 GMT on 18 January 1967 a depression was situated in the Hebrides with a small wave near the Moray Firth running north-east. By 06 GMT this wave had developed into a separate centre near Shetland with the old low filling. At 00 GMT a cold front lay from Inverness through Newcastle to Southampton, moving steadily eastwards during the night (Figure 8). The

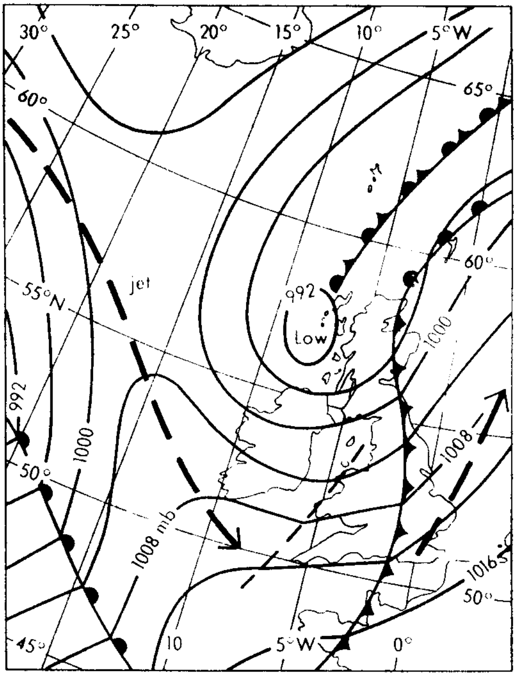


FIGURE 8—SYNOPTIC SITUATION AT 00 GMT ON 18 JANUARY 1967
Broad pecked arrow marks jet stream.

500-mb chart showed a broad trough over the Irish Sea with a south-westerly flow over England and the North Sea at 00 GMT. Over Scotland the winds at 500 mb were relatively light; the pattern at 300 mb was similar.

The upper air soundings from Aughton and Shanwell showed weak inversions at about 700 mb but the Long Kesh ascent clearly showed the cold air below the upper trough to the rear of the cold front. Wind structures were not typical of a strong wave situation but Shanwell did show a change through the inversion with a steady increase of wind above this, to reach a maximum of 65 kt at 400 mb. This had decreased considerably by 06 GMT. Winds at Aughton showed a similar pattern but were lighter. At Long Kesh the light winds veered to north-westerly by 06 GMT.

Table III shows the results obtained from Casswell's method using the 00 GMT data. It is interesting to note that results were obtained for Shanwell

TABLE III—MOUNTAIN LEE WAVES OBSERVED AND PREDICTED, 18 JANUARY 1967

Location	Time	Wind at 900 m	Wind components* 850 mb	500 mb	Wavelength (Observed)	Vertical speed (Observed)	Height (Observed)
	GMT	*deg/kt*	*knots*		*n. miles*	*ft/min*	*ft*
Observations							
Newcastle to Prestwick	0215				13·0	300–400	8 500
Calculations					(Computed)	(Computed)	(Computed)†
Long Kesh	00	260/42	41	37	no result	—	—
Shanwell	00	230/40	37	56	11·0	680	12 000
Aughton	00	230/23	23	42	5·4	506	6 700

*Components at right angles to ridge.
†Level of maximum amplitude from Casswell's graph.

and Aughton but not for Long Kesh which lay in the colder air mass. Taking Shanwell as typical of the Southern Uplands, a vertical speed of 680 ft/min was obtained with a wavelength of 11 n. miles. Estimated level of maximum amplitude was 12 000 ft. Because of the lighter low-level winds, waves calculated for Aughton were of a lower magnitude.

A mean wind of 250° 40 kt at 8500 ft on the aircraft flight path with an aircraft heading of 300° gave a resultant headwind of 26 kt. The airspeed of this type of aircraft is normally 145 kt, so in this case ground speed would be about 120 kt. In 10 minutes flying time a distance of 20 n. miles would be covered. An actual wavelength of 13 n. miles could be deduced from this report, allowing for the divergence of the track from a route parallel to the airflow. This agrees well with the computed value using Casswell's method and a value of 14 n. miles using the equation (based on Figure 12 of Corby[4]) in the World Meteorological Organization *Technical Note* No. 34[5]

$$\lambda = 0{\cdot}585\bar{u} - 2{\cdot}8,$$

where λ is the lee wavelength in kilometres and $\bar{u}$ is the wind speed (metres/second) meaned over the layers contributing to the wavelength assessment.

The interest of this case lies not only in the verification of the wavelength but in the occurrence of waves in the apparently unfavourable conditions on the cold side of a weak jet stream. The wind profile was not ideal and the inversions were weak; however, Casswell's method does yield useful results.

Conclusion. The three cases selected from several aircrew reports collected show that a quantitative method of assessing mountain lee-wave situations can be of use to forecasters.

Acknowledgement. The writer is indebted to Captain Read of the Civil Aviation Flying Unit for advice on the aviation aspects of mountain lee waves, and to the numerous aircrew providing reports.

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551.515.33

A NOTE ON OBSERVED DUST—WHIRL DAMAGE AT NICOSIA, CYPRUS

By J. B. McGINNIGLE

At 1315 GMT, on 31 July 1969, damage to the roof of a house (Plates III, IV) in Nicosia was caused when a dust whirl of considerable intensity passed north-eastwards as shown in Figure 1. About 40 roof tiles each weighing

3 to 4 pounds (nearly 2 kg), were torn from the roof and some landed in the garden on the east side of the house. Damage occurred only on the north-east side of the roof.

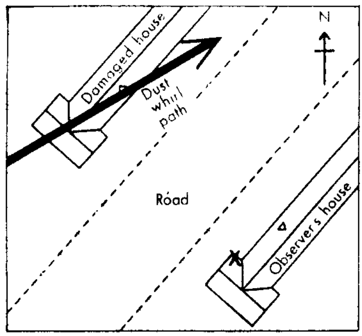

FIGURE 1—POSITION OF HOUSES
X Point of observation

During the incident, light items (papers, etc.), which lay well inside the house, were blown through open french windows on the east side of the house by a strong through draught from open windows in other rooms on the west side of the house. Most articles were lodged at the walls of surrounding houses 30 to 40 ft (about 10 m) away, mainly east and north-eastwards. Chairs were blown from the covered verandah in front of the french windows into the front garden.

At the observer's house (Figure 1), a very strong and sudden wind was experienced for about 10 seconds and windows, shutters and other loose items were blown about violently. Quantities of earth, twigs, etc., were blown from the front garden into the house and all items adjacent to windows at the front of the house, the west side, were covered by a thick layer of grit which had been blown through window-frame cracks.

The dust whirl was thereafter seen to be moving north-eastwards at an estimated speed of 20 kt (1 kt ≈ 0·5 m/s), rotating cyclonically. The estimated vertical development was 300 ft (100 m) and the diameter of the circulation top appeared to be around 150 ft (50 m).

Observational data. The nearest meteorological observing station is at Nicosia Airport, 35°09′N 33°17′E, 219 m (719 ft) above mean sea level and this is situated about 1 n. mile (2 km) south-west of the site of the dust-whirl damage.

Figure 2 shows, diagrammatically, the record of wind speed and direction made by the anemograph at Nicosia Airport and Table I shows the sequence of routine observations of temperature and humidity from 1158 GMT to

TABLE I—OBSERVATIONS AT NICOSIA AIRPORT, 31 JULY 1969

Time	Surface wind		Temperature	Dew-point	Relative humidity
GMT	*degrees*	*kt*	*degrees Celsius*		*per cent*
1158	360	07	36·0	9·3	20
1237	360	08	36·0	8·4	19
1337	280	15	35·5	14·6	29
1437	280	14	34·0	15·2	33

Anemogram shows onset of sea-breeze at 1310–1315 GMT.

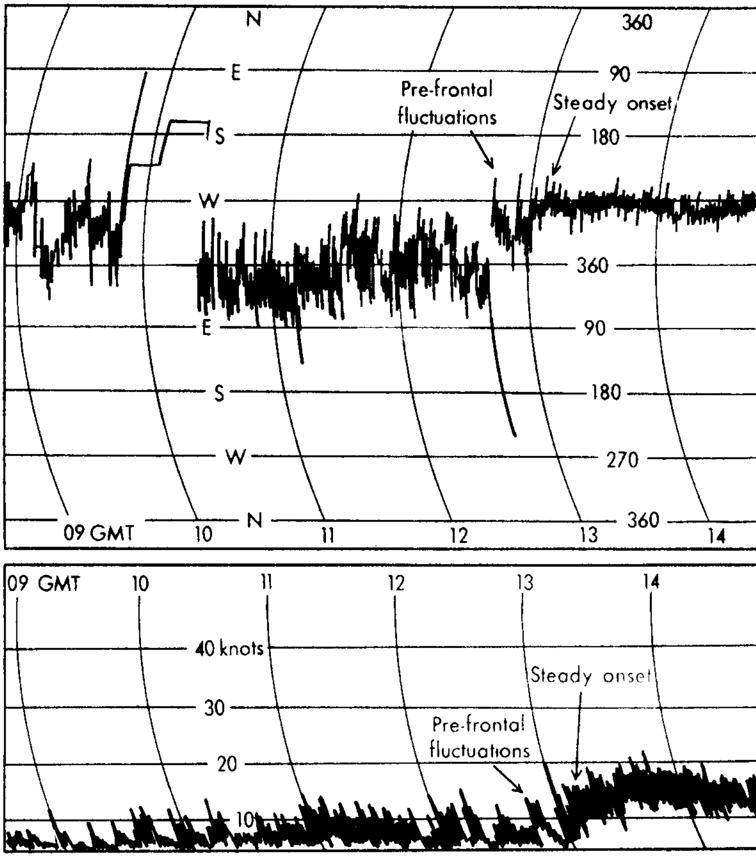

FIGURE 2—DIAGRAMMATIC REPRESENTATION OF ANEMOGRAM AT NICOSIA AIRPORT ON 31 JULY 1969

1437 GMT. Little pressure change was recorded during these times and there were no clouds except small amounts of cumulus, base 7000 ft, over the Troodos mountain range.

After a morning of variable winds, marked fluctuations in both direction and speed began to occur at 1245 GMT, when the wind veered from north-east to north-west (through south) thereafter varying in the range 230° to 010°, with a speed range of 3 to 20 kt. After 1310 GMT, the direction became much steadier at around 280° and the mean wind speed increased to 13–16 kt with gusts to 22 kt. From the temperature/humidity records (Table I), the passage of the sea-breeze front occurred between the 1237 GMT and the 1337 GMT reports. The temperature decreased and the relative humidity rose sharply. These records therefore show that the sea-breeze front passed through Nicosia Airport at 1310–1315 GMT, after a 25-minute period of pre-frontal wind fluctuation.

In summer, the sea-breeze at Nicosia sets in normally from west to north-west in the late morning or early afternoon, penetrating from Morphou Bay between mountain ranges to both north and south (Figure 3). Wind speeds

PLATE III—DAMAGE TO ROOF OF HOUSE IN NICOSIA, CAUSED BY DUST WHIRL ON
31 JULY 1969
See page 118.

To face page 121

PLATE IV—DAMAGE TO ROOF OF HOUSE IN NICOSIA, CAUSED BY DUST WHIRL ON 31 JULY 1969

See page 118.

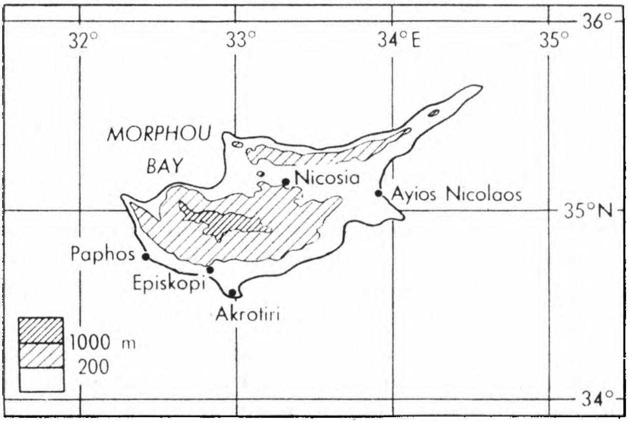

FIGURE 3—MAP OF CYPRUS

are generally 12 to 18 kt with gusts to 25 kt. On this occasion, with a sea-breeze direction of 280°, the frontal orientation is assumed to be 010–190°, at right angles to the wind direction and parallel to the coastline of that part of Morphou Bay nearest to Nicosia.

Pilot-balloon ascents are made at Paphos and Ayios Nicolaos on a routine basis, as well as at the radiosonde station at Episkopi. Unfortunately, none of these reporting stations are in a geographical position to assist with the low-level wind structure on this occasion, except to demonstrate that at 06 GMT, the low-level winds over Cyprus were generally light and variable. At Nicosia Airport, pilot-balloon ascents are made on a non-routine basis and, on 31 July, an ascent at 08 GMT also showed that the low-level winds were light.

Surface	030°	03 kt
3000 ft	335°	07 kt
5000 ft	270°	05 kt
7000 ft	290°	16 kt

The 12 GMT radiosonde ascent for Episkopi is shown as Figure 4. When the Nicosia surface temperature/dew-point convection path is plotted as

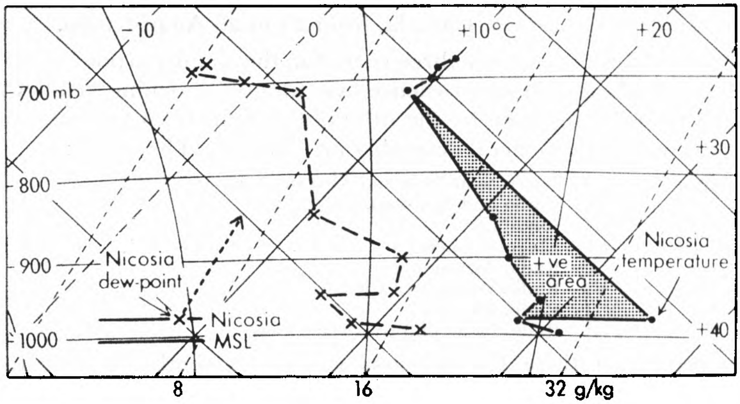

FIGURE 4—EPISKOPI RADIOSONDE ASCENT, 12 GMT, 31 JULY 1969
x – – – x Dew-point · ——— · Temperature

shown, it can be seen that a large positive energy area exists and this, in combination with the reported light wind structure, fulfils the required conditions for dust-whirl development as defined by a previous work.[1]

The 12 GMT synoptic chart showed a surface trough from Turkey to a small depression complex with central pressures of 1002 mb over the north-east part of the island and 60 n.miles north-west of Cyprus.

Discussion. Dust whirls occur fairly commonly in summer in the central plain area of Cyprus, generally appearing to be of 100–200 ft (30–60 m) vertical development. On this occasion the dust whirl was of greater vertical development and occurred with the onset of the sea-breeze.

A dust whirl usually moves with the wind speed and direction at the top of the circulation. The dust whirl described in this paper did not follow the east-south-eastward movement of the wind as would normally occur but moved across the flow at an angle of 40–50°, clearly in association with the sea-breeze front.

A previous paper[2] has described a similar occasion in Libya, where the dust whirl passed directly over the meteorological office at Idris Airport; all the evidence suggests that the dust whirl reported in this note was generated and maintained in a similar manner.

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551.501.8:061.3

XVITH GENERAL ASSEMBLY OF THE INTERNATIONAL UNION OF RADIO SCIENCE, OTTAWA, AUGUST 1969

By W. T. ROACH

Introduction. The International Union of Radio Science (or Union Radio Scientifique Internationale (URSI)) held its XVIth General Assembly at Carleton University, Ottawa, Canada, from 18 to 28 August 1969.

These assemblies occur every three years for the main purpose of reviewing the progress of research in radio science over an ever widening field. A general idea of the scope is conveyed by the titles of the eight Commissions into which the proceedings of the General Assembly are divided. These are :

Commission	I	Radio Standards and Measurements
	II	Radio and Non-ionized Media
	III	Ionosphere
	IV	Magnetosphere
	V	Radio Astronomy
	VI	Radio Waves and Circuits
	VII	Radio Electronics
	VIII	Radio Noise of Terrestrial Origin

The meetings of these Commissions run concurrently, so that it is not generally practicable to attend the meeting of more than one Commission, although some meetings were shared by two or more Commissions. The writer attended Commission II meetings.

Historically, the main area of overlap between meteorology and radio science has been in the study of electromagnetic propagation through the atmosphere, and its practical applications to communication links over a very wide range of operating frequencies and distances. The communications engineer, in common with the aeronautical engineer, is not interested in the atmosphere for its own sake, but only as rather a nuisance which often interferes with his interests, and has therefore to be accounted for. There is a long history of liaison between radio interests and the Meteorological Office in a field common to both called radio-meteorology. This subject formed the main business of Commission II. It should, however, be noted that URSI (by definition) is at least as much concerned with the use of radio as a tool in scientific research as with its practical communications applications.

Commission II meetings. Proceedings of the scientific meetings of the XVIth Assembly will be published in due course, so this account will be confined to a brief outline of the main features of scientific interest discussed in Commission II.

During the past five years or so, the dominant research interest has been in theoretical and experimental studies of the electromagnetic scattering properties of the atmosphere, not only from the communications point of view, but also for the information on the structure of the atmosphere that can be inferred from such studies. Readers will recall Professor Atlas's lecture to the Meteorological Office on his analysis of radar echoes from clear-air turbulence.* Since then, other (more powerful) radars have been used to study clear-air echoes, which have now been detected at heights of up to 25 km at ranges in excess of 100 km. The writer has made a plea for a more systematic study of these echoes for the information they might yield on the evolution of clear-air turbulence patches and movement relative to their environmental wind fields.

Also of interest was a discussion of the main features of the Inter Union Commission on Radio Meteorology (IUCRM) Colloquium on the 'Spectra of atmospheric variables' held in Stockholm in July 1969. Evidence of the widespread occurrence of Kelvin-Helmholtz instability (KHI) in the atmosphere was combined with observations of KHI in the ocean thermocline and in laboratory investigations to give a reasonably consistent picture (with good support from theory) of this particular mechanism of transition from laminar to turbulent flow. This led to further discussion of the physical differences between gravity waves and turbulence, and their roles in the scattering of radio waves.

The current importance of this general field of investigation was recognized by URSI by devoting one afternoon to a session on 'Electromagnetic probing of the atmosphere' at a joint meeting of all the Commissions. At this session, the word 'atmosphere' covered the total depth from the troposphere, stratosphere, mesosphere, ionosphere out to the magnetosphere.

Leaving the atmosphere altogether, it is clear that space science (and the reverberations of Apollo 11) is perhaps displacing the atmosphere as the dominant research interest of URSI. Space science leaked into the proceedings of most, if not all, the commissions. At the opening scientific session of

* ROACH, W. T.; Lecture by Professor David Atlas. *Met. Mag.,London*, **95**, 1966, pp. 379–381.

Commission II, observational results of radio and radar studies of the lunar surface and of the planetary atmospheres were discussed. As a result of this, new terms of reference of Commission II were proposed as follows :

> 'Commission II is concerned with the phenomena associated with the propagation of radio waves through the media on the earth, the moon and the other planets, including the effect of boundaries, but excluding the effects of ionization.'

The current title of Commission II (Radio and Non-ionized Media) is perhaps slightly misleading, as ionization is present in some degree throughout the earth's atmosphere, but below the ionosphere the level of ionization has no significant effect on radio propagation.

Turning now to research of a more applied nature, it was clear that there had been an increase in studies of the effect of the atmosphere on line-of-sight links in optical, infra-red and micro-wave frequencies.

The effect of heavy precipitation on micro-wave communication links received considerable discussion. A loss of communication of only a few hours per year due to heavy rain is undesirable; but this loss can be considerably reduced by the use of path diversity, i.e. simultaneous transmission over two or more links spaced far enough apart (≈ 1 km) to make it unlikely for all paths to be seriously affected by rain at the same time. The related subject of rainfall measurement by means of radar received some discussion, with particular reference to problems arising in the comparison of rainfall rates obtained from radar echoes with those obtained from rain-gauges, e.g. fluctuations in precipitation on scales less than the rain-gauge spacing, and the fall velocity of raindrops as a function of their size.

The main item of interest emerging from infra-red and optical attenuation studies was the suggestion that water vapour might exist in polymer form in the atmosphere, and that the diamer of H_2O would be expected to produce discrete lines in the 30–300 μm region plus a continuous absorption over a wide range of wavelengths.

Other topics touched on included radio-glaciology — the use of radar for probing ice sheets in Greenland and the Antarctic — and the possible use of radio techniques from earth satellites for earth resources studies. This, however, was the only time earth satellites were referred to in Commission II.

At the final meeting, it was suggested that IUCRM should consider holding symposia on the following subjects :

(i) Planetary atmospheres and the lunar surface.
(ii) Atmospheric spectroscopy and its uses.
(iii) Electromagnetic techniques in earth resources studies.

In conclusion, it appears that future growth points which may involve Commission II interests should be :

(i) Radar studies of clear-air turbulence with adequate meteorological support.
(ii) Studies of planetary atmospheres, etc.
(iii) Studies of polymer forms of H_2O in the atmosphere.
(iv) Applied research on measurement of rainfall by means of radar and path diversity systems.

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METEOROLOGICAL OFFICE LONG-RANGE FORECASTS: SIX YEARS OF PROGRESS

By R. A. S. RATCLIFFE

The Meteorological Office commenced the issue of long-range (30-day) forecasts in December 1963 and the practice has continued twice a month from that date. Freeman[1] reviewed the success of the first 33 months of forecasts in an article in this magazine in 1966 and this note is intended to bring the reader up to date.

The style of the forecast has not changed very much over the 6 years although over the last year or two it has been the practice whenever possible to start the forecast with a brief description of the salient features of the expected weather over the first 5–7 days. This has become possible with the increasing reliability of numerical forecasts for 2–3 days ahead which has allowed them to be used as a basis for the application of empirical methods of forecasting, thus extending the range by a further 3–4 days. With this exception the main part of the forecast remains unaltered and includes statements on the expected monthly mean temperature and the total amount of rainfall together with additional information on the probable frequency of such elements as snow, frost, gales, etc., during the 30-day period.

As stated in Freeman's article but repeated here for convenience, the expected monthly mean temperature is given as one of five categories: much above average, above average, near average, below average or much below average.

Monthly rainfall totals are quoted as one of three categories: above average, average or below average. The boundaries between the categories in both cases are arbitrarily selected so that in the period 1931–60 each category occurred equally frequently. The category boundaries vary somewhat from month to month and for different areas of the British Isles, examples being quoted in Freeman's paper. The temperature and rainfall forecasts are checked separately for each of the 10 areas of the British Isles shown in Figure 1. These areas have remained unchanged over the 6 years but, in some cases, names have been changed to avoid confusion with similar names used in BBC regional forecasts.

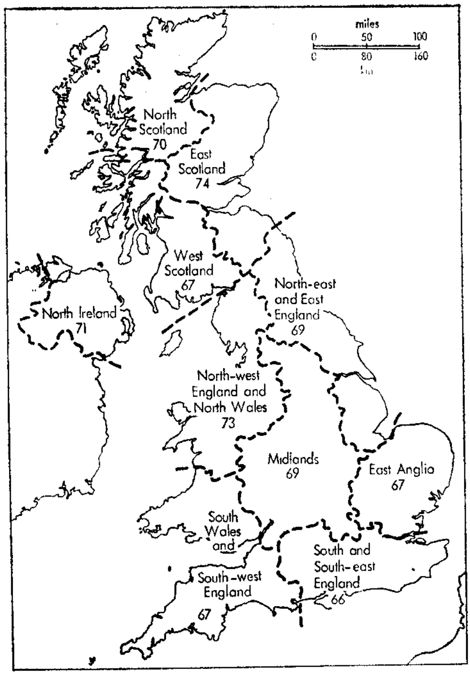

FIGURE 1—FORECAST REGIONS OF THE BRITISH ISLES

The numbers are percentages of correct or nearly correct temperature forecasts in the 6-year period.

For each area there are four to six check stations depending on the area; in this respect a better representation of some areas has been gradually achieved over the years. For example, East Scotland is now represented by Edinburgh and Kinloss as well as by the original check stations Aberdeen and Leuchars, while South and South-east England which previously had no check station near the south coast, now includes both Manston (Kent) and Deal.

The method of calculating the area mean anomalies of temperature and rainfall is entirely objective and was fully described by Freeman in the earlier paper. The calculations are carried out using *Daily Weather Report** stations as far as possible and involve extensive use of the Meteorological Office computer.

A score for each area is calculated from Table I.

TABLE 1(*a*)—SCORES FOR TEMPERATURE FORECASTS

Actual	FORECAST Much below	Below	Average	Above	Much above
Much below	4	1	−3	−4	−4
Below	2	4	1	−2	−2
Average	0	1	4	1	0
Above	−2	−2	1	4	2
Much above	−4	−4	−3	1	4

*London, Meteorological Office. *Daily Weather Report.*

TABLE I(*b*)—SCORES FOR RAINFALL FORECASTS

Actual	FORECAST Below	Average	Above
Below	4	−2	−4
Average	0	4	0
Above	−4	−2	4

Over a long period when the frequency of occasions in each category is about equal, the average score by chance will be zero and zero will also be the average score obtained by always forecasting the normal (i.e. climatology). From the scores for each area an average score for the whole country is calculated and is used to assess the accuracy of the forecast in one of the five categories :

A No serious error

B Good agreement

C Moderate agreement

D Little agreement

E No real resemblance

All negative scores are placed in classes *D* or *E*.

The additional information cannot in general be so objectively assessed but each statement made is considered after the event by a panel of meteorologists and a combined mark for all statements is given on the scale *A* to *E*. Some statements can be objectively assessed, e.g. 'frost will be more frequent than usual'. Such a statement would be evaluated by comparing the number of days with frost during the forecast with the normal (1931–60) for the period for all check stations in the British Isles. Similar checks are made for statements about the frequency of snow, gales, thunderstorms, fog, wet days, etc., and also for the monthly total of sunshine which is often forecast in summer as one of three categories : above average, average or below average.

Finally, an overall mark for the accuracy of each forecast is given, compounding the marks for temperature, rainfall and additional information. Freeman's paper quoted the frequency with which the various assessments were made for the first 66 forecasts, ending in August 1966. Table II shows similar frequencies for the 78 forecasts in the period from September 1966 to November 1969.

TABLE II—NUMBER OF FORECASTS IN THE VARIOUS CATEGORIES OF SUCCESS, SEPTEMBER 1966 TO NOVEMBER 1969

Category		Mean temperature	Rainfall	Additional information	Overall marking
A	No serious error	18	5	20	4
B	Good agreement	20	18	30	27
C	Moderate agreement	17	28	21	33
D	Little agreement	13	17	5	11
E	No real resemblance	10	10	2	3

It is gratifying to note that whereas moderate agreement or better was attained in 73 per cent of the earlier sample of forecasts, Table II shows that 64 out of 78 of the more recent forecasts were assessed as being at least in moderate agreement, a figure of 82 per cent. The improvement is perhaps more easy to appreciate from the figures for individual years, which are quoted in Table III.

TABLE III—NUMBER OF FORECASTS SHOWING AT LEAST MODERATE AGREEMENT

Year	Mean temperature	Rainfall	Additional information	Overall marking
1969	19	19	23	22
1968	17	15	24	19
1967	16	15	20	18
1966	14	13	18	18

It would be easy to exaggerate recent success much of which has been due to better 'additional information' rather than to an improvement in the temperature and rainfall forecasts. In particular it must be noted that 'moderate agreement' is not a very high standard. However, *A* and *B* forecasts are good forecasts by any standard and Table II shows that 31 of the 78 more recent forecasts (40 per cent) have been assessed in those categories compared with 38 per cent in the first 66 forecasts, a much more modest improvement. It is interesting and informative to look at the breakdown of poor *(D* or *E)* forecasts by months. It has been known for some years that autumn is a difficult season to forecast for but Figure 2 shows, rather

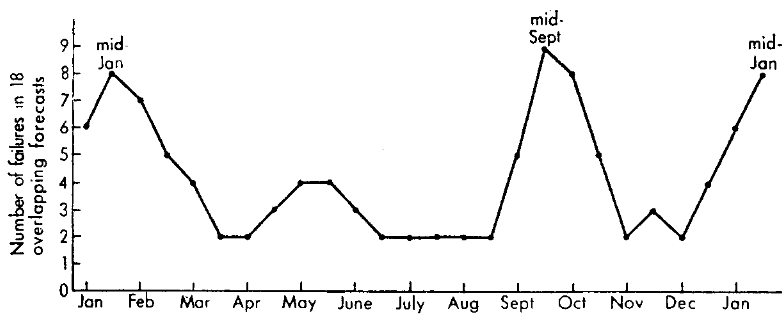

FIGURE 2—VARIATION IN LONG-RANGE FORECAST ACCURACY THROUGHOUT THE YEAR

surprisingly, that there is another peak in failures around the midwinter period and a lesser one about May. This graph is based on a small number of cases (6 forecasts for each of the 24 forecast periods) but each plot is made up from the results of three sets of overlapping forecasts plotted on the centre one, e.g. the figure of 9 for mid-September includes 1 failure in September, 4 in October and 4 in the mid-September to mid-October period. The maximum possible number of failures at any point on the graph is therefore 18. Clearly the long-range forecasts are most likely to be reliable from March to September and also around November and December.

Although Table III shows that rainfall results have improved, good forecasts of temperature are still made more often than good forecasts of rainfall. If the forecasts are broken down into the individual areas shown in Figure 1 the results in Table IV are obtained. Rainfall is forecast as one of three categories so it is not meaningful to quote the percentage of occasions one category out because average rainfall tends to be forecast more often than the two extremes and with a forecast of average an error of more than one category cannot be made.

It is interesting to note that there is apparently a geographical distribution to the success figures, temperature forecasts in particular being better in the

TABLE IV—PERCENTAGE OF CORRECT OR NEARLY CORRECT FORECASTS WHEN THE 10 AREAS* ARE CONSIDERED SEPARATELY, COMPARED WITH CHANCE EXPECTATION

(a) Temperature forcasts

	CHANCE EXPECTATION Assuming 1931–60 distribution	Assuming distribution which occurred 1964–69	First 66 forecasts	Next 78 forecasts	1969
			per cent		
Correct	20	23	26	27	33
One category wrong	32	40	42	43	42
Correct or nearly correct	52	63	68	70	75
(b) Rainfall forecasts					
Correct	33	34	36 (35·9)	36 (36·3)	41

*As shown on Figure 1.

northern and western districts than in the south-east. The percentages of temperature forecasts correct or nearly correct over the whole 6-year period are indicated for each area in Figure 1.

As noted by Freeman,[1] middle categories of both temperature and rainfall were forecast too often and the extreme categories too rarely, but this factor has if anything been over corrected in the more recent temperature forecasts as can be seen from Table V. Average rainfall has occurred a little more frequently than would be expected but the 'over forecasting' of average rainfall has been entirely at the expense of 'above average'. Below-average rainfall occurred 31 per cent and was forecast 30 per cent of occasions. Attempts are being made to correct this bias in rainfall forecasts.

TABLE V—PERCENTAGE DISTRIBUTION OF OCCURRENCES AND FORECASTS FOR THE EARLIER PERIOD (66 FORECASTS) COMPARED WITH THE DISTRIBUTION FOR THE LATER PERIOD (78 FORECASTS)

(a) Temperature

	December 1963–August 1966		September 1966–November 1969	
	Occurrences	Forecasts	Occurrences	Forecasts
	per cent		*per cent*	
Much below average	29	4	15	19
Much above average	9	3	5	9
(b) Rainfall				
Average	35	49	37	59

The modest but real improvement in the last few years in the long-range forecasts has been due to two main causes. Firstly, there has been considerable expansion in the data library used for analogue purposes in the preparation of the forecasts. This now includes historical series of sea surface temperature maps back to 1888, mid-month to mid-month mean surface pressure maps for the period back to 1899 and 500-mb charts for the period back to 1873, the earlier years of which have been produced by the adoption of a statistical technique developed in the Meteorological Office. Secondly, a good deal of research work has been carried out and is continually being integrated into the monthly forecast routine. One of the more successful pieces of research has been the uncovering of relationships between Atlantic ocean temperature anomalies and surface pressure anomalies a month ahead (Ratcliffe and Murray[2]) but there have been other notable advances including work by Ratcliffe[3] relating 500-mb monthly mean patterns to rainfall in England and Wales a month ahead and several papers by Murray[4,5,6] on persistence of monthly mean temperature and sequences of monthly rainfall.

Results still leave a good deal to be desired but it is hoped that further advances can be made. Forecasts would be more useful if a broad description of the expected sequence of weather could be given over the whole period rather than just for the first week. Certainly there is no complacency among the long-range forecasters, but progress will continue to be slow.

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THE EFFECT OF CHANGES OF ATMOSPHERIC STABILITY AND SURFACE ROUGHNESS ON OFF-SHORE WINDS OVER THE EAST COAST OF BRITAIN

By P. E. FRANCIS

Summary. The variation in the ratio of wind speed over the sea to that over the land is examined for various stability conditions and for different initial land winds. An attempt is made to explain the observed variation by reference to the theory of turbulent boundary-layer flow.

Introduction. It is an observable fact that surface winds are affected by changes in surface roughness and in atmospheric stability. In particular, winds blowing across a coastline undergo changes in direction and speed because of the change in the surface roughness characteristics and also because of the changes in the atmospheric stability of the lower layers, due to the different thermal properties of the land and sea surfaces. A knowledge of the winds over the sea is of obvious importance to shipping, sailing enthusiasts and fishermen, who have a direct interest in the wind strength and direction, and in the waves and currents that the winds induce. Not so obvious is the interest of river-authority engineers and coastguards. Their concern in this respect is the generation of storm surges (abnormally high tides) by strong wind fields over the sea. Because it is relatively shallow and partially enclosed, the North Sea is nearly ideally suited for the generation of wind-induced surges. As a result of this interest in the structure of the wind over the sea, the meteorologist is often required to supply relevant information and this, in view of the lack of on-the-spot observations, is a difficult task.

At any given time a coastal observing station on the east coast can supply anemograph data which determine the local wind field. These local winds will differ from station to station because of the varying effects of topography and exposure. The North Sea itself is almost devoid of wind observations except for a few reports from lightships and the occasional report from a commercial vessel. In order to gain some insight into the structure of the wind field over the main sea areas, say up to 50 miles from the coastline, the following investigation was undertaken. A long series of simultaneous wind observations taken at a coastal station and at a lightship stationed in adjacent waters were examined and an empirical relationship between the observed winds at the two stations was arrived at.

A description of some previous work on this subject, together with a review of other, earlier, work may be found in Richards, Dragert and McIntyre[1] referred to in this paper as (A). All the work referred to in (A) was carried out over the Great Lakes of North America, and the findings of that work will be compared to the results arrived at in this account. One major difference must be pointed out from the beginning; since the length of fetch over water was an important factor in investigation (A) it was decided to consider only off-shore winds in this paper so that the variations in fetch for our observations would be small.

Data. The observing stations used in this investigation were Gorleston, on the Norfolk coast, and the Smith's Knoll Lightship. The lightship is positioned about 20 miles off-shore on a bearing of approximately 070° from Gorleston, this direction being nearly perpendicular to the coastline. Observations from the 10 years 1957–66 were used. Off-shore winds were defined as blowing from between 210° and 290° at Gorleston, and to ensure that both observations were made in the same air mass the criterion that the wind directions at Gorleston and Smith's Knoll should not differ by more than 30° was applied. Observations not satisfying this criterion were discarded and in this way the chance of there being an intervening frontal discontinuity was minimized. Under these conditions a total of 3366 simultaneous observations were retained as being suitable for analysis. The data were extracted from punched cards in the Meteorological Office records and put on magnetic tape, each individual observation consisting of the following information :

Year, month, day, hour, wind direction, wind speed, temperature.

For the Gorleston observations the temperature recorded was that of the air, while in the Smith's Knoll observations the sea surface temperature was recorded. Air temperatures before 1961 and all the sea surface temperatures were in degrees Fahrenheit, so this was chosen as the reference scale for temperature, especially as the American work was also in Fahrenheit. Accordingly the air temperatures from 1961 were converted from degrees Celsius. Wind speed measurements were recorded in knots, to the nearest whole knot, and wind directions in tens of degrees.

Method and results. From each pair of simultaneous observations three indices were tabulated :

(i) $R = \dfrac{U_s}{U_L} = \dfrac{\text{wind speed over sea}}{\text{wind speed over land}}$

(ii) D_d = (wind direction over land) – (wind direction over sea)

(iii) T_d = (air temperature over land) – (sea surface temperature)

The index T_d was taken as a measure of the instantaneous stability of the surface layers of atmosphere as they were advected from the land to the sea. Following the method in (A) it was proposed to investigate the variation of R with the wind speed over the land, U_L, and with T_d, and, in addition, to find out whether any information concerning the variation of D_d with U_L and T_d could be obtained.

To facilitate the analysis the range of U_L was divided into four arbitrary sub-ranges called 'wind-speed classes'. These classes and the frequency of observations within them are given in Table I. The range of value of T_d in the observations was from -21 to $+24$ Fahrenheit degrees. Once again this complete range was split up into sub-ranges, called 'stability classes'. As might have been expected the frequency distribution of T_d values was very peaked, having a maximum near 0 Fahrenheit degrees. The total range was split up in a manner designed to give approximately equal frequencies to the five sub-ranges. Consequently the middle class was narrow while the outer classes were quite wide. Thus these stability classes have no inherent physical basis, but a terminology of the form :

very unstable unstable neutrally stable stable very stable

may be applied as long as it is remembered that no strict definition is being made.

TABLE I—WIND-SPEED AND STABILITY CLASSES, WITH THE FREQUENCY OF OBSERVATIONS IN EACH CLASS

Stability index, T_d degF	Ranges of wind speed over land, U_L (kt) 1–5	6–10	11–15	≥ 16	All winds
≤ -6	157	557	126	55	895
-5 to -2	119	334	140	57	650
-1 to $+1$	94	230	108	77	509
$+2$ to $+5$	81	234	151	101	567
$\geq +6$	86	270	229	160	745
All temps	537	1625	754	450	3366

A total of 20 classifications was then possible, as the combination of four wind-speed and five stability classes. For each of the 20 classifications the mean values of R and D_d were calculated, also the standard deviations of R and D_d and the maximum and minimum values of R. The results of these calculations are tabulated as Table II.

The influence of wind speed and stability on change of direction. Before any use was made of the results set out in Table II it was necessary to justify the classifications of D_d, the change in direction, by wind speed U_L and stability T_d. While such a classification may facilitate the analysis and presentation of results it might also introduce an unnecessary degree of complication. Accordingly an analysis of variance was performed on the mean D_d values of the classification in order to test whether or not there was a significant variation in the mean values among the classes in each of the main classifications. The results were :

$$\frac{\text{variance due to wind-speed classification (3)}}{\text{residual variance (12)}} = 2{\cdot}36$$

and $$\frac{\text{variance due to stability classification (4)}}{\text{residual variance (12)}} = 36{\cdot}88,$$

TABLE II—MEAN VALUES AND STANDARD DEVIATIONS OF R AND D_d FOR EACH CLASS, TOGETHER WITH THE MAXIMUM AND MINIMUM VALUES OF R

U_L	T_d		Mean D_d	Standard deviation of D_d	Mean R	Standard deviation of R	Maximum R	Minimum R
kt	*degF*		*tens of degrees*					
	−21 to	−6	−0·66	1·79	3·39	2·61	18·0	0·4
	−5	−2	−0·24	1·79	3·07	1·85	10·0	0·4
1–5	−1	+1	−0·06	1·81	2·95	2·34	14·0	0·6
	+2	+5	−0·11	1·84	2·59	2·08	12·0	0·2
	+6	+24	0·41	1·79	2·53	1·79	12·0	0·4
	−21	−6	−0·84	1·64	1·90	0·68	4·3	0·2
	−5	−2	−0·41	1·71	1·83	0·61	4·2	0·2
6–10	−1	+1	−0·08	1·72	1·57	0·54	3·5	0·3
	+2	+5	0·27	1·72	1·40	0·43	2·6	0·4
	+6	+24	0·34	1·73	1·31	0·50	3·0	0·2
	−21	−6	−0·64	1·53	1·78	0·45	2·7	0·7
	−5	−2	−0·33	1·63	1·61	0·42	3·5	0·7
11–15	−1	+1	0·11	1·68	1·48	0·32	2·4	0·5
	+2	+5	0·20	1·73	1·29	0·32	2·3	0·1
	+6	+24	0·77	1·57	1·11	0·32	2·2	0·1
	−21	−6	−0·33	1·79	1·55	0·30	2·3	0·7
	5	−2	−0·23	1·41	1·54	0·29	2·4	0·7
⩾16	−1	+1	0·00	1·75	1·35	0·26	2·2	0·6
	+2	+5	0·08	1·68	1·23	0·27	2·2	0·5
	+6	+24	0·68	1·50	1·06	0·27	1·6	0·2

the numbers in brackets being the respective degrees of freedom. At the 95 per cent level of significance $F_{3,12} = 3{\cdot}49$, while at the 99·9 per cent level $F_{4,12} = 9{\cdot}63$. It was concluded from these results that the variation of mean D_d values among the wind-speed classes was not significant while the variation among stability classes was highly significant. In view of this conclusion there was nothing to be gained by classifying D_d according to wind speed, so the mean values and standard deviations for the stability classes were recalculated using data for all wind speeds. The results are shown in Figure 1 together with the 95 per cent confidence limits that were ascribed to the class means.

The change in direction, D_d, was measured in units of 10° of arc. It can be seen in Figure 1 that the mean D_d values for each class were all less than unity, and that the standard deviations (and hence confidence limits) were relatively large. In view of this, only a qualitative interpretation of the results is possible since the actual numerical values can hardly be significant. It is perhaps possible to state that off-shore winds tend to back if initial conditions over the sea are very stable, and tend to veer if initial conditions are very unstable. This change in direction is thought to be independent of the wind speed over the land.

The influence of wind speed and stability on the ratio R. It became apparent from the results set out in Table II that there was more variation in R values in the 1–5 kt wind-speed class than in any of the other wind-speed classes. For the whole class, irrespective of any stability classification, the range in R values was 0·2 to 18·0, the standard deviation of the R values was 2·23 and the mean R value was 2·98; these results are very different from the corresponding statistics of the other wind-speed classes. The 95 per cent confidence limits placed on this mean were $\pm 0{\cdot}19$, and it was concluded that no significant result could be deduced from the data for this class. When winds

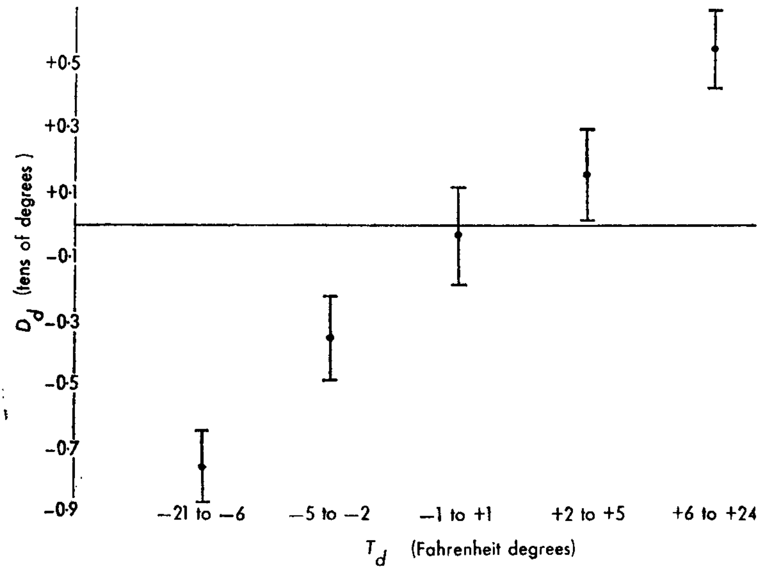

FIGURE 1—VARIATION OF MEAN CHANGE IN DIRECTION, D_d, WITH STABILITY CLASS, T_d

in the 1–5 kt range are being measured, the inaccuracy of the anemometer could perhaps be the main source of the observed peculiarity of the class results, but it is interesting to note that a similar result was recorded in (A) where it was apparently taken at its face value. Because of this suspicion of the results the 1–5 kt class was ignored for the remainder of the analysis.

An analysis of variance was carried out on the class mean R values and the resulting F values indicated that there were significant variations among the classes in each of the main classifications. It was of interest to note that the percentage of the total variance accounted for by the wind-speed classification fell from 86·7 per cent to 19·4 per cent when the 1–5 kt class was omitted, thus confirming the suspicion that the class as a whole was unrepresentative. Figure 2 is a graphical statement of the results for all winds >6 kt over land.

An inspection of the results shown in Figure 2 revealed several general trends in the mean R values. Firstly, however, it was noticed that the 95 per cent confidence limits on all the mean values were small, amounting to a maximum of 5 per cent of the actual values, thus a high significance could be attached to the numerical values obtained for the means. Within each wind-speed class the mean R values decreased as the stability index (T_d) increased, this being clearly shown in Figure 2. Thus, the more unstable the conditions over the sea became the greater was the increase in wind speed. Another general observation was that for all stability classes the stronger land winds were less affected by changes in stability, e.g. even in the most unstable régime the $\geqslant 16$ kt wind-speed class increased by only 55 per cent while in neutrally stable conditions the 6–10 kt class increased by 57 per cent. These trends were reflected in the overall results for all winds and all temperature differences. The mean R value, for all winds $\geqslant 6$ kt, and for all stability indices, was $1·53 \pm 0·02$.

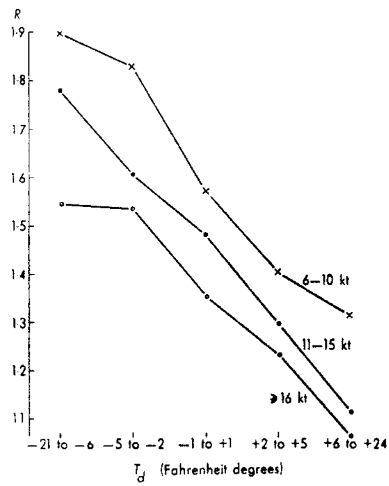

FIGURE 2—VARIATION OF MEAN R VALUES WITH STABILITY CLASS, T_d, FOR EACH WIND-SPEED CLASS, U_L

Comparison of results. The general variations of R with wind speed and stability, noted in the previous paragraph, were also observed in (A). Since the Great Lakes region experiences greater extremes of temperature than the North Sea area, the stability classification in (A) includes a larger total range, i.e. −47 to +42 Fahrenheit degrees. However, the central stability classes are comparable to those in this paper if our central three classes are amalgamated. The mean R values for the extreme stability classes in (A) confirm the relationships observed for the central classes. On comparison of results the general impression is that for the corresponding stability classes the mean R values for the North Sea region are higher than those for the Great Lakes.

TABLE III—MEAN VALUES OF R FOR WIND-SPEED AND STABILITY CLASSIFICATIONS OVER THE GREAT LAKES AND OVER THE NORTH SEA

(a) Over the Great Lakes[1]

Stability index, T_d *degF*	Range of wind speed over land, U_L (kt) 6–10	11–15	≥16
−22 to −8	1·82	1·40	1·30
−7 to +7	1·49	1·31	1·02
+8 to +22	1·15	0·90	0·94

(b) Over the North Sea

Stability index, T_d *degF*	6–10	11–15	≥16
−22 to −6	1·90	1·78	1·55
−5 to +5	1·63	1·45	1·34
+6 to +22	1·31	1·11	1·06

These results are tabulated for easy comparison in Table III. The results in Table III*(a)* are for an over-water fetch of 16–25 n.miles roughly the same as for the North Sea data. The differences between the two sets of mean R values were tested and found to be significant at the 95 per cent level. The mean R value over the Great Lakes for 16–25 n.miles of fetch, ≥6 kt, and for $-22 \leqslant T_d \leqslant +22$ Fahrenheit degrees was 1·38, significantly different from the value of 1·53 for the North Sea.

As already mentioned the mean R values in the 1–5 kt range recorded in (A) are also very different from the means for other wind-speed classes. Accordingly they are not included in the comparison.

Interpretation of results. The changes in the wind field as the wind blows from the land to the sea arise from two different physical sources. One is the result of the abrupt change in the roughness characteristics of the surface over which the wind is blowing. Some accounts of theoretical and experimental work on this problem are to be found in Panofsky and Townsend,[2] Bradley[3] and Taylor.[4,5,6] The other physical process is effected by the different thermal structure of the atmosphere over the sea. The effect of stability on the velocity profile in lower layers has been investigated at great length by Deacon,[7] Swinbank[8] and Lettau and Zabransky.[9] Other references to associated works may be found in the papers cited, and a general account is given in Priestley.[10]

The work on changes of terrain roughness introduces the concept of an internal boundary layer, arising at the region of discontinuity. From all the accounts, it may be supposed that the over-water fetch in this investigation is of a more than sufficient length to allow the profile of surface wind to attain an equilibrium form again, after passing through the transition zone of this internal boundary layer. The assumption is therefore made that the wind speed profiles at the observing stations are functions of the atmospheric stability at those stations and also of the roughness characteristics of the surface surrounding those stations.

For conditions of neutral stability the wind-speed profile follows the well-known logarithmic law,

$$u(z) = \frac{U_*}{k} \log_e \left(\frac{z}{z_0}\right)$$

where $u(z)$ is the mean horizontal wind speed at height z, U_* the so-called friction velocity, z_0 the roughness length and k von Kármán's constant $\approx 0{\cdot}4$. For non-neutral stability conditions this form is deviated from considerably and many empirical formulations have been made, to fit observational findings. Deacon[7] suggests

$$u(z) = \frac{U_*}{k(1-\beta)} \left[\left(\frac{z}{z_0}\right)^{1-\beta} - 1\right]$$

where $\beta > 1$ for unstable conditions and $\beta < 1$ for stable conditions. This formulation reduces to the logarithmic law as $\beta \rightarrow 1$ and as $(z/z_0) \rightarrow 1$, i.e. for small heights.

A different formulation suggested by Swinbank[8] was

$$u(z) = \frac{U_*}{k} \log_e \left[\frac{\exp(z/L) - 1}{\exp(z_0/L) - 1}\right]$$

$$\text{where} \quad L = -\frac{\rho U_*^3 c_p T}{kgH}$$

and ρ is the air density, c_p the specific heat at constant pressure, T the air temperature, g the acceleration of gravity, and H the heat flow, defined as positive when directed upwards. Hence negative values of L indicate unstable conditions and positive values indicate stable conditions. For neutral stability L becomes infinite and Swinbank's formulation reduces to the ordinary logarithmic profile.

It is difficult to make use of the theoretical models described above when attempting to interpret and explain the results of this paper, the main reason being that the index T_d is only a measure of the initial stability over the sea. After an interval of time the temperature profile of the air is modified into a state more in equilibrium with the sea surface temperature. However, it is possible to make general statements about the physical processes involved which do explain some of the observations.

The first observation to explain is that the mean R values recorded in this paper are all greater than unity. This phenomenon becomes obvious when it is realized that the value of z_0 is at least 10 times less for the sea surface than for the land. As T_d becomes more positive, i.e. conditions become more stable over the sea, then $\beta_s < \beta_L$ and $L_s > L_L$, where the subscripts denote sea and land values. This effect induces a process in opposition to that brought about by the decrease in value of z_0, so much so that for the extreme conditions of stability recorded in (A) the value of R was observed to be less than unity. This explains why the increase in wind speed is less when conditions over the sea are stable. Finally, there is the fact that for strong winds the velocity profile is dominated by the effect of mechanical turbulence and hence the effect of changes in stability is very small. This fact explains why the stronger land winds are less affected by the changes in stability.

Conclusions. From a series of simultaneous wind measurements made at Gorleston and the Smith's Knoll Lightship it is deduced that :

(i) The ratio between wind speeds over the sea and over land, for off-shore winds, increases as the initial instability over the sea increases.

(ii) This increase is most marked for light land winds.

(iii) When initial conditions over the sea are stable the wind backs, when unstable the wind veers.

Acknowledgements. I wish to thank Mrs M. Mann who carried out the programming work necessary for this investigation, and Mr J. F. Keers who was instrumental in assembling the data.

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551.509.32:629.13

WEATHER FORECASTING FOR SUPERSONIC TRANSPORT

By M. H. FREEMAN, O.B.E.

Summary. The meteorological factors which will affect the operation of supersonic transport aircraft are discussed, and assessments are made of the accuracy which can be expected in forecasting the relevant meteorological elements. The items discussed are wind, temperature, turbulence, cloud, rain and hail. The problems of sonic boom and cosmic radiation are also considered.

Characteristics of Concorde. The appearance of Concorde is now familiar to all (Plate I). It is comparable in size to a Boeing 707 or a VC 10, but with a much smaller wing span. Concorde will be able to carry 128 passengers on stage lengths of 4000 nautical miles (approximately 7400 km) compared with about 140 passengers on legs of 5000 n. miles for a 707 or VC 10. The vital difference is that Concorde will do the London–New York trip in 3½ hours compared with 6–7 hours for the best subsonic jet aircraft.

The flight of a Concorde can be considered in four stages. During the take off and the climb at subsonic speeds to about 25 000 feet (400 mb), the aircraft will behave much as subsonic aircraft (though the rate of climb will be greater); the requirements for meteorological information will be similar. The transonic phase, when the aircraft will accelerate from Mach 0·93 to Mach 1·3, will normally take place between about 400 and 200 mb. This is when sonic boom will be most of a problem, and there may be restrictions imposed as to where the transonic acceleration will be allowed, e.g. only over sea. During this phase sudden manoeuvres are to be avoided, as are turbulence, hail or heavy rain and cumulonimbus generally. Acceleration will continue until Mach 2·2 (1200 kt) is reached at about 53 000 ft (100 mb) when the cruise phase will commence. This will probably be a cruise climb in which the aircraft gradually rises to about 60 000 ft (70 mb); as fuel is used the weight decreases. Later, as the number of supersonic transports (SSTs) increases, Air Traffic Control may require this phase to be operated in a series of steps to higher levels. In the final phase deceleration to subsonic speeds will be at about 50 000 ft, and thence Concorde will operate much as a subsonic jet aircraft during descent and landing.

Meteorological organization for Concorde. Since its maiden flight from Filton to Fairford in April 1969, Concorde 002 has operated from Fairford. Attached to the meteorological office serving the Royal Air Force there is a meteorological officer whose responsibility is liaison with Concorde's personnel and briefing of its aircrew. Forecasts for Concorde are prepared at the meteorological office at London/Heathrow Airport, and are transmitted to Fairford on a special facsimile line. At Heathrow, charts for 100 mb and 70 mb are plotted and analysed twice daily. In addition to forecasts for operational flights, Heathrow prepares forecasts twice daily for BOAC for simulated SST flights to New York and to Anchorage, Alaska. By the time Concorde is in regular airline service (about 1972), in most respects it will be 'just another aircraft' as far as provision of meteorological services is concerned. There will, however, be some differences in the importance attached to certain meteorological elements, and these will be considered in turn here.

Wind. Wind will be less of a problem than it is for subsonic aircraft. Wind speeds in the lower stratosphere (between 100 and 70 mb where Concorde will be cruising) are in general lower than those found in the jet streams of the upper troposphere. The much higher cruising speeds and lighter winds will mean that it is less profitable to deviate from the great circle in order to find a least-time track. The day-to-day variability of wind between 100 and 30 mb is much less than that between 300 and 200 mb and forecasting will be correspondingly easier. In fact the most recent actual chart may well provide the best 12- or 18-hour forecast, and should easily meet the stated requirement for root-mean-square vector error of less than 15 kt over 500-n. mile segments. At 50 mb the standard deviation of 24-hour vector change in wind has been quoted as about 10 kt (1 kt $\approx$ 0·5 m/s).

The Meteorological Office computer (COMET) at present provides objective analyses and forecasts at 100 mb for use at Heathrow. These are on a scale of $1:20 \times 10^6$ and cover the North Atlantic and North America. The 100-mb forecasts use a barotropic model and are produced independently of the 3-level model used for lower heights. Forecasts for 70 mb are produced subjectively at Heathrow, largely by noting the change predicted by the computer at 100 mb and applying a similar change to the 70-mb chart. On the next computer it is expected that the numerical forecasts will use a 10-level primitive-equation model extending from 1000 to 100 mb. Some further technique will be needed for forecasts for higher levels.

Temperature. The provision of accurate temperature forecasts will be of much greater importance to SSTs than it now is for subsonic aircraft. In the cruise phase at Mach 2·2, kinetic heating will raise the skin temperature of parts of the aircraft to near the acceptable limit and if ambient temperature is much above that of the International Standard Atmosphere (ISA) some reduction in speed may be needed, with a consequent increase in total fuel used. Temperature also affects fuel consumption because the higher the ambient temperature, the lower is the thrust produced by jet engines. It is worth remembering, however, that in the early days of jet engines, forecasters were asked to provide much greater precision in temperature forecasts than is now needed, and as SSTs develop the same thing may happen again. Meanwhile the performance of SST engines appears rather sensitive to changes in temperature of the environment, and forecasters will be called on to improve the accuracy of their temperature forecasts.

Temperature forecasts at eight levels from 850 to 150 mb are currently produced by COMET, using regression techniques based on forecast heights at 1000, 500, 200 and 100 mb. A requirement has been stated for temperature forecasts having a standard error not exceeding 3 degC. This is already largely being met at 300 mb and at lower altitudes, but at 200 mb the accuracy is not so good. In summer the required accuracy is just about being achieved, but some errors greater than 10 degC occur especially when the tropopause is low. Winter temperature forecasts at 200 mb are still not good enough. However, Brady* is developing a more sophisticated type of regression technique which attempts to take account of the tropopause and it is expected that when this is introduced operationally there will be a further improvement in upper-troposphere temperature forecasts.

In the lower stratosphere above 100 mb the day-to-day variability of temperature is small for much of the year. At 50 mb over the Atlantic between April and October the use of monthly mean temperatures as forecasts would give standard errors of less than 3 degC, and elementary persistence forecasting would improve on that. During the winter months quite large temperature changes, the so-called 'sudden warmings', can occur. These are not, however, so sudden as to be unforecastable. The effect is often first observed at high levels (30 mb or above) and propagates downwards, and a warm area once found moves comparatively slowly from chart to chart, so that extrapolation methods will produce quite good forecasts for much of the time. If nothing better than a 24-hour persistence forecast were attempted a standard error of 2·7 degC would be achieved at 50 mb, taking the year as a whole.

A factor of importance to the designers of SST aircraft is the occasional occurrence of large temperature changes in short distances. An extreme figure of 10 degC in 1 n.mile has been recorded near cumulonimbus and 21 degC in 1 n.mile in a mountain wave. Temperature changes alter the Mach number, with a consequent need for the geometry of the air intakes to be altered. The design has to be able to cope with rapid changes. There is no possibility of forecasting the occurrence of localized large temperature gradients in advance.

Before leaving temperature it is worth considering the method of presenting the forecast information. Nowadays, forecast documentation for long-distance flights is in the form of several fixed-time constant-level charts with temperatures inserted at representative spots. Probably the part of flight for which temperature will be most critical is the transonic phase, which will normally take place in the upper troposphere. If temperatures in the usual transonic layer are much above standard but higher up there is a layer with standard or below-standard temperatures, then it would be profitable to delay the transonic acceleration to the higher level. Temperature forecasts are therefore presented as difference from ISA rather than as absolute values. Flight planning this phase is simplified if a vertical temperature cross-section along the prescribed climb route is provided. This should be practicable in the early days when routes and flights are fairly limited in number. After that most flight planning is likely to be on a computer-to-computer basis, and meteorological documentation for crews could perhaps be much simplified.

Turbulence. Turbulence will be at least as important to supersonic as to subsonic aircraft and, especially in the transonic phase, may be more so. The existing methods of forecasting clear-air turbulence (CAT) depend largely on locating zones with large vertical or horizontal wind shears or large temperature gradients, with mountain or other waves as additional factors. CAT is commonest below the tropopause but it can occur in the

*BRADY, W.R.; A method of deriving representative temperature profiles, including the tropopause, from the three-level forecast model. *Met. Mag., London*, **98**, 1969, pp. 373–386.

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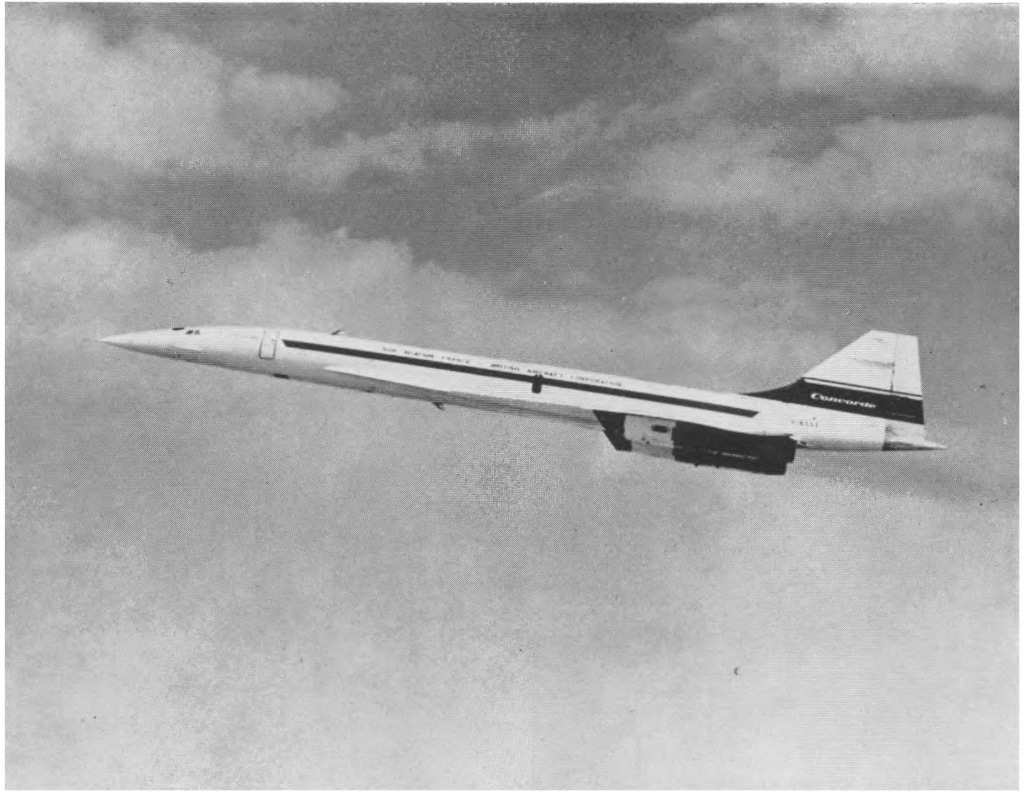


Photograph by courtesy of the British Aircraft Corporation.

PLATE I—CONCORDE 002 ON A TEST FLIGHT FROM ITS BASE AT ROYAL AIR FORCE, FAIRFORD, GLOUCESTERSHIRE

See page 138.

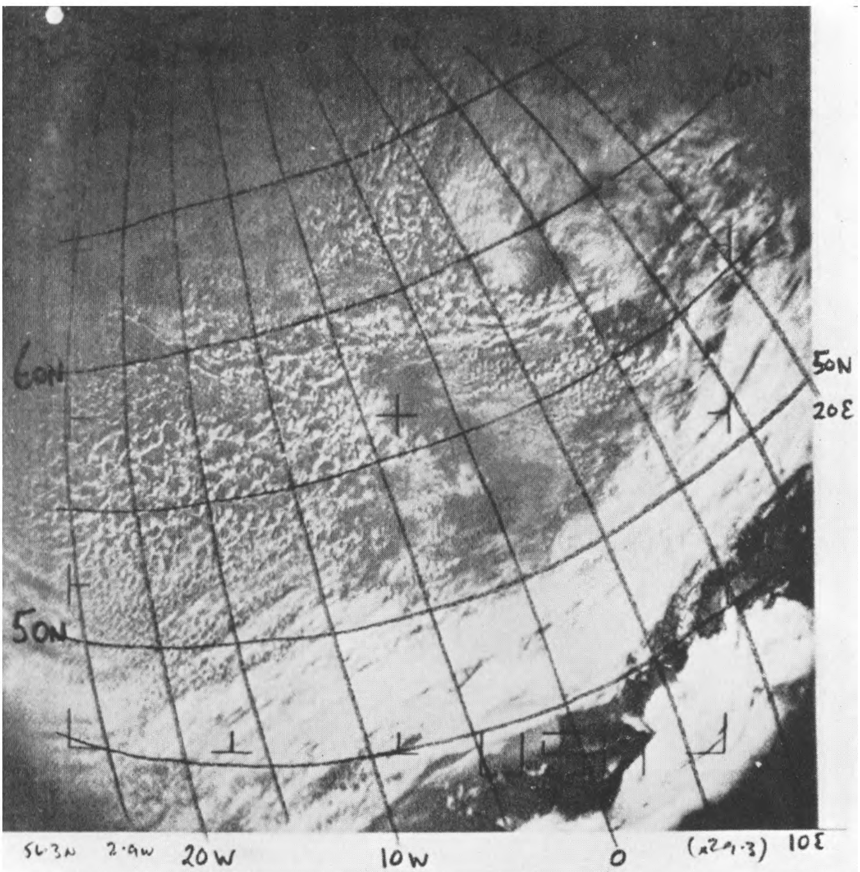
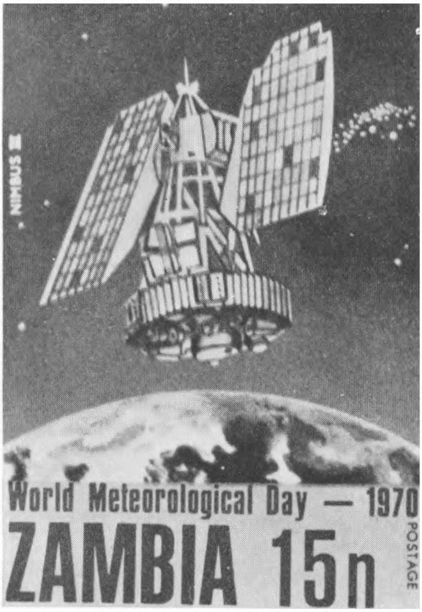


PLATE II—CLOUD PHOTOGRAPH FROM ESSA 8 AT 1041 GMT ON 20 NOVEMBER 1969 SHOWING THE BRITISH ISLES 'DISPLACED' 2° OF LONGITUDE EAST OF ITS TRUE POSITION

See page 152.



Photograph by courtesy of Crown Agents Stamp Bureau

PLATE III—SPECIAL STAMP ISSUED BY THE GOVERNMENT OF ZAMBIA TO COMMEMORATE WORLD METEOROLOGICAL DAY IN 1970

The stamp shows the artist's impression of the U.S. weather satellite NIMBUS III in orbit above the earth's surface.

Reproduced by permission of the Hydrographer of the Navy

PLATE IV—PROTOTYPE SELF-RECORDING METEOROLOGICAL BUOY SYSTEM BEING TESTED DURING THE ATLANTIC TRADE-WIND EXPEDITION IN FEBRUARY 1969

Instruments mounted on the buoy measure air and sea temperatures and run of wind, the data being recorded on magnetic tape. Similar buoys will be used during the preliminary Royal Society air-sea interaction experiment in June 1970, but will carry additional instruments to measure atmospheric pressure.

lower stratosphere, and must be expected in some degree at all levels of supersonic flight. Experience of forecasting CAT at high levels is small and there will be a need to develop further techniques during the proving-flight stage. The effect of turbulence on an aircraft depends on its characteristics and speed, as well as on the state of the atmosphere, so knowledge of the susceptibility of SSTs to turbulence can be built up only gradually. Present forecasts of CAT indicate the areas and heights which are considered favourable for it, but many aircraft fly in these areas without meeting it, and those who do experience CAT are unlikely to find it over the whole segment predicted in the forecast. In other words the forecasts tend to be definitely on the pessimistic side. A good proportion of CAT actually met is covered by the forecasts. Existing techniques can probably be extended to higher levels, but there is not much immediate prospect of significantly improving on the standard of forecasting clear-air turbulence.

During the climb and transonic phases the SST will suffer the same hazards from turbulence in and near cloud as does the subsonic aircraft, though the effects of such turbulence may be of greater importance to the SST as it goes transonic. Cumulonimbus is far the most likely source of severe turbulence in cloud and it will clearly be desirable for SSTs to avoid such clouds. Ordinary forecasting techniques can indicate fairly well the general areas in which cumulonimbus clouds of given extent are likely to occur, but they cannot, nor are they likely to be able to, say exactly where or when a cumulonimbus will occur. Ground-based weather radar can provide useful instantaneous information on the presence of cumulonimbus if suitable communication with the pilot is established. Such equipment is not likely to be available at all airfields and so a good deal of reliance will have to be placed on the evidence from airborne radar. Large temperature gradients and turbulence have been reported in clear air near cumulonimbus clouds, so it is important that any tops detected are avoided by a sufficient margin.

Cumulonimbus in the troposphere, for the climb and transonic stages, will be quite common, but cumulonimbus tops can extend into the stratosphere in favourable conditions. This is not likely to be a hazard to the cruise phase over the Atlantic, but in summer in central U.S.A. and in the tropics heights of 60 000 feet have been exceeded. If airborne radar shows a line of cumulonimbus clouds ahead the pilot has to decide whether to turn or attempt to overfly the tops long before they are reached. Since the radar indication of the height of the tops may not be as accurate as would be desired, good forecasts of the maximum possible heights of tops along the route would be of definite value, and should not be too difficult to provide.

Cloud, rain and hail. Cloud as such will not present any particular hazard. Since an SST will be climbing fairly quickly through any cloud layer, significant amounts of ice are likely to be uncommon, and in general the de-icing equipment will cope with it. The effect of impact of heavy rain and especially of hail is much more serious, and it is clearly desirable that flight through these conditions should be avoided. They are usually associated with cumulonimbus, which may be isolated or embedded in other cloud, and so are in regions which should be avoided anyway because of turbulence. Once again the pilot will have to rely on forecasts indicating the general areas in which the hazards of heavy rain or hail can occur, supplemented by more precise information from weather radar, both ground-based and airborne.

Sonic boom. The intensity of the sonic boom at the ground depends on characteristics of the aircraft such as its size, weight and the way it is being handled and also on the wind and temperature structure between the aircraft and the ground. In order to assess the magnitude of the boom and plan a flight path and speed which will comply with any government regulations on booms, the flight planners will need detailed forecasts of wind and temperature in the region where transonic flight commences, the most critical zone being for Mach numbers between 1·0 and 1·3. A vertical cross-section up to 50 000 ft for the first 200 n. miles from the departure aerodrome may well be the most convenient form of presentation, since the temperature inversions and wind shears which may produce focusing of the boom can readily be depicted by isotherms and isotachs. Local and short-lived variation in the fine structure of temperature and wind will occur, and could produce localized booms much in excess of the general level. There will be no possibility of producing forecasts of these minor, but maybe important, variations.

Cosmic radiation. Cosmic radiation, similar to radiation from radioactive material, is continually entering the earth's atmosphere from space and being absorbed. In normal conditions the level of activity is easily low enough not to present any hazard to passengers in a Mach 2 aircraft, and probably also at the greater heights flown by a Mach 3 aircraft. During periods of maximum solar activity, rare (i.e. 2 or 3 per year) but important outbreaks of cosmic radiation can occur associated with solar flares. Unacceptably high radiation doses may then be experienced, especially at the Mach 3 levels. Fortunately protection can readily be obtained by descent to lower altitudes, where screening by the atmosphere above is adequate. The problem is worst in high geomagnetic latitudes, and on transpolar flights descent to 40 000 ft may be necessary.

Forecasts for some 10 to 100 minutes ahead might be made on the basis of observations of the sun's disc and by monitoring the high-energy protons reaching the ground, but reliable warnings could not be passed to the aircraft in flight because these are just the times when radio communication is likely to be interrupted. It will be necessary therefore for SST aircraft to carry radiation monitoring devices, perhaps including an audible warning, so that suitable avoiding action can be taken. If practicable a warning that an aircraft had experienced exceptional cosmic radiation should be passed to other aircraft as soon as possible.

The Space Disturbance Forecast Center of the U.S. Environmental Science Services Administration makes available its longer-period warnings that conditions are suitable for cosmic outbursts. These are disseminated by the Aeronautical Fixed Telecommunications Network, and serve to alert airlines, pilots and ATCs to the possible need for avoidance action. It has been stated that 70 per cent of solar proton events could be predicted with a 3 to 1 false-alarm rate.

Conclusions. On the whole, meteorological services should be able to meet the operational requirements of SSTs for forecasts. Wind will not be difficult; in the early days the accuracy of temperature forecasts may be only barely good enough but this will become less critical as forecasts and engines both improve. Precise forecasts of the position of turbulence and cumulonimbus will not be generally possible, but the broad indications of the areas in which they are likely to occur should gradually improve. Cosmic radiation is not a matter for which meteorological services will be responsible, beyond perhaps disseminating warnings, and airborne detectors will be the main safeguard.

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EXTREMES OF MONTHLY AND ANNUAL SUNSHINE DURATION IN THE BRITISH ISLES

By E. N. LAWRENCE

Summary. Long-period extremes of monthly and annual sunshine duration over the British Isles are studied in relation to general meteorological data for the period 1890 to 1968 and Kew Observatory sunshine data for the period 1881 to 1968.

Results show that (i) the upper extremes occurred in coastal areas of the extreme south, south-east and south-west and (ii) the lower extremes occurred mainly in the north, particularly at high-level sites but also in urban industrial areas. The upper extremes usually occurred with anticyclones and dry easterly and northerly winds but also with north-westerlies in winter: the lower extremes occurred with cyclones and moist westerly airstreams but also with anticyclones and uniform pressure gradients in urban industrial areas in winter and at stations on the north-east coasts exposed to airstreams with a long North Sea track.

The upper extremes of sunshine duration occurred mainly in those years with odd dates, thus confirming the well-known '2-year' periodicity. The time-distribution of monthly extremes over the British Isles and the year-to-year variation of sunshine duration at Kew showed the '11-year' cycle with (i) the sunshine peak occurring with decreasing sunspots, at about two years after the sunspot maximum and (ii) the sunshine minimum occurring with increasing sunspots or near the sunspot minimum.

Introduction. The present note describes the results of a study of some time and space variations of the extremes of monthly and annual sunshine duration in the British Isles.

Data. Table I gives a list of monthly and annual extremes of sunshine duration since 1890. These data are based on records of extremes maintained by the Meteorological Office and refer to networks of sunshine-recording stations mainly as indicated in the *Monthly Weather Report.*[1] The locations of stations listed in Table I are shown in Figure 1. Relevant atmospheric pressure data and details of the synoptic features and surface winds were obtained from the *Daily Weather Report.*[2] Sunshine data (1881–1967 inclusive) used for the statistical analysis of Table II refer to Kew Observatory (51° 28′N, 00° 19′W, 18 ft (5·5 m) above MSL). Figures 2 and 3 are based on annual sunshine summaries.[3]

The data refer to the duration of bright sunshine as measured by the Campbell-Stokes type of sunshine recorder, but for some of the earlier records (for example, at Westbourne, Sussex, in 1893) a Jordan recorder may have been used. Records from these two instruments may show relatively large day-to-day differences but if the two instruments are exposed side by side, their records of total sunshine over a long period are not greatly different.[4] It is assumed, for the present investigation, that over a period of a month, the relatively small proportion of data which is obtained from Jordan recorders can be used to supplement data from the Campbell-Stokes type.

In the most favourable circumstances, sunshine can be recorded when the sun is three degrees above the horizon, say 20 minutes after sunrise or before

TABLE I—EXTREMES OF MONTHLY AND ANNUAL TOTALS OF BRIGHT SUNSHINE IN THE BRITISH ISLES, 1890–1968

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Upper extremes													
Total sunshine (hours)	115·5	167	253	302	353	382	384	325	281	207	145	116·5	2340
% of possible sunshine	44	59	69	73	74	78	77	73	74	62	53	47	53
Year	1959	1891	1929	1893	1909	1925	1911	1899	1959	1920	1923	1962	1893
Year relative to year *X**	+2	−2	+1	0	+4	−3	+6	+6	+2	+3	+6	+5	0
Place	Bournemouth	St Helier	Aberystwyth	Westbourne (Sussex)	Worthing	Pendennis Castle	Hastings Eastbourne	Villa Carey (St Peter Port)	Gorey Castle	Felixstowe	Falmouth	Eastbourne	St Helier
Latitude (N)	50° 43′	49° 11′	52° 25′	50° 52′	50° 49′	50° 09′	50° 52′ 50° 46′	49° 27′	49° 12′	51° 57′	50° 09′	50° 46′	49° 11′
Longitude	01°53′W	02° 06′W	04° 05′W	00° 55′W	00° 22′W	05° 03′W	00° 34′E 00° 17′E	02° 32′W	02° 01′W	01° 20′E	05° 05′W	00° 17′E	02° 06′W
Ht of ground above MSL(ft)	125	25	69	30	35	200	240 35	180	0	15	167	35	25
Ht of recorder above ground (ft)	57	5	6	6	55	40	40 100	45	270	5	33	86	5
‡Mean pressure (mb)	1013	1032	1017	1022	1018	1022	1018	1020	1021	1016	1010	1017	1016
‡Mean pressure 1931–60 (mb)	1016	1017	1015	1016	1017	1017	1016	1017	1017	1016	1014	1015	1016
Main synoptic features† and surface winds	C & NW'ly → A	A E'ly	A E'ly to N'ly	A E'ly	A	A N'ly	A	A E'ly	A E'ly	E'ly, SE'ly	NW'ly	A & E'ly, NW'ly	
Lower extremes													
Total sunshine (hours)	3·6	4·3	25·0	35·9	59·6	60·9	50·1	43·9	34·3	8·0	4·9	0·0**	696·2
% of possible sunshine	1·5	1·6	6·8	8·6	12·0	11·4	9·2	9·4	8·9	2·4	1·9	0·0	15·6
Year	1901	1966	1916	1920	1967	1912	1961	1912	1967	1968	1942	1890	1961
Year relative to year *N**	0	+2	+3	−3	+3	−1	−3	−1	+3	+4	−2	+1	−3
Place	Morpeth (Cockle Park)	Great Dun Fell	Whitworth Park (Manchester)	Whitworth Park (Manchester)	Great Dun Fell	Crathes	Strathy	Eskdalemuir	Baltasound (Shetland)	Great Dun Fell	Burnage (Manchester)	Westminster (London)	Great Dun Fell
Latitude (N)	55° 13′	54° 40′	53° 28′	53° 28′	54° 40′	57° 02′	58° 31′	55° 19′	60° 46′	54° 40′	53° 26′	51° 30′	54° 40′
Longitude (W)	01° 41′	02° 26′	02° 14′	02° 14′	02° 26′	02° 25′	04° 01′	03° 12′	00° 53′	02° 26′	02° 12′	00° 08′	02° 26′
Ht of ground above MSL (ft)	324	2780	125	125	2780	140	120	794	80	2780	147	27	2780
Ht of recorder above ground (ft)	4	3	11	11	3	6	4	5	5	3	5	80	3
‡Mean pressure (mb)	1013	1000	1006	1005	1007	1008	1011	1006	1008	1012	1025	1013	1013
‡Mean pressure 1931–60 (mb)	1011	1014	1015	1015	1016	1014	1011	1013	1010	1013	1012	1011	1014
Main synoptic features† and surface winds	S & SE'ly → W'ly	C	C NE'ly	C	C	C	NW'ly	C	C	SW'ly	A	A E'ly	

**X* and *N* are the years of the relevant maximum and minimum annual sunspot-relative-number, respectively.
†C = cyclonic   A = anticyclonic.
**0·1 h at Bunhill Row, 51° 31′N, 00° 05′W, 80+80 ft; 0·3 h at Kew Observatory, 51° 28′N, 00° 19′W, 18+44 ft.
‡Sea level.

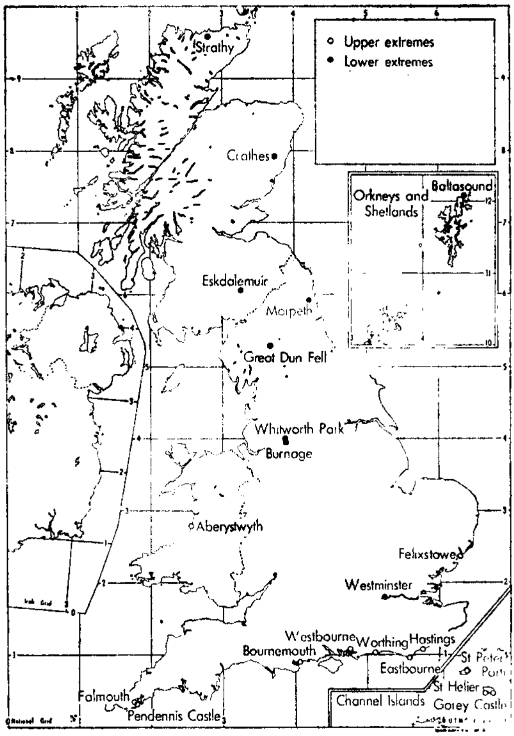

FIGURE I—STATIONS WITH MONTHLY EXTREMES OF DURATION OF BRIGHT SUNSHINE

Stations are listed in Table I.

sunset; but this implies a very clear atmosphere when the loss of record due to reduction of intensity of transmitted sunlight by atmospheric absorption and scattering is minimal. There is also a slight obstruction by the instrument when the sun's angle of elevation is very low, so that in general for half an hour at either end of a fine day, there is no record trace. Hence, the effective length of the possible duration of 'bright sunshine' may be about an hour less than the total length of daylight which is used to calculate the percentage of possible sunshine duration in Table I. Daylight is defined as beginning and ending when the upper limb of the sun is apparently on the horizon, due allowance being made for refraction and assuming that both observer and horizon are at sea level.[5]

Restriction of the exposure of a sunshine recorder by hills, buildings, etc., should also be taken into consideration. For the stations of Table I, the percentage loss of sunshine for angles of solar elevation greater than three degrees is estimated not to exceed approximately five per cent. In this connection, it must be remembered that the loss of record due to low-angle obstruction is small because within an hour or so of sunrise and sunset, sunshine is limited by cloud, haze or atmospheric absorption even when the horizon is unobstructed (see, for example, Furmage[6] Figure 1 of reference). Many stations in west Scotland have considerable natural obstructions and are consequently excluded from the present investigation.

Geographical distribution and synoptic features. The extreme values of sunshine duration recorded in Table I, though dependent on the local topography of the sites, are generally representative of large areas where the overall conditions are primarily dependent on the macrometeorological or synoptic situation; the statements in *Monthly Weather Reports*[1] draw attention to the occurrence of sunshine duration extremes over extensive areas in the months concerned.

Table I and Figure 1 show that all of the upper extremes of monthly sunshine duration occurred on or near coasts in the south, whereas the lower extremes of sunshine were mainly in the north of the British Isles, particularly at high-level stations and those exposed to moist Atlantic air masses but also in urban industrial areas, exposed to smoke pollution.

The geographical distribution for non-urban stations persists throughout the year and so does not depend solely on the latitudinal variation in the length of daylight. In summer, the north has the lower extremes of sunshine despite the longer days, while the south has the upper extremes. This spatial pattern of extreme sunshine duration is similar to that for sunshine averages[7] and furthermore, the pattern is very similar to that obtained for the extremes of yearly totals of bright sunshine for individual years, as indicated in Figure 2 for 1967 and Figure 3 for 1968.

The geographical distributions of the upper extremes for both 1967 and 1968 (Figures 2 and 3) are strikingly similar to that indicated in Figure 1 for the monthly extremes over the period 1890 to 1968. With reference to the lower extremes, Figure 2 (for 1967) is rather more like Figure 1 than is Figure 3 (for 1968), presumably because in 1967 the difference between the north and south of the British Isles (with more sunshine in the south) was enhanced, whereas in 1968, the difference was reduced. For example, the sunshine in 1967 expressed as a percentage of the 1931–60 average for England and Wales, Scotland, and Northern Ireland was 109, 102, and 97 respectively, but the corresponding values for 1968 were 88, 97 and 107.[1]

The spatial distribution of the stations of Table I suggests that 'continental' sites (or locations with possible short sea track from the continent) are liable to upper extremes of sunshine duration while the more 'oceanic' sites (or locations with possible long North Sea track), especially high-level ones, are much more liable to low extremes of sunshine. Also, the fact that all the upper extremes occurred at coastal sites suggests that inland convection cloud in summer, and radiation fog in winter, play an important role in reducing sunshine.

Further evidence of the effects of topography is found in the results of a synoptic analysis (Table I). The upper extremes of sunshine usually occurred with anticyclones and dry easterly and northerly winds but also with north-westerlies in winter : the lower extremes of sunshine occurred with cyclones and moist westerly airstreams but with some important exceptions which are described later. These relationships between sunshine and the synoptic pattern are clearly reflected in the corresponding values of mean monthly atmospheric pressure. Thus, as indicated in Table I, the upper extremes of sunshine usually occur with above-average pressure and the lower extremes of sunshine tend to occur with below-average pressure, at least for non-urban sites.

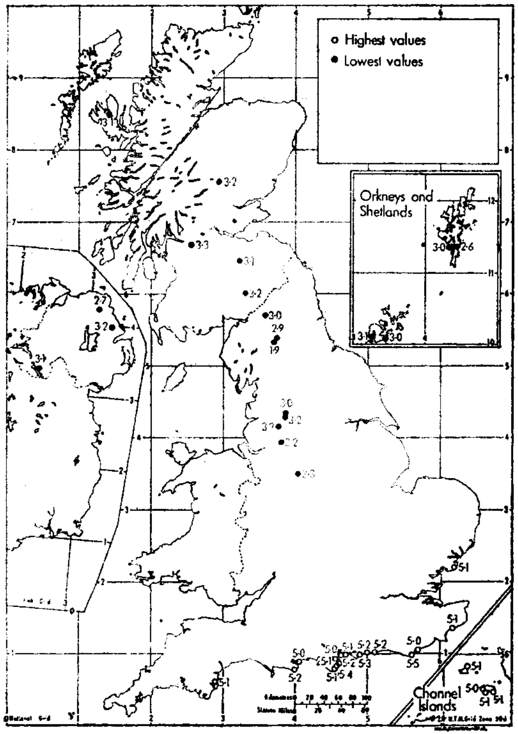

FIGURE 2—THE 20 STATIONS WITH THE HIGHEST VALUES AND THE 20 STATIONS WITH THE LOWEST VALUES OF MEAN DAILY DURATION OF BRIGHT SUNSHINE IN 1967

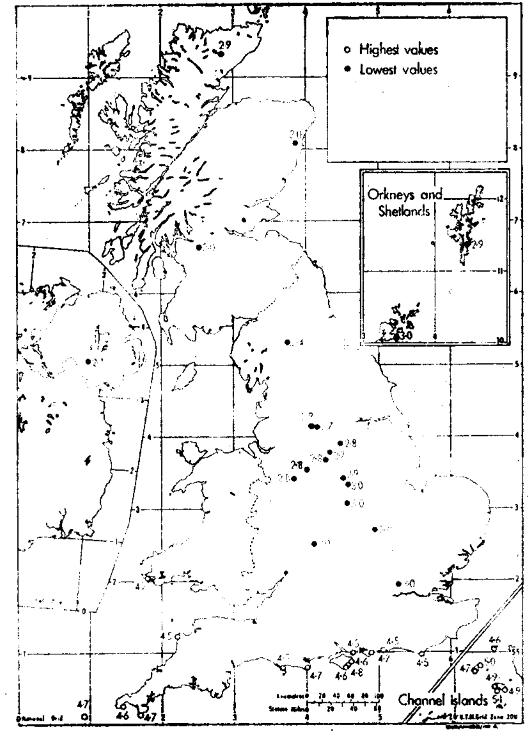

FIGURE 3—THE 20 STATIONS WITH THE HIGHEST VALUES AND THE 20 STATIONS WITH THE LOWEST VALUES OF MEAN DAILY DURATION OF BRIGHT SUNSHINE IN 1968

Excluding stations for which the estimated percentage loss of sunshine because of obstructions exceeds approximately 5 per cent.

A notable exception to the occurrence of low extremes of sunshine with cyclonicity and below-average pressure took place in November 1942 at Burnage, Manchester (Table I). This month was quiet, dry and anticyclonic, and fog and poor visibility developed frequently, especially in large towns. Similar conditions (but with easterlies dominating) prevailed when, in December 1890, Westminster was sunless, and only 0·1 and 0·3 hours were reported at Bunhill Row (in the City of London) and at Kew Observatory, respectively. The low extreme at Kew occurred within five years of the upper extreme at Kew, namely 72 hours in December 1886.[8] The low extremes at Whitworth Park, Manchester, though caused mainly by cyclones, were probably affected by smoke pollution. Following the Clean Air Act of 1956, it would be expected that the chance of air pollution causing low extremes of sunshine duration in the major urban centres would be lessened.

Further exceptions to the association of very low sunshine values with below-average atmospheric pressure occurred at Morpeth (Cockle Park) and Strathy (see Table I). The low extremes of sunshine at these stations were caused by persistent moist airstreams, and at Morpeth at least, partly by North Sea stratus.

Sunshine duration tends to decrease with height above sea level because there is a tendency for increased cloud on hills (see Table 1). A comparison[9] between durations at Fort William (100 ft + 5 ft) and Ben Nevis (4405 ft + 15 ft), which are only about three miles apart, showed that, for the period 1891 to 1902, the duration of sunshine was similar in midwinter but that in midsummer the duration of bright sunshine at the summit of Ben Nevis was only about two-thirds of that at the low-level station, in spite of obstruction at Fort William causing a 15 to 20 per cent loss of sunshine during the summer.

Year-to-year variation. The upper extremes of sunshine, with the exception of those for October and December, occurred in odd-dated years (Table I), thus confirming a well-known periodicity.

All but two of the upper extremes of sunshine occurred in the period from sunspot maximum to sunspot minimum, that is, in the decreasing-sunspot period of the '11-year' solar cycle (Table I). The average date of the upper sunshine extremes is 2·5 years after a sunspot maximum.

The lower extremes of sunshine duration for non-urban sites occurred in the approximately opposite part of the '11-year' solar cycle, namely in the increasing-sunspot period and around the sunspot minimum. Excluding the urban sites in London and Manchester, seven of the eight remaining low extremes occurred from 1 year before the sunspot minimum to 4 years after it, the average date being about 1 year after the sunspot minimum. This position in the solar cycle is equivalent to about 3 years before the sunspot maximum because the increasing-sunspot period is, on average, about 4 years long as compared with about 6 to 8 years for the decreasing-sunspot period. The two urban low extremes of sunshine duration which were associated with anticyclones occurred near the sunspot minimum or rather earlier.

The relationship between sunshine and the '11-year' solar cycle is confirmed by the results of a correlogram analysis between monthly sunshine duration at Kew (using data from 1881 to 1967) and the annual sunspot-relative-

TABLE II—LAGGED CORRELATION COEFFICIENTS BETWEEN THE SEASONAL DURATION (D) OF BRIGHT SUNSHINE AT KEW* AND THE ANNUAL SUNSPOT-RELATIVE-NUMBER (t) EXPRESSED AS A PERCENTAGE OF THE MAXIMUM VALUE OF THE RELEVANT SUNSPOT CYCLE

Season	Period of data from :		** Lag (in years) −5	−4	−3	−2	−1	0	+1	+2	+3	+4	+5	+6	+7	+8
June, July and August	1881	Correlation coefficient × 10^3	−092	−131	−203	−196	−053	+067	+145	+192	+162	+098	−067	−088	−018	−156
		No. of years†	83	84	85	86	87	87	87	87	87	87	87	87	87	87
		Latest year of sunshine data	1963	1964	1965	1966	1967	1967	1967	1967	1967	1967	1967	1967	1967	1967
		p‡			0·07					0·07						
October, November and December	1881	Correlation coefficient × 10^3	−154	−221	−181	−131	−044	+103	+152	+181	+106	+056	−051	−125	−154	−067
		No. of years†	83	84	85	86	87	87	87	87	87	87	87	87	87	87
		Latest year of sunshine data	1963	1964	1965	1966	1967	1967	1967	1967	1967	1967	1967	1967	1967	1967
		p‡		0·04						0·09						
	1900	Correlation coefficient × 10^3	−214	−313	−279	−246	−118	+097	+195	+289	+238	+165	−001	−138	−206	−137
		No. of years†	64	65	66	67	68	68	68	68	68	68	68	68	68	68
		Latest year of sunshine data	1963	1964	1965	1966	1967	1967	1967	1967	1967	1967	1967	1967	1967	1967
		p‡		0·01					0·01–0·02							
		Sign of correlation coefficient			Negative					Positive					Negative	

*Kew Observatory : 51° 28′N, 00° 19′W, 18 ft above MSL.

**Lag used in calculating the correlation coefficients = (year date)$_D$ − (year date)$_t$

†The value of the sunspot-relative-number for 1968 was assumed to be a cycle maximum of 100.

‡p is the significance level.

number, expressed as a percentage of the maximum value of the relevant sunspot cycle. When the sunspot-relative-number is at a minimum it is expressed as a percentage of the mean of the two adjacent sunspot maxima. The use of this solar variable emphasizes the importance of the *position* of a year within a solar cycle. Table II shows that for both summer (June, July and August) and autumn-winter (October, November and December), the sunshine peak tends to occur about two years after a sunspot maximum, while the lower extremes of sunshine tend to occur around the sunspot minimum and during the sunspot-increasing period.

The higher correlations between sunshine and 'sunspots' for the somewhat shorter period (from 1900), shown in Table II, reflect the effects of phase change in the relationship. A suggested explanation of the relationships between sunshine and solar cycle is given elsewhere.[10-12]

Conclusions. Results show that (i) the upper extremes occurred in coastal areas of the extreme south, south-east and south-west and (ii) the lower extremes occurred mainly in the north, particularly at high-level sites but also in urban industrial areas. The upper extremes usually occurred with anticyclones and dry easterly and northerly winds but also with north-westerlies in winter: the lower extremes occurred with cyclones and moist westerly airstreams but also with anticyclones and uniform pressure gradients in urban industrial areas in winter and at stations on the north-east coasts exposed to airstreams with a long North Sea track.

The upper extremes of sunshine duration occurred mainly in those years with odd dates, thus confirming the well-known '2-year' periodicity. The time-distribution of monthly extremes over the British Isles and the year-to-year variation of sunshine duration at Kew showed the '11-year' cycle with the sunshine peak occurring with decreasing sunspots, at about two years after the sunspot maximum, and the sunshine minimum occurring with increasing sunspots or near the sunspot minimum.

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THE LAPLACIAN AND ITS RELEVANCE FOR ANALYSIS

By T. H. KIRK

The Laplacian operator, symbolically written $\partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$ or more briefly ∇^2, occurs frequently in meteorology. Examples are the expression for geostrophic vorticity in terms of the geopotential, and the 'omega' equation. Recently, the use of the Laplacian in analysis has been advocated.[1,2]

The purpose of this note is to show that the physical interpretation of the Laplacian, first given by Maxwell[3] and recently re-emphasized,[4] can lead to a wider appreciation of its function and to a more general concept of meteorological analysis.

If φ is any scalar continuous function of position, having a value φ_0 at a point o, then it can be shown[4] that the average value of φ in the immediate neighbourhood of o, denoted by φm, is given by

$$\varphi m = \varphi_0 + \frac{h^2}{24}(\nabla^2\varphi)_0$$

where h is a small measure of distance and $(\nabla^2\varphi)_0$ is the value of the Laplacian at the point o.

Rearrangement of this equation gives

$$(\nabla^2\varphi)_0 = \frac{24}{h^2}\ (\varphi m - \varphi_0)\ .$$

The important result of immediate physical interest is therefore :

(i) The Laplacian of a function at a point o is a measure of the local anomaly of that function relative to the function's average in the immediate neighbourhood of o.

It follows directly from (i), or it may be deduced independently, that if the distribution of φ is *linear* then $\nabla^2\varphi = 0$. The second important interpretation may therefore be expressed as follows :

(ii) The value of the Laplacian of a function is a rough indication of the *non-linearity* of its distribution. In particular, the vanishing of the Laplacian denotes a *quasi-linear* distribution of the function.

These results may be used to clarify the concept of 'air mass', hitherto only qualitatively defined in terms of a quasi-constancy of property. If the property is S, e.g. potential temperature, then a constancy of S implies $\nabla^2 S = 0$. In practice, more generally, the term 'air mass' comprehends a uniform variation of property rather than a constancy. It is therefore still possible to conceive of an air mass as specified ideally by $\nabla^2 S = 0$.

At the present time, when numerical methods are being employed to produce distributions of most meteorological elements, it might appear somewhat anomalous that subjectively analysed fronts are still a feature of surface charts. It is conceded that these are useful at a level below the synoptic scale, although their positions are subject to some uncertainty and there is occasionally doubt about what, in fact, is being depicted. It might be argued that the pristine simplicity of the frontal concept has been lost and that its use will be unnecessary in the future at a time when all meteorological elements can be calculated and printed out at will. We may ask the question, 'What is the essence of the frontal concept as far as the *synoptic* scale is concerned ?' In other words, what is worth while depicting on the charts interchanged between nations ? Is it possible to retain the essential character of the concept and at the same time achieve a greater objectivity consistent with the use of numerical methods ?

An immediate solution suggested by the above results is to recognize non-linearity of property as the fundamental characteristic worthy of representation in addition to the distribution of the property itself. This is consistent with the use of the vorticity chart in relation to the contour chart.

In the application to frontal analysis, it must be recognized that the different aspects of fronts and frontal activity[2] may be expressed by a suitable choice of parameter. Traditionally, fronts have been associated with the non-linearity of the thermal field and this aspect finds expression in the use of the thermal vorticity chart. This type of chart is in current use at Bracknell for the interpretation of frontal zones.

In recent years, fronts have come to be identified in terms of their dynamical properties, in particular the vertical velocity. This is derived as a product of the computer programme and is also implicit in the cloud photographs from satellites. In the light of the foregoing argument, a chart of $\nabla^2 \mathrm{d}p/\mathrm{d}t$, expressing the non-linearity of the distribution of the vertical velocity, is suggested as an appropriate method of depicting fronts on the synoptic scale. Although, with present models, the grid lengths are too large for the optimum calculation of Laplacians, this state of affairs is rapidly changing. New models will soon be available, employing much shorter grid lengths, and new techniques of objective analysis[5] will permit calculation to a higher degree of accuracy.

This method of analysis is independent of the details of current frontal theory and practice — a very desirable characteristic !

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THE DISPLACED BRITISH ISLES

By G. C. JOHNSON

The satellite picture reproduced in Plate II was taken by ESSA 8 at 1041 GMT on 20 November 1969. It appears to show the displacement of the British Isles some 2° of longitude to the east of its true position.

An obvious possible explanation is that the grid was incorrectly drawn, but close scrutiny showed that this was not so. The calculated centre fiducial point value of 56·3°N 02·9°W is correct, and further checks on identifiable geographical features of Norway (the coast, and Sognefjord at 61°N) the French coast at 44°N, and the Alps, confirm this.

The explanation of the apparent displacement is thought to be as follows. At the time of the picture pressure was low over Scandinavia with the British Isles lying in an unstable west-north-west airstream which followed the passage of a cold front on the 19th. Cumuliform cloud forming in the unstable airstream was carried across western coasts, in general only as far as the main high ground barrier presented by the Welsh Mountains, Pennines, etc., though some degree of penetration is evident even over high ground. This is particularly noticeable over the southern Pennines into Lincolnshire. The apparent western coastline at 3°W is therefore not the true coastline, but indicates the eastern limit of penetration of the cloud.

On the eastern side of the high ground the air was a little too dry and temperatures too low for marked convection to occur. After leaving the coast, however, the air would pick up moisture from the sea, and also be affected by the higher temperatures of the water surface; convection would then be expected to become increasingly vigorous with length of sea track, i.e. after sufficient moistening and warming had taken place. This, together with the fact that the newly formed cloud would only become visible on the picture upon attaining the size and amount capable of detection by the automatic picture transmission system, means that the cloud edge would therefore be found at roughly the same distance from the east coast for most of the length of the British Isles, and thus have the same shape as the coastline, but be displaced further to the east.

The fact that the true coastline cannot be seen, even where cloud free, is due to the very similar reflective qualities of land and sea throughout the British Isles under most conditions. Only when favourable conditions exist, enhancing the reflective nature of either the sea (sun–satellite relationship giving 'sun glint') or the land (snow), can the true coastline of the British Isles be seen.

REVIEW

Essentials of meteorology (Volume 3 of the *Wykeham Science Series*), by D. H. McIntosh and A. S. Thom. 215 mm × 140 mm, pp. 239, *illus.*, Wykeham Publications (London), Cannon House, Macklin St, London WC2. Price : £1 (paperback).

This book by two meteorologists on the staff of the Department of Natural Philosophy at Edinburgh University, is one of a series which, according to the publishers, is intended 'to broaden the outlook of the senior grammar school pupil and to introduce the undergraduate to the present state of science as a university study'. The approach is therefore that of the scientist rather than that of the geographer; as the authors roundly declare in their opening words, 'Meteorology is a branch of physical science'.

The book follows the conventional order of teaching the subject to meteorologists. After a brief but cogent statement of what meteorology is about, there are chapters on the physical properties of the atmosphere, heat transfer, condensation and precipitation, the tephigram, winds, instruments and observations, synoptic meteorology, micrometeorology, the general circulation and weather forecasting.

It is a very good book, clearly and concisely written. There are useful exercises at the ends of chapters. The diagrams are well drawn. The index is sufficient. The book is well printed and attractively produced. An experienced synoptic meteorologist to whom the reviewer lent his copy thought that synoptic meteorology was a little less thoroughly treated than some of the other topics, but it must always be a matter of opinion how deeply one should go in writing about a subject.

Will the book serve its purpose ? The mathematics and physics should present no difficulties to a senior sixth-form student, though the book probably goes into more detail than the average sixth-former requires (in devoting, for example, a whole chapter to the tephigram) — more especially as the publishers offer six other books for sixth-formers to read in the same series. But it will undoubtedly serve as a very useful introduction to the subject for the university student or the budding professional meteorologist. At the rate at which the subject is progressing, especially in such fields as World Weather Watch and numerical forecasting, the book will need revision with each new edition (for it certainly deserves to run to several editions), but at the price of £1 anyone who wishes to keep up to date ought to be able to afford to discard an old edition after a few years and buy a new one.

S. E. VIRGO, O.B.E.

LETTER TO THE EDITOR

551·509·314:551·509·323

Forecasting night minimum air temperature by a regression equation

Gordon, Perry and Virgo* developed a regression equation between $(T_{12}+D_{12})$ and $T_{\min}$ for Mildenhall, based on data for 1967 and 1968. T_{12} and D_{12} are, respectively, the screen temperature and dew-point recorded at 1200 GMT and $T_{\min}$ is the screen minimum temperature recorded on the succeeding night. Excluding nights on which the dew-point changed by more than 2 degC and nights when fog formed or when there was a noticeable front in the area, they found the equation

$$T_{\min} = 0{\cdot}395\ (T_{12} + D_{12}) - 1{\cdot}334$$

to be valid throughout the year, the correlation between $T_{\min}$ and $(T_{12}+D_{12})$ being 0·87 and the root-mean-square error 2·34 (temperatures are in degrees Celsius throughout).

Temperatures at Yeovilton in 1967 and 1968 have been examined. In 1968, 102 days were identified as satisfying the above criteria. Temperatures on these days produced the regression equation

$$T_{\min} = 0{\cdot}482\ (T_{12}+D_{12}) - 2{\cdot}67$$

*GORDON, J., PERRY, J. D. and VIRGO, S. E.; Forecasting night minimum air temperature by a regression equation. *Met. Mag., London*, **98**, 1969, pp. 290–292.

with a correlation of 0·91 and a standard error of estimate of T_{min} of 2·18. The scatter diagram exhibits no tendency to non-linearity and, by chance, the extreme values of T_{min} lie close to the regression line. In 1967, 103 days were identified and the temperatures of the 205 days of 1967 and 1968 produced the regression equation

$$T_{min} = 0{\cdot}463\ (T_{12}+D_{12}) - 2{\cdot}30$$

with a correlation of 0·88 and a standard error of estimate of T_{min} of 2·34, these latter two figures being similar to those obtained by Gordon, Perry and Virgo. The composite scatter diagram exhibits no tendency to non-linearity.

On the assumption that the actual T_{min} will be normally distributed about the value predicted by this regression line, it is a short step to produce the following table for forecasting air frost, that will be applicable at Yeovilton on those days, on average two days a week, which are in the category under consideration. Similar tables could, of course, be produced for forecasting the probability of T_{min} falling below any other given value which may be of particular interest.

$T_{12} + D_{12}$ (degC)	>11·1	11·1	9·0	7·5	6·2	5·0	<5·0
Probability that T_{min} will be $\leqslant$0°C (per cent)	<10	10	20	30	40	50	>50

RNAS Yeovilton INSTRUCTOR COMMANDER J. MARSH, M.A., A.F.I.M.A., R.N.
Ilchester, Somerset

OBITUARY

It is with regret that we have to record the death of Mr K. R. Suche (Senior Scientific Assistant) on 16 January 1970.

RECENT PUBLICATION

Artificial modification of clouds and precipitation

World Meteorological Organization *Technical Note* No. 105* discusses the difficulty of evaluating the results of rain-making experiments and emphasizes the fact that more research is required before any technique could be recommended for operational purposes.

The case is much the same for the suppression of hail and lightning, which are also considered, but as regards dissipation of supercooled liquid fog over airports, for example, techniques are now known well enough to warrant operational use.

This publication, which is mainly a revision of the *Technical Note* No. 13 issued in 1955, shows that research and operational experience in the intervening 14 years have given no grounds to alter the basic conclusions reached at that time.

Professor Morris Neiburger of the U.S.A., who undertook the task of bringing this information up to date, has produced a lively treatment of the subject which will interest a range of readers much wider than professional meteorological circles.

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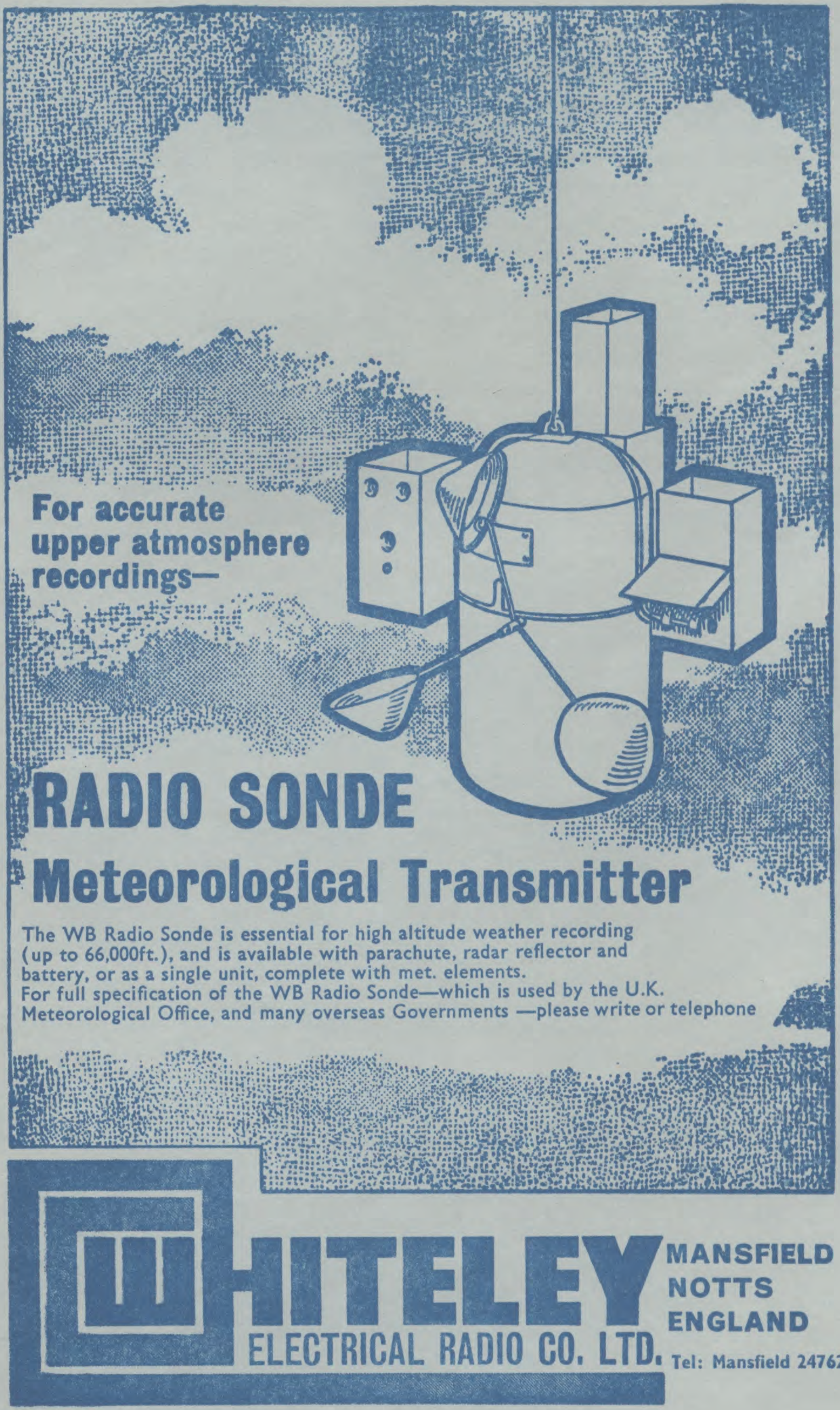
*NEIBURGER, M.; Artificial modification of clouds and precipitation. *Tech. Notes Wld met. Org., Geneva,* No. 105, 1969. (Available from WMO Secretariat, Geneva. Price: 16*s*.)

OFFICIAL PUBLICATION

SCIENTIFIC PAPER

No. 30. Orthogonal polynomials as a basis for objective analysis. By R. Dixon, B.Sc.

In current meteorological practice computer analyses of meteorological fields are done by grid-pointwise techniques in which the analytical process is repeated at every one of a large number of grid points. This paper presents an alternative approach in which a high-power bivariate polynomial is fitted to the data over a large area; the results for several such areas are joined together to form the complete analysis. Orthogonal polynomials are used to overcome certain computational difficulties in the fitting of high-powered polynomials.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A COMPUTING AID TO STUDIES OF AIRFLOW OVER MOUNTAINS

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Summary. A method is described for using a high-speed computer to compute and plot flow patterns and orographic cloud over and in lee of given high-ground profiles. Care is needed in making boundary assumptions and in interpreting the results, but the method can be a powerful aid to observational studies of mountain airflow, including lee waves, rotor flow and, possibly, local blocking and high-level turbulence.

Introduction. In two papers in 1949 and 1953, Scorer[1,2] discussed the occurrence of lee waves in the atmosphere and showed how the values of possible lee wavelengths may be calculated for an airstream that can be divided into two or more layers each with a constant value of a parameter depending on the wind and temperature structure. The calculations become very lengthy if the number of layers exceeds three, so early calculations were restricted to simplified airstreams with only a few distinct layers. Corby and Wallington[3] showed that in some situations lee-wave amplitudes are very sensitive to small changes in the airstream, and although simplified models may be adequate in many situations there is no simple criterion for assessing whether such simplification is justifiable for any particular airstream. Therefore, when calculating lee-wave amplitude it is wiser to overcome the computing problem than to apply the theoretical technique to a crude approximation of a real airstream.

Use of a high-speed computer for numerical studies of lee waves was described by Wallington and Portnall[4,5] in 1958. This work was exploratory and programmes were not designed for general purpose numerical study of the lee-wave features of mountain airflow. With a modern computing system it is possible to compute and present some mountain airflow calculations in such a way that they can be used not only to study lee waves but also as an adjunct to studies of rotor flow, local blocking by mountain ridges and high-level turbulence. This paper describes the operational features of a computing programme that has already been written and indicates why the use of such a programme and interpretation of results must be accompanied by an understanding of the physics and formulation of the problem.

Formulation of the problem. We shall consider only small perturbations in frictionless, steady, isentropic flow in two dimensions in a vertical plane

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and limit the discussion to waves that are short enough for the Coriolis force to be neglected. This is not the only way to formulate the problem, nor is it the best way, but it is a method that has already proved to be practicable and to produce useful results. If ψ is the perturbation displacement of a streamline from its original level z, then the gas equation, the adiabatic equation and the equations of motion and continuity can be manipulated to show approximately that

$$\frac{\partial^2\psi}{\partial z^2} + \left(\frac{2}{U}\frac{\partial U}{\partial z} - \frac{1}{\theta}\frac{\partial\theta}{\partial z}\right)\frac{\partial\psi}{\partial z} + \left(\frac{g}{U^2\theta}\frac{\partial\theta}{\partial z}\right)\psi + \frac{\partial^2\psi}{\partial z^2} = 0, \qquad \ldots (1)$$

where U is the undisturbed component of the wind in the x direction at height z, x being the distance along the horizontal axis of the vertical cross-section,

θ is the undisturbed component of the potential temperature at height z,

and g is gravitational acceleration.

In order to seek solutions which are sinusoidal in the x direction we substitute ψ = the real part of $\mathrm{f}(z)e^{ikx}$, where $\mathrm{f}(z)$ is a function of z only, k represents wave numbers to be determined, and $i = \sqrt{-1}$. Equation (1) may then be written in the form

$$\frac{\partial^2\mathrm{f}(z)}{\partial z^2} + 2S\frac{\partial\mathrm{f}(z)}{\partial z} + (l^2 + k^2)\,\mathrm{f}(z) = 0, \qquad \ldots (2)$$

where S and l are functions of z only.

If we follow Scorer and consider the flow across a mountain ridge whose height, h, is given by

$$h = \frac{Hb^2}{b^2 + x^2}, \qquad \ldots (3)$$

where H is the height of the crest and b is a width parameter, then the solution for the streamline displacement becomes

$$\psi = \text{real part of } Hb\int_{k=0}^{k=\infty} e^{-k(b\pm ix)}\,\frac{\mathrm{f}(z)}{\mathrm{f}(0)}\,dk, \qquad \ldots (4)$$

where f(0) denotes the value of this function at ground level, $z = 0$.

The integral will have singularities for any values of k that yield $\mathrm{f}(0) = 0$. These values of k ($= K$, say) are the lee-wave numbers, and the flow pattern corresponding to them are called the lee waves. On the assumption that these lee waves do not occur upstream of the mountain ridge that gets them in action, equation (4) may be written

$$\psi = \text{real part of } Hb\int e^{-k(b\pm ix)}\,\frac{\mathrm{f}(z)}{\mathrm{f}(0)}\,dk -$$

$$- 2\pi Hbe^{-kb}\,\frac{\mathrm{f}(z)}{[\partial\mathrm{f}(0)/\partial k]_{k=K}}\sin Kx, \qquad \ldots (5)$$

where the integral is taken around a circuit that excludes singularities, and the second term is repeated for all wave numbers but applies only to the downwind side of the mountain ridge.

The first part of the solution involving the contour integral is called the barostromatic flow, while the second part refers to the lee-wave flow.

It can be shown that if $b \gg 1/l$ at all heights, the integral for the barostromatic flow is dominated by the contribution at $k = 0$. Thus the barostromatic displacement ψ_B, is given approximately by

$$\psi_B = \text{real part of } \frac{Hb}{b^2 + x^2} (b \pm ix) \left(\frac{f(z)}{f(0)}\right)_{k=0} . \qquad \ldots (6)$$

This solution includes an ambiguity as the boundary conditions can be satisfied by either the positive or negative sign before the ix. The effect of the ix in the equation is to shift the crests or troughs in the barostromatic streamlines over a mountain ridge in the upwind or downwind directions, but for the present it will be assumed that the tilt is small enough to be neglected. Then equation (6) becomes

$$\psi_B = \text{height of ground} \times \text{real part of} \left(\frac{f(z)}{f(0)}\right)_{k=0} . \qquad \ldots (7)$$

The flow pattern across any high-ground cross-section can be determined by analysing the cross-section into a number of ridges of the type specified in equation (3), computing the flow across each of these ridges, and adding these flows together to form the complete pattern across the high-ground cross-section. A computing programme has been written to calculate flow patterns in this way, and to compute, as by-products, wave-flow parameters, such as the l in equation (2), and the effects of the wave flow on radiosondes ascending through the disturbed airstream.

The computing programme. Data required for the programme comprise :

(i) *Airstream data.* Winds, temperatures and dew-points at as many levels as are available. The levels at which these items are given can be in millibars, feet, kilometres, or metres; the programme deals with any of these units. Wind directions are in degrees; speeds are in kilometres or miles per hour, metres per second, or knots. Temperatures are in degrees Kelvin, Celsius or Fahrenheit; dew-points are not essential if cloud computations are not required.

(ii) *High-ground data.* A list of heights at specified regular intervals on a cross-section of the high ground in a specified direction. Alternatively, if an experimenter wishes to study the flow over one or more ridges of the type specified by equation (3), he need only give the height, width and position parameters of the ridges.

(iii) *Boundary levels and number of computing levels.* The heights of the upper and lower boundaries between which the airflow calculations will be made and the number of levels between these boundaries that will be used for finite differences in the vertical finite difference form of equation (2).

(iv) *Release points and rates of ascent of simulated radiosondes.* If the experimenter wants the programme to calculate the temperatures, dew-points and wind speeds that would be measured by a radiosonde ascent in the flow, he must specify the radiosonde release point and the rate of ascent.

With the data in (i) to (iv) the computing programme goes through all or a selection of the following actions :

(a) The airstream data are printed out and plotted in graphical form on a plotter. Figure 1 shows a typical plot.

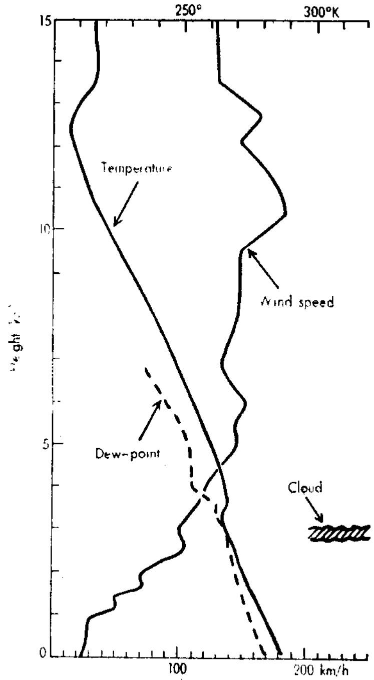

FIGURE 1—PROFILES OF TEMPERATURE, DEW-POINT AND WIND COMPONENT FROM 270° FOR 0950 EST, 17 APRIL 1966 AT HOBART, TASMANIA

The shaded layer is the cloud assumed likely if the dew-point is within 1 degC of the temperature.

(b) Temperatures, dew-points and wind components across the high ground for the levels to be used in vertical finite differences are calculated by interpolation from the airstream data.

(c) The parameters S and l for equation (2) are computed and graphs of l and $2\pi/l$ are plotted against height.

(d) Starting with arbitrary values (to be discussed in the next section on page 162) at the top two levels, the simplest finite difference form of equation (2) is integrated down to the lower boundary with $k = 0$.

(e) Starting with similar boundary conditions to those just described, lee-wave numbers, K, are found by the method described by Wallington and Portnall.[4]

(f) Graphs of the barostromatic displacement factor and $2\pi[f(z)/(\partial f(0)/\partial k)]_{k=K}$ are plotted against height.

(g) The high-ground profile is analysed into ridges of the form specified by equation (3) by the method described by Wallington.[5]

(h) The heights of 20 streamlines between the upper and lower boundaries are calculated such that they represent the undisturbed wind components, i.e. the wind speed is proportional to the streamline gradient.

(i) The following calculations are made for each streamline. For each point over the given ground cross-section a search is made from ground level upwards to find the height, or heights, at which the streamline should be to make its displacement equal to the sum of the barostromatic displacement and the displacements due to lee waves from all upstream ridges. The streamline is drawn on the plotter in a vertical cross-section showing the flow over the high ground.

(j) If the airstream data include dew-points, the programme computes and draws the cloud pattern in the airflow on the assumptions that cloud forms if the temperature is within 1 degC of the dew-point and that descending air in a layer of cloud does not become unsaturated until it descends below the base of the layer.

(k) If the data include release points and rates of ascent of simulated radiosondes, the paths of the sondes are calculated and drawn on the cross-section, graphs of the temperatures, dew-points and wind speeds that the sonde would measure are plotted, and the vertical speeds of the air through which each radiosonde ascends are plotted for each level used in the computations.

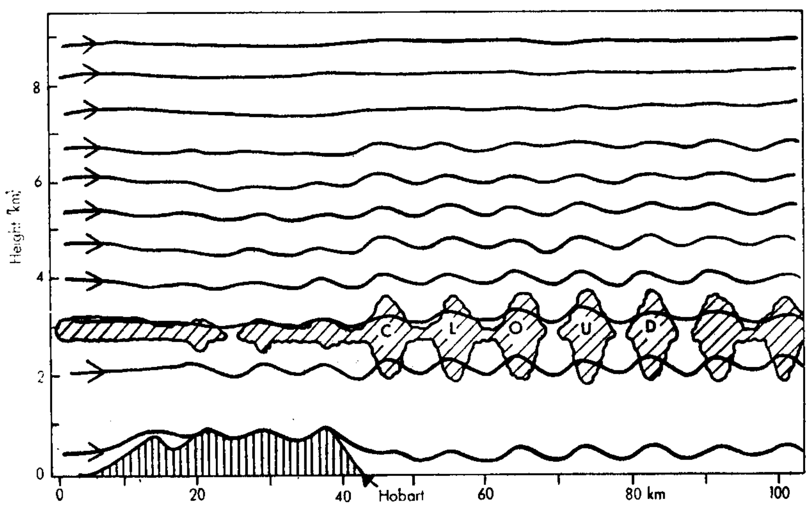

FIGURE 2—COMPUTER-PLOTTED STREAMLINE AND CLOUD PATTERN FOR THE AIRSTREAM REPRESENTED BY THE DATA IN FIGURE 1 FLOWING OVER A HIGH-GROUND WEST-TO-EAST CROSS-SECTION THROUGH HOBART

The clouds were shaded in by hand but their outline was drawn by the computer plotter. The computed lee wavelength of 18·5 km (10 n.miles) is in good agreement with a wavelength of 11 n.miles observed by satellite photography.

Figure 2 shows the airflow and cloud pattern computed for a flow whose wind and temperature profiles are illustrated in Figure 1. The clouds were shaded in by hand after the computation but the cloud outlines were drawn by the computer-controlled plotter. Airstream winds and temperatures for this computation were those measured by radiosonde at Hobart, Tasmania, at 09 EST (GMT + 10 h) on 17 April 1966. This airstream produced bars of lee-wave clouds clearly visible on a photograph taken by ESSA 2 satellite on orbit 600 at 0740 EST on 17 April 1966. Andersen[6] described the occurrence and measured the wavelength from the photograph as 11 nautical miles. The computed lee wavelength was 10 nautical miles, which is in good agreement with the observations.

The boundary assumptions. The experimenter can choose the upper and lower boundary levels for the computed flow pattern. The lower boundary is taken to be either ground level or some surface which is taken to be an effective lower boundary, e.g. if winds are practically calm in a shallow layer of stable air below, say, a few hundred metres, the experimenter may wish to try a calculation on the assumption that the lower boundary is virtually the top of this almost stagnant air together with whatever high ground protrudes up through it. In some computations streamline displacement is found to be zero at a level below the top of the high ground in the region. In such a situation it must be assumed either that the theory is inapplicable or that the high ground will block or divert the low-level flow. If a level of zero displacement is below the crests of a mountain range but above the level of some of the passes, it may be argued that the airflow will be concentrated as particularly strong winds through these passes. But this is conjecture at present. The main points being made here are that in some situations the choice of a low-level boundary is a subject for experimental and observational studies, and that the computing facility is an aid to such studies.

In setting the upper boundary conditions the experimenter can set the height and the value of $f(z)$ at the top two levels. By setting these values of $f(z)$ he virtually sets the ratio of the values at the top two levels; the magnitudes of the displacement values are scaled by the lower boundary factors in the displacement terms. There is no *a priori* reason why any particular set of upper boundary conditions should be correct, and no special justification for assuming that displacements will become negligibly small at or towards some great height. In this numerical method the procedure is to choose one or more sets of upper boundary conditions arbitrarily, and then consider the nature of the computed flow patterns. If the computed displacements close to the upper boundary turn out to be very small compared with the low-level displacements, or if the low-level flow appears to be insensitive to variations in the choice of upper boundary conditions, it can be argued that the computed flow pattern at low levels is as valid as the formulation of the problem. Otherwise it must be accepted that the computed flow pattern cannot be justified without justification for the particular upper boundary conditions chosen. Wallington and Portnall[4] have discussed the effect of the upper boundary assumptions on lee-wave calculations in detail.

The upper boundary effect on barostromatic displacement is similar to its effect on lee-wave computations in that there appear to be many situations in which the low flow is not very sensitive to variations in the assumed conditions at some upper boundary. But the barostromatic computations are more complicated because the imaginary part of $f(z)$ must be considered. If the real part of $f(z)$ in equation (6) is almost independent of the assumed upper boundary conditions it will have a vertical distribution of shape similar to that of the imaginary part. Therefore, the factor $[f(z)\,/\,f(0)]_{k\,=\,0}$ will be almost entirely real, in which case the crests or troughs in the barostromatic flow will have negligible tilt from the vertical over the mountain ridge and the ambiguity of sign is unimportant.

However, if the flow pattern is sensitive to variations in upper boundary assumptions the real and imaginary parts of $f(z)$ will not necessarily have similar profiles and the computed magnitudes and precise locations of troughs and crests over or near the mountain ridge will both be of doubtful accuracy.

Rotors. Because the displacement calculated for a level z refers to displacement at that level and not from that level it is possible for a streamline to have more than one level over any point on the ground profile. If a streamline has three possible positions it must have either an S shape or be part of a closed circulation in the vertical cross-section. It must be stressed that the perturbation assumptions are not strictly justified where a local reversal of flow occurs. However, comparison of computed and observed patterns suggests that a local breakdown does not necessarily invalidate the whole computed flow pattern. A computed rotor or reversal in the flow pattern can be taken to indicate a local breakdown of the flow into chaotic or unsteady flow, rather than a simple circulation in a vertical plane. Figure 3 shows a computed pattern with reversed flow and rotor features. When this situation occurred turbulence below about 2 km was so violent that light-aircraft flying was abandoned for the day. Turbulence associated with this type of rotor flow is not produced merely by a vertical circulation; it is the result of the smaller-scale instability that is generated when overturning of air in the stable layer associated with the wave flow forces warm air under cooler air from below.

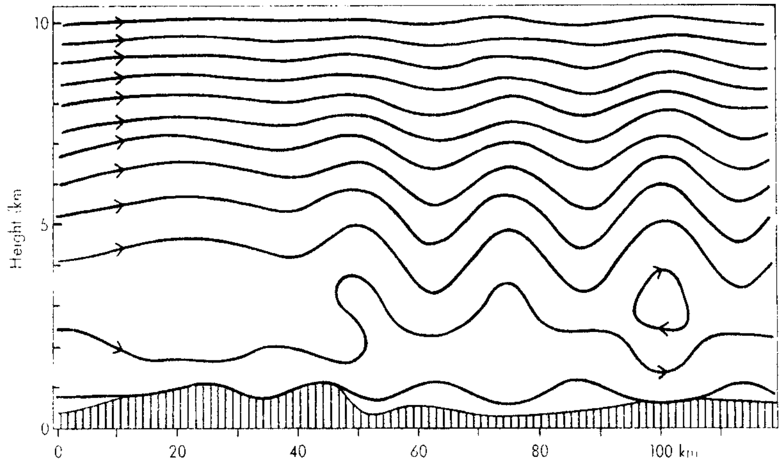

FIGURE 3—COMPUTED FLOW PATTERN OVER A WEST-TO-EAST CROSS-SECTION OF THE BRINDABELLA MOUNTAINS, AUSTRALIA

Wind and temperature data used were those measured by radiosonde at 09 EST, 12 July 1966 at Wagga Wagga, New South Wales. If streamlines had been drawn at closer intervals they would have shown additional closed circulations, or rotors, under the two wave crests near the centre of the pattern. The airstream contained a shallow temperature inversion of 5 degC between 900 and 890 mb.

Figure 4*(a)* shows a well-developed wave and rotor flow investigated during the Sierra Wave Project. This has been described by Holmboe and Klieforth.[7] Figure 4*(b)* shows the computed flow pattern for the situation. The airstream data used were those from Merced, California, at 13 PST (21 GMT), 16 February 1952. The computed pattern is in good agreement with the observations;

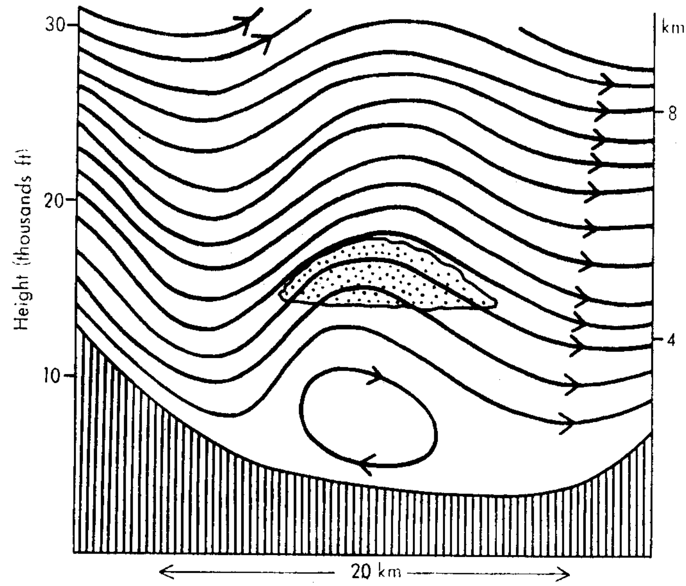

FIGURE 4(*a*)—FLOW PATTERN DEDUCED FROM OBSERVATIONS AND MEASUREMENTS ON 16 FEBRUARY 1952

The observed lee wavelength was 18 km at about the 3-km level.

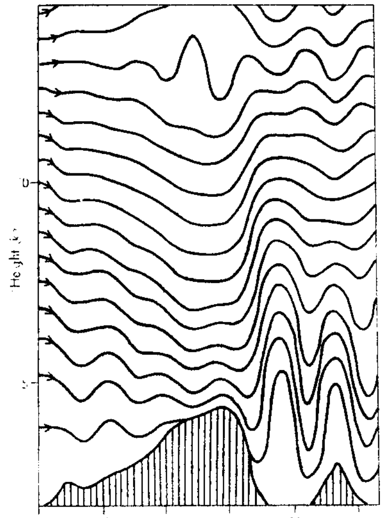

FIGURE 4(*b*)—COMPUTED FLOW PATTERN FOR 16 FEBRUARY 1952

Airstream data used were those obtained at Merced at 13 PST (21 GMT), 16 February 1952 The computed streamlines do not include an isopleth to outline a rotor circulation, but such a circulation beneath the wave crest was evident in more-detailed printed results. The orographic cloud pattern is omitted for clarity; it contained wave clouds in the correct locations with tops at 5 km, but the bases were much too low.

both observed and computed lee wavelengths were 18 km, and although the plotted streamlines do not happen to include a closed isopleth, rotor-flow circulation below the wave crests was evident from more-detailed printed results.

Some computed flow patterns have rotor-flow features at high levels. These may well be indicators of high-level turbulence; the computing technique can be an aid in investigations of such turbulence, which can be favoured rather than inhibited by static stability. But in the computations made so far there is not enough evidence to assert whether the high-level rotors are likely to be real or spurious by-products of upper boundary assumptions.

Conclusion. Care is needed in making boundary assumptions and interpreting the results of a mountain airflow computation, and there are occasions when an experimenter must not be tempted to place undue confidence in a computed flow pattern; but, if this need for caution is realized, the perturbation and computing technique described here can be a powerful aid to observational studies of mountain airflow including lee waves and rotor flow and, possibly, local blocking and high-level turbulence.

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METEOROLOGICAL NOTES ON TRAVEL OF DEBRIS FROM AN ATOMIC EXPLOSION AT MURUROA ON 7 JULY 1968

By C. L. HAWSON

Summary. The likely dispersal of debris from the first of a series of atomic explosions at Mururoa in July 1968 is considered, including spread by eddy diffusion. Times of first detection at Pretoria, Aspendale and Bombay of debris from this explosion are compared with tracks and times inferred from charts of average upper winds over the world for July and their associated standard vector deviations. Good agreement is found. In particular, rapid inter-hemispheric exchange in the lower troposphere is in accord with recent studies of wind fields over the Indian Ocean.

Introduction. Atomic explosions took place at Mururoa, 22°S 139°W, at 2200 GMT on 7 July 1968 and on subsequent dates from 15 July to 8 September. Debris from these explosions was first observed on detectors exposed at ground level at Pretoria, 26°S 29°E on 16–17 July, Aspendale (Melbourne), 38°S 145°E, on 15–22 July and Bombay, 19°N 73°E on 23 July (Peirson[1]).

This note compares these observations with tracks and travel times deduced from average winds and their associated standard vector deviations at various levels (Heastie and Stephenson,[2] Tucker[3]) and from papers concerning winds at low levels over the western Indian Ocean (Findlater[4-6]).

To avoid ambiguity the term 'average wind' is used to indicate an average over a long period of time of the winds at a level, and the term 'mean wind' to indicate the mean through a layer. Hence, 'average mean wind' denotes the average over a long period of time of the mean wind in a given height interval for a given track.

Basic meteorological factors affecting the spread of debris. Debris from atomic explosions of sufficient size can be expected to rise quickly to near the top of the troposphere (about 16 km at 22°S) at least, and then move with the winds encountered at each level. Subsequently debris moving almost horizontally at any one level can also change level by various mechanisms, including gravitational settling, turbulent or eddy diffusion, and vertical motion of the air in organized weather systems.

In a cloud formed by an atomic explosion a very wide range of particle sizes would be generated and in the circumstances of the explosions under consideration it is reasonable to assume that a plentiful supply of a wide range of particle sizes was injected into the high troposphere (16 km), sufficient to take all times between hours and months to fall through the air under gravity to the ground. Turbulent or eddy diffusion, like molecular diffusion, acts to transfer matter from volumes of higher average concentrations to volumes of lower average concentrations. The diffusion coefficient which can be used to describe this transport when meteorological effects are included is very much larger than the molecular one, and the horizontal diffusion coefficient is very much larger than the vertical one. Values of latitudinal horizontal eddy diffusion coefficients, K, of about 10^{10} cm²/s seem likely in the free atmosphere in tropical regions, and values of about 10^5 cm/²s are likely for the vertical eddy diffusion coefficient in the troposphere (Bolin[7]). With these values the depth (kilometres) and width (degrees of latitude) of a layer in the atmosphere within which 50 per cent of radioactivity injected at a point would be found after various times is shown in Table I. It must be appreciated that these eddy diffusion coefficients and associated depths and widths are based on long-term average behaviour and so are only coarse estimates for a specific occasion.

TABLE I—DEPTH AND WIDTH OF A LAYER IN THE ATMOSPHERE WITHIN WHICH 50 PER CENT OF RADIOACTIVITY INJECTED AT A POINT WILL BE FOUND, IF THE DIFFUSION COEFFICIENTS ARE ASSUMED TO BE AS SHOWN

Days after injection	DEPTH $K = 10^5$ cm²/s (troposphere) *km*	WIDTH $K = 10^{10}$ cm²/s (tropical troposphere) *degrees latitude*
1	1·8	5
2	2·5	7
4	3·5	10
8	5	14
16	7	20
32	10	28

K = diffusion coefficient   1 degree of latitude ≈ 111 km

Vertical motion arising from organized weather patterns may be upward or downward. Anticyclones are characterized by slowly descending air (subsidence) throughout a large part of the troposphere. The subsidence proceeds at a maximum rate in the early stages of formation of the anticyclone and is greatest in mid-troposphere when values of about 1 km/day may be reached, but they are usually very much less. Cloud and rain are associated with upward vertical air motion and for widespread rain average velocities are usually small, about 5 to 10 cm/s in moderate rain; but in thunderstorms violent upward and downward air motion occurs with speeds of 5–10 m/s or more. Photographs from satellites show that the relevant areas between Mururoa and South Africa and Australia were mostly free of cloud during the period 7–22 July 1968. This indicates an absence of significant upward organized vertical air motion and probably very slow anticyclonic subsidence. Any such slow descent, added to the descent due to gravitational settling through the air of the very wide range of particle sizes assumed, would change the particular particle sizes which would descend from a specific height in a specific time and vary the relative times such particles spent in specific layers of the atmosphere (increasing the time in the high troposphere relative to that in the middle troposphere), but would not affect the assumption that particles would take all times between hours and months to fall from the high troposphere to the ground. Indeed, the absence of cloud suggests that aggregation processes would be operating in unfavourable conditions so that long-time fallout from the very small particles would be prolonged beyond the average.

Discussion. Charts of the 5-year average wind fields during July at 100 mb (16 km), 150 mb (14 km), 200 mb (12 km), 300 mb (9·5 km), 500 mb (5·5 km), and 700 mb (3 km) are available.[2,3] These show Mururoa to be situated near the northern edge of a broad belt of westerly average winds which extend right round the southern hemisphere at all these levels. Streamlines from 22°S 139°W pass across Africa between latitudes 30° and 22°S for all these levels from 100 to 500 mb, and across western Australia between latitudes 18° and 22°S. At 700 mb, streamlines over southern Africa and over Australia are westerly with small perturbations. Some sample average wind speeds (all the average wind directions are from the west) and associated standard vector deviations of wind at the various levels, read from the charts for Mururoa, Pretoria and Aspendale, are given in Table II.

TABLE II—AVERAGE WIND SPEEDS AND ASSOCIATED STANDARD VECTOR DEVIATIONS OF WIND AT STANDARD LEVELS DURING JULY

Level		Mururoa		Pretoria		Aspendale	
		Average	s.v.d.	Average	s.v.d.	Average	s.v.d.
mb	*km*			*knots*			
100	16·5	45	25	40	30	42	25
150	14	60	30	60	37	50	35
200	12	60	33	60	38	50	40
300	9·5	55	33	50	44	38	40
500	5·7	33	24	20	25	25	30
700	3	<10	17	<10	20	10	22

Notes

(i) Values are extracted from *Geophysical Memoirs* Nos 103[2] and 105.[3] Average wind directions are all westerly.

(ii) At 200 and 150 mb average winds to the south of Mururoa increase by up to 20 kt within 2° or 3° of latitude.

(iii) The mean tropopause pressure in the area of Mururoa is close to 100 mb.

(iv) s.v.d. = standard vector deviation.

It is assumed (i) that the settling speeds (including the effects of diffusion) of radioactive particles arriving at the ground at Pretoria were uniform with height and (ii) that the particles commenced their fall from various heights over Mururoa and moved with the average winds for the heights and locations encountered *en route*. It follows that the mean average westerly wind components are 35 kt for the layer 16 to 0 km, 32 kt for the layer 14 to 0 km and less for layers starting at lower levels and finishing at the ground. Values for layers from levels greater than about 18 km to the ground would be less than 35 kt. Values for layers to 3 km above the ground would also be a maximum from a level of about 16 km, for which 43 kt is indicated.

If it is assumed that the filter at Pretoria was placed in position during the morning of the 16th and removed 24 hours later, the elapsed time between the first explosion at Mururoa and the first detection at Pretoria is between $8\frac{1}{2}$ and $9\frac{1}{2}$ days. The maximum mean westerly wind component Mururoa–Pretoria indicated by the radioactive debris transit is thus 45–41 kt, corresponding to travel times of $8\frac{1}{2}$ to $9\frac{1}{2}$ days respectively. Sample values of standard vector deviation of the winds at the standard levels during July are given in Table II. The standard vector deviation of mean wind cannot be inferred directly from the appropriate values along tracks since it depends also on the correlation of wind with height, distance and time. These are not specifically known but, considering the manner in which correlations change with these three factors, it is plausible to assume in the circumstances here that although winds in narrow layers will be highly correlated the correlation will fall off very rapidly with increasing layer thickness (Durst,[8] Kochanski[9]). Assumptions of correlations of 1 over layers 2 km thick and of 0 between such layers suggest a standard vector deviation of mean winds 16–0 km for the track Mururoa–Pretoria of about 10 kt. With the further assumption of a circular normal vector distribution about the average mean wind of 35 kt, a 13 per cent chance of encountering a mean westerly wind component of 43 kt or more is indicated for the 16–0 km layer Mururoa–Pretoria. The value obtained from the radioactive debris transit Mururoa–Pretoria thus readily accords with the average charts and the assumptions made that the debris involved started from the top of the troposphere and fell steadily (in the mean) to the ground. An alternative explanation that the debris fell more slowly in the high troposphere than elsewhere is also possible.

Considerations similar to those discussed above, applied to the track Mururoa–Aspendale, yield an average mean wind 16–0 km of 37 kt, a standard vector deviation of about 10 kt, and probabilities of 18 and 4 per cent that the mean 16–0 km wind exceeds 44 and 51 kt respectively. Radioactivity first appeared at Aspendale upon a filter exposed from 15 to 22 July; this indicated minimum travel times of 7 to 14 days corresponding to mean westerly wind speeds of 88 to 44 kt respectively (51 kt for 12 days' travel). These figures suggest that the radioactive debris first arrived at Aspendale towards the end of the period covered by the filter, began its voyage near the top of the troposphere and fell for the most part steadily to the ground. The departure of the latitude of Aspendale from that of the mean latitude given by the average streamlines is some 18° and appears rather large. However, the concentrations of barium-140 observed at Aspendale are appreciably lower than those observed at Pretoria and the ratio of the two concentrations, appropriate to the times of first detection at the two stations, accords quite well with those to be expected from considerations of eddy diffusion about the average mean tracks 16 km to the ground which were assumed.

Turning attention to the first arrival of debris at Bombay it is convenient to begin by considering back tracks from Bombay using Findlater's average charts below 3 km. These indicate a curving track over Somaliland and thence south and south-eastward to an area east of Madagascar and average mean wind speeds between about 20 and 30 kt, corresponding to travel times to the region of 15°S 60°E of 9 and 6 days respectively. By comparison between the average mean winds 16–0 km and 16–3 km obtained for the track from Mururoa to Pretoria, the mean 16–3 km wind from Mururoa to 60°E is likely to be 5 to 10 kt greater than the mean of 43 kt indicated by the debris travel time from Mururoa to Pretoria. This suggests that the 3-km level around 15°S 60°E probably first became polluted 9 days after the explosion. This pollution gradually falling to lower and lower levels below 3 km would then be likely to follow the track explored above to reach the ground at Bombay some 6 to 9 days later, giving a total minimum travel time to Bombay of 15–18 days. This total is in good agreement with the observed first appearance at Bombay on a filter exposed on 23 July, about $15\frac{1}{2}$ days after the explosion. Whilst there seems little doubt that this route to Bombay is probably close to that actually followed by the debris, it should be noted that the average descent rates used in the two parts of the argument are different, i.e. descent from 16 to 3 km in 9 days (1·4 km/day) and from 3 to 0 km in 6 days (0·5 km/day). This can be qualitatively justified by the assumption of subsiding air in anticyclonic conditions in mid-troposphere, as discussed earlier (p. 166). Debris from the explosion following substantially the suggested route to Bombay and passing on eastward in the lower troposphere would be expected to be largely washed out in the Indian monsoon. Other trans-equatorial flows exist at relatively low levels that would feed debris into the northern hemisphere from the broad belt established around the world in the tropical regions of the southern hemisphere. However, these would not usually be expected to carry air far from the equator before pollutants were washed out by rain associated with these currents. The arrival of debris at stations in the northern hemisphere remote from Bombay indicates that debris was carried across the equator by flows other than the Findlater current during this period. Unfortunately investigation is complicated by the succession of explosions and the broad periods for the times of arrival of the debris at the stations, so that detailed study becomes unprofitable.

Conclusions. The times of first detection of radioactive debris at the ground at Pretoria, Aspendale and Bombay following an atomic explosion at Mururoa on 7 July 1968 accord well with times and tracks inferred from charts of average upper winds over the world for July and their associated standard vector deviations. In particular, rapid interhemispheric interchange in the lower troposphere over the Indian Ocean is in agreement with recent studies by Findlater of the wind fields in that area.

Acknowledgements. The author wishes to thank Dr Peirson of the Atomic Energy Research Establishment, Harwell, who brought the observations to his attention, and Mr R. F. Jones, Meteorological Office, Bracknell, for helpful advice and encouragement.

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AGROMETEOROLOGY IN THE METEOROLOGICAL OFFICE

By G. W. HURST

Summary. A survey is given of the work and organization of the Agricultural Branch of the Meteorological Office over the last five years (1965–69). Reference is made to the scope of research and field experiments undertaken, and also to several co-operative investigations (mostly with the Ministry of Agriculture, Fisheries and Food) into major agricultural and horticultural problems. Some indication is given of future trends.

Introduction. A short account was given some time ago (Hurst[1]) of services which the Agricultural Branch gave to the agricultural community, based on a colloquium on the subject in November 1964. In five years much can happen, and it is perhaps appropriate to review the present situation, particularly in relation to research projects which have been, or are being, conducted.

The Branch still continues to work closely with the Ministry of Agriculture, Fisheries and Food (MAFF) in England and Wales and, in particular, with its National Agricultural Advisory Service (NAAS), which has eight Regional Headquarters including those at Bristol, Cambridge and Leeds at each of which two or three meteorological staff are based. Of the others, Reading is supported from Bracknell, and Aberystwyth, Derby, Newcastle and Wolverhampton at present rely for advice on the meteorological staff at Bristol, Cambridge or Leeds as geographically appropriate; but it is hoped that eventually agrometeorologists will be located at all eight Headquarters. The task of such a meteorologist is to advise the Regional Director, to assist in solving problems raised by his staff, and to consider the application of meteorology to agricultural and allied problems. This type of organization does not obtain in Scotland and Northern Ireland. Inquiries in Scotland are handled by specialists at the agricultural colleges, who, as necessary, consult the agrometeorologists in Edinburgh. Inquiries in Northern Ireland are dealt with by the Meteorological Office, Belfast, with some support from Edinburgh.

Close contact is also maintained, from both Bracknell and outstations, with the various agricultural research organizations — some of which come under MAFF, and some under the Agricultural Research Council (ARC), Forestry Commission, etc. — and, of course, with several university departments of agriculture and horticulture. In this context, a Senior Scientific Officer is seconded to the Grassland Research Institute at Hurley, Berkshire, for a minimum period of two years to assist in problems of meteorology and grass production. It is hoped that this will be the first of a series of secondments of this type, probably for periods longer than two years in order to allow sufficient time for the development and completion of a worthwhile programme. The strength of the Branch numbers under 20 — most of whom own gum boots !

Services. These were mentioned in the earlier review as falling into two classes: routine and non-routine. Little change in routine has taken place, e.g. weekly weather summaries are still prepared and sent to NAAS and other recipients, and warnings are still issued for potato blight and apple scab, though such warnings are increasingly being channelled through NAAS (either Regional Centres or the Pathology Laboratory at Harpenden). Similarly, weather information related to potential severity of liver fluke and other diseases is passed to the Central Veterinary Laboratory at Weybridge. Transpiration figures are issued for irrigation need.

Non-routine services include the answering of queries received either direct from farmers and others or, more frequently, through NAAS and similar channels. Lecture invitations unfortunately have usually to be refused because staff does not exist for the purpose, but certain commitments are accepted, such as the annual lectures to Wisley, or Kew, horticultural students, and the bi-annual symposium for the benefit of the agrometeorological observers course at the Meteorological Office Training School. In 1969, the first Voluntary Service Overseas Briefing Course was held at Reading University and the Branch participated actively in the programme. Again unfortunately is is seldom possible to spare personnel to support agricultural shows but occasionally an exhibition is mounted (see Plate I); in addition to instruments familiar to most meteorologists, this display included a wetness recorder, where dew deposited on the 'toffee apple' polystyrene knob is counterbalanced and a record is made on a barograph type of chart. These instruments are particularly used by apple and potato growers in spring and early summer.

Research over the last five years. The area covered has been very wide and an article of this length cannot cover all aspects. A representative selection is therefore discussed below, with brief indication of what has been done and of future developments, if appropriate. This is perhaps the place to mention that during the last 5 years 10 workers in the Branch published over 80 papers amongst them.

Foot-and-mouth disease. Following the unprecedented scale of development of the disease after the outbreak in October 1967, the Branch was consulted early in 1968 on what meteorological factors might be involved in the spread of the disease. Work was soon completed by one member of the staff on the possibility of spread from the continent; it was shown that the disease could not have so originated in 1967, though almost certainly it had in some earlier years. The main effort concerned the spread of the disease within the country, and two members of the staff worked very closely with a pathologist at the Central Veterinary Laboratory, Weybridge, and found striking relationships between the spread of the foot-and-mouth virus and the wind and rainfall during the incubation period. Thus Figure 1 shows the spread of an earlier outbreak in Hampshire in January 1967; there were seven primary sources and although from 3rd onwards the wind varied widely, the sector in which wind was associated with rain was confined to well under 180°, and subsequent outbreaks were all within this sector. Papers elaborating the results of these researches have been published in several journals.

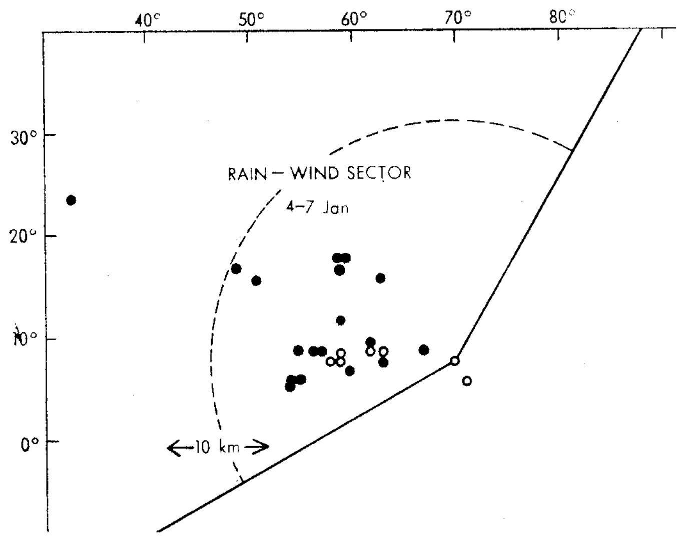


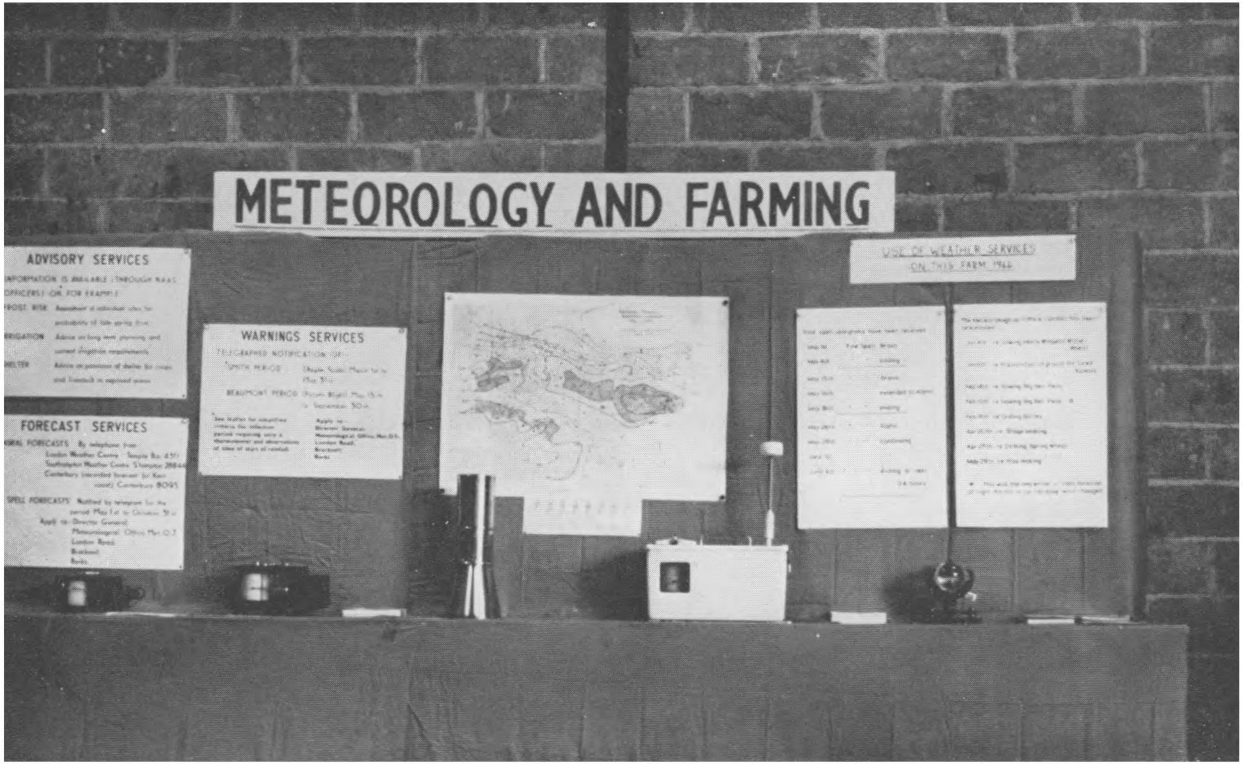
FIGURE 1—SPREAD OF FOOT-AND-MOUTH DISEASE IN HAMPSHIRE IN JANUARY 1967

o Sources • Infections from 8–22 January

Figures on axes are National Grid references, not degrees.

Evidence was given by three Branch members to the Northumberland Committee of Inquiry, an outcome of which has been the creation of a scheme for putting a team (including meteorologists) on the spot without delay in future outbreaks.

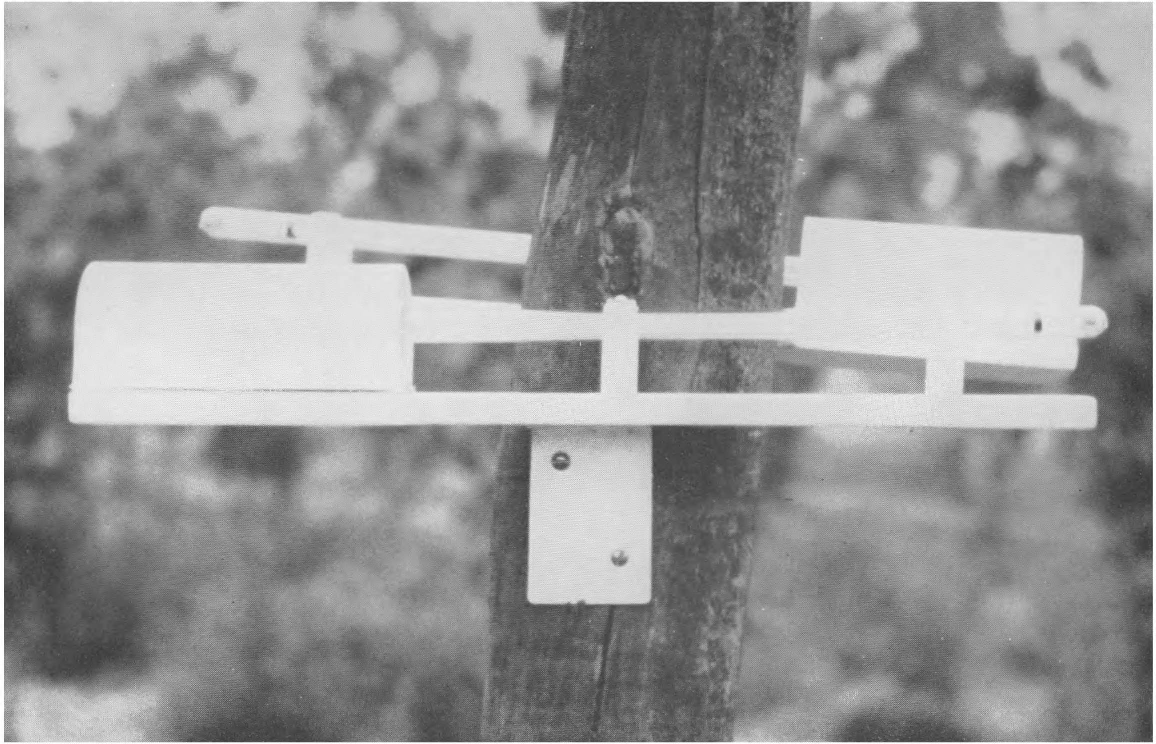
Irrigation and water balance. Two particularly important events have happened; first, the new average transpiration figures were completed for the revised MAFF *Technical Bulletin* No. 16,[2] which was issued in 1967, and second, in 1967 MAFF published an atlas of long-term irrigation needs for England and Wales[3] compiled by a member of the Branch. This atlas indicates the irrigation required over varying periods of the summer half of the year to ensure that various planned soil moisture deficits (SMDs) are not exceeded, considering the needs of the driest year in 20 and also those of the 5th driest year in 20. Figure 2, based on a plate from this atlas, shows the irrigation required in the 5th driest year in 20 to restore the ground to field capacity every time a 2-inch SMD is reached in the 4-month period May to August.



Photograph by J. Cochrane

PLATE I—METEOROLOGY AND FARMING EXHIBITION

The wetness recorder is just right of centre. See page 171.



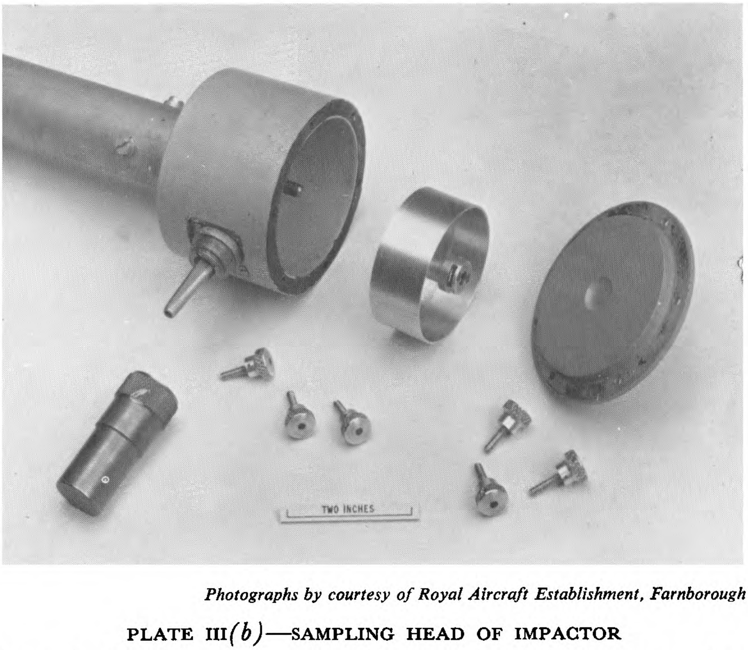
Photograph by J. Cochrane

PLATE II—MAXIMUM AND MINIMUM THERMOMETERS IN TWO COCOA-TIN MOUNTS IN HOP-FIELD TRIALS IN KENT

See page 174.

PLATE III(*a*)—IMPACTOR USED FOR SPORE COLLECTION BY AIRCRAFT

The right half of the instrument projects horizontally out of the aircraft, perpendicular to the side, in free airflow. See page 175.

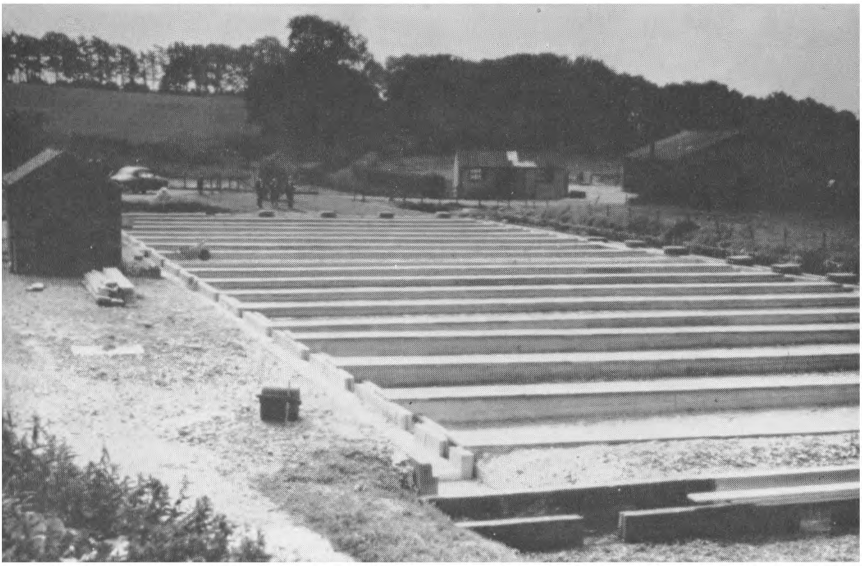


Photographs by courtesy of Royal Aircraft Establishment, Farnborough

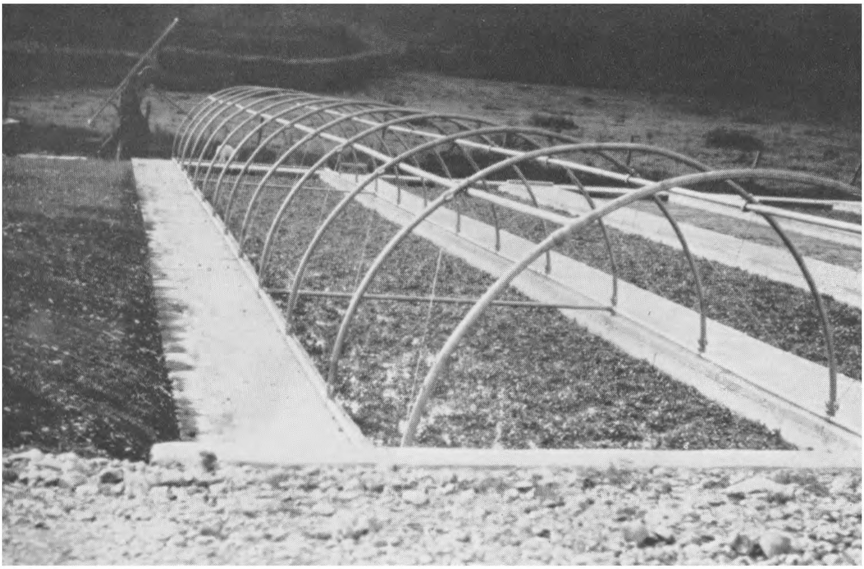
PLATE III(*b*)—SAMPLING HEAD OF IMPACTOR

The orifice on the side of the head is protected by a cover (lower left) before operation. Spores are impacted on sticky transparent tape wrapped round the drum (centre). See page 175.

To face page 173



(a) Whole site of 17 beds.



Photographs by J. Cochrane

(b) Single bed showing framework for polythene cover.

PLATE IV—WATERCRESS BEDS AT FOBDOWN, HAMPSHIRE

See page 176.

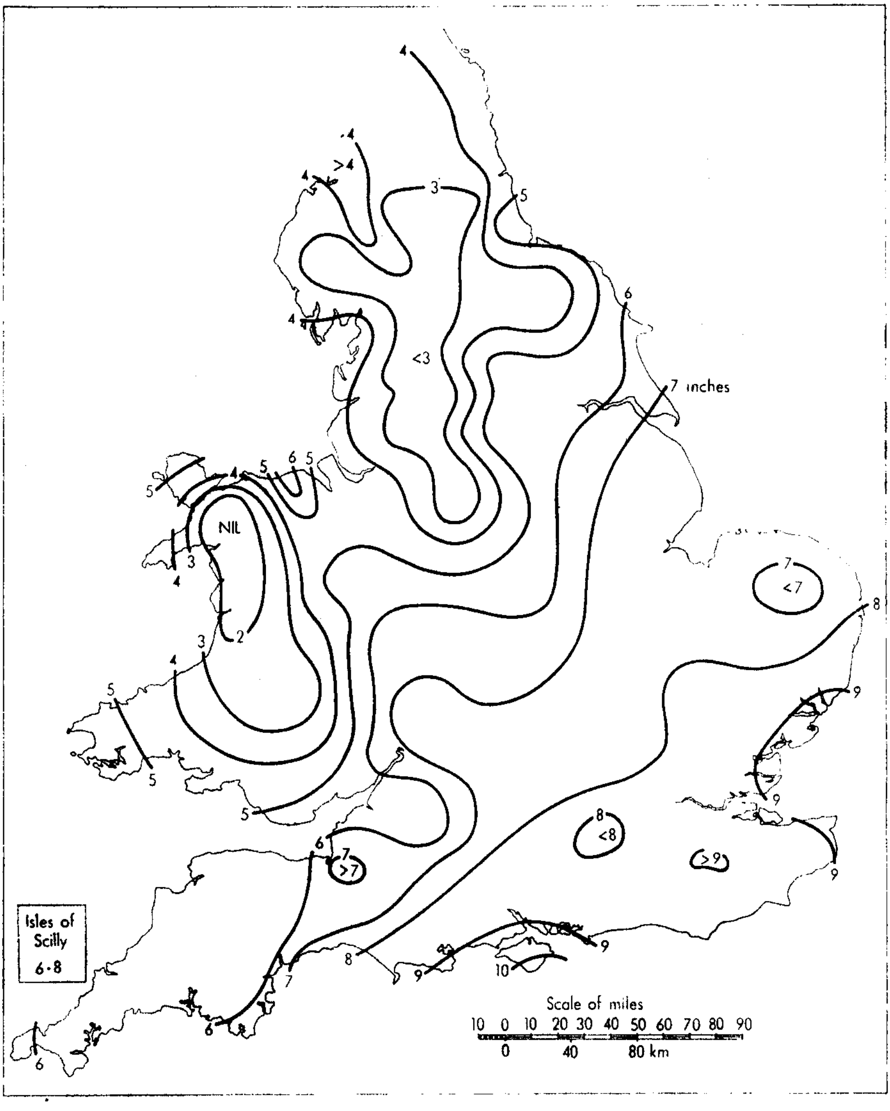


FIGURE 2—IRRIGATION NEED IN 5th DRIEST YEAR IN 20 FOR THE PERIOD MAY TO AUGUST (after Hogg[3])

Shows irrigation required to restore the ground to field capacity whenever a 2-inch soil moisture deficit is reached.

Work continued on rainfall effects on agriculture and included studies, principally through SMD considerations, of excess rainfall in autumn and winter, with consequent leaching and poaching problems, and of return to field capacity in autumn with subsequent flooding, etc.

Work being done on machinery 'work days' is related to water-balance considerations; very broadly the approach is to assess the wet days in spring and the water balance in autumn.

Cropping and meteorological factors. Some work has already been done relating cropping to current and preceding weather and this continues to be an important and active field of research. An approach has been made to consider effective transpiration, defined as the calculated actual transpiration occurring when the SMD is less than 2 inches in the root zone, and in particular the problem of effective transpiration and the growth of grass has been studied. Some work has been done on the harvesting and quality of crops such as hops, wheat and barley; with hop yields for example, the main meteorological variables considered are effective transpiration in spring and early summer and sunshine in late summer and the beginning of autumn. Work is being done relating hop quality to meteorological factors, especially temperature, for a period before harvesting; Plate II shows maximum and minimum thermometers in cocoa tin mounts in hop-field trials in Kent. A study is just starting to help to assess the suitability of the climate in southern England for maize production.

An important application of the research on grass growth has led to good forecasts being made in March and June of the probable milk yields up to the following spring. The most important meteorological factors are the soil temperature excess above 43°F (in March) and the effect of June rainfall on subsequent hay quality — dry weather at this stage goes with good quality hay. Figure 3 shows well the accuracy of the forecast of annual milk yields made at the end of June for the year ending in the following March; a regression equation includes factors for the milk yield in the preceding months April to June, and a term for the June rainfall.

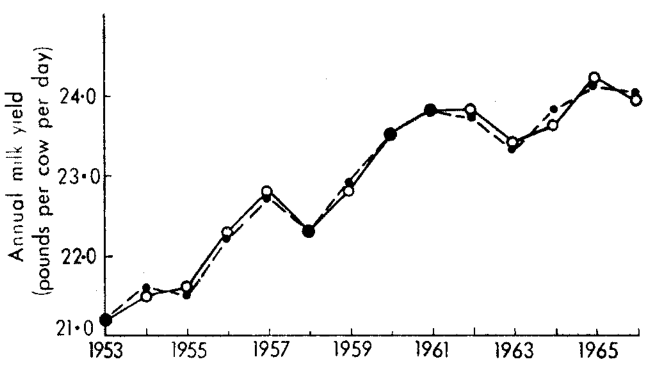


FIGURE 3—FORECASTS OF ANNUAL MILK YIELDS, MADE AT THE END OF JUNE FOR THE YEAR ENDING THE FOLLOWING MARCH

o———o Actual •– – –• Forecast

Mean percentage error 0·31.

Also related to quantity and quality of crops is the study of honey production and meteorology. No short-term forecast technique has been found here as the main weather relation is between high honey yields and hot weather in July (especially) and August, but examination of temperatures over the last century suggests that future prospects for better honey yields are far from rosy.

An approach has also been made to evaluate crop potential by forecasting the level of a particular disease or pest. Thus high February temperatures lead to a high level of yellows virus disease in sugar-beet. Rather similarly, consideration was given to the activity of the shallot aphid, which can be very damaging to strawberry crops; again, high February temperatures are associated with high pest incidence.

Animal diseases. Working closely in conjunction with a very energetic and interested pathologist at the Central Veterinary Laboratory, a member of the Branch has found that the incidence of several diseases of sheep and cattle is closely related to meteorological factors, e.g. liver fluke in sheep to summer rainfall. Examples include pregnancy toxaemia of ewes, the incidence of which was found to be higher in cold wet winters; a numerical relationship with weather was established for this as for the other diseases. Nematodirus of sheep was found to be closely related to the 1-foot earth temperature, and the hatching out of the larvae was related to March temperatures, high temperatures being associated with an early hatch. A useful preliminary forecast was possible in the second half of March. Gastro-enteritis of cattle is associated with late summer or early autumn rainfall and this, with knowledge of the previous year's disease figures, enables a fairly accurate assessment of the following year's disease level to be made.

Other diseases were investigated, such as swayback of ewes and stillbirth in autumn calvers.

Airborne movement. Much has been done in the examination of movements of insects, spores, viruses, pollens, pollutants, etc.; reference has already been made to the movement of foot-and-mouth virus. Many analyses have been made using synoptic charts (usually in collaboration with entomologists from Rothamsted Experimental Station, Harpenden, or elsewhere), for example analyses of particular flights across the Atlantic, and definite patterns of immigration have been established for some species of insects. In this connection, a monthly analysis of trajectories to Great Britain from the continent has been prepared from 1946 onwards using a weather classification approach. Analysis has been made and published of spore trapping over the North Sea and elsewhere by the Meteorological Research Flight in conjunction with Rothamsted. This has shown very interesting patterns of spore and pollen concentrations in relation to the diurnal temperature over the source area (U.K. usually), often with marked maximum counts well away from the English coast; vertical changes were considered in relation to stability and terminal velocities. The impactor trap, as used on a Hastings aircraft of the Meteorological Research Flight, and the sampling head are shown on Plate III. Diffusive processes have also been studied both with the spread of potato blight, fireblight, etc. and (using radioactive tracers) with indoor, controlled movement in animal houses; movement in vegetable stores has also been examined. It has been possible to point out completely wrong design of ventilation systems on at least one occasion.

Field experiments. The Branch has participated in several important field trials and is still doing so. Three of interest are those in Thetford Chase, the orchard trials and the watercress trials. The Thetford experiments were made in conjunction with the Forestry Commission and were concerned with frost damage to young and sensitive Corsican pine saplings. A network of minimum thermometers exposed in 'cocoa tins' was maintained for three years with modifications in the light of experience; results are proving very helpful to the Forestry Commission. The orchard trials were started at the request of NAAS to investigate the weather effects on orchard performance in different parts of southern England and the west Midlands; the experiments were conducted over three years, and preliminary survey of results seems to confirm the meteorologists' expectations that macroscale differences are important, but that mesoscale differences seem to matter much less than factors such as pollination and husbandry. The watercress trials, started late in 1969, also in conjunction with NAAS, are expected to continue for several winters. Seventeen similar parallel concrete beds have been laid down at a cress farm and temperatures are being measured for different water flow rates and for other varying régimes; very interesting results are hoped for, linking varied flow rates, cover and crops with fall of temperature as the (well) water proceeds down the beds. The general layout of the site at Fobdown, Hampshire, is shown in Plates IV *(a)* and *(b)*. Plate IV*(a)* shows the whole site of 17 beds and Plate IV*(b)* shows a single bed with cress growing and a framework for the polythene cover; probes for mercury-in-steel thermographs are located about 2 feet from the ends of several of the beds.

Land use. Work under this heading mostly does not fall under the title of research, apart from certain aspects such as the effect of slope on classification of land grading and the shelter effect of land forms and topographical factors generally. A classification is being done by the Agricultural Land Services with which the Branch co-operates; it is mainly a map exercise with occasional support by field examination. Eventually the whole of England and Wales will be covered, using as the basic map the Ordnance Survey 1 inch to 1 mile.

Work in much more detail is also being done in certain areas for a horticultural survey of land potential.

Miscellaneous. Valuable work continues in various directions, but in a short space, passing mention only can be made of a selection as follows: the relationship of mulching with soil temperatures; the effect of shelter, both natural and artificial; meteorological problems in upland climates, including continued interest in flag tattering as a measure of wind flow. The Branch continues to be represented on the Shelter Research Committee. Important pioneering work is also being done on radiation levels within glasshouses, and a computer programme is being developed for the assessment of glasshouse design and location.

International services. Finally a little must be said of the contribution of the Meteorological Office outside the realms of domestic agriculture and horticulture. Considering first the World Meteorological Organization (WMO) the Branch contribution is distinguished; in addition to providing the President of the Commission for Agricultural Meteorology since 1962 it has provided chairmen for two Working Groups and five rapporteurs on various subjects. Six WMO *Technical Notes* written within the Branch are either already published or well under way.

The Branch has been well represented at conferences. In the five years covered, one or more members have attended at least 12 conferences or meetings overseas and many more in this country, and at most of the conferences, leading papers were presented and sessions and working groups were chaired. Pressure of work and other reasons have necessitated refusal of some quite pressing invitations from abroad.

In 1970, plans are in hand for representation at a symposium on 'Plant Responses to Climatic Factors' in Uppsala (Sweden); it is expected that a three-month visit to Turkey will be made by a member of the Branch in autumn to complete a six-month period of technical assistance in agrometeorology which started in 1967. It is hoped that in November a Branch member will conduct a WMO seminar in Barbados on agrometeorology.

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551.466.3

NOTE ON THE FORECASTS OF WAVE HEIGHT MADE BY THE METEOROLOGICAL OFFICE

By R. F. ZOBEL, O.B.E. and R. DIXON

Summary. The method of forecasting wave heights in the North Atlantic Ocean is discussed and some results presented. The errors obtained are shown to be very similar to those obtained by Pore and Richardson.

Introduction. The Central Forecasting Office (CFO) of the Meteorological Office is designated in World Weather Watch terms, both as the National Meteorological Centre and as a Regional Meteorological Centre. Sea wave analyses and forecasts are required under both headings, firstly in connection with the ships' routeing service provided by the Meteorological Office and secondly as part of the commitments undertaken by a Regional Meteorological Centre. Analyses and forecasts of wave height have therefore been produced twice a day for periods up to 48 hours ahead and broadcast by radio-facsimile since 1 October 1968. An account is given below of the basis of these forecasts and some assessment of the accuracies obtained.

Derivation of working equation. The requirement is to provide analyses and forecasts of the state of sea. This is usually represented by two terms consisting of the wind-formed wave and the swell wave. The former is dependent on the fetch and time for which the wind has been blowing, whilst the latter is related, in a rather complex manner, to events at a distance in the recent past.

Predictions of the height of the wind-formed wave must therefore be based on predictions of wind. Swell forecasts should equally clearly be based on a series of wind analyses.

The wind predictions are made in the Meteorological Office on its KDF 9 computer using an equation derived from data given by Findlater[1] *et alii.*

These data may be used to construct curves showing the relationship between the 900-mb wind and the surface wind for five ranges of instability in the lower layers of the atmosphere. The curves may be converted to curves showing the relationship between 900-mb wind and the wave height in feet by means of an equation due to Scott.[2] The two curves representative of markedly unstable and stable conditions are shown in Figure 1 together with a curve representative of the mean of these conditions. The mean lapse rate is taken to be about 1·8 degC/1000 feet ($\approx$1·8 degC/300 m), and it is further assumed that the 900-mb wind is adequately represented by the geostrophic value obtained from the computer analyses and forecasts for the 1000-mb surface.

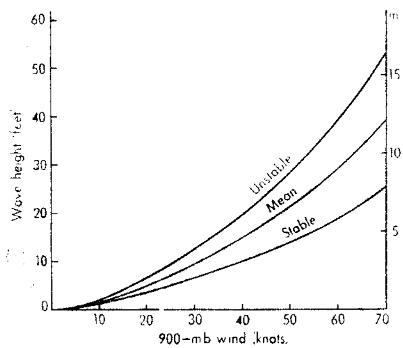

FIGURE 1—RELATIONSHIP BETWEEN 900-mb WIND AND WAVE HEIGHT FOR MARKEDLY UNSTABLE, MARKEDLY STABLE AND MEAN CONDITIONS

The actual equations used are as follows :

$$\frac{V_0}{V_{900}} = 1{\cdot}0055 - 0{\cdot}0101\,V_{900} + 0{\cdot}000075\,V^2_{900}, \qquad \ldots (1)$$

$$H = 0{\cdot}075\ V_0^{3/2} + 5\ , \qquad \ldots (2)$$

where H is the height of the wind-formed significant wave in feet, V_0 is the surface wind and V_{900} is the wind at 900 mb in knots. The significant wave height is defined as the mean height of the biggest one-third of the fully developed waves. Full development is usually considered to occur in fetches in excess of 400 nautical miles.

Combination of equations (1) and (2) leads to the working equation

$$H = 0{\cdot}075\ V_{900}^{3/2}\,(1{\cdot}0055 - 0{\cdot}0101\,V_{900} + 0{\cdot}000075\,V^2_{900})^{3/2} + 5\ . \qquad \ldots (3)$$

The constant 5 in equation (2) merely represents the fact that observations have shown the average height of the swell wave between 50°N and 60°N in the eastern Atlantic to be about 5 feet. This is the only allowance made for swell in the system adopted.

It is of course quite possible to use much more sophisticated techniques for both the wind-formed and the swell wave derivations from the existing and pre-existing wind fields, but the philosophy has been that the accuracy of description, especially when predicted, of the wind field is unlikely to be sufficiently adequate to justify such additional refinements at least for some years. It will appear from the results and discussion below that this philosophy is probably sound.

Findlater *et alii*[1] found that the angle between the 900-mb wind and the surface wind direction averaged about 10°, but on the basis of the philosophy mentioned above it was decided to ignore such a value, so that directions are taken as those of the computed geostrophic wind.

Preparation of wave analyses and forecast charts for issue. The analyses and forecasts received from the computer refer to wave heights which conform to equation (3) and they occur at a regular series of grid points irrespective of fetch and, indeed, irrespective of whether the grid point refers to land or sea. The forecaster has therefore to make subjective adjustments to allow for these features and he also makes such other adjustments as he feels desirable. For example, the analyses have so far been made without any regard to observed wave values, but have been deduced from geostrophic wind values with an extremely coarse adjustment for swell. The forecaster now pays careful attention to the observations, particularly from ocean weather ships, in making his adjustments to the analyses and he also remembers that adjustments may be required to allow for cyclostrophic wind effects and for marked departures in stability from the average condition assumed in developing the working equation. Figures 2–6 show a computer analysis, the forecasts for 24 and 48 hours ahead and the analyses for these times.

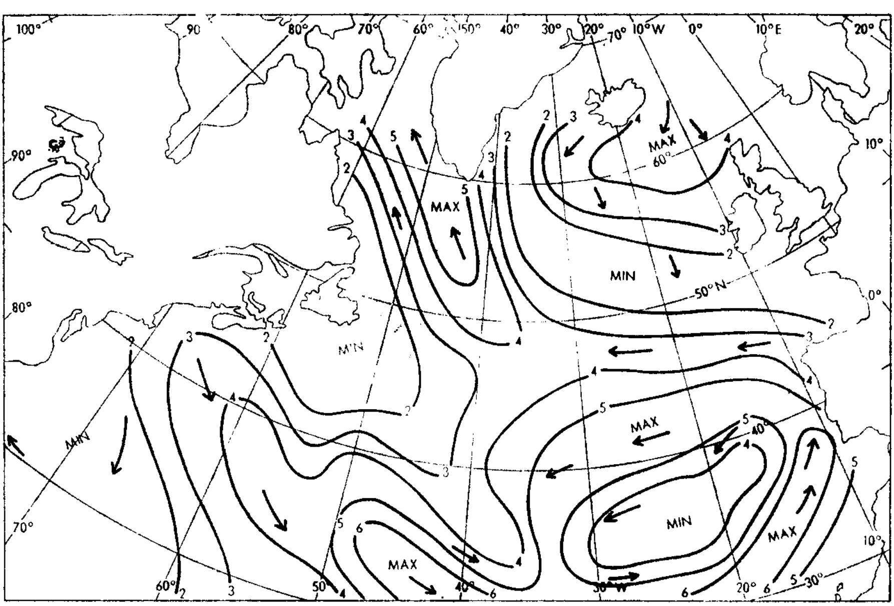

FIGURE 2—COMPUTER WAVE-HEIGHT ANALYSIS, 00 GMT, 3 JANUARY 1970

Wave heights in metres.

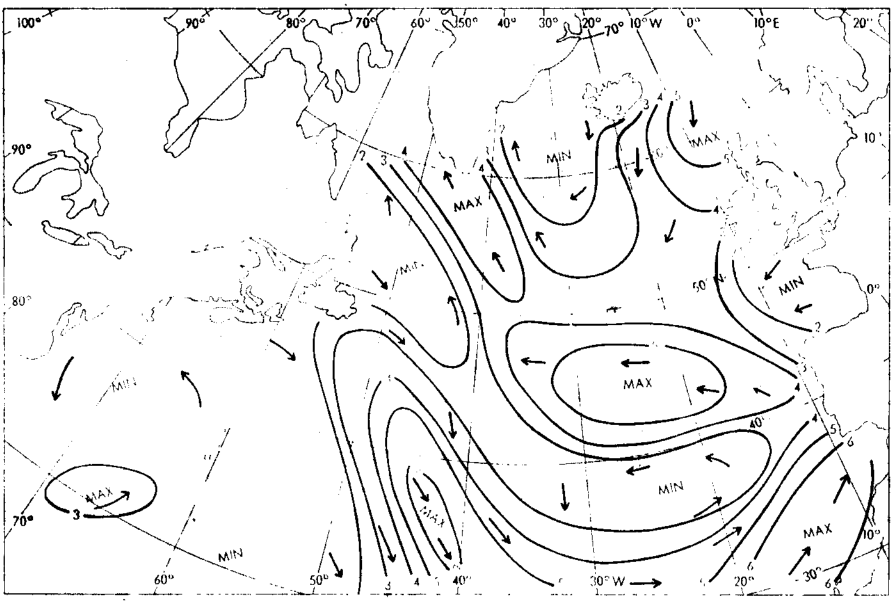

FIGURE 3—24-HOUR FORECAST OF WAVE HEIGHT FOR 00 GMT, 4 JANUARY 1970
Wave heights in metres.

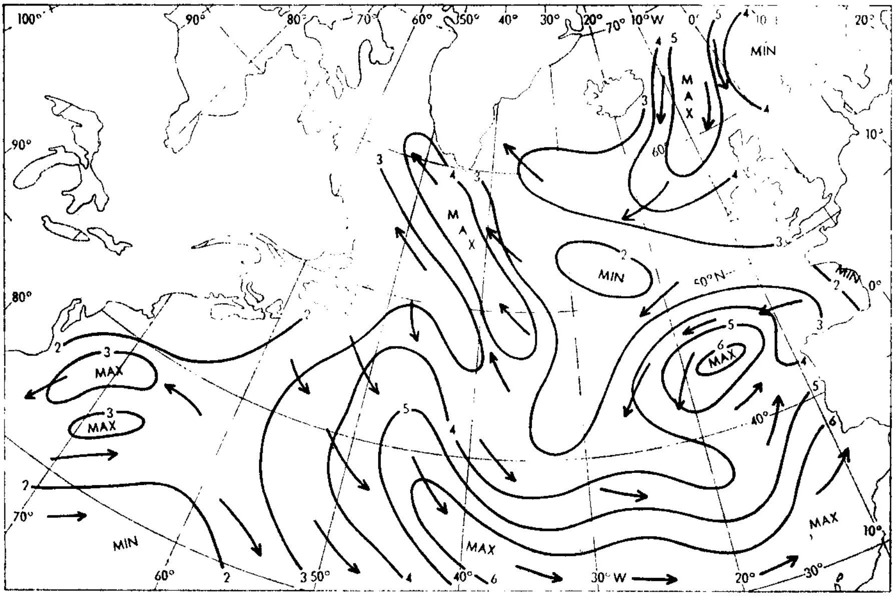

FIGURE 4—COMPUTER WAVE-HEIGHT ANALYSIS, 00 GMT, 4 JANUARY 1970
Wave heights in metres.

FIGURE 5—48-HOUR FORECAST OF WAVE HEIGHT FOR 00 GMT, 5 JANUARY 1970
Wave heights in metres.

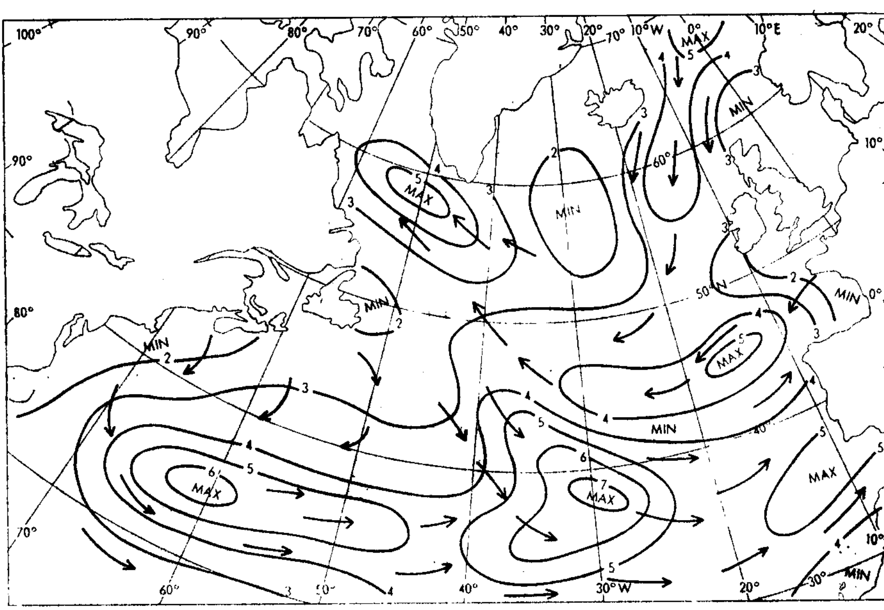

FIGURE 6—COMPUTER WAVE-HEIGHT ANALYSIS, 00 GMT, 5 JANUARY 1970
Wave heights in metres.

Results obtained. Table I shows the monthly mean root-mean-square errors of the twice-daily computed analyses and 24- and 48-hour forecasts, together with the corresponding errors in the charts actually drawn by the forecaster. For comparison, the errors in persistence forecasts at 24 and 48 hours are also given along with the actually observed monthly mean combined sea and swell wave. Unfortunately the 'forecaster's' errors are only available from August 1969, but it is nevertheless clear that the forecaster's analyses are more in conformity with the observations than the computer analyses are. On the other hand, the errors in the hand-analysed charts might be expected to be zero but are not, no doubt because observations of wave height are notoriously difficult to make and discrepancies of the kind noted are inevitable. It is also clear that the forecaster improves the forecasts at both 24 and 48 hours — more at the former than the latter. Both the computer and the forecaster beat persistence quite handsomely.

TABLE I—MONTHLY VALUES OF ERRORS IN WAVE ANALYSES AND FORECASTS FOR OCEAN WEATHER STATIONS I AND J, DECEMBER 1968 – NOVEMBER 1969

Ocean weather station	Month	ROOT-MEAN-SQUARE ERRORS Computer Analysis	Computer Forecast 24-h	Computer Forecast 48-h	Forecaster Analysis	Forecaster Forecast 24-h	Forecaster Forecast 48-h	Persistence 24-h	Persistence 48-h	Mean observed combined sea and swell wave
						feet				*feet*
	December 1968	6·3	7·6	8·4				7·6	7·8	14·5
	January 1969	5·1	5·6	6·5				8·2	9·2	15·6
	February	5·9	6·7	6·6				6·8	9·9	14·5
	March	3·7	3·5	4·2				5·1	5·1	12·3
I	April	4·3	3·3	4·3				4·3	5·5	10·3
59° 00′N	May	3·3	4·0	4·2				5·0	6·2	7·9
19° 00′W	June	4·4	4·6	4·7				4·5	4·4	10·0
	July	5·4	6·6	7·3				7·2	7·8	13·8
	August	3·0	3·7	4·1	1·4	2·8	3·7	4·6	6·9	11·3
	September	4·6	5·3	5·3	1·0	5·0	5·3	7·1	7·3	13·9
	October	5·7	5·1	5·8	1·4	5·1	6·9	8·5	9·5	14·7
	November	4·0	6·2	7·8	0·2	4·3	5·8	7·8	8·6	12·7
	December 1968	5·3	6·0	6·7				7·0	7·7	15·0
	January 1969	7·8	7·8	9·0				8·0	9·6	16·6
	February	6·3	6·5	6·7				7·7	8·9	13·8
	March	4·8	5·0	5·8				6·1	7·3	10·5
	April	3·7	5·4	4·2				5·5	6·3	12·7
J	May	3·7	4·3	4·6				5·3	6·6	9·9
52° 30′N	June	4·1	3·6	4·0				2·8	3·3	6·5
20° 00′W	July	4·4	4·6	5·1				4·9	5·2	7·8
	August	3·5	3·9	4·1	1·8	3·3	3·9	4·5	5·7	9·8
	September	3·3	4·0	4·3	1·2	3·4	3·9	5·4	5·6	9·7
	October	4·5	4·9	5·5	1·2	4·6	5·0	7·3	7·8	13·0
	November	2·2	3·3	3·1	1·0	2·4	3·0	3·7	5·4	14·6

Table II shows the same quantities, but as 12-monthly averages, for the ocean weather stations A – E and I – K. It will be seen that the results are, in general, similar at all stations. The published analyses are much better fits to the observations than those from the computer, the forecaster improves

TABLE II—12-MONTHLY AVERAGE ERRORS IN WAVE ANALYSES AND FORECASTS FOR EIGHT OCEAN WEATHER STATIONS ON THE NORTH ATLANTIC, DECEMBER 1968 – NOVEMBER 1969

Ocean weather station			ROOT-MEAN-SQUARE ERRORS Computer Analysis	Computer Forecast 24-h	Computer Forecast 48-h	Forecaster* Analysis	Forecaster* Forecast 24-h	Forecaster* Forecast 48-h	Persistence 24-h	Persistence 48-h	Mean observed combined sea and swell wave
							feet				*feet*
A	62° 00′N	33° 00′W	4·2	4·5	5·2	1·1	5·3	5·6	6·5	8·0	10·2
B	56° 30′N	51° 00′W	4·1	4·6	5·6	1·2	4·1	5·3	5·3	6·4	8·7
C	52° 45′N	35° 30′W	3·7	4·1	4·9	1·5	4·0	4·6	4·7	5·0	9·0
D	44° 00′N	41° 00′W	4·2	4·5	5·4	1·2	4·4	4·8	5·2	5·7	8·5
E	35° 00′N	48° 00′W	3·8	4·2	4·3	1·2	2·8	3·4	3·7	4·5	7·1
I	59° 00′N	19° 00′W	4·6	5·2	5·8	1·0	4·3	5·4	6·4	7·3	12·6
J	52° 30′N	20° 00′W	4·5	4·5	5·3	1·3	3·4	3·9	5·7	6·6	11·7
K	45° 00′N	16° 00′W	4·1	4·2	4·5	1·2	3·1	3·4	4·3	5·6	9·5

*August–November 1969 inclusive only.

on the computer and both are better than persistence. Station A is however an exception, in that the computer's forecasts are better than the forecaster's. The reason for this is not immediately apparent, though it is noted that average waves at this station are the highest.

It is of interest to compare these results with other published values. The only figures of a similar kind known to the writers are due to Pore and Richardson.[3] Comparisons cannot be strict as Pore and Richardson only give values for May and June 1966 for ocean weather stations A – E, I – J and M in the North Atlantic and N, P and V in the North Pacific. Figure 7

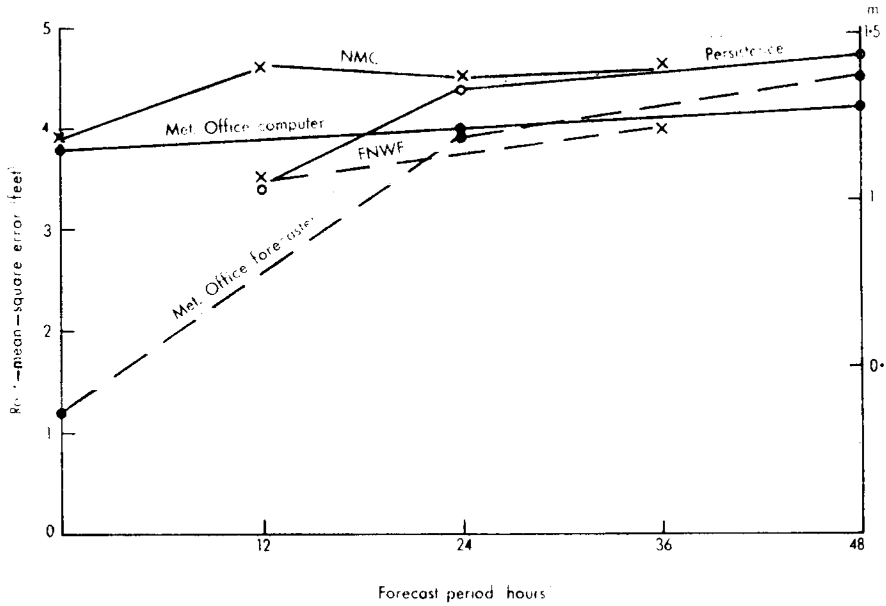

FIGURE 7—ROOT-MEAN-SQUARE ERRORS OF WAVE-HEIGHT ANALYSIS AND FORECASTS IN RELATION TO FORECAST PERIOD

Met. Office computer May–June 1969 Met. Office forecaster 12-month average
NMC (National Meteorological Center, U.S.A.) May–June 1966
FNWF (Fleet Numerical Weather Facility, U.S.A.) May–June 1966
NMC, FNWF and persistence figures are due to Pore and Richardson.[3]

shows their values and on these have been superimposed the Meteorological Office computed results for May and June 1969 together with the forecaster's 12-month average values (Table II). It would appear that the values presented here and by the U.S. authors are very similar and this may indicate that the simple approach to the conversion between forecast wind and wave height is justifiable, since the conversion used in the Meteorological Office is the simplest used by the three institutions concerned.

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551.593.653

NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1969

By J. PATON

Accounts of displays of notilucent clouds (NLC) observed over western Europe during 1969 are contained in Table I. These clouds are normally seen from places between 50°N and 60°N within the period from the end of May to early August (though they may very occasionally be visible outside this period), so included in the table are notes on observing conditions on each night from 31 May to 5 August.

On nights when extensive tropospheric clouds over western Europe prevented the detection of any NLC that may have been present, 'cloudy' is entered in the notes. When the sky at many stations was sufficiently clear to permit the decision that NLC were absent, 'no NLC' is entered.

When NLC were present, the period of duration of reported observations of the display is given in the second column, while the third column contains particulars of the display including forms and brightness. On occasions when it is likely that the cloud field had been observed to be illuminated to its southern border at some time during the night, the approximate latitude of the border is given.[1] In the last four columns are given the maximum elevation above the northern horizon and the limiting azimuths of the visible cloud field recorded at selected stations at stated times during the display.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1969

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
31 May–1 June		No NLC				
1–2 June		No NLC				
2–3		No NLC				
3–4		No NLC				
4–5		No NLC				
5–6	2315–0030	Faint greenish-white bands visible from central Scotland.	56·5°N 3°W	0030	10	305–030
6–7		Cloudy				
7–8	2102–2345	Very weak bands seen from Denmark (Copenhagen) in early part of night. Later one band predominant after 2220 h seen from the British Isles.	55°N 4·5°W	2220	6	360–045
			51°N 0·5°E	2345	8	
8–9		No NLC				
9–10 June	2325–0140	Faint greenish-white veil	56·5°N 3°W	2325	4	360–045
				2345	5	350–050
				0010	6	340–045
				0045	9	330–045
10–11	2230–0045	Faint bands	55·5°N 4·5°W	2345	6	300
				0045	20	030–040
11–12		No NLC				
12–13	2315–0105	Faint cluster of bluish bands.	57·5°N 3·5°W	2315	37	340–360
			57°N 2°W	0100	20	355–005
13–14		Cloudy				
14–15		No NLC				
15–16		No NLC				
16–17		Cloudy				
17–18		Cloudy				
18–19	2345–0145	Veil and bands. Southern boundary about 58°N.	56°N 3°W	0145	15	045
			55·5°N 1·5°W	2345	12	010–030
				0045	14	360–040
				0115	18	
19–20		Cloudy				
20–21		No NLC				
21–22		Cloudy				
22–23		Cloudy				
23–24		Cloudy				
24–25	0001–0220	Small patch of bright bands and billows.	57·5°N 3·5°W	0001	5	350–020
				0130	8	340–360
		Southern boundary about 57°N.	56·5°N 7°W	0050	5	340
			55·5°N 4·5°W	0115	15	360
				0130	15	340–360
				0145	19·5	315–360
			54·5°N 6°W	0220	17	300–020

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths
					degrees	
25–26 June		No NLC seen from British Isles.				
	2330–2345	Faint NLC seen for short period from Denmark (Bornholm).	55°N 15°E	2345	9	360
26–27		No NLC				
27–28	2308–0200	Moderately bright bands and billows with, around 0005 h, small whirls.	57°N 2°W	2345	20	320–360
				0045	25	320–030
			56·5°N 3°W	0005	15	315–035
		Southern boundary about 57°N.		0045	18	330–035
			56°N 3°W	0120	30	320–010
				0130	35	320–010
				0140	40	320–040
			55·5°N 1·5°W	2315	10	340–360
				0050	12	320–010
			54°N 0·5°W	2330	3	340–360
			53·5°N 0°	2308	6	340–350
				2348	4	320–360
28–29		Cloudy				
29–30	2200–2215	NLC seen through low cloud from Denmark.				
	0010–0200	Moderately bright display of bands, billows and whirls seen from British Isles and over the Atlantic.	56·5°N 3°W	0010	19	300–045
				0032	20	345–030
			56°N 30°W (aircraft)	0100	20	
			56°N 15°W (aircraft)	0200	15	
			56°N 12·5°E	2200	10	360–020
				2215	12	360–020
30 June–1 July	0005	Small patch of NLC seen through low cloud.	57·5°N 3·5°W	0005	40	330
1–2 July		Cloudy				
2–3		No NLC				
3–4		No NLC				
4–5	0140–0150	Faint NLC seen low on NNE horizon from Prestwick.	55·5°N 4·5°W			
5–6		No NLC				
6–7		No NLC				
7–8	2310–0150	Faint patches of billows seen through low cloud.	55·5°N 3°W	2345	9	006
				0015	12	010
			55·5°N 45°W (aircraft)	0150	20	045
8–9	2220–2230	NLC seen from Copenhagen.	56°N 12·5°E	2220	8	350–020
	0140–0150	Small bluish-white patch of NLC visible only for short period from British Isles.	55·5°N 3°W	0150	12	350–360
9–10		Cloudy				
10–11	0150	Small patch of NLC seen through low cloud.	57·5°N 3·5°W	0150	10	035
11–12		Cloudy				
12–13		Cloudy over British Isles.				
	2200–2245	Bands seen close to horizon from Denmark (Copenhagen).				
13–14		No NLC seen from British Isles.				
	0058–0120	Greenish parallel bands seen from Copenhagen.				
14–15	2130–0015	Faint bands seen low on horizon at Newton Stewart. Veil and bands seen from Copenhagen.	55°N 4·5°W			
15–16		No NLC				
16–17	2250–0234	Extensive display of faint bluish-white bands and billows.	57·5°N 3·5°W	2320	20	310–045
				0050	15	
			56·5°N 3°E (aircraft)	2300	35	
		Southern boundary about 55°N.	56·5°N 3°W	0001	25	020–030
				0230	110	300–100
17–18	0140–0250	Faint NLC seen low on northern horizon from Prestwick.	55·5°N 4·5°W			
18–19		No NLC				
19–20		Cloudy				
20–21		Cloudy over British Isles.				
	2140–2355	Moderately bright veil and bands seen from Denmark through low cloud.	56°N 10°E	2140	10	045
21–22		Cloudy				
22–23		Cloudy				
23–24		No NLC				
24–25		No NLC				
25–26		Cloudy				
26–27		No NLC				
27–28		Cloudy				
28–29		Cloudy				
29–30		No NLC				
30–31		No NLC				
31 July–1 Aug.		No NLC				
1–2 Aug.		Cloudy				
2–3		No NLC				
3–4		Cloudy				
4–5, 5–6		No NLC				

NLC were observed on 21 nights during 1969. During the previous two summers they were seen on more than 30 nights.[2,3] Only part of this decrease in frequency can be attributed to the greater prevalence of ordinary clouds at night during the summer of 1969. The first display occurred a few days later and the last, on 20–21 July, at least 10 days earlier than in the previous five years. The majority of the displays were faint, only those of 27–28 and 29–30 June and 20–21 July being of moderate brightness. Whirls were seen only during the first two of these three brighter displays.

We are grateful to the many observers whose reports have been used in making this analysis. These synoptic studies are continuing and we invite the co-operation of observers who may be prepared to contribute to them. Notes on observation of NLC appeared in the *Meteorological Magazine,* June 1967, p. 189. An *International noctilucent cloud observation manual* has just been prepared and has been published this year under the auspices of the World Meteorological Organization, Geneva. Observations made in western Europe should be sent to the Balfour Stewart Laboratory, University of Edinburgh, Drummond Street, Edinburgh EH8 9UA, Scotland.

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REVIEW

Frederick C. Fuglister. Sixtieth anniversary volume. Deep-Sea Research, Supplement to Volume 16. 255 mm × 165 mm, pp. v+470, *illus.,* Pergamon Press, Headington Hill Hall, Oxford, 1969. Price: £5 (paper-back).

Thirty-seven papers, mainly on physical oceanography and written with a few exceptions by American 'east coast' oceanographers, are combined in this special volume of *Deep-Sea Research* to celebrate the sixtieth birthday of Frederick Fuglister, the friend and colleague of the contributors and, since his conversion from art to oceanography, a dedicated and successful student of the Gulf Stream. A surprising proportion of the contributions are of interest to meteorologists as well as oceanographers; some are specifically concerned with the atmosphere. Haurwitz and Fogle provide a useful review of 'Wave forms in noctilucent clouds' (though it lacks reference to some recent work on billows); Namias's paper 'Autumnal variations in the North Pacific and North Atlantic anticyclones as manifestations of air–sea interactions' was written too early to benefit from the recent detailed documentation by the Synoptic Climatology Branch; Joanne Simpson's review 'On some aspects of sea–air interaction in middle latitudes' emphasizes the role of convection in connecting the friction layer with synoptic-scale motions. Theoretical treatments primarily directed at explaining the structure and movement of the ocean frequently have a direct relevance to the atmosphere, for the relevant fluid dynamical quantities (the dimensionless numbers named after Rossby, Richardson, Brunt–Väisälä and Reynolds) are similar in the two fluids;

contributions in this category include Faller and Kaylor on 'Oscillatory and transitory Ekman boundary layers' (assumed adiabatic and having either uniform or a quadratic eddy viscosity), and Geisler and Kraus, who treat 'The well-mixed Ekman boundary layer' as a rigid slab and so neglect the turning of the wind with height.

The papers on experimental (or rather, exploratory, since cruises are usually planned with the aim of measuring ocean quantities rather than testing hypotheses) oceanography reflect the present transition from the classical problem of establishing the general circulation and ocean climate, to the growing interest in variability, the oceanographer's equivalent of weather. Of course, there is no simple demarcation between these two aspects of physical oceanography and many papers in this volume contain elements of both. Especially interesting to meteorologists (since the authors tackle phenomena whose atmospheric equivalent has been rather neglected) are the two papers, one by Fofonoff the other by Webster, which examine the fluctuations in current meter records caused by internal waves (although Webster chooses to cover all such variations under the general name 'turbulence'; better, in my opinion, to avoid this confusing definition, which arises from the regrettably pervasive $-5/3$ power law in geophysical spectra).

Taken together, these varied contributions combine to reveal the richness of opportunity offered by physical oceanography, and how profound is our ignorance of the ocean. Worthington illustrates the latter with his admirably honest paper 'An attempt to measure the volume transport of Norwegian Sea overflow water through the Denmark Strait'. This costly experiment, involving a sophisticated array of moored current meters, ended with most of the apparatus strewn in an irrecoverable tangle on the sea floor. Happily, Worthington was able to reconstruct what had happened from the record of one surviving current meter located on the edge of the Strait; apparently the overflow is not a steady weak current but occurs as sporadic torrents of unprecedented strength, one of which destroyed his apparatus.

Meteorologists and oceanographers will both benefit from reading the many excellent papers in this birthday presentation to Frederick Fuglister.

J. WOODS

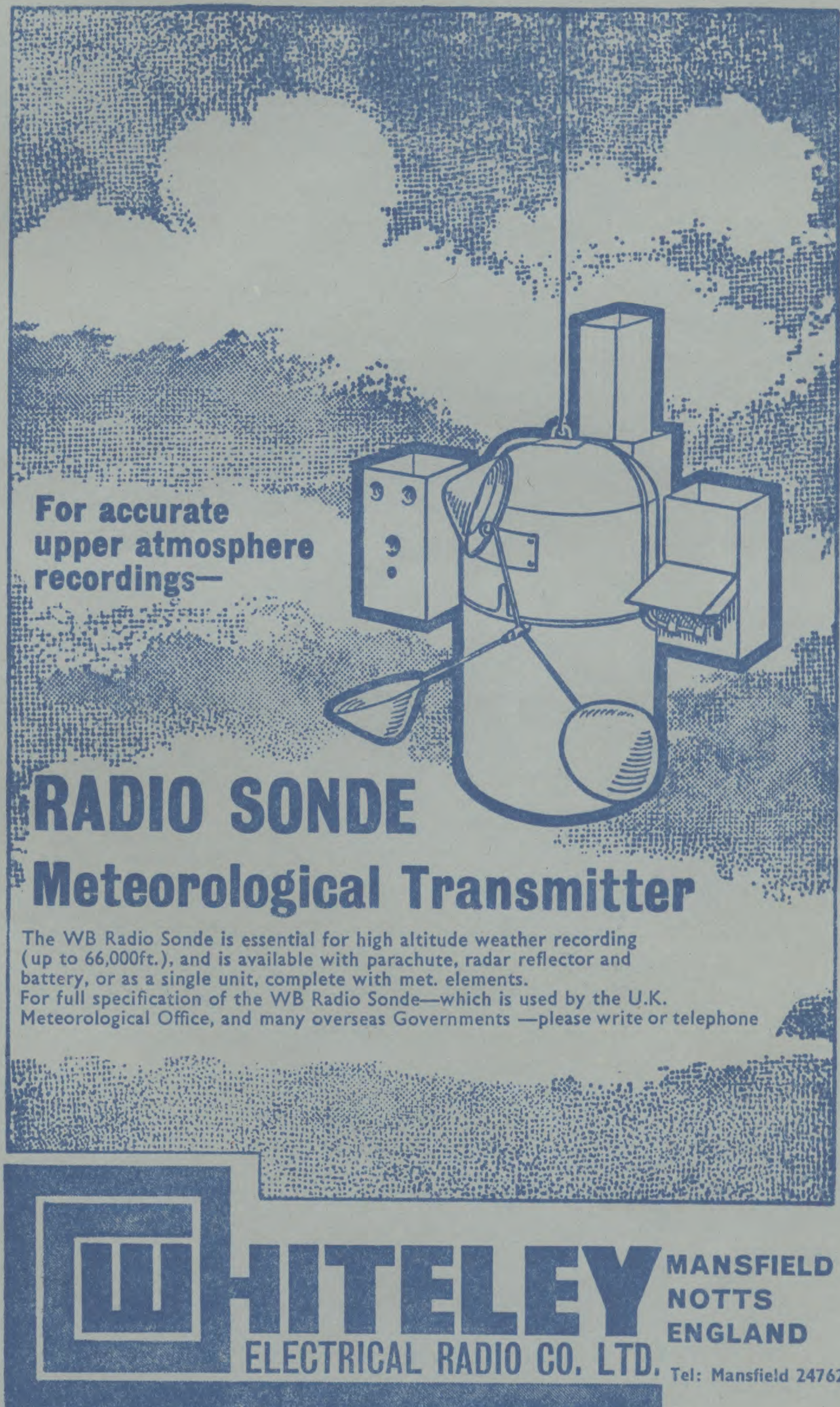
OFFICIAL PUBLICATION

Geophysical Memoirs

No. 112 Average temperatures, contour heights and winds at 50 millibars over the northern hemisphere. By R. A. Ebdon.

This memoir uses data mainly for the period 1957–61 to describe the climatology of that part of the stratosphere near 50 mb (approximately 20·5 km). Charts are included which show average temperatures, contour heights and winds and also the variability of each over the northern hemisphere during the months of January, April, July and October. Similar charts are included for regions north of 45°N for the months of February and March in order to assist in the understanding and interpretation of events leading up to the 'final warming' and the usually rapid breakdown of the winter régime in high latitudes. The very different thermal régimes and the often bimodal character of the temperature distribution in high latitudes in winter are described.

The approximately '26-month oscillation' in tropical stratospheric winds, i.e. the alternation between easterly and westerly régimes, is described. The elliptical nature of the wind distributions at the 50-mb level over much of the hemisphere is discussed.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FURTHER ANALYSIS OF MONTHLY MEAN PRESSURE PATTERNS NEAR THE BRITISH ISLES (1874–1968)

By R. F. M. HAY

Summary. Monthly pressure patterns (1874–1968) in Hay's catalogue have been used to derive monthly and seasonal indices of flow, progression and meridionality (C_m, P_m and S_m indices) over the British Isles. A number of interesting relationships derived from these indices are found between pairs of monthly and seasonal pressure patterns over Britain at lags of up to 6 months and up to 8 seasons, and also between monthly and seasonal pressure patterns and simultaneous and subsequent monthly and seasonal temperature (central England) and rainfall (England and Wales) at lag intervals up to 6 months and up to 8 seasons. Results from the catalogue have also been used to show that significant differences exist between the synoptic patterns of summers in Britain in the odd and even years of the same period.

Introduction. A previous paper[1] analysed relationships between monthly and seasonal pressure patterns and simultaneous and following seasonal temperatures in central England (mainly for winter), using only part of the material included in Hay's catalogue of monthly pressure patterns. In this extension of the work use is made of all of the elements tabulated in the original catalogue to derive a homogeneous set of monthly and seasonal indices of flow (C_m), progression (P_m) and meridionality (S_m) over the British Isles covering the period 1874 to 1968, and corresponding to the C, P and S indices of Murray and Lewis.[2]

Indices of flow (C_m), progression (P_m) and meridionality (S_m). Full details of the information included in Hay's catalogue and of the procedures followed in deriving the indices are available for reference in the Meteorological Office, Bracknell. The following short description of the catalogue may also help in the interpretation of the results included in the remainder of this paper.

Derivation of flow indices (C_m). A flow index was devised which yielded a numerical measure of the cyclonicity or anticyclonicity of the mean pressure pattern near the British Isles for each month in the period. The index was made dependent upon flow curvature, flow pattern, pressure and pressure gradient; a method of scoring was devised which allowed for the effect of each of these elements and which gave consistent and satisfactory results in terms of synoptic patterns. The flow index was readily obtained from the sum of these scores, positive values being related to cyclonicity, negative values to anticyclonicity.

Derivation of indices of progression (P_m) and meridionality (S_m). Procedures broadly similar to those just described were followed to derive indices of progression and meridionality. Positive values of P_m indices were related to westerly flow; positive values of S_m indices were related to southerly flow.

Treatment of the data. The whole of the data (1874–1968) including the monthly and seasonal values of the C_m, P_m and S_m indices, together with ranked values and quintiles of the three indices for the same periods, were obtained by means of a computer programme and are available for reference in the Meteorological Office, Bracknell. For each index the minimum values are in quintile 1 and the maximum in quintile 5.

Monthly and seasonal pressure patterns derived from C_m, P_m and S_m indices. When C_m, P_m and S_m indices for months and seasons had been allocated to their appropriate quintiles, each flow pattern in the vicinity of the British Isles could be described by a group of three digits referring to the quintiles of C_m, P_m and S_m indices respectively. Thus a flow pattern for which the C_m, P_m and S_m quintiles were 5, 5, and 5 respectively, implied that the pressure pattern was strongly cyclonic, strongly westerly and strongly southerly.

This preliminary classification, according to the quintiles of the three indices, gives 125 patterns and these were divided into five sets or types of synoptic patterns as shown in Table I.

TABLE I—ALLOCATIONS OF 3-DIGIT* GROUPS AMONG FIVE TYPES OF SYNOPTIC PATTERN

Pattern type	3-digit groups included in pattern type	Number of 3-digit groups included in each pattern type
Blocked cyclonic (*bC*)	511 to 515, 521 to 525, 531, 535, 541, 545 411 to 415, 421, 422, 424, 425, 431, 435, 441, 445	27
Blocked anticyclonic (*bA*)	111 to 115, 121 to 125, 131, 135, 141, 145 211 to 215, 221, 222, 224, 225, 231, 235, 241, 245	27
Mixed	311 to 315, 321 to 325, 331 to 335, 341 to 345, 351 to 355	25
Progressive cyclonic (*pC*)	551 to 555, 542 to 544, 532 to 534, 451 to 455, 442 to 444, 432 to 434, 423	23
Progressive anticyclonic (*pA*)	251 to 255, 242 to 244, 232 to 234 223 151 to 155, 142 to 144, 132 to 134	23

* The digits represent quintiles of C_m, P_m and S_m indices.

This classification of monthly pressure patterns into five main types was used to derive contingency tables (i) relating monthly and seasonal pressure patterns over Britain with similar patterns at a lag of up to 6 months and up to 8 seasons and (ii) relating monthly and seasonal pressure patterns with simultaneous and subsequent monthly and seasonal temperatures (central England) and rainfall (England and Wales).

No attempt has been made to analyse all the results included in the individual rows (pressure pattern types) contained in the contingency tables, but all associations of possible value for forecasting or likely to be of synoptic interest are shown in Tables II, III and IV.

TABLE II—ASSOCIATIONS BETWEEN PRESSURE PATTERNS (C_m, P_m, S_m INDICES ASSOCIATED WITH C_m, P_m, S_m INDICES)

Lag *months/seasons*	Months/seasons associated	Chi-square	Initial pressure pattern	Pattern of following month/season *number of cases* *bC*	*bA*	Mixed	*pC*	*pA*	Totals
(a)	Monthly relations								
1	No cases								
2	February, April	28·8	*bC*	0	6	3	1	5	15
			bA	4	6	9	4	4	27
			Mixed	5	3	6	3	1	18
			pC	10	4	4	4	2	24
			pA	1	2	0	3	5	11
2*	October, December	26·9	*bA*	4	7	8	5	2	26
			pC	10	1	3	2	7	23
3	No cases								
4	May, September	30·2	*bC*	1	7	2	4	1	15
			bA	8	11	2	4	1	26
			pA	2	1	4	5	1	13
5	March, August	28·4	*bA*	3	9	7	1	3	23
			Mixed	6	2	4	5	1	18
6*	May, November	26·9	*bC*	2	1	8	3	1	15
			bA	7	3	3	8	5	26
			pC	2	9	3	6	4	24
(b)	Seasonal relations								
1, 2, 3 and 4	No cases								
5	Spring, summer (1 year later)	26·2	*bC*	5	0	6	4	1	16
			Mixed	5	5	0	2	4	16
			pC	4	6	5	1	8	24
5	Autumn, winter (1 year later)	27·3	*bC*	5	8	3	3	1	20
			pC	4	10	2	7	3	26
			pA	3	2	8	4	0	17
6, 7, 8	No cases								

* See also Table IV. Bold figures show a large departure from expected values.
In the 5×5 contingency tables from which these data are derived, chi-square values for the significance levels are :

Significance level *per cent*	Chi-square
90	23·5
95	26·3
98	29·6
99	32·0

Pressure patterns

bC blocked cyclonic
bA blocked anticyclonic
Mixed mixed patterns (broadly includes the middle quintiles of C_m, P_m and S_m indices)
pC progressive cyclonic
pA progressive anticyclonic

Lag associations between monthly mean pressure patterns. Associations between monthly mean pressure patterns near the British Isles were found to be significant at the 95 per cent level for each of the following pairs of months (see Table II) :

February and April*	October and December	May and September*
March and August*	May and November	

* See further discussion upon the validity of the results (page 195).

The May–September association is significant at the 98 per cent level.

Other cases of interest and deserving a mention are as follows :

February and June
June and September
October and March

These three associations are all significant at about the 90 per cent level.

Lag associations between seasonal mean pressure patterns. Relations between seasonal pressure patterns with lags of 1 to 8 seasons similarly yielded two associations reaching the 95 per cent significance level, namely spring with summer one year later and autumn with winter one year later.*

Pressure patterns and simultaneous temperatures. An association is found between monthly mean pressure patterns near the British Isles, defined in terms of quintiles of C_m, P_m and S_m indices, and simultaneous monthly mean temperatures over central England, which is statistically significant (at better than 95 per cent level) for each of the months September to March (inclusive). In September, October, January, February and March the relation is significant at better than 99 per cent level. The similar relation between simultaneous seasonal pressure patterns and temperatures is significant at the 95 per cent level in winter and spring and at better than 95 per cent level in summer, but not in autumn (significance below 90 per cent level). A scrutiny of the contingency tables (not included here) shows that the significance of these relations derives mainly from a tendency for progressive cyclonic patterns to be associated with mild months in autumn and early winter, and similarly for blocked patterns (both cyclonic and anticyclonic) to be associated with cold months during the winter half-year.

These results relating pressure patterns and simultaneous temperatures, and those in a later paragraph relating pressure patterns and simultaneous rainfall, broadly confirm the results already found by Murray and Lewis[2] on interrelations between their indices (C, P and S in their notation) and temperature and rainfall on a monthly time-scale.

Pressure patterns and subsequent temperatures. Tests for associations between pressure patterns and monthly temperatures (central England) made with lags from 1 to 6 months showed only one association which reached 95 per cent level of significance, namely that between October and November (1-month lag) (see Table III). Two other cases of possible interest are given in a footnote to Table III; these show the associations between pressure pattern in June and temperature in July, and between pressure pattern in June and temperature in August. In both cases results suggest that there is a tendency for cool summer months to follow progressive cyclonic Junes.

Another relationship between June pressure pattern and subsequent December temperature was significant at almost 95 per cent level, namely that blocked cyclonic and progressive anticyclonic Junes tend to precede very cold and cold Decembers respectively.

Similar tests in respect of seasons with lags between 1 and 8 seasons yielded one association which reached 95 per cent level, namely that between winter

* See further discussion upon the validity of the results (page 195).

TABLE III—ASSOCIATIONS BETWEEN PRESSURE PATTERNS (C_m, P_m, S_m INDICES) AND TEMPERATURES (CENTRAL ENGLAND)

(a) Monthly relations

Lag	Months/seasons associated	Chi-square	Initial pressure pattern	Temperature quintile 1	2	3	4	5	Totals
months				*number of cases*					
1	October, November	27·2	*bC*	1	1	4	5	1	12
			bA	**9**	**2**	**2**	4	**8**	25
			Mixed	1	5	4	3	4	17
			pC	5	4	7	4	2	22
			pA	1	**6**	3	2	1	13
2, 3, 4, 5 and 6	No cases								

(b) Seasonal relations

Lag	Months/seasons associated	Chi-square	Initial pressure pattern	Temperature quintile 1	2	3	4	5	Totals
seasons									
1 and 2	No cases								
3†	Winter, autumn	27·3	Mixed	**0**	1	4	5	**6**	16
			pC	**9**	3	4	2	1	19
4, 5, 6, 7 and 8	No cases								

† See also Table II. Bold figures show a large departure from expected values.

Two further cases of possible interest are shown below :

Lag	Months associated	Chi-square	Initial pressure pattern	Temperature quintile 1	2	3	4	5	Totals
month				*number of cases*					
1	June, July	24·4	*pC*	4	6	5	3	0	18
2	June, August	24·0	*pC*	6	4	3	4	1	18

pressure patterns and the temperature of the following autumn (3-season lag) (Table III). Also 25 progressive cyclonic autumns were followed by 5, 9, 6, 1 and 4 winters respectively in temperature quintiles 1, 2, 3, 4 and 5. This result suggests a tendency for a cold winter (T_2) to follow a progressive cyclonic autumn, in broad agreement with previous work by the author.[3] In this case, however, the significance level was just under 90 per cent.

Pressure patterns and simultaneous rainfall. A relation between pressure patterns and simultaneous monthly and seasonal rainfalls (England and Wales) is significant at better than 99 per cent level in all months and all seasons. In autumn and winter this result arises mainly because a strong association is apparent between progressive cyclonic patterns and wet months and between blocked anticyclonic patterns and dry months; while in spring and summer, blocked cyclonic patterns mostly occur with wet months and progressive anticyclonic patterns with dry months.

Pressure patterns and subsequent rainfall. Several lag associations (Table IV) were found between pressure patterns and monthly rainfall (England and Wales), significant at the 95 per cent level as follows :

1-month lag	No cases*
2-months lag	June with August
	September with November
	October with December
3-months lag	November with February
4-months lag	September with January

* See further discussion upon the validity of the results (page 195).

5-months lag	April with September
	May with October
	August with January
	October with March
6-months lag	May with November
	July with January

A significance level of 99 per cent attaches to the relation between October and March.

An additional case of interest is an association between February pressure pattern and April rainfall (significant at nearly 90 per cent level). For the 15 Februarys in which the pressure pattern was blocked cyclonic, the frequencies of April rainfall in terciles 1, 2 and 3 were 10, 3 and 2 respectively.

TABLE IV—ASSOCIATIONS BETWEEN PRESSURE PATTERNS (C_m, P_m, S_m INDICES) AND RAINFALL (ENGLAND AND WALES)

(*a*) Monthly relations

Lag	Months/seasons associated	Chi-square	Initial pressure pattern	Rainfall tercile 1	Rainfall tercile 2	Rainfall tercile 3	Totals
months				*number of cases*			
1	No cases						
2	June, August	17·2	*pC*	**2**	8	8	18
			pA	**9**	8	**1**	18
2	September, November	18·8	*bA*	**4**	8	**13**	25
			Mixed	**10**	7	**0**	17
			pA	1	3	6	10
2*	October, December	15·5	*bC*	**7**	**0**	5	12
			pC	**3**	**13**	6	22
3	November, February	16·7	*bA*	9	3	9	21
			pC	5	**14**	**3**	22
			pA	5	2	8	15
4	September, January	15·5	*bC*	**7**	4	2	13
			Mixed	**9**	6	**2**	17
			pC	**2**	11	11	24
5	April, September	16·4	*bC*	**1**	9	8	18
			pC	7	7	**1**	15
5	May, October	18·9	*bC*	3	1	**10**	14
			Mixed	**5**	**10**	**1**	16
5	August, January	15·6	Mixed	**2**	7	**9**	18
			pC	8	**10**	**2**	20
5*	October, March	23·2	*bA*	5	8	12	25
			Mixed	4	4	9	17
			pC	**15**	7	**0**	22
6*	May, November	18·8	*bA*	**3**	7	**15**	25
			pC	10	6	6	22
6	July, January	15·7	*bA*	13	4	10	27
			pC	**3**	**12**	6	21

(*b*) Seasonal relations

Lag	Months/seasons associated	Chi-square	Initial pressure pattern	Rainfall tercile 1	Rainfall tercile 2	Rainfall tercile 3	Totals
seasons							
1, 2, 3 and 4	No cases						
5	Spring, summer (1 year later)	16·9	*bC*	3	6	7	16
			Mixed	9	4	2	15
			pC	9	8	4	21
6	Autumn, spring (1 year later)	18·2	*pA*	7	7	3	17

* See also Table II. Bold figures show a large departure from expected values.
In the 5×3 contingency tables from which these data are derived, chi-square values for the significance levels are :

Significance level	Chi-square
per cent	
90	13·4
95	15·5
99	20·1

For seasonal rainfall two associations reached 95 per cent level, namely spring with summer one year later (i.e. 5-seasons lag), and autumn with spring one year later (i.e. 6-months lag). Additionally for the 19 autumns with blocked anticyclonic patterns, the frequencies of winters following with rainfall in terciles 1, 2 and 3 were 11, 4 and 4 respectively (significant at nearly 90 per cent level).

Validity of results. For the lag relations between monthly pressure patterns, 5 pairs of months out of a total of 72 pairs showed an association significant at 95 per cent level or better. Since 72 months were included in the tests, up to 4 months (more exactly 3·6 months) could reach 95 per cent level as a result of chance, and this suggests that some of the relations found are likely to be real.

For the association between pressure pattern and temperature there was one case (almost two cases, since the June–December relation also almost reached 95 per cent level) which was significant at 95 per cent level or better. Application of the argument above suggests that the one (almost two) case observed here could have occurred by chance.

For the relationships of pressure pattern and rainfall there were 11 pairs of months out of a total of 72 pairs for which an association at 95 per cent level, or better, was found. This suggests that some at least of the lag relations found for monthly rainfall here are real.

For seasonal relations the numbers of significant pairs of seasons associated at 95 per cent level were 1, 2 and 2 respectively for pressure pattern with temperature, pressure pattern with rainfall and pressure pattern with pressure pattern, with totals of 32 seasons involved in each case. Since up to two cases (more exactly 1·6 cases) of 95 per cent level of significance could arise by chance, the results for seasonal associations are of doubtful validity.

In the case of the associations between monthly pressure patterns with different lags, listed below, caution may be required in using the results, since for one or occasionally two cells in the contingency tables relating these pairs of months and pairs of seasons, the expected value, E, falls slightly below the figure of 2 quoted by Craddock and Flood[4] as a minimum value for safe application of the chi-square tests. Rather less reliance should be put upon the results for the cases shown below than for the remaining contingency tables where the expected value is above 2 in every one of the cells.

Monthly pressure patterns associated	Number of cells where the expected value $E \leqslant 2$
February and April	1
May and September	2
March and August	2
Autumn and winter (one year later)	1

A point of interest lies in the fact that in all three types of lag associations, the significance level for a lag of 1 month was found to be much lower than for lags of $\geqslant 2$ months. This result applies particularly in the case of the pressure pattern – rainfall relations, and evidently merits further study.

Synoptic patterns in the summers of odd and even years. The synoptic patterns derived from combinations of quintiles of C_m, P_m and S_m

indices have been used here to extend the conclusions of Sutton,[5] Davis,[6] Murray,[7] Poulter,[8] and others, regarding significant differences found by them between summers in Britain during odd years (mostly warmer and drier than average, i.e. good summers) and during even years (mostly cooler and wetter than average, i.e. bad summers). Table V shows how frequencies of synoptic patterns near the British Isles have been distributed between summers in odd and even years.

TABLE V—FREQUENCIES OF SYNOPTIC PATTERNS NEAR THE BRITISH ISLES IN SUMMER (1874–1963)

	SYNOPTIC TYPE					
	Blocked cyclonic	Blocked anticyclonic	Mixed	Progressive cyclonic	Progressive anticyclonic	Totals
Odd years	10	15	9	5	6	45
Even years	8	5	10	12	10	45
Totals	18	20	19	17	16	90

Chi-square = 9·16

A chi-square test applied to this table shows that such an uneven distribution between the frequencies in the different classes could only occur by chance on about one trial in 19 (significance level just below 95 per cent).

Using values of the Poulter index[5,8] for summers in London (Kew) for the period 1880–1965, Davis[6] found the scores for the odd-year summers averaged some 20 points higher than the scores for the even-year summers, and thence showed that this difference was significant at the 1 per cent level. Since the period considered by Davis has all but 8 years in common with the period considered in this paper (1874–1963), it seems reasonable to assume that the excess of good summers in odd years as compared with even years is associated with the excess of blocked anticyclonic types in odd years (as shown in Table V), and similarly that the excess of bad summers in even years occurred mainly in association with a higher frequency of progressive types (especially progressive cyclonic) in the even-year summers as compared with the summers in odd years (but see Table VI).

Support for these assumptions was readily obtained from Poulter's data for London. The 86 summers were divided into two classes which included 43 summers with Poulter indices above the median value and 43 summers with Poulter indices below the median value respectively. After subdividing both these classes into odd- and even-year summers, the incidence of summers in the four classes thus obtained was related to the five synoptic patterns as used in Table V. The resulting contingency table is shown at Table VI.

The value of chi-square = 29·4 in Table VI implies that the differences between frequencies of the odd- and even-year summers with Poulter indices respectively above and below the median value of the Poulter index are significant at the 99·5 per cent level. Large contributions to the high value of chi-square are made by the large differences, in rows 2 and 3 of Table VI, between actual and expected frequencies of blocked anticyclonic and of progressive cyclonic types. This table therefore gives support to the assumption that good summers in odd years are associated with blocked anticyclonic types and that bad summers in even years are associated with progressive cyclonic types.

TABLE VI—FREQUENCIES OF SUMMERS IN LONDON (KEW) RELATED TO THE POULTER INDEX, ODD AND EVEN YEARS AND SYNOPTIC PATTERNS NEAR THE BRITISH ISLES (1880–1965)

		SYNOPTIC TYPE					
Years	Poulter index values	Blocked cyclonic	Blocked anticyclonic	Mixed	Progressive cyclonic	Progressive anticyclonic	Totals
EVEN	>median value	**1** (3·5)*	4 (4·0)	3 (4·2)	4 (4·0)	**7** (3·3)	19
	<median value	**7** (4·5)	**0** (5·0)	7 (5·3)	**8** (5·0)	**2** (4·2)	24
ODD	>median value	**1** (4·5)	**10** (5·0)	6 (5·3)	**3** (5·0)	4 (4·2)	24
	<median value	**7** (3·5)	4 (4·0)	3 (4·2)	3 (4·0)	2 (3·3)	19
		16	18	19	18	15	86

* Expected values are shown in brackets. Values differing by 2 or more from expected are shown in bold. Chi-square = 29·4.

Synoptic patterns in the winters of odd and even years. The work described in respect of odd- and even-year summers was repeated for odd- and even-year winter synoptic patterns near Britain. The result is given in Table VII below. A chi-square test showed that the differences between the frequencies for odd and even years were not significant and could have arisen by chance.

TABLE VII—FREQUENCIES OF SYNOPTIC PATTERNS NEAR THE BRITISH ISLES IN WINTER (1874–1963)

	SYNOPTIC TYPE					
	Blocked cyclonic	Blocked anticyclonic	Mixed	Progressive cyclonic	Progressive anticyclonic	Totals
Odd years	8	11	9	13	4	45
Even years	9	14	7	6	9	45
Totals	17	25	16	19	13	90

Conclusions.

(i) An association is found between monthly mean pressure patterns near the British Isles, defined in terms of quintiles of C_m, P_m and S_m indices, and simultaneous monthly mean temperatures over central England, which is statistically significant (at better than 95 per cent level) for each of the months September to March (inclusive). In five of these months the 99 per cent level is exceeded. The similar relation between simultaneous seasonal pressure patterns and temperatures is significant at the 95 per cent level in winter, spring and summer, but not in autumn.

(ii) A relation between pressure patterns and simultaneous monthly and seasonal rainfalls (England and Wales) is significant at better than 99 per cent level in all months and all seasons.

(iii) Associations were found between monthly mean pressure patterns near the British Isles for each of the following pairs of months : February and April, October and December, May and September, March and August, and May and November.

However, in view of the large number of associations tested (72), the significance of these apparent associations is doubtful.

(iv) Eleven lag associations were found between pressure patterns and monthly rainfall (England and Wales), significant at the 95 per cent level as follows :

1-month lag	No cases
2-months lag	June with August, September with November, October with December
3-months lag	November with February
4-months lag	September with January
5-months lag	April with September, May with October, August with January, October with March
6-months lag	May with November, July with January

By chance about 4 relationships would be expected to arise so that some at least of these apparent associations are likely to be real.

(v) In summer, blocked anticyclonic patterns near Britain have been found to occur in odd years more frequently than would be expected by chance, while progressive cyclonic patterns occurred in even years more frequently than would be expected by chance. This result agrees with work by Sutton, Davis, Murray, Poulter, and others, on significant differences between summers in odd and even years of the past 90 years.

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551.507.352:551.508.74:551.578.11

SAMPLING OF RAIN FROM A VARSITY AIRCRAFT

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Summary. Flights have been made in rain by the Varsity aircraft of the Meteorological Research Flight to determine the liquid water content field in the air above the top surface of the aircraft. The results have shown that the use of droplet sampling instruments is certainly unreliable within 120 cm of the surface because of splashing and concentration effects in the water-droplet field.

Introduction. The Meteorological Research Flight (MRF) has in the past sampled cloud and precipitation particles from the Varsity aircraft, and from the data obtained concentrations of water droplets, ice crystals and liquid water content were calculated (Singleton and Smith,[1] Cornford[2]). The instruments used to sample the drops and their efficiency in doing so have been discussed in detail elsewhere (Garrod[3]). However, no matter how efficient an instrument is in sampling droplets in flight, unless it is situated in a position where the droplets are representative of the free airstream, the results obtained will always be suspect.

Singleton and Smith[1] estimated the error in the droplet concentrations at the sampling position on the Varsity aircraft by applying the results of Dorsch and Brun's[4] mathematical investigation into the path of water droplets flowing around an ellipsoid of revolution. They concluded that there was a concentration effect for drops greater than 100-μm diameter, but stated that Dorsch and Brun's results were not entirely applicable because of the sharp discontinuity in the aircraft's profile.

This present note describes an instrument designed to measure water contents at positions spanning the original sampling position, in an attempt to estimate quantitatively the error in measuring the liquid water content of clouds from this position on the Varsity aircraft.

The water-droplet field near an aircraft. The air rises ahead of an aircraft (upwash) and sinks behind (downwash), and the streamlines are considerably distorted in the vicinity of the aircraft. The passage of air through propellers further complicates the flow. For turbulence investigations involving measurement of airflow angle, it is essential to have the instruments mounted as far forward as possible so that they are in a region where the flow distortion is small. When an aircraft enters a cloud, the local flow field deviates the individual drops or ice crystals by an amount dependent on their inertia. It has been found that near an aircraft's skin there can be regions where no droplets occur (shadow zones), while concentrations of droplets can occur at other locations (concentration zones). These effects have been noted in practice on struts of aircraft which have flown in supercooled cloud (Figure 1). Dorsch and Brun[4] have shown that concentration factors of 2 or 3 can occur, and that each droplet size has its own concentration factor at a given position.

Although Dorsch and Brun's work can be qualitatively applied to aircraft which approximate in shape to an ellipsoid of revolution, because of the huge computational effort necessary they could not take into account the effect of wings, bulges on the fuselage, engines, etc., all of which influence the airflow and hence the droplet field near an actual aircraft. In practice, the only way

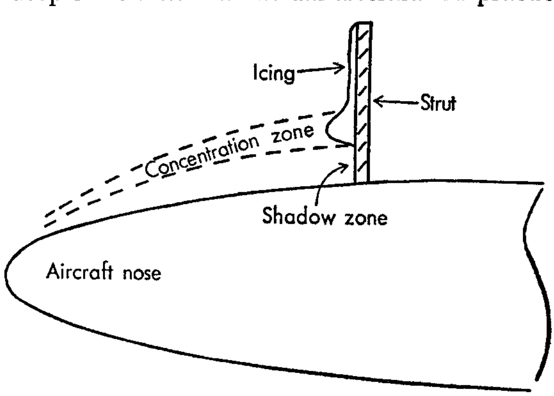


FIGURE 1—VARIATION IN LIQUID WATER CONTENT AROUND AIRCRAFT SHOWN BY THE THICKENING OF ICING ON STRUT

to find if there are concentration effects at a chosen sampling position is to measure the drop size distribution or liquid water content at various positions spanning the sampling position and determine whether gradients occur in these quantities at the sampling position. If they do occur, then the conclusion must be that the sampling position is not located in a region representative of the free stream conditions. An estimate must then be made of the magnitude of the error involved, and this usually necessitates the free stream values being measured simultaneously.

The sampling position. The location of the sampling position originally in use, and now under discussion, is 6 m from the nose of the aircraft and 45 cm above the top surface on the centre line (see Figure 2). Instruments, such as the aluminium-foil impactor, are held there by a long 38-mm diameter tube which is rigidly attached to a vertical structure inside the aircraft.

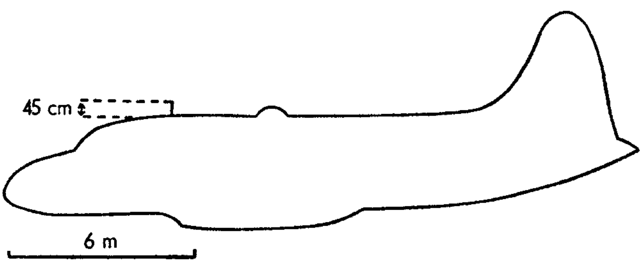


FIGURE 2—ORIGINAL SAMPLING POSITION ON AIRCRAFT

Indicated airspeed measurements have been made in this position out to 1·5 m from the skin. They are shown in Figure 3 for the pilot's indicated airspeed (IAS) of 110 kt (1 kt≈0·5 m/s). The air has accelerated over the top of the aircraft and its speed is still 10–15 kt higher than the pilot's IAS

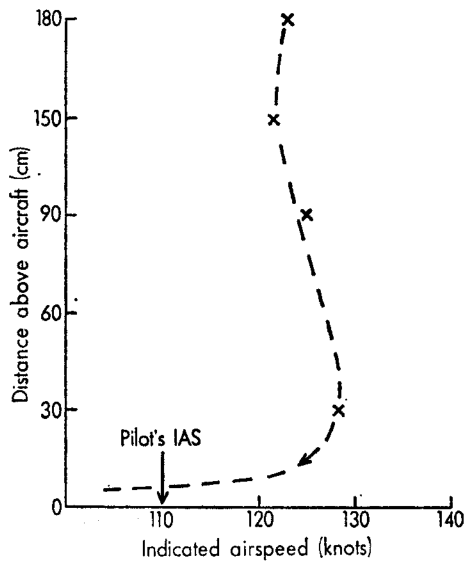
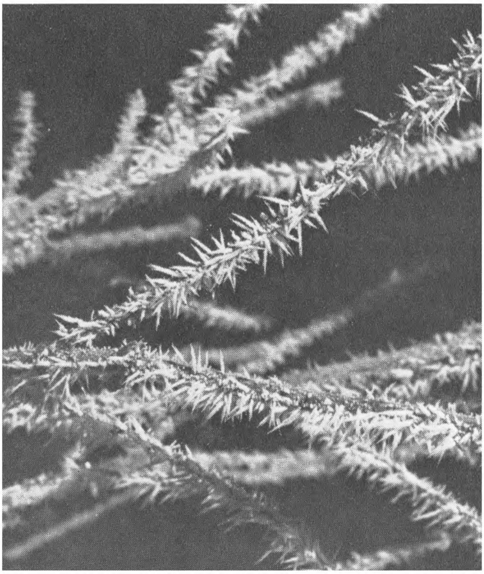
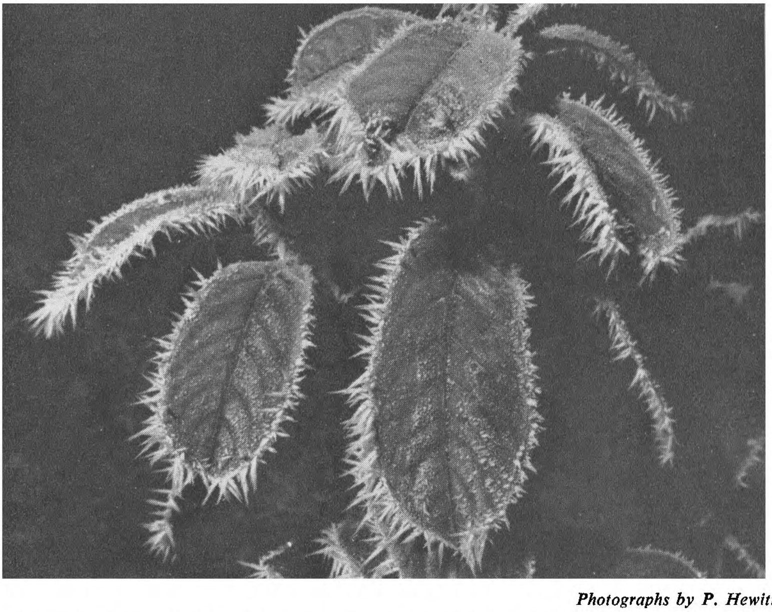


FIGURE 3—INDICATED AIRSPEED VARIATIONS ABOVE VARSITY AIRCRAFT



(a) Ice accretion on young lilac tree which was about 15 ft from an 8-ft gap between two houses, down which the wind had been funnelling all night. The longest needle was slightly less than 1 inch. There was no appreciable ice at 2100 GMT the previous evening so the total accretion had occurred in a maximum period of about 9 hours.



Photographs by P. Hewitt

(b) Ice accretion on laurel bush a further 10 ft away from the gap described in *(a)* above.

PLATE I—ICE ACCRETION AT PRINCES RISBOROUGH ON THE MORNING OF 5 JANUARY 1970

The photographs were taken at 0615 GMT. The visibility was about 1000 m with 8/8 stratus at 100 ft and a light northerly drift. Freezing fog which had formed the previous evening had lifted into stratus at about 0545 GMT. Minimum air temperature recorded during the night at HQ Strike Command (about 3 miles away and 400 ft higher) was – 5·2°C.

To face page 201

Photograph by courtesy of Royal Aircraft Establishment, Farnborough

PLATE II—VARSITY AIRCRAFT OF THE METEOROLOGICAL RESEARCH FLIGHT SHOWING THE WATER CATCHER MOUNTED IN THE INBOARD POSITION

See page 201.

even at 1·5 m from the skin. The differences between drop size distributions measured above the aircraft and the free stream distributions cannot be calculated from a knowledge of the airspeed profile alone; such differences can only be found by actual sampling.

The most complete way of sampling would have been to make simultaneous measurements of drop size distributions at several positions above the aircraft, but the complex instrument required for this would have involved a prohibitive time in design work and manufacture. It was therefore decided to measure the liquid water field above the aircraft, which instrumentally was far easier.

Design of water catcher. The final design of the water catcher was a compromise between what was meteorologically desirable and what was structurally possible. Ideally, simultaneous sampling every 15 cm out to some 3 m would have been desirable, but the final structure would have been aerodynamically unsafe, as the instrument was required to be mounted on the available structure inside the aircraft. Six sampling positions at 15-cm intervals were included in the final design, which meant that the outermost sampler was at 90 cm from the skin. However, the whole boom could be pushed out 30 extra centimetres, taking the outermost sampler to 120 cm from the skin, and the inner one to 45 cm (Figure 4*(b)*). The boom was made from a 63-mm diameter steel tube reducing to a 50-mm diameter tube inside the aircraft, where it was attached to the vertical structure.

The samplers, or water catchers, were 25-mm diameter recessed traps made of glass fibre and they extended forward about 50 mm from the boom (Figure 4*(a)*).

The samplers themselves affect the local airflow and hence the drop size distribution. If they are too large the distorted airflow patterns from each sampler will mutually interfere and reduce the samplers' collection efficiency; if the sampler is too small a very long exposure time is required. A 25-mm diameter sampler was considered small enough for the turbulence effects between samplers to be small, but large enough to ensure a short exposure time; it was also structurally safe. The samplers were in the shape of a recessed trap, which Golovin and Putman[5] have shown to be a most effective collector of airborne particles. Theoretically, such traps have a collection coefficient of about 80 per cent for 20-μm diameter droplets at an airspeed of 70 m/s. Wind-tunnel tests showed that the air inside the trap was relatively stagnant and that there was little tendency for air currents to force water back out of the traps. The collected water trickled down 6-mm diameter polythene pipes into collecting bottles in the aircraft. The bottles could be removed easily and the water emptied into a measuring cylinder. The bottles were not completely airtight, and the consequent small airflow down the pipes helped the downward flow of water but was not sufficient to cause appreciable evaporation in the bottles. The instrument mounted on the Varsity is shown in Plate II.

The collection efficiency of recessed traps is proportional to airspeed. However, no correction was made to the collected amounts of water for this effect as the airspeeds at the sampling positions were within 5 per cent of the mean. About 1–2 cm^3 of water remained in each tube in the form of small drops adhering to the walls. This gave an upper estimate of the error in measuring the amounts of water caught, although this would be mainly apparent in the first sample of each flight when the tubes were initially dry. On some samples, noted in Table I, too little water was collected to be of value and these samples were not analysed. The error in measuring the amount of water caught is estimated at between 5 and 10 per cent of the total, depending on the amount of water caught.

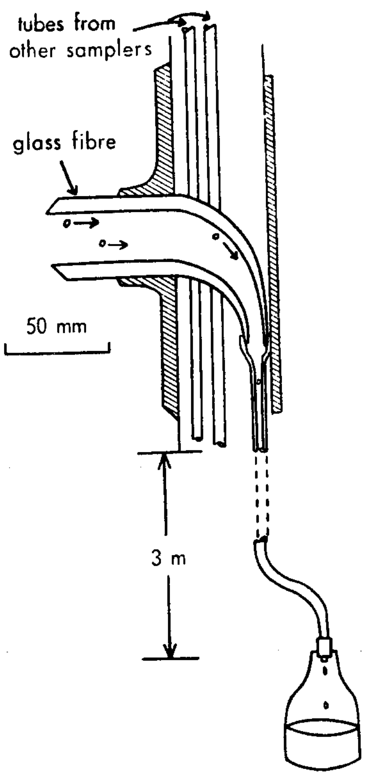


FIGURE 4(*a*)—INDIVIDUAL WATER CATCHER

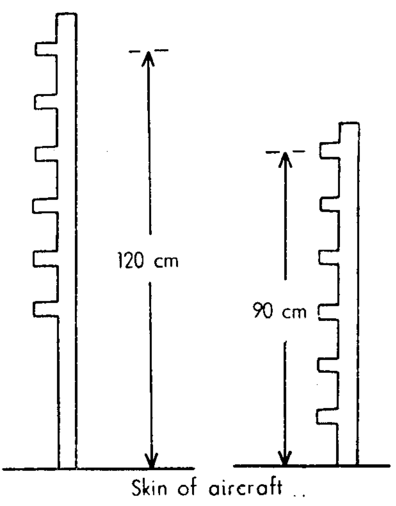


FIGURE 4(*b*)—OUTBOARD AND INBOARD SAMPLING POSITIONS OF WATER CATCHER

Flight technique. Flights were made over southern England on rainy days. During each sampling period the aircraft flew at a constant true air-speed in the range 120 to 180 kt. Sampling continued until about 30 cm^3 had been collected in each of the bottles, and the time to reach this figure was noted. The sampling time varied from 10 minutes to over an hour depending on the rainfall intensity. On each flight the object was to take as many samples as possible over the full speed-range, but on occasions few samples were obtained because the rain ceased, or the rain area drifted into controlled airspace.

Results. Table I presents the complete results of the eight flights made. For four of the flights the catcher was mounted in the 'inboard' position and there were 13 sampling periods; for the other four flights, the catcher was mounted 'outboard' and 18 sampling periods were obtained. The column *V* indicates the actual volume of water caught at each level, and under column *R* is recorded the ratio of the amount caught at that level to that caught at the 90-cm level. Ninety centimetres was chosen as a reference level because it was the farthest common sampling position from the skin for both the inboard and outboard positions. It was expected that there would be less variability in the amounts caught at 90 cm than at the inboard common sampling positions.

From Table I it can be seen that at any one level there is considerable variability in the relative amounts of water caught, the greatest variability being near the skin of the aircraft. The mean profile, Figure 5, does show that there is considerably more water near the skin and that the water content increases by 5 per cent between 90 and 120 cm. The high water content near the skin is probably due to splashing off the top of the aircraft. The increase above 90 cm can be attributed to either a concentration zone at or beyond 120 cm, or to a partial shadow zone at about 90 cm. It is not possible to say which is true, or if both are, as the free stream values are not known.

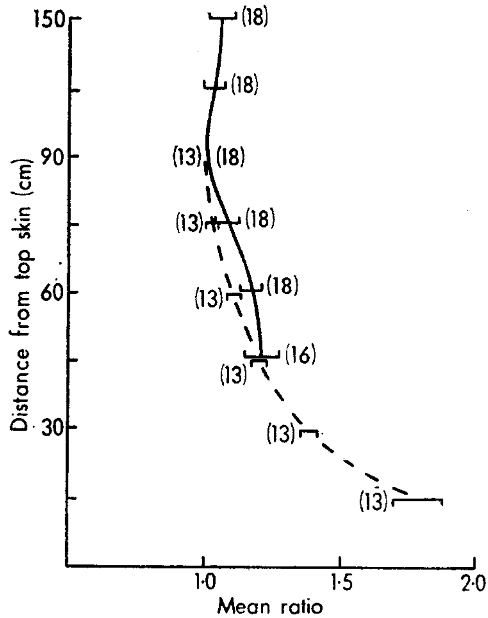


FIGURE 5—MEAN RATIO OF WATER CAUGHT AT GIVEN DISTANCE TO THAT CAUGHT AT THE 90-cm DISTANCE, WITH STANDARD DEVIATIONS
Number of samples is given in brackets.

Figure 6 shows the mean profiles for the inboard and outboard positions and they show the same general trend.

An analysis was made to see if there was a speed or 'rain intensity' effect. Rain intensity was defined as the amount of water caught at 90 cm divided by the sampling time. This was in no way an accurate determination of the

TABLE I—SUMMARY OF THE EIGHT WATER-CATCHING FLIGHTS

Distance above aircraft	16 June 1969		17 June 1969 Sample 1		17 June 1969 Sample 2		17 June 1969 Sample 3		17 June 1969 Sample 4		23 June 1969 Sample 1		23 June 1969 Sample 2	
cm	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*
90	15½	1	24	1	20½	1	19	1	35	1	17	1	10½	1
75	16½	1·06	25	1·04	20	0·97	19	1·00	38	1·08	19	1·12	10½	1·00
60	18	1·16	26½	1·10	20½	1·00	20½	1·08	34	0·97	18	1·06	10½	1·00
45	19½	1·26	30	1·25	25	1·22	22½	1·18	41½	1·18	22½	1·32	12½	1·18
30	23½	1·52	35	1·46	28½	1·39	28	1·47	45	1·29	25	1·47	14½	1·38
15	32	2·03	39	1·62	34	1·66	30	1·58	51	1·46	37	2·18	20½	1·95
True airspeed (kt)	140		120		120		140		180		140		120	
Sample period (min)	100		40		25		30		45		45		25	
Rain intensity (cm³/min)	0·16		0·60		0·82		0·63		0·78		0·38		0·42	

Distance above aircraft	28 August 1969 Sample 1		28 August 1969 Sample 1		28 August 1969 Sample 3		10 September 1969 Sample 1		10 September 1969 Sample 2		10 September 1969 Sample 3		10 September 1969 Sample 4		10 September 1969 Sample 5		10 September 1969 Sample 6	
cm	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*
120	16	1·06	13½	1·08	1·0		17½	1·25	16	1·14	13½	1·65	17½	1·25	13½	0·96	15½	1·15
105	15	1·04	13	1·04	1·0		18	1·28	16	1·14	11½	1·43	16	1·14	14	1·00	14½	1·07
90	16	1	12½	1	1·0		14	1	14	1	8	1	14	1	14	1	13½	1
75	17	1·04	13	1·06	1·0		18½	1·32	15	1·07	11½	1·43	14½	1·04	15	1·07	16	1·16
60	18	1·28	16	1·12	1·0		21	1·50	15½	1·10	6½	0·81	20½	1·46	16	1·14	18	1·33
45	Nil	(Leak)	Nil	(Leak)			19	1·35	18½	1·32	14½	1·81	19½	1·39	16	1·07	18	1·33
True airspeed (kt)	150		180		Not		150		120		120		150		110		180	
Sample period (min)	45		65		analysed		60		30		30		20		35		30	
Rain intensity (cm³/min)	0·36		0·19				0·23		0·46		0·27		0·70		0·40		0·45	

V = amount of water in cm³. R = ratio of amount caught to amount caught at 90-cm level.

TABLE I—*continued*

Distance above aircraft	11 September 1969 (a.m.) Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		Sample 7		Sample 8	
cm	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*
120	8	1·00	6	0·75	12½	1·00	7½	1·07	10½	1·17	13	1·08	7½	1·07	1½	–
105	8½	1·06	7	0·88	12	0·96	7	1·00	8	0·94	11½	0·96	6	0·86	1	–
90	8	1	8	1	12½	1	7	1	9	1	12	1	7	1	1	–
75	9½	1·18	7½	0·94	13½	1·08	8	1·14	11½	1·28	10½	0·88	8	1·14	1½	–
60	10	1·25	8½	1·06	15	1·20	8	1·14	9½	1·05	14	1·17	6½	0·93	1½	–
45	10½	1·32	8½	1·06	16	1·28	8½	1·21	8	0·89	13	1·08	6	0·86	1½	–
30															Not analysed	
15																
True airspeed (kt)	150		180		120		120		150		180		180		150	
Sample period (min)	15		20		15		15		20		20		15		20	
Rain intensity (cm³/min)	0·53		0·40		0·83		0·47		0·45		0·60		0·47		–	

Distance above aircraft	11 September 1969 (p.m.) Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		12 September 1969 Sample 1		Sample 2		Sample 3	
cm	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*	*V*	*R*
120													10½	0·64	16	0·91	16	1·00
105													12	0·73	17½	1·00	17½	1·09
90	14	1	6½	1	17	1	13	1	15½	1	8½	1	16½	1	17½	1	16	1
75	14	1·00	6	0·92	16	0·94	13½	1·04	17½	1·13	8	0·94	12½	0·76	17½	1·00	17	1·06
60	14	1·00	7	1·08	19	1·12	18	1·38	21½	1·38	9½	1·12	14	0·85	19½	1·11	18½	1·16
45	16½	1·18	8	1·24	19½	1·15	15½	1·19	20	1·29	9½	1·12	15	0·91	21½	1·23	20	1·25
30	20½	1·47	8	1·24	21½	1·26	18½	1·42	23	1·48	9½	1·12						
15	18½	1·32	7½	1·15	31	1·82	28	2·15	34	2·19	12	1·41						
True airspeed (kt)	150		110		120		175		170		140		150		120		180	
Sample period (min)	60		25		15		15		15		30		30		50		40	
Rain intensity (cm³/min)	0·23		0·26		1·13		0·87		1·03		0·28		0·55		0·35		0·40	

V = amount of water in cm³. *R* = ratio of amount caught to amount caught at 90-cm level.

true rainfall rates experienced, but it gave a means of comparing the average rates of rainfall between samples. These rates varied between 0·16 and 1·13 cm^3/min, and 0·50 cm^3/min was chosen as a mean rain intensity to divide

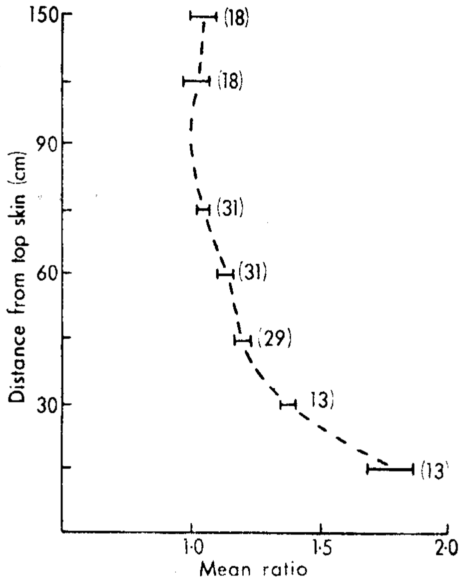


FIGURE 6—MEAN RATIO OF WATER CAUGHT AT GIVEN DISTANCE TO THAT CAUGHT AT THE 90-cm DISTANCE FOR INBOARD AND OUTBOARD POSITION, WITH STANDARD DEVIATIONS

Number of samples is given in brackets.

the samples. Figure 7 shows the four profiles obtained. All show basically the same shape but the profile for low speed/low rain has a greater value of water content at 120 cm.

Discussion. Ideally, to find the concentration factors for a given droplet size the aircraft would need to fly through a cloud of uniformly sized drops and to repeat for different sizes. This obviously is not possible and the actual amounts of water caught at each level has been the summation over all the drop sizes in the clouds through which the aircraft flew. The natural variability in drop size and water content in cloud and rain might be responsible for the differences in the profiles measured. For example, a portion of the sampling time might be in rain of a predominant drop size which had a large concentration factor at one level. The profile for that sample would show a peak at that level.

The previously used sampling position at 45 cm above the skin of the aircraft does appear to be unsuitable. Overall, that position caught 20 per cent more water than was caught at 90 cm. Splashing off the aircraft and local concentrations were no doubt responsible for this. Because of the increase in water caught above 90 cm, and because the sampling was restricted by instrument length to 120 cm, the free stream values of water content cannot be said to have been reached. A much longer instrument would be required to extend into the free stream region, but structurally this would be difficult.

Theoretical studies by the U.S. Naval Research Laboratory led to the design of a 14-ft (4·2 m) dorsal fin for their C-54 aircraft (slightly bigger than the Varsity) which was engaged on turbulence studies.[6] The fin was considered long enough to position the instrument in the undistorted airstream, but the author is unaware if confirmatory experiments were carried out. As the airflow is 10–15 kt higher than the true airspeed at a position 150 cm out from the Varsity, it is likely that a fin of similar size would be required to position instruments in the free airstream.

It is concluded that the measurements of drop size and liquid water contents in clouds from the present vertical sampling position in the MRF Varsity aircraft are certainly unreliable within 120 cm of the aircraft. The actual error in the measurement of liquid water content cannot be quantitatively given, as the free airstream values could not be measured.

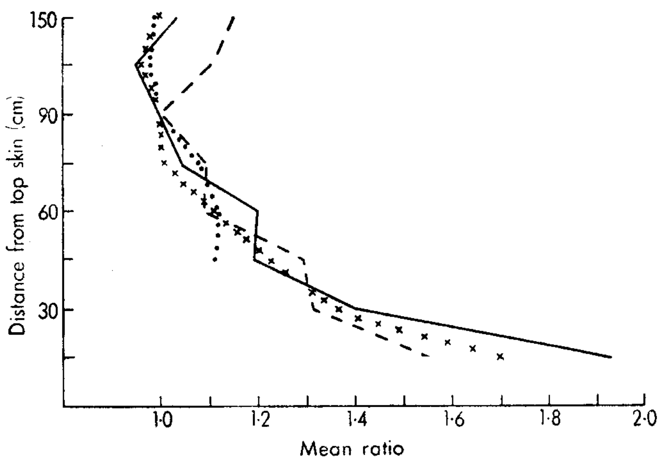


FIGURE 7—MEAN RATIO OF WATER CAUGHT AT GIVEN DISTANCE TO THAT CAUGHT AT THE 90-cm DISTANCE. RATIOS ARE MEANS FOR HIGH AND LOW TRUE AIR-SPEEDS AND HIGH AND LOW RAIN INTENSITIES

— — Low true airspeed and rain intensity
xxxxxx Low true airspeed and high rain intensity
. . . . High true airspeed and low rain intensity
——— High true airspeed and rain intensity

Distance above aircraft	LOW TRUE AIRSPEED				HIGH TRUE AIRSPEED			
	Low rain intensity		High rain intensity		Low rain intensity		High rain intensity	
	SD	Nos of samples	SD	Nos of samples	SD	Nos of samples	SD	Nos of samples
cm								
120	0·12	5	0	1	0·11	4	0·03	2
105	0·07	5	0	1	0·05	4	0	2
75	0·06	7	0·03	4	0·04	4	0·04	5
60	0·02	6	0·03	4	0·07	4	0·07	5
45	0·06	7	0·03	4	0·09	4	0·04	4
30	0·05	2	0·05	3			0·05	3
15	0·30	2	0·05	3			0·19	3

SD = standard deviation

Acknowledgements. The author would like to express his thanks to the MRF aircrew and observers for their fortitude in flying in such inclement weather, and to the Aerodynamics Department of the Royal Aircraft Establishment for the use of a wind-tunnel.

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AN OCCURRENCE OF HIGHLY LOCALIZED CLEAR-AIR TURBULENCE OVER THE SOUTHERN MEDITERRANEAN

By J. B. McGINNIGLE

At 1550 GMT on 28 November 1963, a report of highly localized clear-air turbulence was received from an aircraft *en route* from Tunis to Tripoli at flight level 19 500 ft (5·85 km). The track of this aircraft and the position where the turbulence was encountered are shown in Figure 1. A rapid temperature rise of 8 degC from −28 to −20°C was also reported to have occurred almost simultaneously.

On landing at Tripoli, the pilot described the turbulence as very severe, being in the form of only one 'bump' upwards, which dislodged many loose articles in the aircraft. Before and after the turbulence, the flight was completely smooth. At the time of the report, the aircraft was flying above a layer of altocumulus, whose top was estimated at 16 000 ft (4·8 km). Very shortly after the turbulence the edge of the cloud sheet was passed and thereafter generally clear skies were reported for the rest of the route.

Another aircraft *en route* from Rome to Tripoli flew over the turbulence position at 31 000 ft (9·3 km) within 25 minutes of the times of severe turbulence but reported only slight turbulence at debriefing.

Synoptic situation. Figure 1 shows the surface synoptic situation at 15 GMT on 28 November 1963. The cold front which extended south and south-west from the depression over southern Italy was moving south-east at 20 kt (1 kt ≈ 0·5 m/s) in the southern Mediterranean area. The front was very active in the north, near to the depression centre, but its passage along the north African coastline was marked only by a temporary increase in cloud and a slight veer of surface wind.

PLATE III—A 500-mb CONTOUR AND A 500–1000-mb THICKNESS CHART BEING PLOTTED BY THE 'ON-LINE' LINE DRAWER IN THE COMPUTER LABORATORY, BRACKNELL

The 500-mb contours are drawn first then the thickness (pecked) lines. The data are taken from a magnetic tape previously written during a numerical forecast run on the computer.

Magnetic tapes, which form part of the magnetic-tape library (now containing 4000 tapes and still increasing), can be seen in racks behind the operator. The equipments in front of the racks are paper-tape punches.

PLATE IV—A 200-mb CONTOUR CHART BEING PLOTTED BY THE 'ON-LINE' DRAWER IN THE COMPUTER LABORATORY, BRACKNELL

Behind the line drawer is a line printer on-line to the KDF 9 computer. Although shown loaded with plain paper this equipment can be loaded with pre-printed stationery to produce charts of the 'zebra' type.

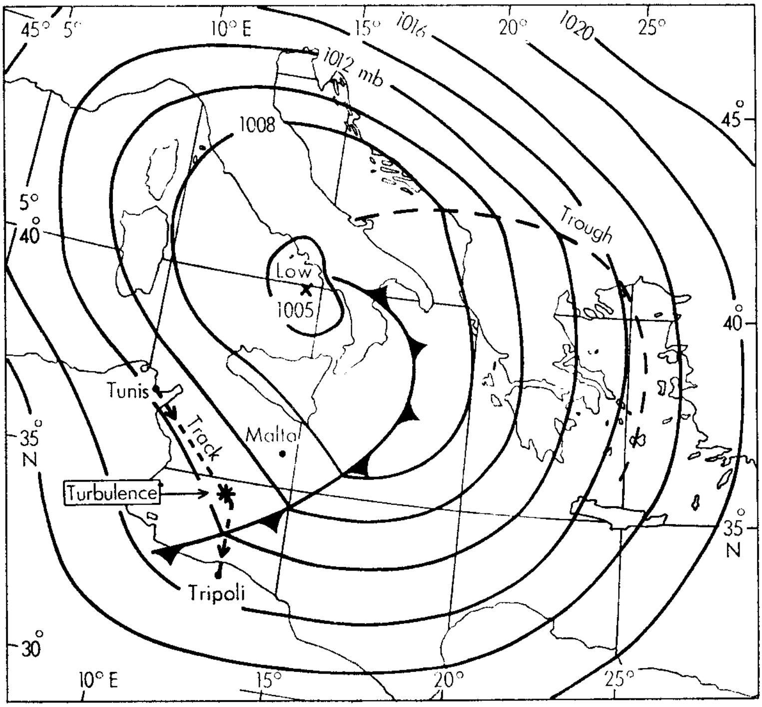

FIGURE 1—SURFACE ANALYSIS 15 GMT, 28 NOVEMBER 1963

The depression had been a feature over southern Italy for some days, and a cyclonic circulation was in evidence to above the 200-mb level. A belt of strong winds extended from southern France to Algeria and Tunisia and thence eastwards over Malta. A marked upper trough associated with the cold front existed at all levels up to 300 mb but was most sharp around the 500-mb level. A jet stream lay over Malta at 12 GMT on 28 November, when a maximum wind of 250° 110 kt was reported at 320 mb.

Discussion. The Malta radiosonde ascent for 12 GMT on 28 November was used for the analysis of the cold front. The tephigram is reproduced as Figure 2, and Figure 3 shows the hodograph which was constructed from the ascent winds. Inspection of these figures in combination with the surface analysis suggests that the upper frontal surface was at 520 mb, where a temperature inversion was reported.

The increases, with height, of the wind component normal to the front in the warm air shows that the front was a katafront, as can be seen from Figure 3, and this explains why there was a subsidence-type inversion at the frontal surface, completely masking the vertical increase of wet-bulb potential temperature which would be expected.

The position and time of the turbulence report indicate that the aircraft was in the frontal zone at the time and the very sudden temperature increase of 8 degC shows that this zone was very narrow.

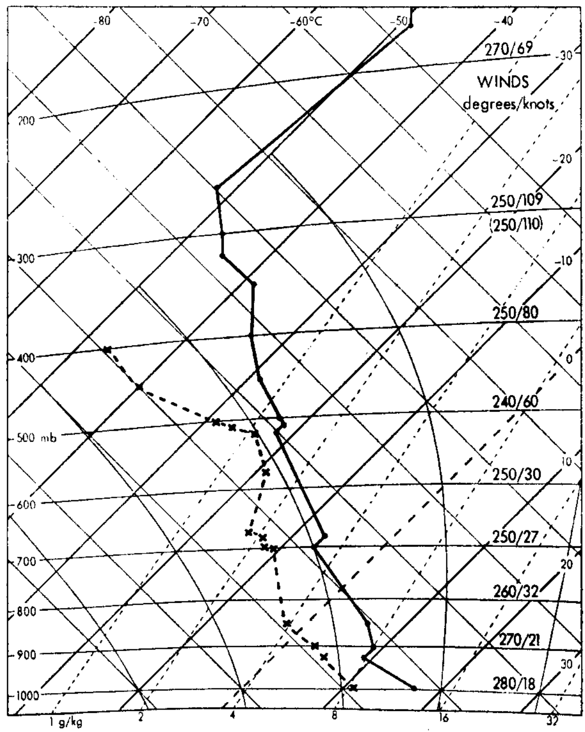

FIGURE 2—MALTA UPPER AIR ASCENT 12 GMT, 28 NOVEMBER 1963
——— Temperature - - - Dew-point

It is, however, surprising that there was no cloud in the frontal zone as the Malta ascent (Figure 2) shows that a lift of only 20 mb at 570–520 mb would produce condensation.

It therefore seems likely that the strong shear effect around 500 mb was inhibited by the downslope motion on the katafront, such that the effect was limited to less than 20 mb. Freeman* has shown that fronts have a dry zone within the frontal zone and the lack of cloud in the turbulence layer is most probably explained by this and the katafront effect. There is some indication of this dry zone between 700 and 600 mb on the Malta ascent although this ascent may have been too far into the cold air to indicate this feature properly.

The turbulence produced by the wind shear would be severely limited in vertical extent. The aircraft seems to have passed through the frontal zone within this dry and extremely turbulent layer, moving at sufficient speed (around 230 kt) to experience only one severe bump.

The other report of slight turbulence is assumed to be due to the normal shear effects adjacent to a jet-stream core.

* FREEMAN, M. H.; Fronts investigated by the Meteorological Research Flight. *Met. Mag., London*, **90**, 1961, pp. 189–203.

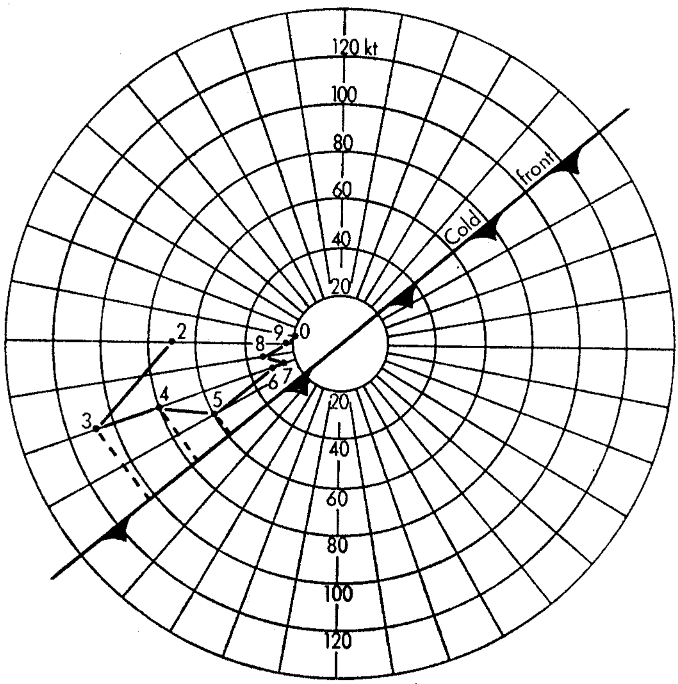

FIGURE 3—HODOGRAPH CONSTRUCTED FROM MALTA UPPER AIR ASCENT 12 GMT, 28 NOVEMBER 1963

0 = 1000 mb, 9 = 900 mb, 8 = 800 mb, etc.

REVIEWS

World survey of climatology Volume 8, Climates of northern and eastern Asia, edited by Hidetoshi Arakawa. 300 mm×215 mm, pp. 248, *illus.*, Elsevier Publishing Co. Ltd, 22 Rippleside Commercial Estate, Barking, Essex, 1969. Price: 225*s*.

With this volume Elseviers have now brought out three of the planned 15 volumes of the *World survey of climatology* under the direction of Professor Landsberg (formerly of the United States Weather Bureau), President of the World Meteorological Organization Commission for Climatology. No climatological reference work on this scale has appeared since Köppen and Geiger's famous *Handbuch der Klimatologie*, the first parts of which were published in 1930 and which stopped short of world coverage owing to the intervention of the Second World War before it was completed. This new work is therefore to be welcomed and this volume especially so, since it includes areas which never appeared in Köppen and Geiger.

The name of the volume here reviewed is misleading, because the Asiatic territories of the U.S.S.R. are to appear in Volume 7 *(Climates of the Soviet Union)*. The areas included in Volume 8 actually range from China (with some references to Mongolia), Korea and Japan in the north to Indonesia, straddling the equator, in the south. Volume 9 (called *Climates of southern and western Asia)* will deal with all the rest of Asia from Vietnam to the Near East. The editor of Volume 8 is the well-known meteorologist Hidetoshi Arakawa, now Professor of Physics at the Tokai University, Hiratsuka City, Japan, but from 1931 to 1968 a member of the staff of the Japanese weather service. The chapter on Japan is by Arakawa and S. Taga; that on China is by I. E. M. Watts, formerly Director of the Royal Observatory, Hong Kong.

More than one-third of the book is devoted to climatic tables in a standard format, giving for each month of the year average values of atmospheric pressure, surface air temperature and its diurnal range, sunshine, cloudiness, rainfall and evaporation, the observed extremes of some elements (including, where appropriate, deepest snow) and the frequencies of various kinds of weather such as precipitation days, thunderstorms, fog, gales and sandstorms. Completeness of these tables is, of course, subject to availability of data but a remarkable fullness has been achieved. Such tables are given for 40 places in China, 2 in Korea, 27 in Japan and 10 in the Philippines but none in Indonesia. Additionally, some items are given for a number of places in central Asia (e.g. Sinkiang) and Taiwan, for 44 places in the Philippine Islands and 10 places in Indonesia. The data for China are for somewhat varying periods, generally between about 1900 and 1950; those for Japan are all 1931–60. Many of the Philippine observational records were lost in the war, and the available data here given are for periods varying from about 7 to 59 years, mostly in the first half of this century. All the Indonesian information is recent, for periods ranging from 8 to 30 years between 1931 and 1960. This unfortunately includes nothing on thunderstorms, for which Java has long been renowned as having the highest frequency in the world. For the climatology of these islands reference will still have to be made to the prolific, high-quality data obtained and published during the Dutch colonial period: for some places more than 100 years of record exist.

The text of the present volume is liberally provided with maps, diagrams and subsidiary tables, and handsomely printed with lavish margins. Seventy-one pages are devoted to China and Korea, 12 to Japan, 45 to the Philippines and 15 to Indonesia. Systematic understanding is aimed at by considerable use of standard climatic classifications, particularly that of Köppen which is used in three of the four chapters. The chapter on Japan aims at being little more than a guide to the voluminous work and literature on the subject. The chapter on China is the most comprehensive and will be valued both by reason of the scarcity of informed texts in a western language on the climate of that country and for its attention to the meteorological and oceanographic influences at work. Nevertheless, rather more attention to the flow of the upper air and, particularly, the moisture transports involved in the rains of different seasons in China, would have been an advantage. This chapter has a specially good bibliography. The climate of the Philippines is also painstakingly described, with due attention to the atmosphere in depth and the main meteorological processes at work.

Among the special characteristics of the regions covered by this volume are the incidences of typhoons, exceptionally heavy rainfalls and disasters due to weather. Extreme rainfalls of around 1200 mm in 24 hours have been measured in the mountains both on Luzon (Philippines) and Taiwan, though outdone by one of 1870 mm on Réunion (21°S 55°E). Climatic history, and the two-thousand-year history of applied climatology in China, receive some notice in the book; but the range of behaviour of the present climate throughout the regions covered, as recorded, for instance, in the table (p. 19) on fatalities during typhoons at Hong Kong, in the frequent river floods and landslides in China and in the tabulation of weather disasters of various kinds in Japan since 1918, is more than sufficient to disrupt human planning regardless of any secular shifts of the average values and frequencies of various disturbances.

H. H. LAMB

World survey of climatology Volume 4, Climate of the free atmosphere, edited by D. F. Rex. 300 mm × 215 mm, pp. 450, *illus.*, Elsevier Publishing Co. Ltd, 22 Rippleside Commercial Estate, Barking, Essex, 1969. Price: 335*s*.

This volume is one of the 15 volumes planned under the direction of the recently elected President of the World Meteorological Organization Commission for Climatology, H. E. Landsberg, who is Editor in Chief of the series. The first 3 volumes discuss general climatology while the remaining 11 refer to the detailed climatology of different regions of the world. Only 3 volumes have so far been published (Volumes 2, 4 and 8) and it is likely to be several years before all volumes of this major work appear in print. D. F. Rex from the National Center for Atmospheric Research, Boulder, Colorado, has acted as editor for this volume and he has assembled an impressive list of authors for the eight chapters.

Chapter 1 is a brief but adequate introduction by the editor, the main part of the study being contained in the following seven chapters. Most readers will probably not quibble about the omission from the volume of any reference to the electrical properties of the atmosphere but some no doubt will be surprised not to find any reference to the climatology of the boundary layer which undoubtedly is important enough to merit a chapter on its own. Others will be equally surprised at the planned omission of any reference to chemical constituents of the natural atmosphere (except water vapour and ozone) or to the naturally occurring particulate matter suspended in the air. Although 'references' are given to reviews of pollution and atmospheric chemistry some discussion of these topics would have been desirable. The main part of the book starts with a rather lengthy dissertation on standard and supplementary atmospheres. This chapter is written very largely from the American point of view with most of the space being allocated to discussion and tables of the U.S. Standard Atmosphere, 1962 devised by the Committee on Extension to the Standard Atmosphere (COESA); COESA, representing a group of American organizations, has defined the atmosphere up to a height of 700 km and is attempting to get the International Civil Aviation Organization (ICAO) Standard Atmosphere extended upwards. To some extent it has a different approach from the Committee on Space Research (COSPAR) which likewise has produced a reference atmosphere (COSPAR International Reference Atmosphere, 1965) for the higher levels but which uses satellite data to define these and attempts to integrate downwards, while the COESA atmosphere is a logical extension of the ICAO atmosphere upwards.

This chapter also includes tables defining reference atmospheres for each 15° of latitude between 15° and 75°N up to 90 km. It is doubtful whether these data are very useful as they are ostensibly means round a latitude band.

In practice however, at the higher levels there are large departures from the proposed reference atmosphere in some longitudes and in general the variability of the lower stratosphere is much greater in some sectors than in others.

Chapter 3 on 'Temperature and humidity' in the troposphere contains some useful maps and diagrams but in some of them (notably Figure 5) the method of presentation is not ideal. In addition the readability of the text is occasionally spoiled by too frequent references with no clear connecting thread between the sentences.

To the reviewer the chapter by Reiter on 'Tropospheric circulation and jet streams' is easily the best in the book. It gives an excellent description of the dynamics of jet streams and their origin on a rotating globe. Of particular interest is the section showing the inadequacy of contour charts to describe even approximately the atmospheric motions in some synoptic situations, e.g. near converging jets and sharp upper troughs. In these cases the author clearly demonstrates that isentropic analysis sheds more light on what atmospheric motions are actually taking place. The chapter also contains more conventional but very readable descriptions on the origins of the subtropical jet, the tropical easterly jet, the polar-front jet and even the low-level jet. Some discussion is also included on the origin of tropical storms and on cyclones and anticyclones.

Chapters 5 and 6 on 'Major cloud systems' and 'Global distribution of cloudiness and radiation as measured from weather satellites' complement each other, both making extensive use of satellite data. These chapters tend to be out of date because of the rapid increase of knowledge attained from weather satellites over the last few years, practically all the examples inevitably being culled from data prior to 1965, but they do make very interesting reading and form one of the best accounts of the subjects yet seen in book form. No doubt some maps will need amendment in the light of later more accurate data but it is most interesting to see first attempts at maps of seasonal mean cloud cover over the globe and also similar maps showing the mean seasonal outgoing long-wave radiation and albedo over the globe. These maps are based on only one year of data; there is a liability to error in the albedo and radiation maps because of the fall-off with time in performance of the radiation instruments, and in the maps of mean cloudiness because of the technique of preparing the maps by allocating arbitrarily a brightness to each grid point and then averaging the brightness to produce a mean cloudiness. As the authors say, this technique leads to difficulty especially in distinguishing between snow or ice and cloud. Nevertheless these two chapters fulfil a useful function in presenting much comparatively new data and clearly indicate the great promise for the future which satellites present.

The chapter on the stratosphere is slanted towards the upper stratosphere and in particular on observations obtained from the Meteorological Rocket Network (MRN). This inevitably refers mostly to American data as the MRN began there in 1959 but it is a little surprising to find no reference at all to rocket observations from Europe and, in fact, the British Isles do not even appear on the map showing the location of rocket observations stations! This chapter in general gives the impression of being written some time ago, especially as no mention is made of rocket observations later than 1963; however, it does include summaries of upper stratospheric wind data for the four years 1960–63.

The last chapter, on ozone is one of the best and covers most aspects — photo-chemical theory, methods of observation, mean vertical distributions at different latitudes, seasonal variations in the distribution of ozone, transport by the general circulation, the importance of ozone in stratospheric dynamics, etc. Altogether the chapter contains about the most comprehensive account of the role of ozone in atmospheric studies that has appeared in a general volume.

The book as a whole is well produced, with good print and few mistakes. Diagrams are mostly clear, although there are a few exceptions to this, the reproductions of some of the satellite photographs in particular being fuzzy. Figure 7 on page 222 has an erroneous caption and there are other small errors, but overall these are very few.

Altogether this is a very useful volume although, in common with most books written by several authors, the standard is rather variable. The price will not commend the book to many private meteorologists but it is hoped that the series will be given a place in all worthwhile meteorological libraries.

R. A. S. RATCLIFFE

World survey of climatology Volume 2, General climatology, 2, edited by H. Flohn. 300 mm×215 mm, pp. xii+266, *illus.*, Elsevier Publishing Co. Ltd, 22 Rippleside Commercial Estate, Barking, Essex, 1970. Price: 225*s.*

This is Volume 2 of a series of 15 planned to cover the whole field of climatology. The first 4 volumes deal with general aspects and include one on the climatology of the free atmosphere. Five general topics are covered in the five chapters of the present volume. They and their authors are: General circulation, H. Riehl; Physical processes near the earth's surface, E. L. Deacon; Topoclimates, R. Geiger; Local wind systems, H. Flohn; Climatic fluctuations, H. H. Lamb. The treatment is descriptive, supported by typical observations and the outlines of theory. Broad results of the more important researches are presented, supplemented in all sections by comprehensive reference lists. The text throughout is illustrated with clear and informative diagrams.

In Chapter 1 the as yet incompletely solved problem of the general circulation is discussed having regard to the fundamental requirements of the global budgets of heat and momentum and, to a less extent, of water vapour. It is shown that the simple heat engine type of circulation, e.g. the Hadley cell, by itself is not reconcilable with the requirements of momentum balance. Hence follows the necessary part played in the transport of heat and momentum by the long waves of the upper troposphere and the surface anticyclones and depressions — circulations simulated in rotating dishpan experiments. The relevance of these experiments to the problem is discussed.

Chapter 2, on physical processes near the earth's surface, discusses the radiation balance, heat conduction into the ground, evaporation, transpiration and turbulent transfer, from the point of view of the basic physics, with illustrative observational data. The significance of these processes in relation to fog, atmospheric pollution and the diurnal variation of meteorological elements is considered.

The next two chapters are concerned mainly with mesoscale features of climate. That on 'Topoclimates' deals with the relations between land forms and local climates, including such topics as valley and mountain climates, radiation on slopes and the climate in caves. The chapter on 'Local wind systems' includes the thermally driven land- and sea-breezes, mountain and valley winds and the dynamically driven mountain waves. Where appropriate the descriptions are backed by theoretical considerations. The final chapter is a summary of the author's work, extending over at least 15 years, on climatic variation, especially during historical times. Mr Lamb is expert at the marshalling and sifting of evidence, often scanty, and his contribution to this volume surveys, in enjoyable readable form, his many contributions to the subject. In conclusion the possible causes of climatic variation are briefly assessed, for example, astronomical factors, volcanic activity and the extent of the polar ice.

This is a handsomely produced volume containing clearly written and well-illustrated surveys of researches to be otherwise found in numerous and widely dispersed papers. It is a book to be enjoyed by the general meteorological reader who might not have the time or the stamina to digest all the original literature.

A. G. FORSDYKE

Invention of the meteorological instruments, by W. E. Knowles Middleton. 260×155 mm, pp. xiv+362, *illus.*, Johns Hopkins Press, Baltimore, Maryland 21218, 1969. Price: £5 14*s*.

In *'Invention of the meteorological instruments'* Dr Middleton deals with the inventions and improvements which have led, step by step, to the equipment currently employed in meteorology. Perhaps of even greater interest, he considers in detail the early deliberations which eventually resulted in a clear understanding of the physical quantities involved. In no case are the difficulties of this latter stage illustrated more clearly than in regard to pressure, the existence of which is undetectable by human sensation. Short-term variations in the pressure of the atmosphere caused some confusion in interpreting the results of the early experiments designed to demonstrate the nature of pressure within the free air, although eventually it was the equipment used for these demonstrations which provided the Torricellian tube, the basis of the present mercurial barometer.

As Dr Middleton states in his preface, it would require many volumes to cover completely all the variations of design of each of the many meteorological instruments. The general meteorologist, concerned primarily with the derived observation, is taken as concisely as possible through the initial philosophical considerations and the subsequent physical design of measuring equipment applicable for each of the main meteorological observations made at ground level — atmospheric pressure, temperature, humdity, rainfall and evaporation, wind direction and force and the duration of sunshine. Further chapters deal with multiple recording instruments, such as the meteorographs, and with devices for measuring phenomena above ground level. In meteorographs and balloon-borne sonde equipment, whether transmitting by radio or otherwise, no meteorological conceptions are involved, original invention being limited to the mechanics of recording or transmitting the response of sensors already in use at ground level. Although specialized sensors, such as those for measuring ozone in the upper air, have in fact been invented, it has been the author's deliberate intention to exclude reference to devices developed for specific research applications and not as yet accepted for routine meteorological observation. Similarly no descriptions are given of the many older devices which, having played no useful part in the general evolution of meteorology, have now been abandoned.

The term 'invention' is a difficult one to define accurately, and in no field is this more true than when applied to meteorological equipment. It would seem most appropriate in instances relating to a single original conception — an entirely new instrument or method hitherto unknown. Strictly, however, it is equally applicable to many of the smaller steps in a prolonged sequence of improvements, and examples of both cases are illustrated within this volume. The term, although still used in the popular press, has somewhat dropped from favour since Victorian days, when any change of design, however small, tended to be considered as an invention. No doubt Dr Middleton himself had this somewhat outmoded application in mind, when including it in the title of his book, the style of which is intended to conjure up a suggestion of medieval learning.

It is perhaps unfortunate that so many inventors evolved so many variations of design in basically similar instrument, backing each with his own choice of units for the resultant measurement. The results of each school of thought clinging firmly to its own practices are still felt in modern meteorology, to a degree which is not always appreciated, despite international guidance and control.

The great antiquity of some of the observations and of their corresponding instrumentation, albeit by simple methods, will surprise many of Dr Middleton's readers. The earliest known rain-gauge, used in India, is ascribed to the fourth century BC, while as the Grecian 'Tower of the winds' was used to aid the determination of wind direction in 100 BC it is difficult to believe that earlier simple aids to this end were not in fact available. The requirement — a directional reference point and some easily blown material — would leave no permanent trace and no written reference is known. The very active development of refined equipment for observing, recording and, to a limited extent, transmitting observations by mechanical methods was so exhaustive during the eighteenth and nineteenth centuries that little further is possible by such means. Only limited improvements related to cost or convenience can be achieved, using materials or production methods not then available. It is to electronics that further development must now turn, a field already in wide use for the transmission of observations, but one which may eventually suggest entirely new observational techniques and provide measurements not merely at a single point in space, but representative of a prescribed volume or layer of the atmosphere.

The general style used for the presentation of '*Invention of the meteorological instruments*' follows that of the author's earlier works on the barometer and the thermometer, to which it forms a fitting companion volume. Numerous references to the details of the earlier writings on each of the instruments described will satisfy the instrumental specialist, and many of the reproduced letters and diagrams date back to Renaissance times. Dr Middleton has obviously delved deeply into his subject and demonstrates great skill in the work of editing, retaining only those items essential to the development of his theme. The result has been the production of a book which, while most useful for reference, remains easily readable by the student or general meteorologist. Perhaps, above all, the work gives a clear conception of the age and width of scientific thought, and of the associated technical ingenuity displayed throughout the centuries.

A. L. MAIDENS

NOTES AND NEWS

Conference plans detailed atmospheric studies

Approximately 100 scientists from 25 countries meeting in Brussels completed a 5-day conference on 20 March 1970 with a unanimous agreement on plans for two major international projects within the so-called Global Atmospheric Research Programme (GARP). The broad objective of GARP is to increase our understanding of the large-scale behaviour of the atmosphere with a view to determining for what period of time ahead it is physically possible to forecast the weather. This increased understanding of these processes would also help us to know more about the factors which determine climate and hence perhaps to assess the possibilities of artificial climate modification.

Weather forecasts at present are fairly accurate for one day ahead but the accuracy decreases rapidly as the period of the forecast increases. The useful limit of forecasts is at present of the order of 5 days. Recent theoretical studies have however indicated that useful forecasts may be possible for up to 2 or 3 weeks ahead. GARP is aimed at testing and improving these theories. For this purpose we need observational data in more detail than is available for daily use by the World's Meteorological Services. The two projects discussed at the Brussels conference are designed to obtain these additional observations.

The first project, known as the GARP Tropical Experiment, will include a 3-month period of intensive observations in the Atlantic between 10°S and 20°N. It will be held in 1973 or 1974, the exact date depending on the availability of a geostationary meteorological satellite over the area. In addition to the observations from this and other orbiting satellites it is expected that there will be a fleet of 20 or more research ships from about 8 countries making special observations over the area of the experiment. Some research aircraft are also to be used and commercial ships and aircraft in the area at the time of the experiment will be invited to participate. The resulting observations will be used by research groups in many countries to find out more about the energy-exchange processes in the tropical atmosphere.

The second project will cover the whole world and includes an observing experiment lasting a whole year, beginning some time in 1975 or 1976. The proposed observing system includes four geostationary satellites, at least two polar orbiting satellites and two balloon sub-systems. The first of these will consist of some 300 balloons drifting with the winds at a height of about 12 km. The balloons will measure temperature and pressure and the observations will be collected by an orbiting satellite which will also determine the position of the balloons from which it will be possible to deduce the wind. The second balloon sub-system consists of large carrier balloons at a much greater height from which radiosondes can be dropped by parachute when required. As it falls, the radiosonde will be located by a navigational aid system and the observations will again be collected by satellite.

The proposals made by the conference will be considered by the two sponsoring bodies, namely the World Meteorological Organization and the International Council of Scientific Unions. It is expected that the countries willing to participate in the GARP Tropical Experiment will meet in London in the summer of 1970 to discuss the plans in more detail.

The conference was held at the Headquarters of the Royal Meteorological Institute of Belgium at Uccle, and was presided over by the Director of the Institute, Professor J. Van Mieghem.

WMO PRESS RELEASE

Further information on GARP may be obtained in the *GARP Publications Series* issued by WMO and ICSU and distributed by the WMO Secretariat, Geneva.

No. 1 An introduction to GARP. (1969)
No. 2 Systems possibilities for an early GARP experiment. (1969)
No. 3 Planning of the First GARP Global Experiment. (1969)

LETTERS TO THE EDITOR

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Winter precipitation over East Anglia

In his paper on the forecasting of winter precipitation over East Anglia, Mr M. F. Smith[1] compares the results he obtained with results from applying relationships which I[2] established. These comparisions are not valid because he uses the relationships in a way that was never intended.

In comparing the accuracy of various methods I made it clear that I was relating each index to the form of the precipitation falling at the time the corresponding temperatures were measured. The usefulness of each method depends on this accuracy and on how successfully the index can be forecast.

On the other hand, Mr Smith relates his predictors to the form of precipitation in the 12 hours following the upper air observation. Moreover, he classes this precipitation as snow if snow falls at any time in the 12-hour period. It is clear that any figures I found to correspond to a 50 per cent probability of snow at the time the upper air observation was made will greatly underestimate the probability of snow falling at any time in the subsequent 12 hours. In general, if an index is devised which relates to a simultaneous weather event in a small area, then if either the area or the period is extended the index is bound to 'under-forecast' the occurrence of the event.

11 St Omer Road
Guildford, Surrey C. J. BOYDEN

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1. SMITH, M. F.; Winter precipitation over East Anglia. *Met. Mag., London,* **99**, 1970, pp. 20–27.
2. BOYDEN, C. J.; A comparison of snow predictors. *Met. Mag., London,* **93**, 1964, pp. 353–365.

In a most interesting and useful article,[1] Smith refers to a short paper[2] which I wrote nearly 20 years ago. The purpose of my early note was to present some statistics on the association between the form of precipitation over the British Isles and four meteorological variables, namely surface temperature, height of freezing level, 1000–700-mb thickness and 1000–500-mb thickness. Information on the association of precipitation with the last two synoptic variables was very desirable since the 'thickness' technique in upper air analysis and forecasting had then become well established in British practice. These simple synoptic climatological statistics, which were quite novel at the time, were intended in particular to give some help in interpreting prognostic maps in terms of the form of precipitation. Some years later another short paper[3] was written in which graphs showed the likelihood of rain or snow in relation to *(a)* surface temperature and height of freezing level (0°C isotherm) and *(b)* surface temperature and 1000–500-mb thickness, but I stated that such diagrams could only be useful as a general guide over longer periods and not in short-period prediction when, to quote my words, 'the forecaster must clearly depend on his scientific diagnosis of the meteorological situation'.

I think it is relevant to say that the data for my papers were collected over three cold seasons from November 1948 to March 1951 from seven radiosonde stations, all but one of which are situated in the north and west of Britain. At these stations and during that particular period there was much showery-type precipitation and this dominated the overall statistics. The mean 'critical' figure for 1000–500 mb thickness was in fact lower than it would have been if most of the data had been collected from stations nearer the continent and during a period in which most of the precipitation had been associated with warm-type fronts approaching from the south-west or south of Britain or with continental airstreams. Both of these synoptic types generally have higher values of 1000–500 mb thickness than have unstable weather types with the same level of surface temperature. Subsequently Boyden[4] found a somewhat higher mean 'critical' 1000–500 mb thickness, but his data were selected from four unusually snowy winters, 1955–56, 1957–58, 1961–62 and 1962–63 which were, on average, synoptically more 'blocked' than my three winters which were characterized by progressive synoptic types.

In view of the practical importance of accurate forecasts of heavy snowfall to road, rail and air traffic I am sure that there is a need for much more work to be done on developing practical forecasting techniques. For very short-period, local forecasts practical techniques need not be linked specifically to numerical forecast procedures. On the other hand, for useful predictions of snow over longer periods, such as a day or so, it would seem most desirable to develop techniques, based on the synoptic and physical factors of relevance to the formation or melting of snow. The techniques should make use of meteorological variables which can be included directly into numerical forecasting procedures or which can be derived from whatever thermal or circulation maps or data are (or will be) produced by computer methods.

Meteorological Office, Bracknell

R. MURRAY

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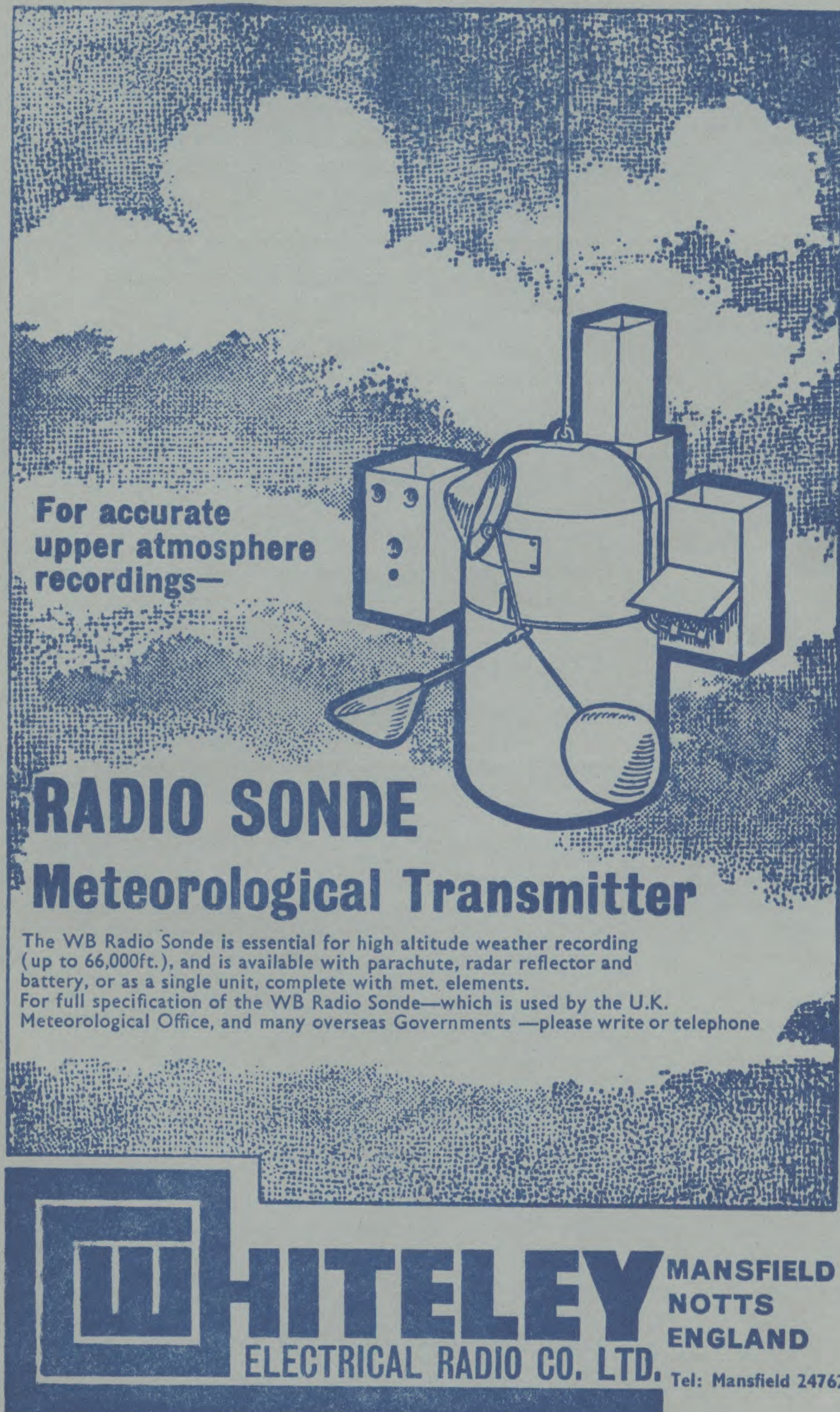
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WORK IN SYNOPTIC CLIMATOLOGY WITH A DIGITIZED DATA BANK

By J. M. CRADDOCK

Summary. An account is given of a bank of digitized data containing over 100 million decimal digits which is used by the Synoptic Climatology Branch of the Meteorological Office. The problems involved in bringing the bank into usable condition are illustrated, and a bibliography is given of papers on long-range weather forecasting and related subjects which have used data drawn from the bank.

The following are the main headings used in the paper: Introduction; The main constituents of the long-range data bank; Routine and research processing; Operational forecasting requirements; Applications of the long-range data bank; Examples of computation; A case history of important data; Quality control and the correction of errors; Comments and conclusions; Bibliography.

Introduction. For the past 100 years most meteorological work has fallen under one of two headings, namely synoptic meteorology (which analyses space fields of contemporaneous data by non-statistical methods with the object of short-range forecasting) and climatology (which uses long records of data from single stations which are analysed statistically and often in isolation). The two aspects have to be considered together in synoptic climatology, a newer study of which the work on long-range forecasting described below forms a part. In the British Meteorological Office, in which a centralized computer installation provides a service to all branches, the power of the central processing unit is determined by the very exacting requirements of short-range numerical weather forecasting, so that the users with mainly statistical interests have access to a computer far more powerful than they could ever justify for themselves. Their problem lies with the supply of data in usable form, and in deciding what to instruct the computer to do with them. Given reasonable organization, the computer time spent on carrying out the instructions is not the prime consideration. Any investigator concerned with long-range weather forecasting and allied projects faces an enormous task in the collection and reduction of data, and from the time we, in the Synoptic Climatology Branch, first attacked the problem in 1953 we concentrated on fields narrow enough to enable visible progress to be maintained. By 1965, when with the new KDF 9 computer we first had facilities for using magnetic tape, we already had a considerable digitized library punched on paper tape, and also the practical knowledge described by Craddock (1966 *(a)*), of working with the far less sophisticated Mercury computer. We decided that as no suitable macrolanguage was on offer we should develop our own, the result being the original METO language described by Craddock (1966 *(b)*).

Apart from fewer than 20 computations, all the work to be described was carried out using a main-store claim not exceeding 48K bytes,* and without ever claiming more than two magnetic tapes at once. Thus almost everything could have been done on a computer very much smaller than that actually used. The effort spent in language design and implementation produced useful returns soon after the installation of the KDF 9 computer, and materially helped in the assembly of the data bank described below.

Long-range weather forecasting differs from short-range forecasting in that the individual situation may last weeks or months and can readily be obscured by short-period fluctuations. Whereas an experienced short-range forecaster can rely on his memory for enough relevant past situations to guide him, a long-range forecaster cannot do so, and must have access to an external memory of relevant data covering as long a period as possible. The build-up of this memory started in 1953, using as media charts, diagrams and edge-punched cards, and has continued ever since. From 1965 onwards both new and existing data have gradually been transferred to magnetic tape. The subject calls for data of two kinds, *(a)* for use as predictors: data covering large areas in space and long periods in time, which between them determine the character of atmospheric processes on the largest scale, and *(b)* for use in determining possible predictands, etc.: very long series of daily measurements of elements for a network of stations covering the British Isles. The data of the first type, which are of interest to all long-range forecasters, can relate to little more than the last 100 years, since before then there is a lack of information from the remote areas which include many of the main centres of atmospheric action. The data of the second type may extend back further, but of course the data on predictands in the British Isles are of less interest in other countries, although they are also used for climatological purposes in Britain. Even with computer facilities the collection of data from many countries and periods, and the reduction of a variety of units, formats and conventions to common standards, is a formidable task, and one which precedes and continues alongside the use of the digitized data bank for productive work.

The main constituents of the long-range data bank. In the following list only the constituents comprising non-trivial numbers of data have been included. Items such as the annual sunspot numbers are too few to involve data-processing problems, though they are often considered in research and operations.

(i) *Hemispheric fields of the 500-mb surface.* These represent the mean airflow of the troposphere. Each daily field is represented by the values at the points of the German Upper Air Grid, which uses 592 numbers per chart.

* $K = 2^{10}$; 1 byte = 8 bits; 1 bit is a binary digit.

The daily data for years 1949 to 1964 were obtained from copies of cards punched by the Deutscher Wetterdienst from charts analysed in Germany. Data for 1965 to the present have been taken from charts analysed by the Meteorological Office. For the years 1951 to 1964 deficiencies over the Pacific Ocean have been remedied to some extent by 5-day mean data received on magnetic tape from the Japanese Meteorological Agency, based on charts analysed in the United States of America or in Japan.

The 7300 daily charts contain about 4·3 million numbers, or *17 million decimal digits.*

(ii) *Hemispheric fields of the thickness of the 1000–500-mb layer.* These fields, which represent the mean temperature of the troposphere, are similar to the preceding item, and were obtained in the same way. They too comprise *17 million decimal digits.*

(iii) *Hemispheric fields of the 1000-mb surface.* These fields, which represent the algebraic differences of the first two, approximate to fields of the MSL pressure. They comprise *17 million decimal digits* but, of course, they only cover the years since 1949, whereas analysis of the MSL pressure existed long before then, and are represented in (iv).

(iv) *Grid values for the* MSL *pressure over the northern hemisphere.* Daily values for the years since 1899 were obtained from the United States Weather Bureau (Washington) on magnetic tapes from cards punched from the historical weather maps. *Total 45 million digits.*

To these have been added daily values for the same grid for the period December 1880 to February 1900. These values cover a more limited area excluding most of the Pacific Ocean, and are taken from the German/Danish charts for the period. They were provided on magnetic tape by the Deutscher Wetterdienst. *Total 10 million digits.*

(v) *Monthly mean values of* MSL *pressure.* For years from 1899 onwards, data at the points of the German Upper Air Grid were extracted from German charts and punched by the Synoptic Climatology Branch. Similar data for years 1873–98 were assembled from whatever sources exist. *Total 0·5 million digits.*

(vi) *Descriptions of the large-scale weather situation near the British Isles.*

(a) Lamb's daily weather catalogue 1861 to 1968 (to be published), 79 000 digits

(b) Ward's catalogue of daily weather 1873 to 1968 70 000 digits

(c) *PSCM* indices (described by Murray and Lewis (1966)) 79 000 digits

(d) Grosswetterlagen daily weather catalogue (1880–1968) (Hess and Brezowsky (1969)) 130 000 digits

Total 358 000 digits.

(vii) *Monthly data taken from the Smithsonian World Weather Records etc.* These are mostly monthly mean temperatures for about 350 stations, and monthly rainfall totals for 100 stations forming a network over the northern hemisphere. Many of the records extend back to 1850 or earlier. *Total 3·75 million digits.*

(viii) *Fields of the sea surface temperature anomaly over the North Atlantic.* These fields, which seem to provide one of the most useful diagnostics of the character of the future weather in the British Isles, are derived from many millions of Hollerith cards prepared by various services (and exchanged internationally) for use in marine climatology. The data are now being averaged in forms suitable for use in long-range weather forecasting. *Total 7 million digits.*

(ix) *Bathythermograph data.* These data give the three-dimensional thermal structure in the oceans. Data on magnetic tape now include most of nine ocean weather stations A, B, C, D, E, I, J, K and M for most days since 1 January 1966. *Total 5 million digits.*

(x) *Data for determining predictands.* These include daily values of three elements — maximum and minimum temperatures and rainfall — for Kew (1881–1968), Bidston (1870–1968), Oxford (1853–1968), Plymouth (1864–1968), Armagh (1867–1968), Edinburgh (1895–1968) and Glasgow (1878–1968). *Total 2 million digits.*

The total number of data in the long-range bank is well over 130 million digits, stored on over 120 magnetic tapes. This is perhaps one hundredth of the total stock of digitized data held by the Meteorological Office, but unlike the main stock, which is held as an archival store to serve all purposes, the long-range bank contains only material selected for relevance to a particular field of study.

Routine and research processing. The data already collected include a large fraction (probably over half) of all the independent measurements which have ever been made and which are relevant to the problem of long-range weather forecasting for the British Isles. A forecaster concerned with future conditions in, say, Hungary or Japan would require further data not relevant to the British Isles and, of course, different selections of data could be made which would have represented the same facts; but the general effect is that the task of data assembly, which has frustrated every investigator into the long-range problem, is becoming less pressing, while attention is shifting to the problem of making better use of the data we have. Doing this is less straightforward than it appears to be, because of the very variable quality of the data. The acquisition of digitized data is only the first step towards using them, and considerable effort and delay is involved in the operations of reducing data to common standards, and eliminating at any rate the larger errors which are described on pages 228 and 229. One of the conclusions of this paper is that these operations of error detection and correction are a function of the research unit using the data, which alone knows the tolerances which can be accepted in the work in hand. In practice a data bank of 10^8 digits cannot be checked and corrected in a few days, so the most important data were treated first and have since been used for productive work while operations of quality control are carried out on other parts of the data bank. The mere effort of punching 10^8 decimal digits represents a substantial investment of man-hours and, wherever possible, data have been acquired by exchange, purchase or extraction of material which has already been converted to digitized form by others, for example, for use in synoptic meteorology or for climatology. Direct punching of data by the staff of the unit concerned with long-range weather forecasting has been kept to a minimum for filling gaps in important records, for making corrections, and for computer programmes.

Operational forecasting requirements. In statistical terms, the data relating to a large-scale weather situation are the predictors in a vast multivariate problem, in which a combination of meteorological insight and statistical reasoning is used firstly to put the predictors into some kind of order of merit, and secondly to discern what is or is not a reasonable target for prediction. The monthly forecasts issued by the Meteorological Office, besides their other functions, serve as a test bed on which new tools can be developed and brought into use, such as the *PSCM* indices described by Murray and Lewis (1966), the applications of eigenanalysis outlined by Craddock and Flood (1969) and the uses of sea surface temperature anomalies described by Ratcliffe and Murray (1970). With only one forecast every fortnight, the evidence for the success or otherwise of any proposed technique grows only slowly, but over 150 official monthly forecasts have now been made, and the rising standards of these have been described by Ratcliffe (1970). This evidence is supported by that of experimental long-range forecasts for other periods, and suggests that gradual progress is being made towards understanding the slower large-scale atmospheric changes.

Applications of the long-range data bank. The long-range data bank is kept in a state of constant activity, partly for operational work, which includes routine steps for updating and for the detection and correction of errors, and partly for research work. Its availability has enabled the Synoptic Climatology Branch to achieve a high level of scientific productivity, as instanced by the publication in the years from 1966 onwards of between 50 and 100 scientific papers and reports. The level of computer activity averages at about 70 computations per week, programmed by one of from 5 to 10 people, involving on average between 90 and 100 claims for magnetic-tape mounting. The monthly consumption of computer time for research is about 30 hours, one tenth of the total non-priority work of the Meteorological Office, while operational long-range work is included with the other priority work which makes up the bulk of the 140- to 150-hour week of the KDF 9 computer. Thus the average user programmer initiates two computations per day, each of which runs for less than six minutes and uses one or two magnetic tapes. However, the part played by the computer is definitely that of a help to, and not a substitute for, the human intelligence. The computer can carry out routine operations far more quickly and accurately than can be done by hand, but the decisions are taken by scientists who can apply judgement to a range of issues wider than those with which the computer is programmed to deal. Only when experience shows that a decision is in fact always made according to definite rules is the computer programmed to make the decision. Thus the computer plays an important and increasing but essentially subordinate role in operational long-range weather forecasting. Among its main tasks are :

(i) the production and printing of time-averaged fields, e.g. mid-month to mid-month surface pressure charts for all 30-day periods from 1880 up to date, from daily data,

(ii) computerized pattern matching, with results displayed in order of merit,

(iii) eigenvector analyses used for matching 500-mb charts, and for error detection,

(iv) producing standard statistics for description and error detection, and

(v) the calculation and statistical description of proved or experimental derived data, such as normals and eigenvector coefficients.

Examples of computation. The following are examples of different applications.

(i) Computed average fields are printed out by means of the 'zebra chart print facility' in which the chart appears in clear and printed stripes, and the contours are drawn by running a pencil or pen along the edge of the stripes. This output may be less elegant than that of the computerized line-drawer, but it is very much quicker and simpler, and the final stages of chart analysis make a break in the monotony of handling endless arrays of figures.

(ii) As an example of a routine computation carried out fortnightly, we may take the selections of analogues by means of Lamb's weather catalogue. The stages are as follows :

(a) The series of daily weather types for the past 30 days is matched against those for the same dates in a preceding year, the measure of similarity being judged by a carefully designed scoring table.

(b) The comparison is repeated, using a shift backwards or forwards of up to 14 days, and the best of the 29 values taken to represent the year.

(c) Stages *(a)* and *(b)* are repeated for all past years from 1873 to 1968.

(d) The year scores are considered, their mean and standard deviation are found, and all scores are normalized in units of the standard deviation.

(e) The years are ranked in order of merit, and for all years the year numbers, scores and shifts are placed ready to print.

(f) Stages *(a)* to *(e)* are repeated three times more using scoring tables designed to measure the northerliness, the blocked character or the cyclonicity.

(g) The results are printed out in tables, ready for consideration, with other evidence, by a panel of forecasters.

(iii) A major research calculation, using some of the 500-mb data, has been described by Craddock and Flood (1969); this forms the basis of much work now in progress. One of the essential steps, carried out in three operations, consisted in the extraction of 130 wanted items from each of over 6000 arrays of 592, the detection and estimation of missing values, and their conversion into a covariance matrix of order 130. This was one of the few (less than 20) operations carried out by the Synoptic Climatology Branch which required a full claim (of 120K bytes) of the core store of the KDF 9 computer. Following this work, the daily values of the 50 next important eigenvectors have been found for every day since 1 January 1949, and have then been sorted into yearly blocks, stored, and used to produce routine statistics. Completion of the work must be delayed pending the elucidation of some impossible values in the earlier years, as mentioned on pages 222 (i) and 228.

(iv) The importance of these 500-mb data makes it desirable to obtain estimates of the same fields for years before 1949, and the efforts to do this described below have proved surprisingly successful.

Comparisons of the fields of the monthly mean anomaly of MSL pressure with the anomalies of 1000–500-mb thickness show that a substantial negative pressure anomaly is usually accompanied by a negative thickness anomaly some 10 degrees further west, and somewhat further north. The data for the recent years for which both measurements are available have been used by Ratcliffe and Collison to produce regression equations which enable the thickness anomaly patterns to be estimated from the MSL pressure anomaly patterns for earlier years. Adding the observed MSL pressure anomaly fields to the estimated thickness anomaly fields gives an estimated 500-mb anomaly field. These fields when used as the basis for selecting analogues of the 500–mb field produce results which appear to have predicitive value.

These examples of the application of the digitized data bank could be multiplied almost indefinitely; the fact is that it has enabled the Synoptic Climatology Branch to reach a state of something near full productivity, but attention must now be given to the important if uninspiring problem of the reduction of data to common standards, and the elimination of errors. This is illustrated by the case history which follows.

A case history of important data. The fields of 500-mb height, mentioned on page 222 (i) and in (iv) above, provide what is probably the most important single diagnostic of the current state of the atmosphere, and the fields of the 1000–500-mb thickness which represent the mean thermal distribution in the greater part of the troposphere are almost equally important.

Charts of these elements have been produced daily since the 1940s, and from 1 January 1949 the values for the points of the German Upper Air Grid were punched on Hollerith cards, 36 cards per chart. Copies of these cards for each day of the years 1949 to 1964 were received by the Meteorological Office from the Deutscher Wetterdienst in exchange for other data, and were transferred to magnetic tape (in blocks of 592 numbers per chart). From 1965 to date, the values from similar charts produced in the British Central Forecasting Office have been read by the Synoptic Climatology Branch at the points of the German Upper Air Grid, punched on paper tape, and transferred to magnetic tape, so that a homogeneous series of fields is stored from 1 January 1949 up to date.

These data, which are stored on four magnetic tapes and regularly updated, are in constant use for the production of time-mean charts for forecasting purposes. A series of the printed versions of the daily charts is kept, but the time-mean charts are discarded after use. These data were checked thoroughly before use, in the way described in the next paragraph, and formed the basis for the large-scale eigenvector analysis described by Craddock and Flood (1969). Once the eigenvectors had been found, daily values of the coefficients of the 50 most important were calculated, sorted into yearly blocks and stored permanently. The calculation of descriptive statistics for these coefficients and the investigation of their interrelationships is still in progress. The scope of this work was limited by shortage of data over the Pacific Ocean, and this deficiency has been reduced by means of data received on magnetic tape from the Japanese Meteorological Agency. These data, before being usable, had to be converted in a manner similar to that used on the German data, but with a complete rearrangement in addition.

Quality control and the correction of errors. The importance of quality control, or the detection of errors and missing or incredible values in data, increases with the size of the data bank. A scientist working on 1000 data has some excuse for thinking that by taking enough care he can ensure that his data are entirely free from error; he can if he wishes, give individual attention to every digit. His colleague with a data bank of 100 million digits (about the number of letters used in the *Encyclopædia Britannica*) can never give his attention to more than a tiny fraction of the total and must realize that some errors may have escaped all previous attempts to eliminate them. For example, the punched cards bearing the 500-mb data discussed in the last paragraph were certainly checked before they left Germany, but the data were tested again after transfer to magnetic tape by comparing every value with the mean and standard deviation for its position and time of year. This check revealed about 40 discrepancies which could be ascribed with some confidence to punching errors. These were corrected, but the analysis of Craddock and Flood (1969) showed that one of the 250 000 punched cards must have been lost at some stage. Later the calculation of eigenvector coefficients produced impossible values for a few fields in the years 1949, 1950 and 1957, so that there is still something to be explained. More recently, Colgate has developed a new and very effective method of error control, in which the field as originally punched is compared with a similar field reconstituted from the coefficients of the 40 most important eigenvectors. This method serves to detect errors which would have escaped previous checking procedures, and is being applied as a routine to all new 500-mb fields as they are added to the data bank. The task of applying it to past data remains for the future.

The question of error control has always been important to synoptic meteorologists who receive their data by telecommunication. There is enough redundant information in most weather messages to allow most of the important errors to be picked out if the data are plotted on a chart, but this protection loses its value if the data are digitized for storage in a way which, although it does not preclude spatial comparisons, makes it difficult for the future investigator to carry them out. The recommendation of the World Meteorological Organization, expressed in *World Weather Watch Planning Report* No. 28 (1969) is that effective quality control of all data should take place when data first enter the world's meteorological archives, but the attainable standards have yet to be determined, and in any case, they can only apply to new accessions to the world's data banks, and not to data which have been digitized in the past. The quality control of meteorological data has been discussed by, among others, Sumner (1969) and Filippov (1968) who quotes the experience of several of the world's main centres for meteorological telecommunications. Their evidence suggests that when land data are punched by professional meteorological staff, one wrong digit is punched on average in every 1000 to 2000. Thus it would appear, if all errors were equally likely, that a system of double punching with comparison should reduce the error rate to one in from 10 million to 40 million. Unfortunately, all errors are not equally likely; for example, an error in which two figures are reversed or in which, say 557 is punched for 577, has far more than the average probability of occurrence. Moreover, figures which are badly made, or smudged in the original document may be misread twice.

Computerized quality control is possible by comparing data against statistical standards such as means and standard deviations, by internal checks between related data in the same observation, by spatial or temporal comparisons between observations, or by the more sophisticated eigenvector technique mentioned on page 228. All methods take time, and all share the feature that the most the computer can do is to indicate a certain value as being probably or certainly wrong, and perhaps to suggest a reasonable replacement value. Moreover, while the computer can be programmed to treat certain values as acceptable, and others as quite incredible, there is bound to be a penumbra of values, including the genuine extremes of the measurement in question, which lie outside the usual limits but may nevertheless be accepted in view of supporting evidence from other sources. In these cases at any rate the question whether to accept the suspected value must be a matter for human judgement, so that the computer must be programmed to retain values which are suspect but not incredible until judgement can be passed on them. Thus while error detection, or the identification of doubtful values, can be computerized to a large extent, error correction remains largely a matter for man, and therefore one which progresses at the working pace of the human mind.

Besides the more obvious types of error, such as punching errors, which occur often enough to be recognized and provided for in computerized schemes of error detection, a very large digitized data bank is liable to contain examples of extremely improbable errors which at first sight should never occur, and against which protection could be secured only at extravagant cost. The work of Badger and Lyness (1969), which describes some meteorological statistics prepared for the gas industry, gives three examples of such errors. In one the data for a whole year were wrongly ascribed to another, in the second the punching instructions had been misunderstood when part of a long record was punched, and in the third a number of data were presented in the wrong order. In each case the mistake, unless detected almost at once, is liable to escape notice until an analysis is carried out which produces peculiar results casting suspicion on these data. Because of the risk of individually improbable errors, it is worthwhile, when planning an investigation based on a large data bank, to produce results in parallel from sections of the data. Results which confirm one another by falling into a reasonable statistical distribution may be pooled to produce results based on the whole evidence, whereas anomalous results can be recognized and given individual attention.

Comments and conclusions. Our conclusion is that the scientist who relies on a digitized data bank for raw material must learn to live with data which are not error free. He must devote some effort to trying to ensure that his data are up to standard, and must plan his work on robust lines, so that a few undetected errors do not lead to catastrophe. His method of computer control, be it macrolanguage or package of subroutines, must be able to cope with problems of the extraction, correction and manipulation of data as well as with those of the intended field of study and must be capable of switching from one type of operation to another with fluency and dexterity. The METO language described by Craddock (1966 *(b)*) and Craddock and Freeman (1967) is one example of the type of tool required for building up and using a digitized data bank on the scale described, and the best evidence of its efficiency is the bibliography which follows.

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PSCM INDICES IN SYNOPTIC CLIMATOLOGY AND LONG-RANGE FORECASTING

By R. MURRAY and P. R. BENWELL

Summary. The *PSCM* indices of Murray and Lewis have been recomputed from a revised and extended Lamb catalogue of daily synoptic types near the British Isles. Long-term and seasonal variations of synoptic types and the correlations of the indices with rainfall and temperature are discussed. Examples of the usefulness of the indices in specifying large-scale circulation anomalies and in weather forecasting on the monthly and seasonal time-scales are presented.

Introduction. The *PSCM* indices, which were introduced by Murray and Lewis,[1] are intended to measure in a succinct and meaningful way the main characteristics of the synoptic situation over long periods from the daily weather types over the British Isles in the catalogue prepared by Lamb.[2]

Since the original work on these indices was carried out, Lamb[3] has reclassified the daily synoptic maps and extended his catalogue back to 1861. This reclassification was desirable in order to homogenize the series since most of the earlier catalogue did not include the south-east, north-east or south-west directional types. The definitions of, and the detailed procedure for obtaining, the indices have not been changed and they are given in the earlier paper.[1] Here it need only be mentioned that the *P* index is a measure of the difference in frequency of days of progressive and days of blocked synoptic types — *P* is positive when the bias is towards progressive synoptic types. The *S* index aims to measure the difference in frequency of southerly and of northerly days over or near the British Isles — *S* is positive when the bias is southerly. The *M* index measures the frequency of days with meridional (i.e. northerly or southerly) synoptic types over the British Isles. The *C* index gives in effect the difference between frequency of cyclonic and of anticyclonic days over the British Isles — *C* is positive when cyclonic days predominate. The ranges over which the indices occur are readily seen in the Appendices. In the present article recomputed values of various quantities and some new synoptic-climatological material related to the indices are presented.

Seasonal and long-term variations.

(i) *Index of progression, P.* The long-period mean values of the *P* index in Figure 1 confirm the marked seasonal variation in progressiveness near the British Isles. Progressive synoptic types predominate in winter (maximum

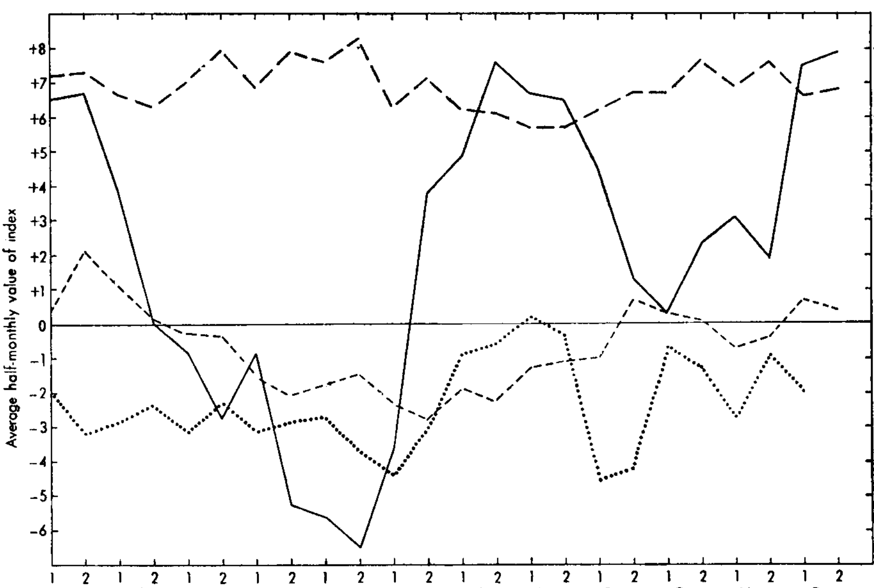

FIGURE 1—AVERAGES OF HALF-MONTHLY VALUES OF *P*, *S*, *C* AND *M* INDICES FOR THE 100-YEAR PERIOD 1865–1964

On the abscissa the period 1st to 15th of each month is indicated by 1 and the remainder of the month by 2.

——— *P* - - - - *S* .... *C* — — — *M* in the second half of December — called, for convenience, late December) and in summer (maximum in late July). Non-progressive or blocking synoptic types are evidently at a maximum in late May with relative maxima of blocking in late March and early October. Examination of the frequencies of half-month periods with $P \geqslant 0$ and with $P < 0$ show only slight changes in the pattern suggested by Figure 1. The winter maximum frequency of $P \geqslant 0$ is actually 72 per cent in early December but the frequency is near 70 per cent from late December to late January; the summer maximum occurs in early July (71 per cent) but the frequency is generally near 70 per cent throughout July and August. The maximum frequency of blocking ($P < 0$) is in early May (67 per cent) but the frequency is only slightly less in late April and late May; relative maxima of blocking occur in late March (58 per cent) and early October (52 per cent) as suggested also by Figure 1.

It is noteworthy that there is a sudden increase in progressiveness from early to late June, shown in Figure 1, related to the development of the so-called European monsoon. Other noteworthy changes in progressiveness are the decrease from early to late February and the increase from late November to early December.

TABLE I—MEAN ANNUAL VALUES OF P, S, C AND M INDICES IN 5-YEAR PERIODS FROM 1865 TO 1969

Period	*P*	*S*	*C*	*M*
1865–69	76	-35	-78	160
1870–74	50	-16	-42	168
1875–79	10	-21	-15	173
1880–84	68	22	-53	185
1885–89	-19	-29	-73	171
1890–94	34	-17	-77	181
1895–99	21	-18	-97	164
1900–04	56	3	-55	180
1905–09	73	-24	-74	156
1910–14	47	2	-44	159
1915–19	40	-48	-43	164
1920–24	149	10	-28	154
1925–29	86	-13	-36	165
1930–34	47	-14	-55	155
1935–39	35	-19	-46	153
1940–44	65	-31	-84	162
1945–49	40	14	-78	144
1950–54	117	-39	-35	161
1955–59	-23	-24	-89	184
1960–64	22	-15	-43	173
1965–69	-24	-37	-25	168

Analysis of the mean annual data in 5-year periods shown in Table I demonstrates the existence of pronounced long-term variations. A maximum of progressiveness occurred in 1920–24, largely arising from great progressiveness in winter and summer, and minima occurred in 1965–69 and 1955–59. The maximum of 1920–24 was within the longest run of years with positive values of *P*, namely the 17 years from 1916 to 1932. It is of interest that the longest run of years with negative *P* was from 1958 to 1960. It is also noteworthy that a very large change in the mean values of *P* took place from 1950–54 to 1955–59. Ratcliffe and Murray[4] have shown that progressive synoptic types near the British Isles are associated with higher than usual sea temperatures near Newfoundland and that the blocked types are associated with the lower than usual sea temperatures. It is of interest to note that almost all months in 1950–54 had higher than usual sea temperatures near Newfoundland, whereas in 1955–59 the sea was generally colder than usual. In the recent past a remarkable change in progressiveness occurred from 1967 ($P = 117$) to 1968 ($P = -99$). These examples should be a warning that large changes from year to year or from one group of years to the next could well happen again.

The seasonal changes (averaged over 100 years) shown in Figure 1 are of course not exactly reproduced every 5-year period. Nevertheless, the half-month maximum of progressiveness over the year occurred in July/August or December/January in most cases, the main exceptions being early March 1875–79 (mean $P = 14$) and early May 1960–64 (mean $P = 13$). Moreover, the yearly maximum of blocking (minimum in P index) every 5-year period was generally a feature sometime between late February and early June, but the yearly maximum occurred in late September in 1905–09 and in early October in 1865–69 and 1910–14.

(ii) *Indices of meridionality, S and M.* The seasonal variations of the S index (southerly bias being positive) are shown in Figure 1. The bias to northerliness in spring and summer and also in late autumn and to southerliness from late September to late October and in winter (especially late January) is quite obvious. Examination of the half-monthly values shows that the maximum frequency of negative S (northerly bias) reaches 65 per cent in late July rather than in late June as suggested by Figure 1, but relative maxima of 63 and 61 per cent occur in late June and late April respectively, in agreement with the indications from Figure 1. Moreover, northerly bias reaches a minimum frequency of 35 per cent in late January.

Long-term changes in the S index are suggested by Table I. The most southerly and the most northerly periods were 1880–84 and 1915–19 respectively. Notable changes from southerly to northerly bias took place from 1880–84 to 1885–89 and from 1945–49 to 1950–54 and the reverse from 1915–19 to 1920–24.

Meridionality (M index) is least in August and generally low in the summer, and greatest in late May and rather high in spring and late autumn, as shown in Figure 1. Figure 1 also shows most meridionality in 1880–84 and least in 1945–49, and it is of interest that both periods were associated with notable southerliness.

(iii) *Index of cyclonicity, C.* Positive values of C indicate a bias to cyclonic types and negative values a bias to anticyclonic (or to less cyclonic than usual). The seasonal variation (averaged over 100 years) is shown in Figure 1.

A well-defined maximum of cyclonicity occurs in early August and minima of cyclonicity (or maxima of anticyclonicity) occur in early June and early September. The frequency of occurrence of $C \geqslant 0$ in half-month periods falls from 56 per cent in the early August maximum to 33 per cent in the early September minimum. There appears to be a relative minimum of the C index in early November which was not in evidence in the monthly data presented by Murray and Lewis.[1]

The changes in the annual mean values of the C index over the long period are shown in Table I. The most cyclonic period was 1875–79 and the most anticyclonic period was 1895–99.

Quintiles and extremes. Quintile boundaries were computed for the 100 years from 1869 to 1968 for various periods from a half-month to a season. Monthly and seasonal data are presented in Appendix I and some extreme values of the indices in Appendix II. These will not be discussed here.

Association between the indices and rainfall. In the earlier paper[1] the association between C and R (average monthly rainfall over England and Wales) was demonstrated by means of contingency tables. It was pointed out that the correlation was generally good between C and R each month but much weaker between P and R and between S and R. Subsequently, from district data for the period 1926 to 1966, Perry[5,6] showed the spatial variation of the relationships over the British Isles. The revised data have been correlated against monthly rainfall over England and Wales (R) and against monthly rainfall over Scotland (R_s).

For England and Wales C has a highly significant correlation with R for every month — the correlation coefficient ranging from 0·87 in July to 0·77 in May. P and R are significantly correlated at the 5 per cent level only in February (0·39), September (0·24) and November (0·28), but their correlations are much lower than those for C and R. Significant correlations obtain between S and R in January (0·25), June (0·39) and December (0·26). M and R are not significantly correlated in any month. Multiple correlation coefficients between R and P, S and C were computed for each month, but these do not differ significantly from the simple correlation coefficients between R and C.

Similar correlations were computed between Scottish rainfall (R_s) and the indices. C and R_s are very significantly correlated each month — the correlation coefficient ranging from 0·75 in September to 0·50 in March. These are all lower than the corresponding correlation coefficients between C and R. However, R_s and P are also very significantly correlated each month (the correlation coefficients vary from 0·72 in February to 0·35 in July). Thus there is a much better correlation between P and R_s than between P and R at all seasons. The biggest difference between the correlation coefficients applies in March when $r(P, R) = 0{\cdot}08$ and $r(P, R_s) = 0{\cdot}68$, but there are quite large differences in all the other months. It is synoptically reasonable that rainfall over Scotland is much more closely related to the progressiveness of the synoptic types over the British Isles than is rainfall over England and Wales. There are three significant correlations between S and R_s, namely in June (0·38), July (0·29) and December (0·25) — these are about the same size as the correlation coefficients between S and R. Unlike the M and R case, the correlations between M and R_s are significant at the 5 per cent level in four months, namely January (– 0·28), February (– 0·21), March (– 0·28) and November (– 0·26). The correlation coefficients between M and R_s in these and in the other eight months are all negative, which is to be expected in view of the inverse correlation between P and M. Multiple correlation coefficients were next computed between R_s and P, S and C; these are bigger than the largest simple correlation coefficient and range from 0·847 in February to 0·692 in May. This should be contrasted with the England and Wales case where the C index alone gives the main information about general raininess.

Association between the indices and temperature. Murray and Lewis[1] discussed the associations between central England* monthly mean temperatures and the indices, and subsequently Perry[5,6] showed the variations of the relationships over different parts of the United Kingdom from an analysis of district data for the period 1926 to 1966. In the present paper the discussion is based on correlations between the indices and monthly mean temperature at stations with long records over the United Kingdom, namely Plymouth, Kew, Oxford, Cambridge, Aberystwyth, Edgbaston, York, Scarborough, Durham, Armagh, Dumfries, Edinburgh, Aberdeen and Braemar, as well as at stations representative of central England.*

Table II lists the correlation coefficients applicable to central England.

TABLE II—CORRELATION COEFFICIENTS BETWEEN MONTHLY MEAN TEMPERATURE, T, IN CENTRAL ENGLAND AND P, S, C AND M INDICES, WITH MULTIPLE CORRELATION COEFFICIENTS BETWEEN T AND P, S AND C FOR THE PERIOD 1869–1968

T correlated with :	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
P	0·79	0·77	0·60	0·24	(0·03)	(–0·11)	(–0·12)	–0·24	(–0·03)	(0·10)	0·51	0·61
S	0·34	0·34	0·52	0·48	0·65	0·30	0·39	0·46	0·66	0·62	0·59	0·45
C	0·20	0·20	(–0·07)	–0·28	–0·22	–0·39	–0·55	–0·52	–0·27	(–0·01)	0·23	0·23
M	–0·33	(–0·16)	–0·28	–0·24	–0·28	–0·34	–0·22	(–0·05)	–0·28	(–0·13)	–0·23	(–0·09)
PSC	0·84	0·81	0·82	0·66	0·73	0·54	0·70	0·73	0·70	0·64	0·74	0·77

Correlation coefficients in brackets are not significant, correlations in bold are significant at the 1 per cent level, and the rest are significant at the 5 per cent level.

The main features of Table II are the positive correlations between S and T in all months, the positive correlations between P and T and between C and T in the colder part of the year and the negative correlations between C and T in the summer half-year. The best correlations in individual months are (i) between P and T in December, January, February and March, (ii) between S and T in April, May, September, October and November and (iii) between C and T in June, July and August. These results agree with the conclusions of Murray and Lewis.[1] The correlations (negative) between M and T are never greater (in absolute magnitude) than the correlations between T and any one of the indices P, S and C each month. In every month the multiple correlation coefficients, shown in the bottom line of Table II, are greater than any of the simple correlation coefficients. The highest multiple correlations occur in winter months and the lowest in June.

The regression equation for January mean temperature (T expressed in degrees Celsius) is

$$T = 2{\cdot}753 + 0{\cdot}058P + 0{\cdot}054S + 0{\cdot}006C. \qquad \ldots (1)$$

In equation (1) P, S and C can be positive or negative within the range given in Appendix I. Clearly if P, S and C are all large positive values, as is the case when progressive, cyclonic and southerly types are dominant over the month, then high temperatures occur over central England. Very cold weather in January is of course associated with negative values of the indices, i.e. when blocked, northerly and anti-cyclonic types predominate. However, it is also evident that particular temperatures can be associated with quite

* Manley, G.; The mean temperature of central England 1698–1952. *Q. Jnl R. met. Soc., London*, **79**, 1953, p. 242-261.

different types of monthly circulations in view of the range of possibilities for *P, S* and *C*.

The regression equation for August is

$$T = 15{\cdot}816 - 0{\cdot}009P + 0{\cdot}077S - 0{\cdot}035C \; . \qquad \ldots (2)$$

This equation confirms that the highest August temperatures are associated with blocked (negative *P*), southerly (positive *S*) and anticyclonic (negative *C*) weather types and the lowest temperatures with progressive, northerly, cyclonic weather types over the British Isles. In August the *C* and *S* indices are much more important than the *P* index, whereas the opposite is the case in January.

The *P, S, C* and *M* indices were correlated with monthly mean temperatures at other places scattered over the United Kingdom. At these stations, readily available temperature records covered 90 years or more. Correlation coefficients for a few stations are given in Table III; the data in this table, together with Table II, are sufficient to portray the main features of the spatial distribution of the correlations over the United Kingdom.

Examination of Table III in relation to Table II and data for other stations which are not reproduced, allows some generalizations to be made. Mean monthly temperatures over the United Kingdom are positively correlated with *P* from November to April, with the highest values in winter. Correlations are insignificant in May and October, but negative and rather weak from June to September over most districts except eastern parts of Britain. Temperature is, not surprisingly, positively correlated with *S* everywhere in all months, but the highest correlations are in May, September, October and November. Temperature is negatively correlated with *C* from April to September in all areas, with the largest negative correlations in high summer; clearly a mainly cyclonic month is generally cloudy and cool and an anticyclonic month is usually bright and warm in the summer half-year. In winter the situation is different. Cyclonic systems over the British Isles are obviously colder in the north than in the south. On the other hand, anticyclonic systems are much more likely to be colder in the southern and central areas than in the far north, owing to the greater coldness from continental winds and the greater likelihood of clear skies and radiational cooling. Thus it is not surprising that *T* and *C* are positively correlated over most of England and Wales and negatively correlated farther north from November to February, although the correlations are generally insignificant except in the south and in the far north. March and October are transitional months when weak negative correlations extend south over all areas except south-eastern England. Finally, temperature and *M* are mostly negatively correlated, as suggested by Braemar and central England data; the correlations are quite insignificant in August and December and usually small in other months.

The multiple correlation coefficients for Edinburgh are about the same size as for central England, the largest being 0·84 in January and the lowest 0·56 in June. The regression equation for January mean temperature at Edinburgh is

$$T = 2{\cdot}479 + 0{\cdot}050P + 0{\cdot}049S - 0{\cdot}034C \; . \qquad \ldots (3)$$

TABLE III—CORRELATION COEFFICIENTS BETWEEN MONTHLY MEAN TEMPERATURES, T, AT SPECIFIED PLACES AND CERTAIN P, S, C AND M INDICES

Place	T correlated with	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Braemar 1866–1966	P	**0·70**	**0·64**	**0·49**	0·24	−0·07	−0·19	(−0·18)	−0·28	−0·22	(−0·05)	**0·36**	**0·50**
	S	**0·37**	0·25	**0·34**	**0·34**	**0·48**	(0·15)	0·25	**0·37**	**0·62**	**0·57**	**0·53**	**0·45**
	C	−0·23	−0·24	**−0·37**	**−0·53**	**−0·35**	**−0·41**	**−0·53**	**−0·56**	**−0·40**	**−0·26**	(−0·12)	−0·20
	M	**−0·37**	(−0·18)	**−0·29**	−0·21	**−0·27**	−0·25	(−0·10)	(0·02)	(−0·18)	(0·05)	(−0·13)	(−0·13)
Armagh 1871–1966	P	**0·71**	**0·67**	**0·47**	**0·28**	(−0·11)	−0·20	−0·20	**−0·36**	(−0·06)	(−0·03)	**0·38**	**0·46**
	S	**0·37**	**0·39**	**0·49**	**0·34**	**0·52**	(0·16)	**0·32**	**0·32**	**0·65**	**0·60**	**0·57**	**0·49**
	C	(−0·08)	(−0·07)	**−0·29**	**−0·44**	**−0·39**	**−0·41**	**−0·52**	**−0·61**	**−0·35**	**−0·27**	(−0·15)	(−0·10)
Scarborough 1872–1966	P	**0·75**	**0·66**	**0·60**	**0·35**	(0·18)	**0·27**	0·25	(−0·05)	(0·13)	(−0·04)	**0·31**	**0·38**
	S	**0·30**	0·23	**0·36**	0·25	**0·52**	(0·15)	**0·42**	**0·39**	**0·57**	**0·56**	**0·51**	**0·41**
	C	(0·09)	(0·00)	−0·24	**−0·31**	(−0·11)	**−0·32**	**−0·28**	**−0·43**	−0·23	(−0·15)	(−0·05)	(0·06)
Plymouth 1865–1966	P	**0·75**	**0·73**	**0·50**	(0·08)	(−0·11)	(−0·11)	−0·23	**−0·35**	(−0·08)	(−0·04)	**0·46**	**0·55**
	S	**0·41**	**0·41**	**0·59**	**0·38**	**0·45**	(0·06)	(0·15)	**0·25**	**0·53**	**0·65**	**0·62**	**0·51**
	C	**0·26**	**0·32**	(−0·06)	**−0·31**	**−0·34**	**−0·56**	**−0·62**	**−0·64**	**−0·36**	(−0·11)	0·20	**0·34**
Edinburgh 1869–1959	PSC	**0·84**	**0·83**	**0·82**	**0·76**	**0·68**	**0·56**	**0·58**	**0·69**	**0·76**	**0·68**	**0·72**	**0·73**

Correlation coefficients in brackets are not significant, correlations in bold are significant at the 1 per cent level, and the rest are significant at the 5 per cent level. Data were complete within the periods shown at Armagh and Edinburgh, but a few monthly mean temperatures were missing at the other stations.

This equation implies that progressive, southerly, anticyclonic months have the highest mean temperatures at Edinburgh in January, whereas blocked, northerly, cyclonic months are the coldest.

The regression equation for August temperature at Edinburgh is

$$T = 14{\cdot}455 - 0{\cdot}003P + 0{\cdot}067S - 0{\cdot}033C\,. \qquad \ldots (4)$$

From equation (4) it is inferred that the warmest Augusts are those with considerable blocking, southerly bias and anticyclonicity, whereas the coldest months are progressive, northerly and cyclonic.

The indices as indicators of anomalous circulation. The *PSCM* indices are very useful as parameters for specifying large-scale anomalous circulations, such as might be indicated by monthly or seasonal pressure anomaly maps. Examples of mean pressure anomaly maps for one-, two- and three- monthly periods are shown in Figures 2, 3 and 4 respectively.

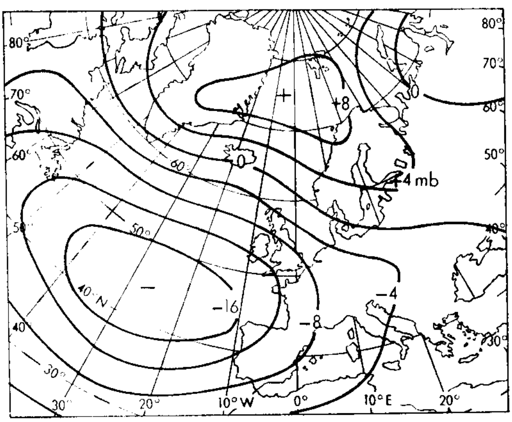

FIGURE 2—MONTHLY MEAN PRESSURE ANOMALIES FOR JANUARY 1970

Anomalies are departures from monthly averages for the period 1873–1968.

January 1970 is classified as P_1 S_5 C_5 M_5 or very blocked, southerly, cyclonic and meridional. P_1 and S_5 together indicate an anomalous bias to south-easterly. The fact that both S and M are in quintile 5 suggests that southerly types predominated and that some northerly types also occurred, or that the southerly types were extremely frequent. The mean pressure anomaly map, Figure 2, is quite consistent with the *PSCM* indications. The very wet period from September to October 1967 is classified as P_5 S_4 C_5 M_1 or progressive, southerly and cyclonic but less meridional than usual. P and S together imply much more west to south-west flow than usual, but little or no northerly in view of M_1. Much more cyclonic weather than usual is indicated by C_5; and from this index in conjunction with P_5 it is inferred that very unsettled weather predominated with depressions often moving east or north-east over or near the north of Britain. The anomaly pattern shown in Figure 3 clearly gives much the same picture as the P_5 S_4 C_5 M_1 classification. The seasonal example shown in Figure 4 refers to the fine summer of 1947. The positive anomaly centre over south Norway and the pronounced south-easterly anomalous flow over Britain agree well with the index classification of $P_1\ S_5\ C_1\ M_1$. In general it has been found that the main features of the large-scale circulation as shown by pressure anomaly patterns near the British Isles are well represented by the *PSCM* indices in quintile classes except when the circulation is not very abnormal.

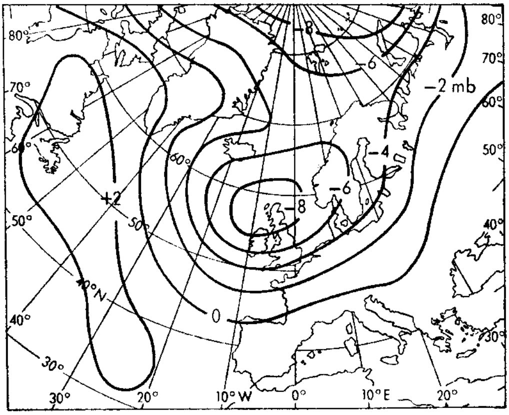

FIGURE 3—MEAN PRESSURE ANOMALIES FOR SEPTEMBER/OCTOBER 1967
Anomalies are departures from two-monthly averages for the period 1873–1968.

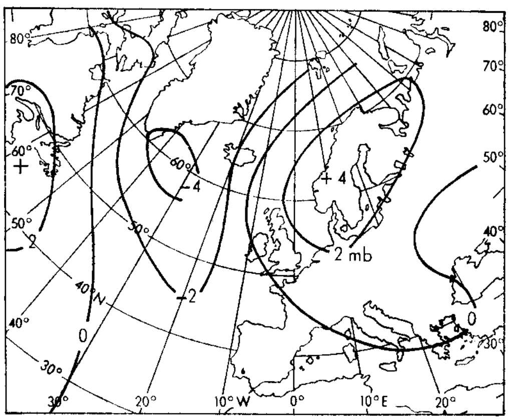

FIGURE 4—SEASONAL MEAN PRESSURE ANOMALIES FOR SUMMER 1947
Anomalies are departures from seasonal averages for the period 1873–1968.

Applications of the indices in long-range forecasting. The indices have been employed in recent years in helping to select monthly analogues. They may also be used in seasonal forecasting. The indices are particularly useful in this respect when the large-scale circulation over the Atlantic and Europe is very anomalous. Classes of years with broad-scale similarity in circulation over periods of from one to three months can readily be selected with the help of the indices. In practice it is not generally possible to obtain an adequate statistical sample of analogues if close similarity in each index is insisted upon. However, useful results have been obtained by selecting analogues from pairs of the indices when they suggest broadly similar anomalous circulations. The weather in the sequel period can readily be obtained and in many cases rainfall and/or temperature tend to have dominant characteristics. One or two cases have already been described by Murray.[7,8] It is not proposed to give a comprehensive account here, but another illustration may be appropriate.

Years with springs in which the predominant synoptic types are progressive and anticyclonic may be selected as those with quintiles 4 or 5 in P and 1 or 2 in C. For brevity these may be called $P_{45}\ C_{12}$ springs. Such springs are rarely followed by cool summers over central England. On the other hand blocked, cyclonic or $P_{12}\ C_{45}$ springs are rarely followed by warm summers.

TABLE IV—FREQUENCY OF QUINTILES OF MEAN TEMPERATURE IN SUMMER OVER CENTRAL ENGLAND AND OF TERCILES OF RAINFALL OVER ENGLAND AND WALES FOLLOWING SPRINGS SELECTED BY SPECIFIED COMBINATIONS OF P, S AND C INDICES. MEAN SUMMER TEMPERATURE FOR EACH GROUP IS ALSO GIVEN

	Spring type	No.	Temperature quintile					SUMMER Mean temperature	Rainfall tercile		
			1	2	3	4	5	°C	1	2	3
(a)	$P_{45}C_{12}$	18	0	3	5	5	5	15·64	8	7	3
(b)	$P_{12}C_{45}$	13	4	4	4	1	0	14.68	3	3	7
(c)	$S_{45}C_{12}$	18	0	3	4	5	6	15·71	7	8	3
(d)	$S_{12}C_{45}$	15	5	2	4	3	1	14·91	5	2	8

Temperature quintile boundaries (1 is very cold) are based on data for the period 1874–1963 with no allowance made for long-term change. Rainfall tercile boundaries (1 is dry) are based on the period 1866–1965.

Table IV contains the summer mean temperature and rainfall following four types of spring, but only the temperature will be discussed. There is a marked difference in the frequency distribution of summer temperatures between *(a)* progressive, anticyclonic springs and *(b)* blocked, cyclonic springs. There is also a marked difference between the contrasting springs of type *(c)* southerly, anticyclonic and *(d)* northerly, cyclonic. However, the data in these 5×1 tables are insufficient for statistical testing by the chi-square test. Nevertheless, t-tests carried out on the average summer temperatures show that there is a highly significant difference between the *(a)* and *(b)* temperatures and between the *(c)* and *(d)* temperatures.

Since *(a)* and *(c)* tend to be associated with warm summers and *(b)* and *(d)* with cool summers, it was decided to classify springs into two types: (i) $P_{45}\ S_{45}\ C_{12}$ or progressive, southerly, anticyclonic and (ii) $P_{12}\ S_{12}\ C_{45}$ or blocked, northerly, cyclonic. These criteria drastically reduced the number of cases. There are only five springs of type (i), namely 1868, 1914, 1933, 1943 and 1945; four of the summers of these years were warm $(T_4$ or $T_5)$ and one was average (T_3). Only three type (ii) springs are in the record, namely 1888, 1891 and 1951; the first two were cool (T_1 and T_2 respectively) and 1951 was on the boundary between T_2 and T_3. Incidentally, none of the type (i) summers was wet and none of the type (ii) summers was dry.

More stringent criteria for selecting springs could be adopted, for instance by insisting on only extreme quintiles in the indices, but then the number of cases is reduced even further.

Concluding remarks. These revised and extended data confirm and refine the synoptic climatology which was presented in earlier papers.[1,5,6]

The *PSCM* indices are of course only one way of looking at the broad-scale circulation. Recently Hay[9] has employed monthly mean pressure maps for classifying synoptic types near the British Isles, and his results have a good deal in common with the work on *PSCM* indices. However, the indices have some advantages such as the ease of computation for any period, for example for 30 days from mid-month or for 90 days, etc. Moreover, they appear to reflect well the main features of the daily synoptic types and the percentile form of the indices is particularly suitable for relating them to anomalous features of the broad-scale circulation which are better represented by mean pressure anomaly maps than by mean pressure maps.

The *PSCM* indices are useful in long-range forecasting but of course they should generally be considered with other procedures, such as the approach through sea temperature anomaly patterns recently suggested by Ratcliffe and Murray.[4]

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Appendix I

Quintile boundary values of *P, S, C* and *M* for *(a)* each month and *(b)* each season, based on the 100 years from 1869 to 1968.

(a) Month

Index	Boundary	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
P	5–4	35	31	20	11	5	15	34	34	24	25	23	36
	4–3	17	8	9	−4	−4	5	17	22	13	8	11	24
	3–2	10	−4	−8	−13	−19	−6	8	8	−2	−4	3	13
	2–1	−2	−23	−28	−21	−28	−16	−4	−8	−13	−22	−14	0
S	5–4	12	11	9	5	5	3	2	4	7	9	8	10
	4–3	7	5	3	1	0	−2	−2	0	3	4	3	4
	3–2	0	0	−5	−5	−5	−5	−6	−3	−1	−2	−4	−1
	2–1	−7	−9	−11	−10	−11	−11	−10	−7	−6	−5	−9	−6
C	5–4	6	9	10	6	6	5	12	15	3	9	10	7
	4–3	0	−1	−1	−2	−2	−2	5	6	−3	0	1	2
	3–2	−7	−10	−11	−9	−9	−8	−4	−3	−9	−8	−5	−5
	2–1	−16	−17	−17	−15	−16	−17	−14	−13	−20	−17	−16	−13
M	5–4	21	19	21	21	22	18	20	16	18	20	20	19
	4–3	16	15	18	17	18	14	15	13	14	15	16	15
	3–2	12	12	14	14	15	11	11	10	12	12	12	20
	2–1	9	7	10	11	11	9	8	7	8	8	8	9

(b) Season

		Winter	Spring	Summer	Autumn
P	5–4	69	5	57	51
	4–3	45	−16	33	26
	3–2	32	−32	23	0
	2–1	−7	−49	−7	−24
S	5–4	18	5	3	11
	4–3	11	−4	−7	3
	3–2	3	−12	−14	−4
	2–1	−9	−19	−23	−16
C	5–4	12	4	15	6
	4–3	−8	−7	1	−10
	3–2	−20	−23	−10	−22
	2–1	−34	−39	−27	−36
M	5–4	52	57	46	50
	4–3	44	50	40	44
	3–2	39	43	36	39
	2–1	33	37	30	32

Note: Quintile 5 applies when index value is $\geqslant$ boundary 5–4, quintile 4 when it is $\geqslant$ boundary 4–3 and $<$ boundary 5–4, etc.

Appendix II

Extreme values of *P*, *S*, *C* and *M*, with dates of occurrence, during the period 1861–1969 for *(a)* each month, *(b)* each season and *(c)* the whole year.

(a) Month

	P		*S*		*C*		*M*	
Jan.	62	(1921)	26	(1924)	27	(1948)	40	(1967)
	−52	(1941, 1963)	−23	(1945)	−36	(1880)	0	(1921)
Feb.	58	(1868)	24	(1872)	24	(1925)	27	(1924)
	−55	(1932)	−24	(1965)	−37	(1934)	4	(1954)
Mar.	60	(1861)	24	(1957)	34	(1909)	30	(1869)
	−48	(1931)	−28	(1869)	−46	(1929)	1	(1934)
Apr.	48	(1943)	14	(1902)	21	(1920)	27	(1928)
	−49	(1861)	−21	(1919)	−45	(1893)	0	(1948)
May	26	(1956)	19	(1867)	28	(1889)	33	(1954)
	−52	(1869)	−29	(1902)	−45	(1896)	2	(1911)
June	42	(1864, 1890)	15	(1935)	29	(1912)	32	(1909)
	−46	(1958)	−32	(1909)	−36	(1889)	1	(1875)
July	53	(1881)	18	(1884)	30	(1936)	34	(1919)
	−41	(1867)	−34	(1919)	−42	(1955)	1	(1920)
Aug.	62	(1861)	17	(1884)	38	(1912)	31	(1887)
	−44	(1947)	−25	(1896)	−38	(1955)	1	(1874)
Sept.	57	(1923, 1950, 1954)	17	(1901)	29	(1866)	28	(1877, 1952)
	−49	(1894)	−28	(1952)	−43	(1959)	3	(1879, 1917, 1966)
Oct.	56	(1967)	30	(1908)	38	(1907)	30	(1908, 1919)
	−53	(1960)	−23	(1887)	−33	(1962)	2	(1942)
Nov.	57	(1877)	25	(1881)	29	(1963)	30	(1878)
	−46	(1945)	−30	(1878)	−35	(1867)	2	(1883, 1887, 1907)
Dec.	59	(1898)	25	(1934)	29	(1876)	32	(1878)
	−49	(1927)	−26	(1878)	−32	(1931)	2	(1930)

(b) Season

	P		*S*		*C*		*M*	
Winter	107	(1869)	44	(1913)	42	(1877)	71	(1924)
	−94	(1963)	−46	(1965)	−82	(1932)	16	(1919)
Spring	70	(1921)	29	(1942)	36	(1889)	75	(1928)
	−91	(1928)	−43	(1962)	−88	(1893)	19	(1920)
Summer	112	(1923)	19	(1884)	70	(1912)	63	(1919)
	−52	(1885)	−59	(1919)	−87	(1869)	13	(1905)
Autumn	131	(1917)	53	(1920)	35	(1935)	72	(1876)
	−81	(1915)	−53	(1952)	−64	(1945)	16	(1954)

(c) Year

P		*S*		*C*		*M*	
263	(1923)	64	(1924)	124	(1872)	229	(1878)
−105	(1963)	−106	(1919)	−160	(1893)	119	(1905, 1920)

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551.511.2

A GEOMETRICAL INTERPRETATION OF THE KINEMATICS OF TWO-DIMENSIONAL FLOW

By R. DIXON and T. H. KIRK

Although vorticity and divergence are familiar terms in elementary meteorology, the role of the deformation is perhaps a little more obscure, although its importance has been stressed, for example by Petterssen.[1] This note attempts a clarification, based on a simple geometrical interpretation.

If we consider two-dimensional flow, having velocity components (u, v), then the vorticity (ζ), the divergence (D) and 'components' of deformation (α , β) may be defined as follows :

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}, \quad D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y},$$

$$\alpha = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}, \quad \beta = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y},$$

where the deformation F is given by $F^2 = \alpha^2 + \beta^2$. The quantities ζ and D are independent of the system of axes chosen, and so is F, but the components α and β vary with the choice of axes.

It is convenient now to visualize two-dimensional flow in terms of speed (V), given by the distribution of isotachs, and direction (ψ), given by the distribution of isogons. Taking a right-handed system of unit vectors ($\mathbf{t}$, $\mathbf{n}$, $\mathbf{k}$), where $\mathbf{t}$ denotes direction along the flow, $\mathbf{n}$ perpendicular to the flow and $\mathbf{k}$ vertical, new vectors $\mathbf{P}$ and $\mathbf{R}$ may be defined as follows :

$$\mathbf{P} = A\mathbf{t} + B\mathbf{n},$$
$$\mathbf{R} = D\mathbf{t} - \zeta\mathbf{n},$$

$$\text{where } A = \frac{\partial V}{\partial s} - V\frac{\partial \psi}{\partial n} \text{ and } B = \frac{\partial V}{\partial n} + V\frac{\partial \psi}{\partial s};$$

$\partial/\partial s$ represents differentiation along the streamlines and $\partial/\partial n$ represents differentiation along the orthogonals; A and B are the 'components' of deformation in this intrinsic system, and so $F^2 = A^2 + B^2$.

It can be shown that the plane vectors

$$\mathbf{P} = A\mathbf{t} + B\mathbf{n} = \nabla V + \mathbf{k} \times V\nabla\psi \qquad \ldots (1)$$

$$\text{and } \mathbf{R} = D\mathbf{t} - \zeta\mathbf{n} = \nabla V - \mathbf{k} \times V\nabla\psi \qquad \ldots (2)$$

where ∇, operating on a quantity, denotes its gradient.

Equations (1) and (2) give **P** and **R** in terms of the isotachs and isogons of the flow field. For any flow for which speed (V) and direction (ψ) are known at each point, it is possible to construct a diagram (Figure 1) as follows :

(i) Draw **t** and **n** axes at right angles.

(ii) In the (**t, n**) plane, draw OX to represent ∇V in magnitude and direction and OY to represent $\mathbf{k} \times V\nabla\psi$ in magnitude and direction.

(iii) Complete the parallelogram OYZX.

Then, from equation (1), **P** is represented by OZ, the projections of OZ on the **t** and **n** axes represent A and B respectively, and the magnitude of OZ represents F.

Similarly, from equation (2), **R** is represented by YX, the projections of YX on the **t** and **n** axes represent D and ζ respectively, and the magnitude of YX represents $\sqrt{(\zeta^2 + D^2)}$.

One thus obtains a diagrammatic characterization of plane flow fields. If, for example, the flow is solenoidal, i.e. $D = 0$, then the diagram must be such that **R** is parallel to **n**. Alternatively, for irrotational flow, $\zeta = 0$ and the vector **R** must be parallel to **t**.

If OX and OY are equal in magnitude, then the figure OYZX becomes a rhombus. Since the diagonals of a rhombus intersect at right angles, it follows that in this particular case **P** and **R** are orthogonal vectors. This implies that

$$AD - B\zeta = 0, \qquad \text{i.e.} \quad \frac{A}{\zeta} = \frac{B}{D}.$$

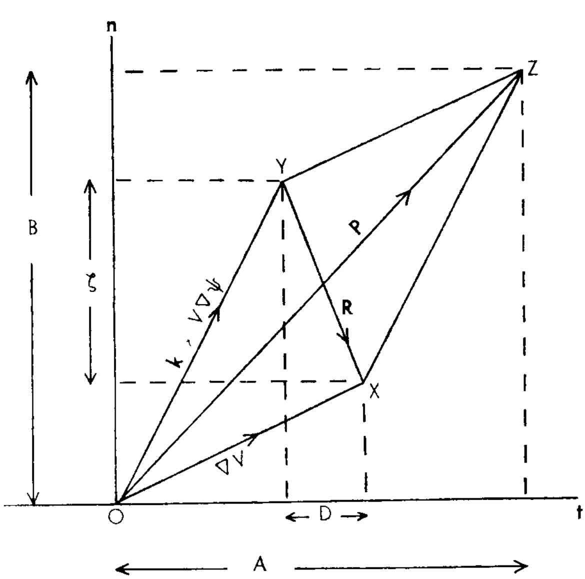

FIGURE 1—DIAGRAMMATIC CHARACTERIZATION OF PLANE FLOW FIELDS

If OX and OY are at right angles and the rectangle OYZX is oriented so that $\mathbf{R}$ is approximately parallel to $\mathbf{n}$ then the diagram is characteristic of geostrophic motion. This follows since Div $\mathbf{V} \approx 0$, and by virtue of the fact that OX and OY are at right angles, $-\nabla V \cdot \mathbf{k} \times V\nabla\psi = 0$.

But $-\nabla V \cdot \mathbf{k} \times V\nabla\psi \equiv J(u, v)$, and thus $J(u, v) = 0$, which is also approximately true for geostrophic motion.

Now consider the application of the cosine rule to triangle OXY. We have

$$R^2 = OX^2 + OY^2 - 2OX \, . \, OY \cos XOY \, . \qquad \ldots (3)$$

From (1) and (2)

$$OX = |\nabla V| = \tfrac{1}{2}|(A + D)\mathbf{t} + (B - \zeta)\mathbf{n}|$$

$$OY = |\mathbf{k} \times V\nabla\psi| = \tfrac{1}{2}|(A - D)\mathbf{t} + (B + \zeta)\mathbf{n}|$$

and $$OX.OY \cos XOY = \nabla V \cdot \mathbf{k} \times V\nabla\psi = -J(u, v).$$

Substitution in (3) leads to

$$F^2 = A^2 + B^2 = \zeta^2 + D^2 + 4\nabla V \cdot \mathbf{k} \times V\nabla\psi.$$

Hence

$$F^2 = \zeta^2 + D^2 - 4J(u, v) \, ,$$

which is the two-dimensional form of Hamel's Identity.[2]

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REVIEWS

Picture atlas of the Arctic by R. Thorén. 295 mm × 215 mm, pp. xii + 449, *illus.* Elsevier Publishing Co., 22 Rippleside Commercial Estate, Barking, Essex, 1969. Price: £19.

This is a substantial reference manual on the Arctic. Many aspects are touched on and illustrated — geography, navigation, transport, climate and ocean currents, radio communication, geology, natural resources and so on. The author, a retired captain of the Swedish Navy and now a consultant in photographic interpretation at the Research Institute of National Defence, Stockholm, is an expert in photogrammetry and photographic intelligence, his knowledge and experience acquired not only in Sweden but in several other European countries as well as the U.S.A. and Canada. Acknowledgement of help and encouragement in production of the book is made to the author's friends and colleagues in many countries, including one or two Soviet scientists. The book is, however, chiefly a picture book, a collection of nearly 600 photographs remarkable for their clarity (within the limits of magnification allowed by the screen used in the printing blocks). There are only some 14 maps which, however, include a detailed bathymetric chart (p. 2) of the Arctic Ocean (compressed into half a page and on an unnecessarily small scale) incorporating the latest knowledge. This brings out the two deep basins in the Arctic, the depth of the channel between Spitsbergen and Greenland, and the extraordinary breadth of the continental shelf north of Siberia. Most of the latter was dry land in the ice age, and in the early postglacial millennia of warmest climate forest spread to near 75°N (p. 404) as against the northernmost limit at 72·4°N 105°E today.

The book will be of prime use to the geographer and to intending Arctic travellers. Many of the (often very beautiful) photographs, taken from the ground and from the air, a number of them being stereopairs taken looking vertically downward, contribute a magnificent album of illustrations of geomorphological (especially ice-age) processes and ice forms, an incomparable reference for teachers and students of these subjects. Some may regard it as indispensable.

The coverage of different areas and different topics is rather uneven, as illustrated by the following table :

Area	*Pages of text*	*Pages of pictures*	*Number of pictures*
Arctic Ocean	14	37	61
Drifting ice stations	9	13	29
Alaska, north of the Arctic circle	4	13	20
Canadian Arctic	77	77	88
Greenland	5	30	63
Iceland	3	2	6
Norwegian islands in the Arctic	7	70	120
Arctic Scandinavia	13	83	146
Soviet Arctic	15	21	45

The frontispiece, a circumpolar map of the Arctic engraved in 1578 by Gerardus Mercator, is of unusual interest. Its central feature, a polar continent within about the 77th parallel of latitude, is pure fantasy; the rivers and Arctic coast of Siberia are wildly erroneous; but much of the rest is oddly near the truth, including the over-all relationships and the position and shape of Bering Strait as well as of a somewhat diminutive Hudson Bay. One cannot help wondering how much various Viking explorers had seen and how much knowledge of it survived in various places until Mercator's time. This and the photograph (Figure 573) of the mammoth recovered from the fossile ice amongst the still frozen ground of north-east Siberia, as well as all the miscellaneous information about the high-atmosphere rocket-sounding range at 81°N in Franz Josef Land, the thickness of the permafrost layer (up to 400 metres) in various places, the use of helicopters, hovercraft, hydrofoils and aerosledges, and many other items, from the first Arctic flight by balloon in 1897 by the Swedish scientist Andrée (p. 219) to the future role of submarine tankers and traders, are prizes of the author's skill as a collector.

Nevertheless the text has weaknesses, despite the high price. Perhaps the project demanded too wide a range of knowledge and judgement. In far too many of the photographs it is difficult (or impossible) to gain any idea of scale. The illustration of the development of ice forecast maps for shipping on the Arctic coasts by a manifest forecast failure (p. 77 and Figures 110–112) is a strange choice if, perhaps, a worth-while warning. The physical phenomena (pingoes, ice wedges, polygon patterned ground, etc.) illustrated are inadequately, if at all, explained. The climate figures quoted are few and haphazard, a mean January temperature here, an extreme there, a July temperature in another place. The sizes of some glaciers in Sweden are given, but not of others, including the largest. Many references to climatic prehistory and to climatic changes in progress today are unreliable. The text implies (p. 301) that there was just one long ice age, lasting throughout the Pleistocene, in Finland and (on p. 225) that there could even have been in the ice age some massive ice-cap covering the Arctic Ocean basin. The Arctic warming of the earlier part of this century is repeatedly described in Ahlmann's language of the 1940s as 'the present climate fluctuation': against this background, the historic closing of Russia's open winter port of Murmansk by ice in 1965–66 is unexplained. The event is misleadingly ascribed to a freak cold winter in northernmost Scandinavia, and the appearance of the Arctic sea ice in a belt along the coast is not mentioned.

A nasty taste is unfortunately introduced by the few paragraphs on submarine warfare in the Arctic without conveying much information likely to be of use either to the strategists or to those who would oppose the whole suggestion tooth and nail. More interesting, and given in rather more detail, are the accounts of the development of the Soviet and Scandinavian rail and road networks which converge towards Lapland and the ice-free Atlantic ports.

There are inaccuracies and incautious statements in other realms, ranging from celebration of the fiftieth anniversary of 'Soviet polar aviation' in 1964 to the description of Beerenberg on Jan Mayen as an 'extinct volcano' (the last eruption was in 1818), and from the First International Geophysical (for this read *Polar*) Year in 1882–83 to tracked vehicles moving over 'bottomless marshes'.

It can be agreed (p. 221) that 'glaciers are very sensitive registers of climatic fluctuations', and the great twentieth century glacier recession from the advanced positions of 1650–1850 is richly documented in this book by pictures from Greenland and Spitsbergen as well as from Scandinavia. But their response to changes of climatic tendency is by no means as quick as that of the polar sea ice: hence the misunderstanding about Murmansk in 1965–66 and the omission of reference to present alarms in Iceland. One learns with interest of the increasing volume of shipping on the Soviet-operated Northern Sea Route (the famous North East Passage) and of convoys to readmit foreign shipping after 1967, against an ever-increasing provision of icebreakers — up to 10 icebreakers in action on one section of the route in 1965 and 1966.

In spite of all these reservations, the book is a mine of information, most of it broadly trustworthy, and a wonderful treasury of photographs.

H. H. LAMB

Rainstorms and hail, by G. K. Sulakvelidze. 250 mm × 180 mm, pp. xx + 320, *illus.* (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), H. A. Humphreys Ltd, 5 Great Russell Street, London WC1, 1969. Price: 108*s*.

This book is effectively a second edition of *Formation of precipitation and modification of hail processes* by Sulakvelidze, Bibilashvili and Lapcheva which appeared in English in 1967 and was reviewed by K. A. Browning in the *Meteorological Magazine* for February of last year.

The earlier book described the theories of hail formation developed at the High-Mountain Geophysical Institute (VGI) in the U.S.S.R. and some early experiments in hail suppression using techniques developed on the basis of these theories. The opening chapters of *Rainstorms and hail* contain essentially the same theoretical treatment as the previous publication, together with some relatively minor additions to take account of more recent developments. The closing chapters of the book — which are probably the most significant part — describe the extension of the hail suppression technique in the years 1964, 1965 and 1966 to protect larger areas in the Northern Caucasus and in Transcaucasia — two regions which have significantly different climatic conditions for hail formation.

The results of these experiments are very impressive indeed. Thus in 1964 an area of 292 000 hectares of agricultural crops was brought under protection and only 5·3 per cent of this area was damaged by hail, compared with 9 per cent of a corresponding control area. The corresponding figures for 1965 were 303 000 hectares protected, 3·5 per cent damaged compared to 19 per cent in the control area and for 1966, 546 000 hectares protected, 1·1 per cent damaged compared with 6·9 per cent in the control area. Thus, although the area under protection was increased each year, the damage to the protected area apparently continued to be markedly less than in the corresponding control area. Sulakvelidze also evaluates several different effectiveness criteria which take into account the natural variation from year to year in the ratio of hail damage on the protected and control areas, and these indicate that there is a definite positive effect for each year, with the possible exception of 1964.

There are however several aspects of the work which lead one to share the opinion which Dr Browning expressed in his review that the results are 'almost too good to be true'. Firstly, the new book does little to dispel the doubts which the earlier one raised about the theoretical model of a hailstorm on which the experiments are based. In particular, it is still supposed that there is an 'accumulation zone' in which large numbers of supercooled raindrops collect to give very large liquid water contents at temperatures below 0°C, but there is little evidence that theoretical models have taken into account the three-dimensional nature of the airflow in convective storms.

Secondly, Sulakvelidze states (p. 258) that the boundaries of the hail growth zone need to be located to within 100 metres and that the size of the hail particles must be estimated. He claims that this is done by using 3- and 10-cm radars, although, as Dr Browning pointed out, there are very considerable difficulties in understanding how this can be done when one considers the variable attenuation of the 3-cm radar beam by the heavy precipitation produced by a hailstorm.

Sulakvelidze also states that it is necessary to introduce into the hail-focus a reagent (either silver iodide or lead iodide) which will cause a proportion of the large, supercooled raindrops to freeze. This is done by firing 'El'brus – II' missiles from the ground into the hail-focus where they explode and disperse the crystallizing reagent. Again it is surprising that the required accuracy can be achieved when one considers the vigorous up- and down-draughts which exist in hailstorms. The explanation may, of course, be that the identification of the hail-focus is not as critical as Sulakvelidze suggests. In any case, it certainly seems very sensible to disperse the nucleating agent as near to the centre of the storm as possible and it would appear that the Russian workers have developed a technique which achieves this objective.

Finally, however, the impression of 'too good to be true' is most strongly conveyed by Sulakvelidze's explanation of the occasions on which hail damage occurred within the protected area purely in terms of failures in the logistics of the field operation. Thus he states (p. 281) that in 1966 when a total area of 1 million hectares was under protection, there were only 22 cases of (mainly weak) hail damage and that these could be accounted for as follows: 7 cases were a result of the work being stopped owing to civil flights, 10 cases were due to the equipment being out of order and the remaining 5 cases were due to 'incorrect application of the hail modification method'.

Despite these misgivings, the results reported in this book are undoubtedly of the greatest significance for all who are interested in the problem of hail prevention. We can only await with interest the results of further work in the U.S.S.R. following the decision made by the Soviet government in April 1967 to extend the protection scheme to every area in the Soviet Union damaged by hail and also the results of attempts to apply the same techniques to hailstorms in Canada and the U.S.A.

J. T. BARTLETT

Planetary electrodynamics, Volume 2, edited by S. C. Coroniti and J. Hughes. 230 mm × 150 mm, pp. xx + 503, *illus.*, Gordon and Breach Science Publishers, 12 Bloomsbury Way, London WC1, 1970. Price: £10.

This is the second of two volumes containing papers presented at the Fourth International Conference on the Universal Aspects of Atmospheric Electricity, held in Tokyo in 1968 (the date and place are not mentioned explicitly). This volume contains the proceedings of sessions five to eight of the conference, including edited discussions on the papers. The volume includes 10 papers on the monitoring of global thunderstorm activity (with particular interest in satellite observations and lightning flash counters) and 8 on the simulation of atmospheric electrical phenomena. Two sections (over half the book) are on the electrical properties of the stratosphere, ionosphere and interplanetary space, and the methods of measuring these properties. A novel suggestion emerges from a development of electrohydrodynamic phenomena by Carstoiu (p. 277) that thunderclouds might represent clusters of magnetically polar particles!

This book with its companion volume should be of interest to research workers in this field.

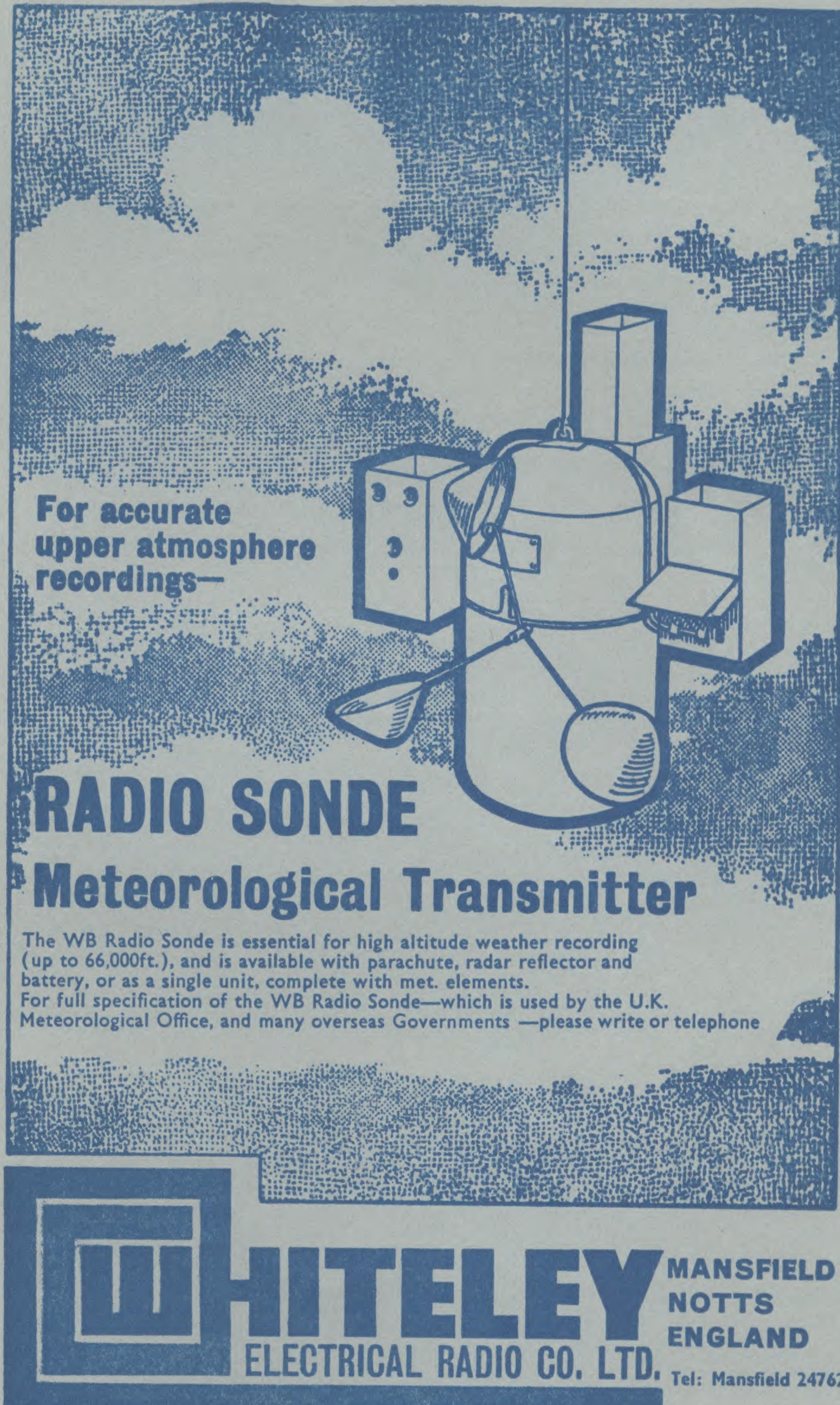
D. A. JOHNSON

HONOUR

The following award to a member of the staff of the Meteorological Office has been announced:

I.S.M.

Mr. Bernard A. Blowers, Radio Supervisor at Headquarters Meteorological Office, Bracknell.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THE METEOROLOGICAL MAGAZINE

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ON THE REPRESENTATIVENESS OF MEASUREMENTS OF HEIGHT OF LOW-CLOUD BASE AT AN AIRFIELD

By L. S. CLARKSON

Summary. Routine observations of cloud base are made at half-hour intervals at each of two sites 3 km apart at Liverpool Airport. Cloud-base recorders are available at each site. During January, March and May 1969 a note was made, for each site, of the lowest cloud height recorded in the 10 minutes previous to the routine weather observations.

If H_x represents the lowest height of cloud base in the range 100–700 ft recorded at one site in a 10-minute period and if H_3 represents the lowest height recorded in the appropriate 10-minute period at another site 3 km away, then at Liverpool Airport these are statistically related by an equation very close to

$$H_3 = 0{\cdot}76\ H_x + 170 \text{ ft},$$

with a standard error of estimate of 320 ft.

The percentage of occasions when H_3 is 0·5 H_x or less varies from 27 per cent when H_x = 100 ft to 16 per cent when H_x = 700 ft.

Introduction. At Liverpool Airport records were examined from two properly maintained cloud-base recorders (CBR) in routine operational use. One is situated in the south-east corner of the airport near the meteorological observing office; the other is about 3 km away in the north-west corner adjacent to the forecast office.

It is thought that an observer making a routine height of cloud-base observation for aviation is considerably influenced by the lowest height that has been recorded in the 10-minute period immediately prior to the time of observation. Accordingly, the staff at Liverpool Airport Meteorological Office were asked to extract the lowest height recorded at each location at any time within the 10-minute period before every half-hourly routine observation, provided that a height at or below 1000 ft was shown on either recorder in this time interval. Heights were read off to the nearest 20 ft for cloud bases below 1000 ft, and F or — was entered when either fog or no cloud base was recorded. Data tabulated in this way for the months of January, March and May 1969 were analysed.

Analysis. The lowest cloud height recorded at the forecast office site was represented by H_f and the lowest cloud height recorded in the same 10-minute period at the observing office site was represented by H_o.

There were (see Table I) 352 pairs of observations of H_f and H_o in which H_f was in the range 100–700 ft. (The value of H_o when it was tabulated as F or — was taken as being zero (i.e. on the surface) if this could reasonably be deduced from the immediately preceding or following half-hourly observation.)

Similarly there were 379 pairs of observations of H_o and H_f in which H_o was in the range 100–700 ft. (In these pairs the value of H_f when it was tabulated as F or — was taken as being zero if this could reasonably be deduced from the immediately preceding or following half-hourly observation.)

The two separate regression equations (of H_o on $H_{f\,(100\text{-}700)}$ and of H_f on $H_{o(100\text{-}700)}$) were formed, where the notation $H_{f\,(100\text{-}700)}$ refers to observations in the range 100–700 ft. The 'standard errors of estimate' and correlation coefficients were calculated, with the results shown in Table I below.

TABLE I—STATISTICAL RELATIONSHIPS BETWEEN H_o AND H_f

Number of pairs of observations	Regression equation *feet*	Standard error	Correlation coefficient
352	$H_o = 0{\cdot}76\ H_{f(100-700)} + 151$	309	0·34
379	$H_f = 0{\cdot}76\ H_{o(100-700)} + 187$	326	0·34

Discussion. From the near identity of the constants in the two regression equations it appears that, over the range of cloud heights considered, any constant systematic difference between the lowest cloud heights recorded at the two sites is negligibly small.

The low value of the correlation coefficient between H_o and H_f and the high 'standard error of estimate' of the cloud base 3 km away from an observation of the height of low cloud in the range 100–700 ft are noteworthy.

If H_x represents the lowest height of cloud base in the range 100–700 ft recorded at one site in a 10-minute period, and if H_3 represents the lowest height of cloud base recorded within the same 10-minute period at a spot 3 km distant, then at Liverpool Airport these are statistically related by an equation very close to

$$H_3 = 0{\cdot}76\ H_x + 170 \text{ ft}, \qquad \ldots (1)$$

with standard error of estimate 320 ft.

Equation (1) is expressed in graphical form in Figure 1, where the upper and lower dotted lines represent the 50 per cent confidence limits of the regression line AB of H_3 on H_x. The dashed line CD is the regression line to be expected when the differences between the observations at H_x and H_3 are evenly distributed about a mean difference of zero. It departs increasingly from the computed regression line AB as H_x decreases. This is because whereas there is no physical constraint on the possible values of H_3 when H_3 is greater than H_x, the presence of the ground puts a lower limit to the range of physically possible values of H_3 when H_x is small.

The standard error of estimate of H_3 from H_x is considerably larger than the value for Heathrow obtained by Harrower using two cloud searchlights in 1955 (unpublished) and quoted by Jones.* This is probably because the observations analysed by Harrower were made simultaneously, and restricted

* JONES, R. F.; Time and space variations of visibility and low cloud within the approach control area. *Tech. Note Wld met. Org., Geneva*, 1969, No. 95, pp. 97–101.

to more than 4/8 of cloud with bases below 300 ft at *both* sites, whereas the range of the observations at the distant site analysed in this note is not artificially limited.

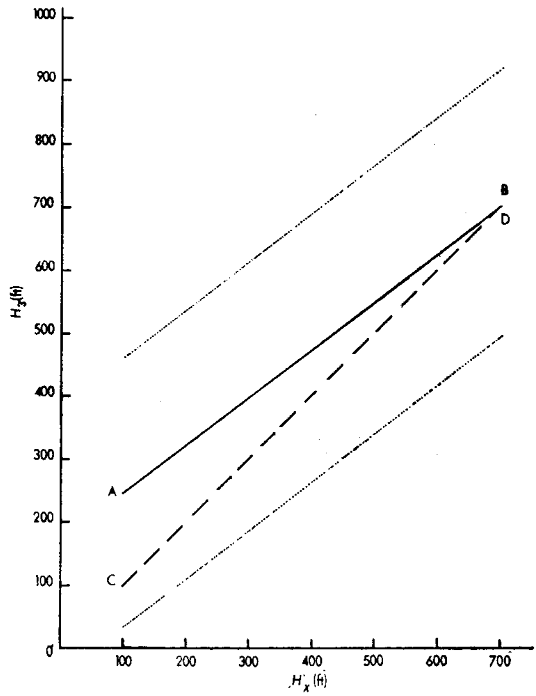

FIGURE 1—REGRESSION OF H_3 ON H_x AND 50 PER CENT CONFIDENCE LIMITS

AB Regression of H_3 on H_x.
CD Regression line to be expected when the differences between the observations of H_x and H_3 are evenly distributed about a mean difference of zero.
.... 50 per cent confidence limits.

From the statistical relationship found between the observations of H_3 and H_x at Liverpool Airport as expressed by equation (1), it is possible to draw up Table II which, for specified values of H_x, expresses the probable frequency of occasions when H_3 is 0·5 H_x or less.

TABLE II—FREQUENCY OF OCCASIONS WHEN H_3 IS 0·5 H_x OR LESS

H_x *feet*	$H_3 \leqslant 0{\cdot}5\, H_x$ *percentage of occasions*
100	27
300	22
500	17
700	16

It must be remembered that the observations H_3 and H_x are not necessarily simultaneous, nor are they time-meaned; they are in fact the instantaneous heights of the lowest cloud recorded by the cloud-base recorders at the two sites during the same 10-minute time intervals. Consequently they must include some instances where the CBR at either or both sites picked up an isolated fragment of very low cloud which chanced to be vertically above the receiver at the moment of scanning.

Nevertheless the frequencies in Table II indicate how significantly unrepresentative such observations of very low cloud base at one spot may be of the lowest cloud base at some other location 3 km distant during the same 10-minute period.

This analysis has a bearing on the problem of siting cloud-base measuring instruments at an airfield so as to obtain measurements representative of some particular spot in the vicinity of the airfield or its approaches.

Acknowledgement. The laborious task of extracting, from the cloud-base recorder charts, the data analysed in this note was undertaken by the Meteorological Officer, Liverpool Airport, and his staff.

551.511.3:532.5

A GEOMETRICAL INTERPRETATION OF BALANCED MOTION

By R. DIXON

Summary. It is shown that the concept of balanced motion in plane fluid flow may be given a simple interpretation in terms of velocital and hodographic areas.

In a plane fluid flow, consider an arbitrary closed plane curve C_r of fluid particles defined by a position vector $\mathbf{r}$, and enclosing a finite area A_r, termed the 'fluid' area (Figure 1). The fluid velocity vectors at each point on C_r will sweep out another closed curve C_v, enclosing the 'velocital' area A_v. A third curve C_h can be obtained by transferring the velocity vector at each point of C_r to the origin. This curve C_h encloses the 'hodographic' area A_h.

Now the three areas A_r, A_v, A_h are given by

$$2A_r = \oint_c \frac{\partial \mathbf{r}}{\partial c} \times \mathbf{k} \,.\, \mathbf{r}\, dc, \qquad \ldots (1)$$

$$2A_v = \oint_c \frac{\partial}{\partial c} (\mathbf{r} + \mathbf{V}) \times \mathbf{k} \,.\, (\mathbf{r} + \mathbf{V}) dc, \qquad \ldots (2)$$

$$2A_h = \oint_c \frac{\partial \mathbf{V}}{\partial c} \times \mathbf{k} \,.\, \mathbf{V}\, dc, \qquad \ldots (3)$$

where $\mathbf{V}$ is the velocity, dc is an element of C_r and $\mathbf{k}$ is the unit vector at right angles to the plane.

By multiplying out the integrand in (2), and using (1) and (3) there follows

$$2A_v = 2A_r + 2A_h + \oint_c \frac{\partial \mathbf{r}}{\partial c} \times \mathbf{k} \,.\, \mathbf{V}\, dc + \oint_c \frac{\partial \mathbf{V}}{\partial c} \times \mathbf{k} \,.\, \mathbf{r}\, dc; \qquad \ldots (4)$$

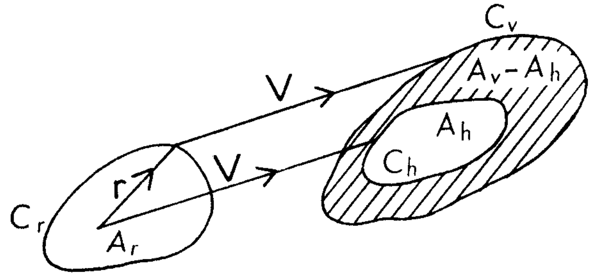

FIGURE 1—DIAGRAM OF FLUID, VELOCITAL AND HODOGRAPHIC AREAS
In balanced motion the shaded area is conserved.

but it may be shown that

$$\oint_c \frac{\partial \mathbf{r}}{\partial c} \times \mathbf{k} \,.\, \mathbf{V}\, \mathrm{d}c = \oint_c \frac{\partial \mathbf{V}}{\partial c} \times \mathbf{k} \,.\, \mathbf{r}\, \mathrm{d}c = \int_{A_r} \operatorname{div} \mathbf{V}\, \mathrm{d}A_r,$$

and so (4) becomes

$$A_v = A_r + A_h + \int_{A_r} \operatorname{div} \mathbf{V}\, \mathrm{d}A_r, \qquad \ldots (5)$$

a simple relationship between the fluid, velocital and hodographic areas, which may also be written as

$$A_v = A_r + A_h + \frac{\mathrm{d}A_r}{\mathrm{d}t} \qquad \ldots (6)$$

since

$$\frac{\mathrm{d}A_r}{\mathrm{d}t} = \int_{A_r} \operatorname{div} \mathbf{V}\, \mathrm{d}A_r \,. \qquad \ldots (7)$$

In deriving the relationship between the velocity field and the mass field in balanced flow in meteorology, the conditions

$$\frac{\mathrm{d}}{\mathrm{d}t}(\operatorname{div} \mathbf{V}) = \operatorname{div} \mathbf{V} = 0 \qquad \ldots (8)$$

have been imposed. Consequently by taking the rate of change of (5), and using Reynolds's Transport Theorem

$$\frac{\mathrm{d}}{\mathrm{d}t} \int_{A_r} \operatorname{div} \mathbf{V}\, \mathrm{d}A_r = \int_{A_r} \left[\frac{\mathrm{d}}{\mathrm{d}t}(\operatorname{div} \mathbf{V}) + (\operatorname{div} \mathbf{V})^2 \right] \mathrm{d}A_r \qquad \ldots (9)$$

and equations (7) and (8), there results

$$\frac{\mathrm{d}}{\mathrm{d}t}(A_v - A_h) = 0, \qquad \ldots (10)$$

or in other words, in balanced motion, the area between the curves C_v and C_h, is conserved. Thus the term 'balanced' motion is geometrically as well as dynamically apposite.

Further information on velocital and hodographic areas and volumes can be found in works by Bilimovitch,[1] and Truesdell.[2]

Finally, it should be noted that (5) is an equation concerning the geometry of Figure 1. For a detailed discussion of the dimensional non-homogeneity of equations of this type see Truesdell,[2] and Bilimovitch.[3]

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551.575.1

RADIATION FOG CLEARANCE AT LITTLE RISSINGTON

By J. HOUSEMAN

Summary. Various workers have formulated empirical rules for forecasting the clearance time of radiation fog at low-lying stations in East Anglia, and in some cases an allowance for upslope motion has been incorporated. An examination was made of 215 fogs which occurred during a recent 3-year period at Little Rissington, an airfield at 750 ft above mean sea level. The fogs were classified and the empirical rules for East Anglia were applied to 87 radiation type fogs. Only 19 fogs cleared before the forecast time of clearance so a special allowance for upslope motion was made to bring the forecast time as near as possible to the actual time of clearance for the maximum number of cases. The results indicate that even at Little Rissington with its unusual exposure the empirical rules can be modified with some success to meet local peculiarities.

Introduction. Over the past few years extensive use has been made of Barthram's diagrams[1] for forecasting the time of clearance of radiation fog by Kennington's method.[2] Atkins[3] has formulated empirical rules for calculating fog thickness and allowing for upslope motion at Wittering and these rules have been tested at Gaydon, Cottesmore and Watton[4] with varied success.

It was thought that it would be of interest to test Atkins's rules at an airfield, considerably higher than any of those mentioned above, where virtually all fog is affected by upslope motion, in order, if possible, to devise a series of adjustments to the basic method to provide a useful local forecasting tool.

The particular airfield, Little Rissington, lies on the top of a Cotswold hill at an elevation of 750 ft (approximately 230 m) above mean sea level. Only on the north-west does the crest of the hill overlook the airfield and beyond this low crest the ground falls away steeply for some 200 ft (approximately 60 m). In all other directions the hillside slopes steeply away from the airfield boundary. Consequently all air approaching the airfield at ground level is subject to an upslope effect in varying degree (see Figure 1).

Observations of all fogs affecting the airfield during the period 1 January 1965 to 31 December 1967 were examined, some 215 cases in all. Individual fogs persisted for periods of time varying from as little as one hour to as much as four and a half days.

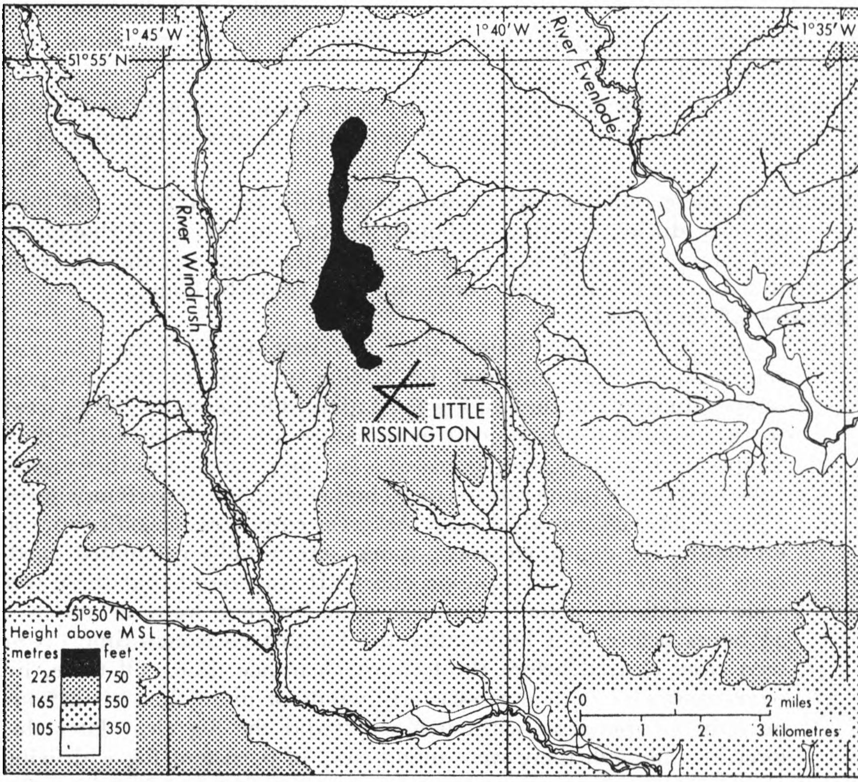

FIGURE 1—MAP SHOWING LITTLE RISSINGTON AND ITS SURROUNDINGS

A preliminary investigation showed that, broadly speaking, the fogs fell into five categories, as follows :

(i) Advection fog which formed widely both on high and low ground in warm, moist air masses.

(ii) Hill fog which, over low ground, was reported as low stratus cloud.

(iii) Fog which formed on clear, radiation nights with some wind. This type often began as an isolated patch of status over the hill, gradually lowering as the wind decreased, to form fog. Sometimes fog also formed in the surrounding valleys but at other times they remained clear.

(iv) Radiation fog which formed first in the valleys and gradually increased in depth to envelop the hilltop.

(v) Radiation fog which formed in the valleys by night, leaving the hilltop clear, but which lifted during the following morning to form stratus over the valleys and fog on the hill before finally dispersing.

Of these five classes, types (i) and (ii) were excluded from the test. Also excluded were fogs obviously cleared by wind and by the spread of cloud sheets over the top.

Fog of type (iii) is formed by a combination of radiative cooling and upslope motion and, since it is usually dispersed by insolation, it was included in the test.

Eventually there remained 87 cases of types (iii), (iv) and (v). Of these, 6 did not clear during the day, although forecast to do so. Although the rest cleared there was a wide scatter of times and temperatures and the results were analysed to see if some basic common factor could be found.

Results of analysis.

(i) *Temperature.* It was found that the best forecast fog clearance temperatures were obtained by adding 1 degC to the dew-point temperature at the time of fog formation. Occasionally (in 13 cases) it was found that this forecast temperature was the same as the dawn temperature and fog still persisted. In these cases clearance usually coincided with a temperature 1 degC higher than the dawn temperature.

(ii) *Upslope time allowance.* Using Atkins's empirical classification for estimating fog depth, clearance times were initially calculated on the basis of there being no upslope effect. It was found that there were wide variations, actual clearance time varying from as much as $4\frac{1}{2}$ hours before to 4 hours after the forecast clearance time. Nineteen cases cleared before the forecast clearance time. Of these, five were associated with north-easterly winds of more than 10 kt* and on only one occasion with such winds did the fog clear later than forecast, although there were many cases of persistent fog with winds of over 10 kt from other directions. Six of the remaining 14 cases had clearance times within the half hour preceding the forecast time.

All the other fogs cleared after the forecast clearance time. Excluding the 6 which did not clear at all that day, there were 62 cases which cleared later than forecast, whereas only 19 cleared earlier than forecast. Therefore, to bring the forecast clearance time as near as possible to the actual clearance time in the maximum number of cases, an allowance was added to all the basic forecast clearance times which had been calculated, except those involving north-east winds of over 10 kt. The allowance was calculated on the basis of obtaining the best results with specific types of fogs. It was found that the allowance did not need to vary with the time of the year and that Atkins's allowances were usually too large, especially (and rather surprisingly) in the case of freezing fogs. The following rules for calculating radiation fog clearance temperatures and times were eventually formulated.

Forecast clearance temperature.

(i) Take the dew-point at the time of fog formation and add 1 degC.

(ii) If this temperature turns out to be the dawn temperature add another 1 degC and recalculate the clearance time.

Forecast clearance time. Calculate this in accordance with the following rules using Barthram's diagrams and the temperature already forecast.

---

* 1 knot ≈ 0·5 m/s.

Description of fog	*Procedure*
Sky visible. Visibility greater than 200 yd (approximately 185 m).	Assume fog depth to be 10 mb and add ½ hour to the calculated clearance time.
Sky visible. Visibility 200 yd or less.	Assume fog depth of 20 mb and add 1 hour to the calculated time.
Sky not visible.	Assume fog depth of 30 mb and add 1 hour.
Freezing fogs.	Calculated as if one of above types, but add ½ hour only to calculated time.
Fogs with north-east winds of over 10 kt.	Calculate as if one of the above types but *subtract* 1½ hours from the calculated time.

On the basis of the above rules all the fog clearance times were recalculated and the results were as follows :

Fogs clearing within ½ hour of adjusted forecast time	34 (39 per cent)
Fogs clearing within 1 hour of adjusted forecast time	57 (66 per cent)
Fogs clearing within 1½ hours of adjusted forecast time	68 (78 per cent)
Fogs clearing more than 1½ hours before forecast time	7
Fogs clearing more than 1½ hours after forecast time	6
Fogs not clearing though forecast to clear	6
Total number of forecasts	87

Discussion. From a forecasting viewpoint these results are not as good as these which Atkins achieved at Wittering but compare very favourably with those for Gaydon and Watton. The most disappointing aspect was that none of the 'nil clearances' could be successfully forecast and no common factor was apparent either in those cases or in those which cleared very late. Nevertheless it seems that investigations such as this can be of value even at stations with an unusual exposure.

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517.512.2

INTRODUCTION TO THE FAST FOURIER TRANSFORM (FFT) IN THE PRODUCTION OF SPECTRA

By R. RAYMENT

Summary. The existence of a powerful technique, generally referred to as the Fast Fourier Transform (FFT), for evaluating Fourier coefficients is presented and the use of this in the production of spectra is explained. A basis for choice between this comparatively new method and a much used conventional technique for producing spectra is put forward and some other uses of the FFT are briefly indicated.

Nomenclature.

$a_0/2$	Mean level of a function represented by a Fourier series.
a_k, b_k c_k, d_k	Fourier amplitudes or coefficients.
C_k	Complex Fourier amplitude $= (a_k + ib_k)/2$.
C_{-k}	Complex Fourier amplitude $= (a_k - ib_k)/2$.
D_k, D_{-k}	Complex Fourier amplitudes for a second function.
g	Number of lags in the Blackman and Tukey (B&T) method.
H	Number of spectrum points averaged in the Fast Fourier Transform (FFT) method.
j	Running time index (i.e. $t = j\Delta t$).
k	Running frequency index for the Fourier series (i.e. $n = k/T$), for the FFT (i.e. $n = k\Delta n$) and for the B&T method (i.e. $n = k/2g\Delta t$).
L	Time span index for a lag in the B&T method (i.e. $\tau = L\Delta t$).
n	Frequency.
N	Total number of measured points in one sample of data.
$O(\tau)$, $E(\tau)$	Odd and even parts respectively of the cross-correlation (i.e. $\sigma_{xy}(\tau) = O(\tau) + E(\tau)$).
$Q_{xy}(n)$	Quadrature spectrum function.
$S_{xy}(n)$	Cospectrum function.
$S_x(n)$	Power spectrum function.
t	Time.
u', w', θ'	Fluctuations in the horizontal wind, vertical wind and temperature respectively.
$x(t)$, $y(t)$	Functions of time.
Δt	Time interval between measured data points.
Δn	Fundamental frequency interval ($= 1/T$).
ν	Degrees of freedom
$\sigma_{xy}(\tau)$	Cross-correlation or cross-product between $x(t)$ and $y(t)$ for a lag of τ.
$\sigma_x(\tau)$	Autocorrelation for $x(t)$.
τ	Lag used in deriving cross-products.
T	Periodic time or total sampling time.
$\varphi_{xy}(n)$	Complex spectral density function.
χ^2	Chi-square probability distribution.
δn	Bandwidth in B&T method.

Introduction. The requirement to produce spectra arises whenever one needs to know which set of repetition rates or frequencies dominate some particular process.

As an illustration of the use of spectra suppose we have a measure of the variance of the wind σ_v^2. Such a measurement is inevitably made from discrete observations separated by a time interval Δt say, over a limited time, say T, using an instrument with a less than perfect response characteristic. Roughly it is clear that if there are significant wind motions which have a frequency greater than the maximum response of the instrument and/or a frequency less than $1/T$ the calculated σ_v^2 could be much in error. Spectral analysis of the wind can show which frequencies contribute most to the variance.

If there is good reason for expecting a certain shape to the spectral curve the analysis can indicate whether the recording time is long enough and, provided Δt is short enough, whether the instrumental response is adequate. This is just one example and a few more will be quoted further on.

Classical harmonic analysis. The classical way of considering the discrete frequencies associated with some process is to visualize this as made up from the superposition of a set of sinusoidal components having different frequencies and amplitudes. This idea is expressed mathematically by expanding the describing function, $x(t)$, in terms of the so-called Fourier components :

$$x(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos (2\pi kt/T) + b_k \sin (2\pi kt/T)) \qquad \ldots (1)$$

where a_k and b_k are the Fourier amplitudes or coefficients and $x(t)$ might be a signal generated in time over a period of T. In complex form (1) may be written :

$$x(t) = \sum_{k=-\infty}^{\infty} C_k \exp (-2\pi ikt/T) \qquad \ldots (2)$$

where

$$C_k = \frac{1}{T} \int_0^{\infty} x(t) \exp (2\pi ikt/T)\, dt = (a_k + ib_k)/2. \qquad \ldots (3)$$

We shall also need a second function :

$$y(t) = \sum_{k=-\infty}^{\infty} D_k \exp (-2\pi ikt/T) \qquad \ldots (4)$$

where

$$D_k = (c_k + id_k)/2,\ D_{-k} = (c_k - id_k)/2 \text{ etc.} \qquad \ldots (5)$$

For the purposes of defining a spectrum we introduce the average cross-correlation (cross-product) for signals of zero mean, which can be written as

$$\sigma_{xy}(\tau) = \frac{1}{T} \int_0^T x(t)\, y(t-\tau)\, dt, \qquad \ldots (6)$$

which is periodic in T and where τ is the lag of one function on the other. From theorems due originally to Wiener[1] (see also Taylor[2] and Lumley and Panofsky[3]) we can express the cross-correlation in terms of a complex frequency or spectral density function $\varphi_{xy}(n)$;

$$\sigma_{xy}^{*}(\tau) = \int_{-\infty}^{\infty} \varphi_{xy}(n) \exp(2\pi i n\tau) dn \qquad \ldots (7)$$

where n is the frequency.

We require at zero lag the covariance given by

$$\sigma_{xy}(0) = \int_{-\infty}^{\infty} \mathrm{Re}\varphi_{xy}(n) dn = \int_{0}^{\infty} S_{xy}(n) dn \qquad \ldots (8)$$

where $\mathrm{Re}\varphi_{xy}(n)$ is the real part of $\varphi_{xy}(n)$, and since $\mathrm{Re}\varphi(n)$ is symmetrical, $S_{xy}(n) = 2\mathrm{Re}\varphi_{xy}(n)$ where $S_{xy}(n)$ gives the contribution to the covariance from different frequencies and is called the cospectrum.

In the atmosphere if one were measuring horizontal and vertical velocity fluctuations, i.e. u' and w' respectively, $\sigma_{u'w'}(0)$ is directly proportional to the turbulent momentum flux. Similarly if temperature fluctuation (i.e. θ') are measured $\sigma_{w'\theta'}(0)$ is proportional to the turbulent heat flux.[3]

There is also a quantity $Q_{xy}(n)$ which measures the $\pi/2$ out-of-phase intensity of the two signals and is called the quadrature spectrum, where $Q_{xy}(n) = -2\mathrm{Im}\varphi_{xy}(n)$ (i.e. $\mathrm{Im}Q_{xy}(n)$ is the imaginary part of $\varphi_{xy}(n)$).

It is interesting to note that $Q_{xy}(n)$ is negative when a positive value of $x(t)$ is followed a quarter of a cycle later by a negative value of $y(t)$. By way of example if one were measuring, as before, u' and w' in the atmosphere, the sign of $Q_{xy}(n)$ enables one to determine, on average, over which frequency bands (if any) one is systematically making measurements in the upper or lower half of revolving eddies.[8]

When we are dealing with a single signal, $x(t)$ say, the cross-correlations are replaced by autocorrelations (i.e. the average of the products between points a distance τ apart). $S_{xy}(n)$ is replaced by $S_x(n)$ which measures the frequency contributions to the variance of $x(t)$ and is called the power spectrum.

By substituting equations (2) and (4) into (6) we can show that

$$\sigma_{xy}(\tau) = \sum_{k=-\infty}^{\infty} D_k C_{\cdot k} \exp(2\pi i k\tau/T). \qquad \ldots (9)$$

Letting $n = k\Delta n$ and $\Delta n = 1/T$ (where k is an integer) the summation version of (7) compared with (9) enables us to write

$$S_{xy}(k\Delta n) = \frac{T}{2}(a_k c_k + b_k d_k) \qquad \ldots (10)$$

$$Q_{xy}(k\Delta n) = -\frac{T}{2}(a_k d_k^{*} - b_k c_k) \qquad \ldots (11)$$

$$\text{and } S_x(k\Delta n) = \frac{T}{2}(a^2_k + b^2_k). \qquad \ldots (12)$$

Much of this analysis can be found in Hsu[4] and some also in Brooks and Carruthers.[5]

This presents a practical scheme for calculating spectra provided that the Fourier coefficients can be found easily.

The cosine-transform method of producing spectra. Until quite recent times (1965)[6] the labour of producing Fourier coefficients for the utilization of equations (10), (11) and (12) in the production of broad-frequency spectra was considered prohibitive and alternative methods were sought. Apart from electronic and physical wave analysers the most popular mathematical technique was the so-called cosine-transform method. We can show in outline what this involves by taking the Fourier transforms of equation (7) which gives

$$\varphi_{xy}(n) = \int_{-\infty}^{\infty} \varphi_{xy}(\tau) \exp(-2\pi i n\tau)\, d\tau. \qquad \ldots (13)$$

The cross-correlation is split into odd and even parts $O(\tau)$ and $E(\tau)$

$$\sigma_{xy}(\tau) = \tfrac{1}{2}[\sigma_{xy}(\tau) - \sigma_{xy}(-\tau)] + \tfrac{1}{2}[\sigma_{xy}(\tau) + \sigma_{xy}(-\tau)] = O(\tau) + E(\tau). \qquad \ldots (14)$$

Using this and expanding (13) gives

$$S_{xy}(n) = 4\int_{0}^{\infty} E(\tau) \cos 2\pi n\tau d\tau, \qquad \ldots (15)$$

and for convenience we also set

$$Q_{xy}(n) = 4\int_{0}^{\infty} O(\tau) \sin 2\pi n\tau d\tau. \qquad \ldots (16)$$

When $x=y$, $E(\tau)$ becomes the autocorrelation and $S_{xy}(n)$ becomes $S_x(n)$, i.e. the power spectrum.

Letting $n=k/2g\Delta t$, $\tau=L\Delta t$ so that $\delta n=1/2g\Delta t$, the summation version of (15) for $x=y$ becomes

$$\delta n S_x\ (k/2g\Delta t) = \frac{2}{g}\sum_{L=0}^{g} \sigma_x\ (L\Delta t) \cos \frac{\pi k L}{g} \qquad \ldots (17)$$

This provides a scheme of calculation and gives $(g+1)$ spectral estimates at frequencies 0, $1/2g\Delta t, \ldots, 1/2\Delta t$ where $1/2\Delta t$ is called the Nyquist frequency which is the maximum usefully analysable frequency for the given data sampling rate $1/\Delta t$. Equation (17) also smooths the results to some extent, and is in fact equivalent to a band-pass filter centred at $k/2g\Delta t$, but having rather large 'side-lobes' outside the bandwidth δn. (This means that adjacent frequencies interfere with one another.) Further smoothing is therefore necessary. Several functions have been derived which minimize the effect of these 'side-lobes' — one such is called 'hanning' which can be written as

$$S'_k = \tfrac{1}{4}\,(S_{k-1} + 2S_k + S_{k+1}) \qquad \ldots (18)$$

so that the terms S'_k form the final spectral estimates. For the practical purposes of estimating the statistical accuracy it is assumed that the spectral values in each frequency band come individually from a multiple of the χ^2 distribution. This being the case the percentage confidence limits applicable to an estimate depend solely on the number of degrees of freedom, ν. In the cosine-transform method $\nu \approx 2N/g$. This arises from the fact that each of the g spectral points effectively averages over the maximum number of possible spectral points (i.e. N/g) in the interval δn and to each of these primitive points are assigned two degrees of freedom corresponding for example to an a_k and b_k or an amplitude and phase. As an example suppose that we require the 90 per cent confidence limits to be roughly 60 per cent and 150 per cent of the value calculated; ν needs to be about 30 and g (the number of lags) must be at the most $N/15$. Inevitably the choice of the number of lags is a compromise between frequency resolution and statistical stability. Several practical details of the cosine-transform method have been omitted and the reader should consult Blackman and Tukey,[7] and Jones[8] for more information. We shall now call the cosine-transform method the B&T method since these authors are generally referred to in the literature.

Concerning the number of arithmetic operations in the B&T method, which we shall need later for a comparison, let an addition (+) and a multiplication (×) each be for convenience half an operation. Then the computation of the autocorrelations requires

$$N + (N-1) + \ldots + (N-g) = (g+1)(N-g/2) \qquad \ldots (19)$$

full (i.e. $(+\times)$) operations. To evaluate the cosine part of each of the $(g-1)$ spectral points (i.e. ignoring the end points) requires a further $g(+\times)$ operations, i.e. to compute all the spectral points, including end points, requires roughly g^2 operations. Smoothing, for example 'hanning', uses $2(+\times)$ operations for each point. Overall then the total number of operations to produce one power spectrum is about

$$(g+1)(N-g/2) + g^2 + 2g \approx N(1+g) + g^2/2. \qquad \ldots (20)$$

To find cospectra and quadrature spectra from two series of data, $(g+1)(N-g/2)$ operations are required to evaluate the cross-correlations, g additions (i.e. $g/2$ $(+\times)$ operations) are wanted to form $E(\tau)$ and $O(\tau)$, there are then $2g^2$ operations to form the cosine and sine transforms plus finally $4g$ smoothing operations, i.e. altogether

$$(g+1)(N-g/2) + g/2 + 2g^2 + 4g \approx N(1+g) + 3g^2/2 \qquad \ldots (21)$$

operations.

The Fast Fourier Transform (FFT). For a discrete, equally spaced time series, of zero mean, where t=time (this could instead be a space variable), N=the number of data points and n=a frequency, writing $t=j\Delta t$, $(j=0, 1, \ldots, N-1)$, $T=N\Delta t$ and $n=k/T=k\Delta n$, $(k=0, 1, \ldots, N-1)$, ignoring end corrections the summation version of equation (3) is :

$$C\,(k\Delta n) = \frac{1}{N}\sum_{j=0}^{N-1} x\,(j\Delta t)\;W^{jk} \qquad \ldots\ (22)$$

where $W=\exp(2\pi i/N)$ and C_k is replaced by $C(k\Delta n)$ to indicate that the Fourier coefficients are evaluated at frequency intervals Δn starting at zero frequency. Only about $N/2$ useful coefficients are produced by (22), the rest being a set of reflected values, and straightforward (i.e. classical) calculation requires about $N^2/2$ $(+\times)$ operations (i.e. each of the N data points has to be multiplied by a trigonometric function to obtain each of the $N/2$ coefficients). In 1965 Cooley and Tukey[6] produced a paper which showed that the number of operations could be reduced to about $2N\log_2 N$ with no loss of information and in fact with increased computational accuracy. By sorting the data this number can be reduced even further to about $N\log_2 N$. The FFT works fastest when $N=3^m$, where m is an integer, but normally factors 2^m and 4^m are used, and for 1024 points the speed of computation can be increased by about 50 times (i.e. $(1024)^2/2(1024\times 10)=51{\cdot}2$). In addition the FFT can ideally be adapted for computer evaluations.

The basis of the FFT is that a large number of the W^{jk} terms are equal, or the negative of each other, so that if the data points (i.e. $x(t)$) which are multiplied by the same term are brought together first a vast saving in arithmetic results. To illustrate this in a simple case let $N=4$ so that immediate evaluation of (22) (ignoring the $1/N$) produces

$$\begin{aligned}
C(0)&=x(0)+x(1)+x(2)+x(3)\\
C(1)&=x(0)+x(1)W^1+x(2)W^2+x(3)W^3\\
C(2)&=x(0)+x(1)W^2+x(2)W^4+x(3)W^6\\
C(3)&=x(0)+x(1)W^3+x(2)W^6+x(3)W^9.
\end{aligned}$$

Now $W^1=i$, $W^2=-1$, $W^3=-i$, $W^4=1$, and the cycle then repeats with $W^5=i$, $W^6=-1$ etc., so that if we let

$X(0)=x(0)+x(2)$, $X(1)=x(0)-x(2)$, $X(2)=x(1)+x(3)$, and $X(3)=x(1)-x(3)$,

we then have

$$\begin{aligned}
C(0)&=X(0)+X(2)\\
C(1)&=X(1)+X(3)W^1\\
C(2)&=X(0)+X(2)W^2\\
C(3)&=X(1)+X(3)W^3.
\end{aligned}$$

The number of steps is thereby cut down from 12 additions and 9 multiplications to 8 additions and 3 multiplications.

A discussion of the theory behind the FFT together with results, references and KDF 9 USER CODE programmes is given by Rayment.[9]

To find spectra therefore the Fourier coefficients are substituted directly into equations (10), (11) and (12). The spectral points will in general require more smoothing than the spectra derived using the B&T method. Probably one or two applications of the previously mentioned 'hanning' formula together with linear averaging over adjacent points will normally suffice. The same statistical arguments apply to these estimates and the number of degrees of freedom to be attached to each final point is $2H$ where H is the number of adjacent points averaged together.

Concerning the number of $(+\times)$ operations we require $N\log_2 N$ to produce the coefficients, $3N/4$ for the power spectrum points and $2N+(1+1/H)\,N/4$ for a double application of hanning and linear averaging. Computation of the variance, i.e. the area under the spectral curve, which is given automatically in the B&T method, requires $N/2$ additions, i.e. $N/4$ $(+\times)$ operations. Cospectra together with quadrature spectra simply need double the number of operations that are required to find the power spectra. The overall number of operations per spectrum is therefore

$$N(\log_2 N+3{\cdot}25+1/4H). \qquad \ldots (23)$$

It should be mentioned that there is a further reduction in the number of degrees of freedom, in both the B&T method and the FFT, connected with end effects which we shall ignore here.[7,10] Also it is possible in both methods to increase stability by averaging over several spectral curves if conditions permit this.

Without discussing any details it may be of interest to list some other applications of the FFT.

(i) Computation of Fourier integrals, Fourier series, convolution integrals, computing difference equations and simulating filters (Ref. 10).

(ii) Trigonometric interpolation, least-squares approximation by trigonometric polynomials, numerical convolution and digital filtering (Ref. 11).

(iii) Calculating high-order correlations (Ref. 12).

Comparison between the FFT and the B&T method. For the sake of a comparison between the two methods we shall take a case where $N=1024$ and $\nu=30$, i.e. $g=N/15$ and $H=15$. To produce power spectra and the variance together with the suggested smoothing techniques requires for the B&T method, substituting in the right-hand side of equation (20),

$$1024(1+1024/15)+\tfrac{1}{2}(1024/15)^2=73\ 259 \text{ operations,}$$

and the FFT requires, referring to equation (23),

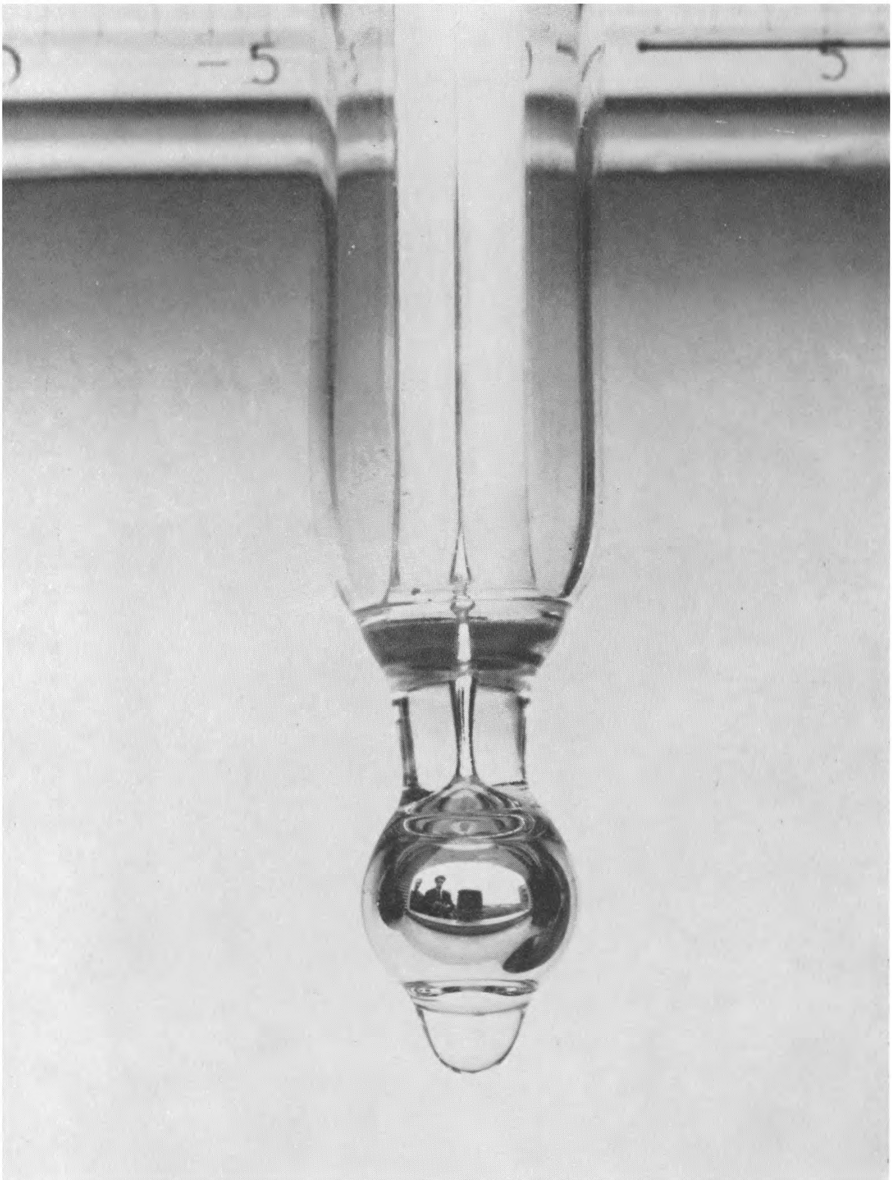
$$1024(10+3{\cdot}25+1/60)=13\ 585 \text{ operations.}$$

The ratio of the numbers of operations is 5·39 so that the FFT is much more efficient.

In this example however if one can accept a coarser frequency resolution such that $g=12$ (i.e. $H=85$ and $\nu=170$) the numbers of operations work out to be nearly equal. The general expression for the number of operations to be equal is :

$$2N/g=2H=\nu\approx\left\{N+\sqrt{[N^2+2N(2{\cdot}25+\log_2 N)]}\right\}/(2{\cdot}25+\log_2 N). \qquad \ldots (24)$$

(In the example we are using therefore $g=12{\cdot}18$ gives exact equivalence though in practice g must be a whole number.) So that if we can accept $g\leqslant 12$, for $N=1024$, the B&T method of producing power spectra is preferable.



Photograph by courtesy of RAE Bedford

PLATE I—THE SPECIAL DRY-BULB THERMOMETER AT RAE, BEDFORD

Moisture which had accumulated during the wet fog of 28 May 1968 had coalesced and run down the thermometer stem, forming an unstable drop some 3·5 mm long on the underside of the thermometer bulb. See page 275.

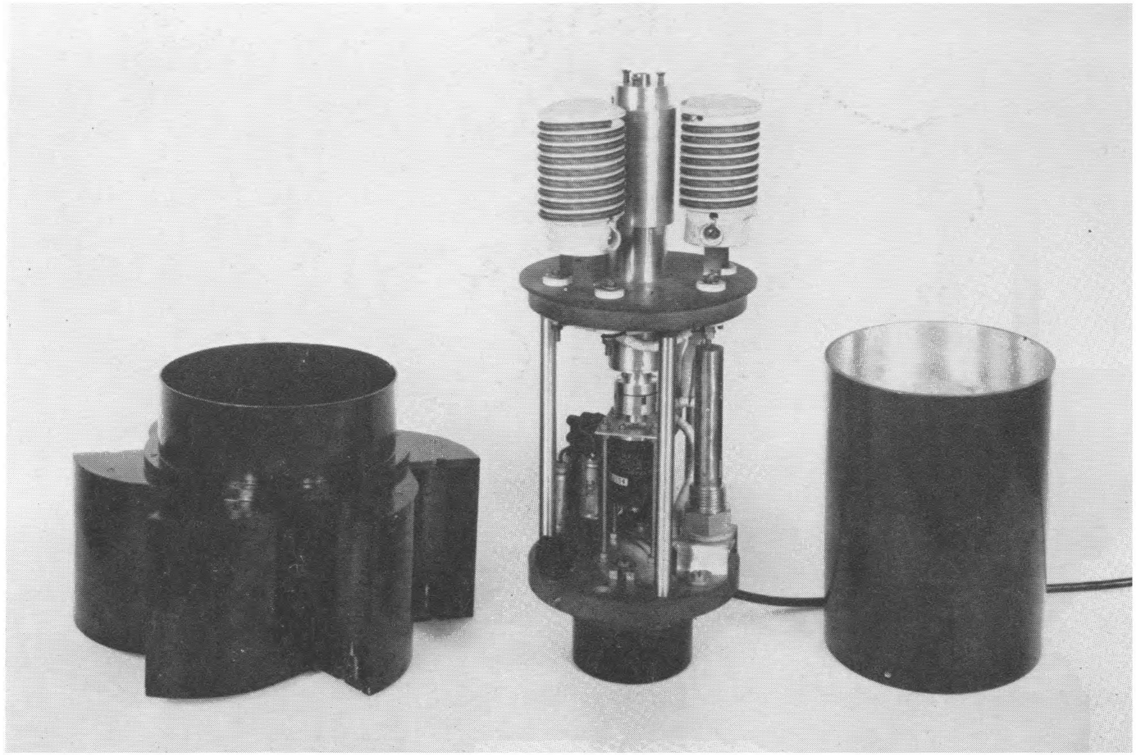


PLATE II—COMPONENT PARTS OF HEATED ANEMOMETER

See page 270.

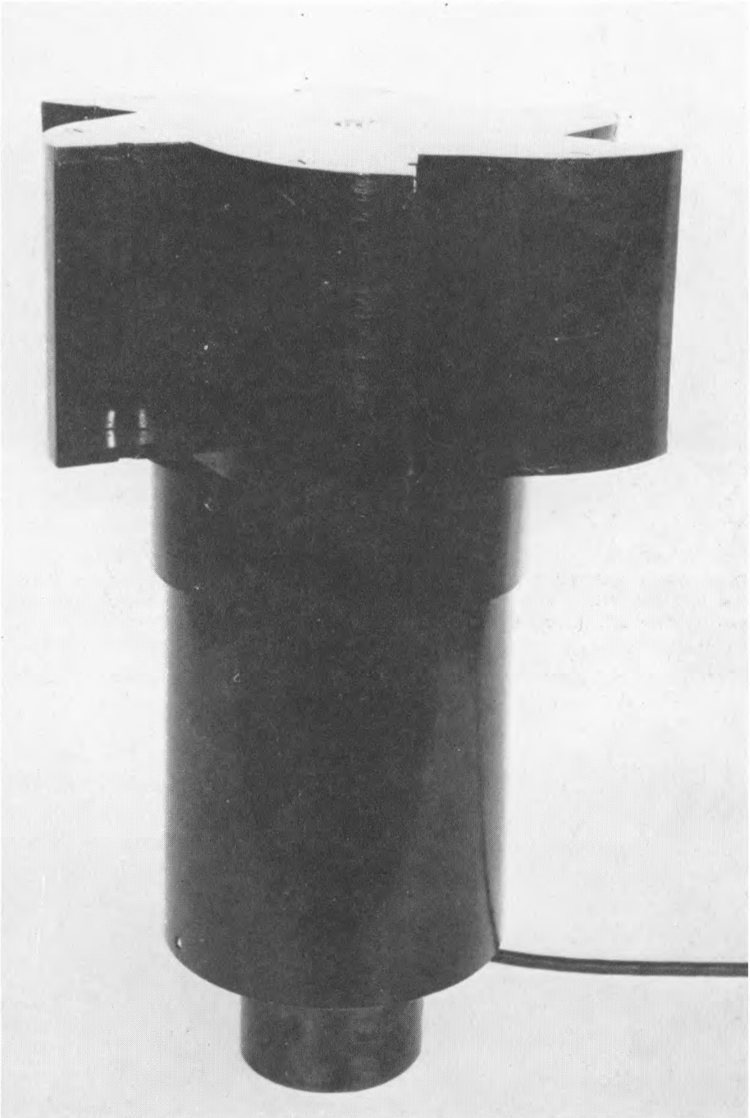


PLATE III—HEATED ANEMOMETER ASSEMBLED

See page 270.

Reproduced by permission of Wing Commander A. B. Walker

PLATE IV—SHALLOW FOG OVER A SNOW SURFACE

The photograph was taken at about 0915 GMT on 15 February 1970 from 300 yd north-north-west of the Control Tower on the airfield at Machrihanish, Argyll, with the camera facing south-south-east. (See page 284.)

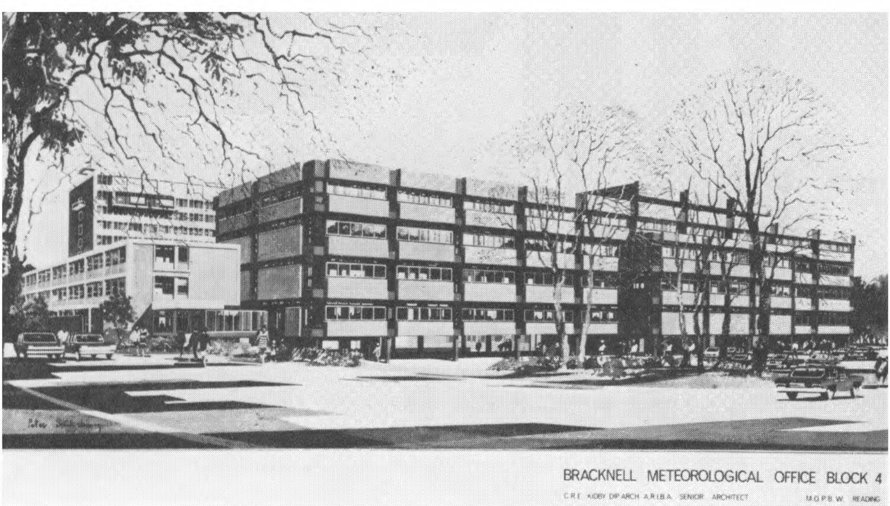


PLATE V—ARTIST'S IMPRESSION OF THE RICHARDSON WING NOW UNDER CONSTRUCTION AT HEADQUARTERS, METEOROLOGICAL OFFICE, BRACKNELL

Going back to the example where $g=N/15$, but where we have two series of data points each of number N, the situation for the production of cospectra and quadrature spectra favours the B&T method slightly more, compared with the FFT, than it did in the power spectrum case. To produce these spectra therefore plus the covariance but not the area under the quadrature spectrum curve requires for the FFT twice the figure for the power spectrum case minus the $N/4$ operations required to find the area, i.e. 26 914 operations. For the B&T method, substituting into equation (21), the number of operations is

$$1024(1+1024/15)+\frac{3}{2}(1024/15)^2=77\ 920.$$

This gives the ratio of the numbers of operations as 2·89.

If all the spectra are required (i.e. cospectrum plus covariance, quadrature spectrum and both power spectra plus the variances) the FFT gains tremendously because the same Fourier coefficients can be used for the power spectra and the cospectra and quadrature spectra whereas the B&T method requires a fresh set of cross-products each time (i.e. three sets altogether, one for each of the power spectra and one set for the cospectra and quadrature spectra). For the FFT therefore the number of operations is twice that for the power spectrum case plus the previously found number for the cospectra and quadrature spectra minus the number of operations to produce two sets of Fourier coefficients (i.e. $-2N\log_2 N$), i.e. $(2\times 13\ 585)+26\ 914-(2\times 1024\times 10)=33\ 604$. For the B&T method we require twice that for the power spectrum case plus that for the cospectra and quadrature spectra, i.e. $(2\times 73\ 259)+77\ 920=224\ 438$ operations, giving a ratio of operations in favour of the FFT equal to 6·68.

Conclusions. The requirement for a small amount of spectral information, with low-frequency resolution, can still be met by the B&T method but it is clear that in many situations use of the FFT can drastically reduce the computational time thereby allowing some problems to be tackled which hitherto could only be solved in a very rough way, if attempted at all. The FFT enables one to perform extensive analysis, if required, not only of spectra and cospectra but also of higher-order spectra (polyspectra) with the maximum possible frequency resolution and computational accuracy.

Acknowledgements. Thanks are due to Dr F. Pasquill and Dr C. J. Readings for constructive criticisms and suggestions.

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A HEATED ANEMOMETER

By G. E. W. HARTLEY

Summary. Some details and drawings are given for a heated anemometer designed by the Meteorological Office and installed on Mount Olympus, Greece in early 1969.

A rotor is arranged so that its six cups have their interior surfaces exposed to two 600-watt bowl-fire elements connected to a 240-volt a.c. supply and controlled by a thermostat set at 36°F. A direct-current generator is driven by the spindle of the rotor and operates a Mk 2 anemometer wind-speed dial adapted for direct current and marked for wind speeds up to 150 knots.

Calibration was done in two stages. A relation was obtained between wind speed and rotor revolutions per minute from 5 to 90 knots in a wind-tunnel and the calibration graph was extrapolated to 150 knots. The generator was then driven at various speeds in the range to calibrate the dial up to speeds of 150 knots.

D. W. Mann and C. F. Marvin* have described a heated rotation anemometer designed and made for use on Mount Washington, U.S.A., and when the Meteorological Office proposed to produce a heated anemometer for use on Mount Olympus, Greece, at a height of about 6000 feet (approximately 1800 metres), this anemometer was considered to be the most hopeful design. The first attempt, which was not successful, was to use a standard Mk 2 cup-generator anemometer, the cups being replaced by a six-cup rotor on the lines of that of the Mount Washington anemometer, and to heat the rotor by means of a 'Thermo-Cord' heating wire, of the kind used to prevent pipes from freezing, wound round a cylinder inside the rotor, the cylinder being held on a circular plate fixed to the generator housing, with a very small clearance between the rim of the plate and the rotor, so as to prevent snow or rain blowing into the rotor.

The rotor consisted of six cups fixed to the outside wall of a cylinder closed at the upper end, the heating coil being as close as possible to the inside of the cylinder. This arrangement was unsuccessful because not enough heat reached the cups through the cylinder wall to melt snow which collected in the cups. Also the torque produced by this rotor was considerably less than that produced by the standard cup assembly, and so the starting speed was about 10 knots; the calibration also differed from that of the standard cups, so that the dial had to be altered.

* *Mon. Weath. Rev. U.S. Dep. Agric., Washington DC*, **62**, 1934, pp. 189–193 (from 'The great wind of April 11–12, 1934 on Mount Washington, N.H. and its measurement' parts II and III).

A second heated anemometer was therefore designed; it is illustrated in Plates II and III, and in Figures 1 and 2. Part numbers in the descriptions refer to part numbers in Figure 1.

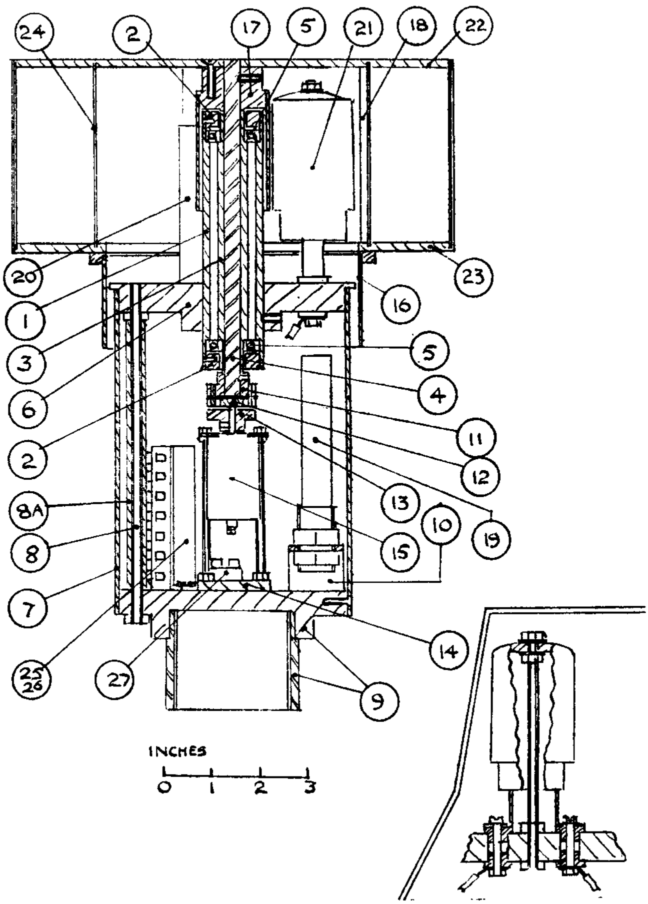

FIGURE 1—GENERAL ARRANGEMENT OF HEATED ANEMOMETER INCLUDING INSET SHOWING STRENGTHENED MOUNTING OF HEATING ELEMENT

List of part numbers and description of parts :

1. Spindle bearing support tube.
2. Ball bearing retaining cups (2).
3. Spindle outer sleeve.
4. Spindle.
5. Ball bearings (2) $1\frac{1}{8}''$ external diameter $\times \frac{3}{8}''$ internal diameter $\times \frac{1}{4}''$ thick.
6. Upper plate.
7. Housing.

8, 8A. Pillars (3).

9. Lower plate and mounting socket.
10. Lower thermostat bracket.

11, 12, 13. Flexible coupling.

14. Generator mount.
15. Generator.
16. Rotor skirt (or weather shield).
17. Rotor boss.

18, 22, 23, 24. Parts of rotor.

19. Lower thermostat.
20. Upper thermostat.
21. Heating elements (2).

25, 26, 27. Terminal blocks and bracket.

The rotor, shown in isometric view in Figure 2, is arranged so that its six 'cups' have their interior surfaces exposed to the heating elements (21). These are two 600-watt bowl-fire elements, strap-mounted in a vertical position on the circular plate (6) which also carries the rotor spindle bearing support tube (1) and a thermostat (20). Pillars (8, 8A) on the underside of plate (6) connect it to the lower plate (9) which carries a second thermostat (19) and two terminal blocks (26, 27), and incorporates a 2-inch* B.S.P. tapped socket (9) for mounting.

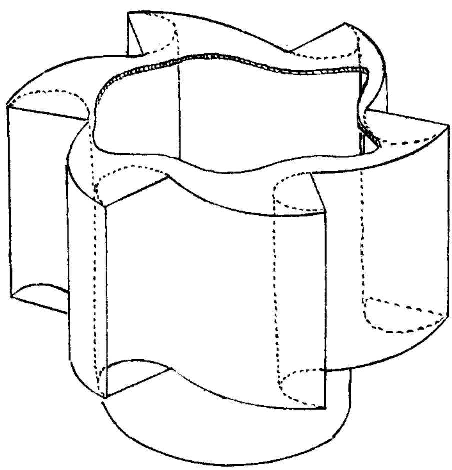

FIGURE 2—ROTOR, WITH ROOF PARTLY CUT AWAY TO SHOW INTERIOR

The rotor has at the centre of its roof a boss (17) which carries a stainless-steel spindle (4), the diameter of which is three-eighths of an inch. The spindle fits inside a brass sleeve (3) carried in two ball bearings (2) in the bearing support tube (1). The rotor and spindle can be lifted out of the sleeve, leaving the sleeve and bearings in position, after taking off the upper generator coupling piece (11).

The generator (15) driven by the spindle through the flexible coupling (11, 12, 13) is a 'Servo-Tek' tachometer generator, type SA 740A–2, giving 7·0 volts d.c. per 1000 rev/min with a driving torque not exceeding 0·20 in ozf. This was chosen because of its small size, low driving torque and the claim by its makers of long brush and bearing life. Its connecting leads are taken out to the terminal block (27). The two heating elements are connected in parallel across the 240-V a.c. supply, one of the connecting leads being

* Dimensions are given in British units because, at the time of making, metric equipment and materials were not readily available.

connected through the two cartridge-type thermostats which are in series. The lower thermostat (19) is set to close at 36°F, and the upper (20) to open at 60°F, to act as a safety device to prevent the rotor getting too hot in case the 36° thermostat fails to open. The thermostat contacts have 0·05 mF (700-V rating) capacitors connected across them to prevent sparking (see Figure 3). The generator, lower thermostat and terminal blocks are enclosed in a cylindrical housing (7) which is overlapped by the weather shield (16) which forms the lower part of the rotor. The terminal block (26) makes the connections between heating elements, thermostats and capacitors easier.

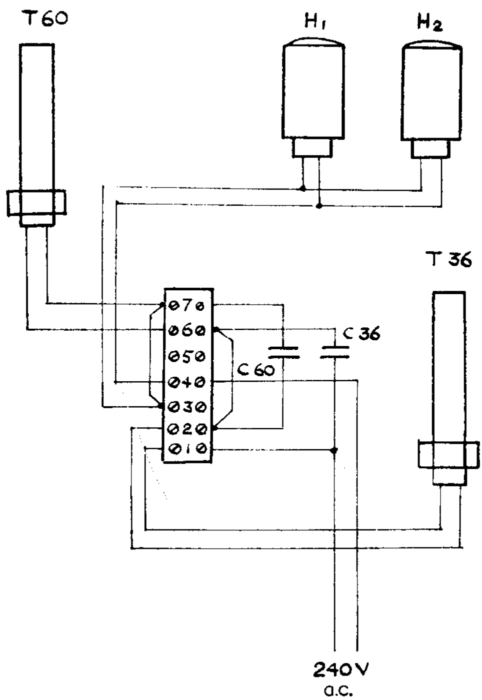

FIGURE 3—HEATING CIRCUIT WIRING DIAGRAM

T_{60}, T_{36} Thermostats; C_{60}, C_{36} Capacitors; H_1, H_2 Heating elements.

The anemometer was only required to operate one dial, and a standard wind-speed dial as used with Mk 2 and Mk 4 anemometers was adapted to direct current by taking out the rectifier, and adjusting the series resistance as required. The anemometer was calibrated first with a worm reduction gear, with a pointer on the worm-wheel spindle, in place of the generator, to obtain a relation between wind speed and rotor rev/min. This was done in the large wind-tunnel at the Meteorological Office, Bracknell, from starting speed up to 90 knots, and the calibration graph was extrapolated up to 150 knots. This means of course that above 90 knots readings are suspect; but the method was the only possible one with the existing wind-tunnel.

The relation between wind speed and rev/min having been obtained, it was required to drive the generator at various speeds in the range, to calibrate the dial. This was done by fitting the generator with a small wind-mill fan, whose spindle also carried a worm reduction gear and pointer, so that revolutions could be counted against a stop-watch. The fan, generator and counter were mounted in the small wind-tunnel, as a means of driving the fan and hence the generator, at speeds up to that corresponding to 150 knots, though of course the wind speed in the small tunnel was not measured.

The generator was connected to the modified dial with an adjustable series resistance. At a speed corresponding to 150 knots, the series resistance was adjusted to make the dial read full-scale deflexion (90 knots on the existing scale) and then the positions of the pointer on the existing scale were noted at various lower speeds. From these readings a graph was drawn up of wind speed against existing dial readings From this graph existing dial readings corresponding to 10, 20, 30 . . . 150 knots were obtained. The angular displacements of these readings from existing scale zero were measured, and a new dial was made and engraved from 0 to 150 knots.

The value of the adjustable series resistance was measured, and it was replaced by a fixed resistor inside the dial case.

The relation between wind speed and revolutions/minute is shown in the following table:

Experimental values

knots	5	10	20	30	40	50	60	70	80	90
rev/min	13	96	235	370	520	675	840	1040	1235	1480

Extrapolated values

knots	100	110	120	130	140	150
rev/min	1740	2020	2320	2620	2950	3300

The engraved dial readings were checked up to 90 knots with the anemometer in the large wind-tunnel.

The anemometer was installed on Mount Olympus early in 1969. Fairly soon the 60° thermostat became unserviceable and was short-circuited out.

It was also found necessary to stiffen the mountings of the heating elements, which were initially held by their brass strip feet which were bolted to the plate (6) with insulating sleeves interposed, the bolts forming the electrical connections. To stiffen the mountings, ¼-inch steel screwed rod held by two nuts in a ¼-inch diameter hole midway between the feet was passed up through the central hole of the ceramic former of the heating element, with a locknut above and below the top of the former, and of such a length that the top of the screwed rod was clear of the roof of the rotor — see inset in Figure 1.

Latest reports from Mount Olympus (spring 1970) suggest that the anemometer is now satisfactory, and that it is questionable whether the 60°F thermostat is necessary.

Acknowledgement. The instrument was made in the workshop of the Operational Instrumentation Branch of the Meteorological Office at Bracknell, and the author acknowledges with thanks suggestions from the head of workshop, and excellent workmanship by the craftsman concerned.

551.508.26:551.571.1

THE EFFECT OF A MOISTURE-COVERED DRY-BULB THERMOMETER ON AIR TEMPERATURE READINGS AND THE DERIVED HUMIDITY VALUES

By D. J. GEORGE

Summary. In certain circumstances moisture may be deposited on the bulb of the dry-bulb thermometer in a standard screen. A photograph is shown of a drop of water which formed on a bulb during a summer wet fog. The moisture-covered thermometer may read up to 1 degC too low during the evaporation stage until all the moisture has evaporated which may not be until several hours after fog dispersal.

Experiments were made in which an extra thermometer was installed in the screen, and allowed to collect moisture during fog while the screen dry-bulb thermometer was kept dry by wiping with a cloth between readings which were made at frequent intervals. Details are given of readings made during a summer wet fog. A summary of the results for 7 summer fogs and 11 winter fogs during 1968–69 at Bedford shows the type of error which can occur. It is shown that errors are likely to be greatest at high temperatures with dry air and moderate winds and least with moist stagnant air at low temperatures.

Introduction. The dry-bulb and wet-bulb psychrometer in a standard screen is in fairly common use in synoptic meteorology for measuring air temperature and wet-bulb temperature, and deriving humidity values (e.g. dew-point, relative humidity and vapour pressure). Much attention has been devoted over the past century and a half to the theory of the psychrometer and to sources of error when using it. Recently, McCaffery[1] has investigated errors due to contaminated wet-bulb muslins, and Zobel[2] has drawn attention to errors due to insufficient ventilation of the wet-bulb thermometer.

Another source of error which does not seem to have had much attention in meteorology (perhaps because of the irregular frequency of occurrence and the simple remedy once the source of error has been detected) is moisture on the bulb of the dry-bulb thermometer, causing the thermometer to act as a partial wet-bulb thermometer, and thus giving low air temperature readings and high derived humidity values. Brief mention of this source of error has been made by Wylie[3] and the National Physical Laboratory.[4] Standard textbooks on observing[5] and meteorological instruments[6] instruct the observer to keep thermometers clean and bright, without defining situations where the observer should be especially watchful for the presence of moisture on the thermometers.

The purpose of this note is to draw attention to the magnitude and persistence of errors in dry-bulb temperature and the derived humidity values, caused by using readings from a moisture-covered mercury-in-glass dry-bulb thermometer in a standard screen, by means of examples observed during 1968–69 at the Royal Aircraft Establishment, Bedford (altitude 85 m). Errors of almost 1 degC in dry-bulb temperature and dew-point, 10 per cent in relative humidity and 0·8 mb in vapour pressure were observed several hours after fog dispersal. Knowledge of situations when moisture is likely to form on thermometers may enable observers to take prompt remedial action and thus obtain more accurate values.

Formation and evaporation of moisture. Moisture commonly forms on all surfaces inside and outside the screen by condensation of water vapour during water fog or hill fog, and may be augmented in hill fog by fog droplets blowing into the screen. Observations show that during water fog a mist forms on the screen thermometers in about 45 to 90 minutes, and in about 10 minutes in wet fog or hill fog. Small droplets coalesce and gravitate to form a drop on the underside of the thermometer bulb after several hours of accumulation (see Plate I). For a spherical bulb of diameter 1 cm, the limiting size of drop is about 4 mm. After growing to this size the drop falls off (particularly if the screen is vibrated) and growth starts afresh. A thin layer of ice grows on the thermometers by deposition of water vapour during supercooled water fog.

Evaporation of the drop commences when the visibility improves from thick fog conditions to over 1 km. The moisture-covered themometer reads low during the evaporation stage until all the moisture has evaporated.

Errors in air temperature and the derived humidity values. The error ΔT in the dry-bulb temperature due to taking readings from a moisture-covered dry-bulb thermometer (T') instead of a perfectly dry dry-bulb thermometer (T) will be proportional to the wet-bulb depression, itself a function of the general temperature level and the rate of evaporation.

Any error in the dry-bulb temperature will be reflected in a reduced wet-bulb depression and in turn will produce errors in the derived humidity values. By combining the hygrometric equation[7] with an expression for relative humidity in terms of vapour pressure, equations may be obtained showing the error in relative humidity ΔU :

$$\Delta U = 100\ \frac{e_{s(Tw)} - Ap\,(T' - T_w)}{e_{s(T')}} - 100\ \frac{e_{s\,(Tw)} - Ap(T - T_w)}{e_{s\,(T)}} \qquad \ldots (1)$$

$$\approx \frac{100\ Ap}{e_{s(T)}}\ \Delta T$$

where $e_{s(Tw)}$ = saturation vapour pressure at the wet-bulb temperature Tw
$e_{s(T)}$ = saturation vapour pressure at the dry-bulb temperature T
Ap = psychrometric constant.

By similarly applying the hygrometric equation it can be shown that the error in vapour pressure Δe is proportional to ΔT. Also, as the dew-point by definition is the temperature at which $e{=}e_s$, errors in dew-point ΔD will also be proportional to ΔT.

Errors in measured air temperature and the derived humidity values are thus likely to be greatest at high temperatures ($>10°$C) with dry air and moderate winds, and least with moist stagnant air or at low temperatures.

Spencer-Gregory and Rourke[8] give equations which show that the rate of evaporation of a given mass of water from a thermometer bulb is proportional to the wet-bulb depression and square root of the wind speed. The longest time for a drop to evaporate from a moisture-covered bulb will occur when there is a large drop after prolonged or wet fog, followed by light winds and high relative humidity (e.g. after fog dispersal in summer with cloudy skies and slow temperature rise, or in winter). A drop will evaporate relatively quickly in summer with moderate winds, clear skies and rapidly decreasing relative humidity.

Experiments. Comparative experiments were made by installing a second dry-bulb thermometer (known as the special dry-bulb thermometer) to the right of the screen dry-bulb thermometer, and allowing the special thermometer to collect moisture during fog. The moisture was allowed to evaporate naturally, while the screen dry-bulb thermometer was kept dry by wiping it with a clean cloth between readings. Frequent readings of temperatures and supporting observations were made during and after the fog until all the moisture had evaporated.

A typical example of summer wet fog occurred on 28 May 1968 when there was a north-east airflow over the Midlands and East Anglia. Fog formed soon after midnight when moist air from the Wash had cooled overland, producing wet fog with visibility <90 m and light north-east wind until 08 GMT, all objects being dripping wet. The fog thinned after 08 GMT, with mist and low cloud during the morning and broken cumulus in the afternoon. Moisture formed on the special thermometer by 0115 and by 0958 it had grown to a drop some 3 to 4 mm long (see Plate I). The readings and errors are shown in Figure 1.

Results of other experiments are summarized in Table I. The heaviest condensation occurred with pure water fogs with very low visibility during the life of the fogs, while short-lived fogs, shallow fogs with variable visibility and fogs with smoke content, produced little condensation.

Experiments continued with 11 fogs during the winter of 1968–69. Although much moisture accumulated during prolonged fogs at temperatures between -2 and $+10$°C, evaporation generally took place slowly, and errors in dry-bulb temperature averaged 0·1 degC, with a maximum error of 0·2 degC.

Another experiment showed that it is possible for melting snowflakes to adhere to the thermometer bulb after being blown into the screen during snow showers, and that errors in air temperature readings and derived humidity values can occur while the snowflakes melt and evaporate.

Discussion. It is apparent from these simple experiments that significant errors in measured air temperature and derived humidity values can occur if moisture forming on the dry-bulb thermometer during water fogs at temperatures above freezing goes undetected and is allowed to evaporate after fog dispersal. Measured and reported air temperatures and dew-points may be up to 1 degC too low and too high respectively during the evaporation stage. If these erroneous values are used for graphical calculation of convection condensation levels (CCLs) on the tephigram, a too-low assessment of cloud base can be made (e.g. CCLs using the readings at 1242 GMT on 28 May 1968 were 1600 ft using the screen dry-bulb temperature, and 700 ft using the special dry-bulb temperature, the estimated cumulus base being 1500 ft).

Although most observers are well aware of the care required with wet-bulb thermometers, the dry-bulb thermometer tends to be taken for granted. A watch should be kept for moisture on thermometers during and after fog or wintry precipitation, and any deposit on the bulbs of screen thermometers should be wiped off with a clean tissue or cloth.

With increasing use of remote indicating thermometers at synoptic stations and on high masts and mountains, this source of error may become more

TABLE I—SUMMARIZED RESULTS OF EXPERIMENTS WITH SUMMER HALF-YEAR FOGS

Date 1968	Type of fog	Duration of fog	Time from beginning of evaporation of drop, to complete evaporation	Max. ΔT	Mean ΔT	Max. ΔD	Mean ΔD	Max. ΔU	Mean ΔU	Max. Δe	Mean Δe
				degrees		*Celsius*		*per cent*		*millibars*	
10 April	wet advection	4 h 30 min	2 h 22 min	0·7	0·27	0·8	0·35	9	3·9	0·4	0·20
24 May	radiation	5 h 30 min	1 h 15 min	0·5	0·38	0·5	0·40	7	5·2	0·4	0·28
28 May	wet advection/radiation	9 h 20 min	4 h 50 min	0·9	0·44	0·9	0·41	10	4·3	0·8	0·38
22 August	shallow radiation	4 h 40 min	no discernible moisture on bulb	0·0	0·0	0·0	0·0	0	0·0	0·0	0·0
23 August	radiation	8 h 15 min	2 h 25 min	0·5	0·32	0·4	0·23	5	3·2	0·5	0·28
5 September	radiation	1 h 50 min	bulb slightly misty at 0653 GMT	0·1	—	0·1	—	1	—	0·1	—
10 September	radiation	8 h 15 min	2 h 40 min	0·4	0·25	0·3	0·18	4	2·6	0·4	0·22
Mean values for 2 advection fogs (10 April and 28 May)				0·80	0·35	0·85	0·38	9·5	4·1	0·60	0·29
Mean values for 3 radiation fogs (24 May, 23 August and 10 Sept.)				0·47	0·32	0·40	0·27	5·3	3·7	0·43	0·26

ΔT Error in dry-bulb temperature
ΔU Error in relative humidity
ΔD Error in dew-point temperature
Δe Error in vapour pressure

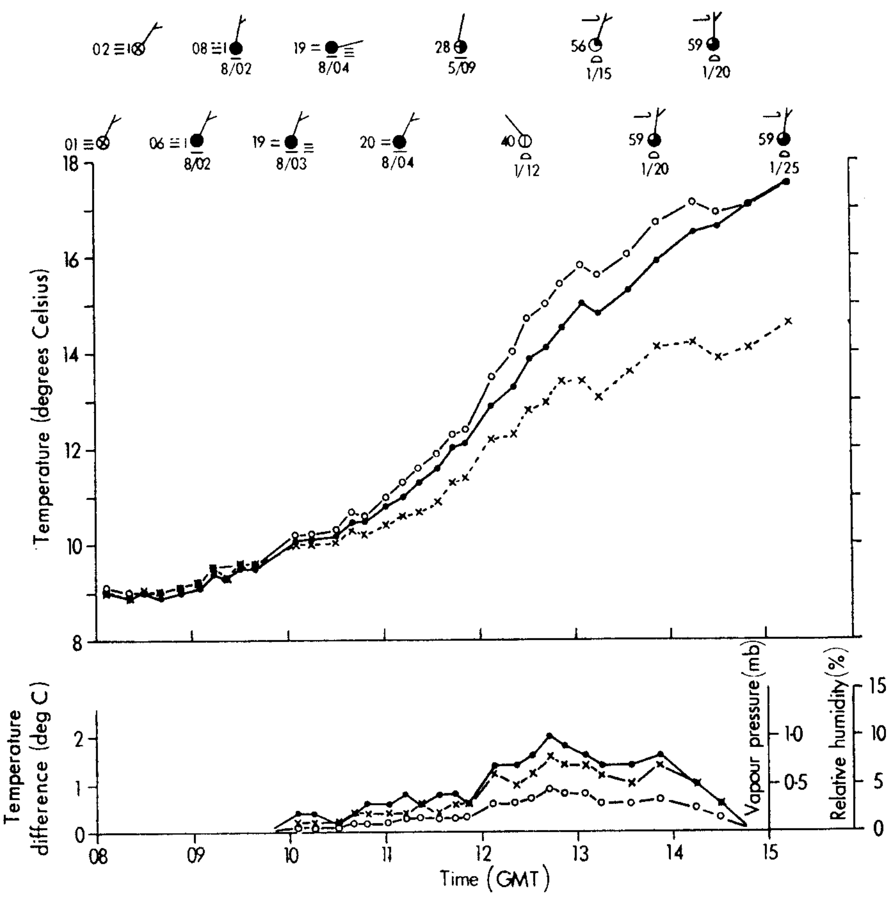

FIGURE 1—THE EXPERIMENT AT RAE, BEDFORD, ON 28 MAY 1968

Upper curves — thermometer readings of :
o———o Dry bulb; •———• Moisture-covered dry bulb; x - - - x Wet bulb.
Lower curves — errors arising from use of moisture-covered dry-bulb thermometer in :
•———• Relative humidity; x———x Vapour pressure; o———o Dew-point temperature.

important, particularly where the temperature elements are exposed to hill fog or cloud for long periods, and only visited at infrequent intervals. The remedy then may be to instal some device for drying off the dry-bulb element after fog.

These errors may be compounded with errors due to insufficient ventilation of the thermometers (described by Zobel[2]), or errors due to the lag of the screen itself (described by Bryant[9]).

Acknowledgements. Thanks are due to the observers at RAE, Bedford, who helped with the frequent careful readings, and to Mr J. Gordon who made some suggestions at the writing-up stage.

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551.515:551.578.45

PERSISTENT SNOW SHOWERS ON SALISBURY PLAIN ON 6 MARCH 1970

By B. J. BOOTH

Summary. On 6 March 1970 a trough which formed over the Bristol Channel in the lee of the Welsh mountains, combined with an existing instability trough, gave rise to an unexpected and prolonged snowfall over Salisbury Plain. Surface observations at Little Rissington and Upavon as well as radiosonde ascents from Aberporth and Larkhill are presented and discussed. The prolonged snowfall is attributed to the backing of the gradient wind by the pressure falls on the trough, and the instability of the air mass with respect to sea temperatures in the Bristol Channel.

The weather over Salisbury Plain is very much subject to local topographical effects, one of the most marked of these being the shelter produced by the Welsh mountains in unstable west-north-westerly – north-north-westerly airstreams during winter. Another effect of the Welsh mountains in north-westerly airstreams is to produce a lee trough over the Bristol Channel. Sometimes the result of this latter is not immediately noticeable, but on 6 March 1970, it helped to produce an unexpected, relatively prolonged snowfall lasting nearly four hours over Salisbury Plain and resulting in nearly half an inch* of snow over the highest ground.

At 06 GMT an unstable north-westerly airflow covered the British Isles. A minor trough lay from Shawbury to Birr in Eire (Figure 1) and was moving south at 15 knots.* Pressure tendencies ahead of the trough were slight, the largest fall being 0·7 mb in 3 hours; further very slight falls were being reported from the Bristol Channel as a lee trough formed. Over southern counties and behind the trough there was a very slight pressure rise. The overall effect was for the gradient to back slightly ahead of the trough and veer markedly behind it. Apart from showers moving through the Cheshire Gap, and reaching as far south as Benson (Oxon), shower activity seemed to be confined to the trough line.

* 1 inch ≈ 2·5 cm. 1 knot ≈ 0·5 m/s.

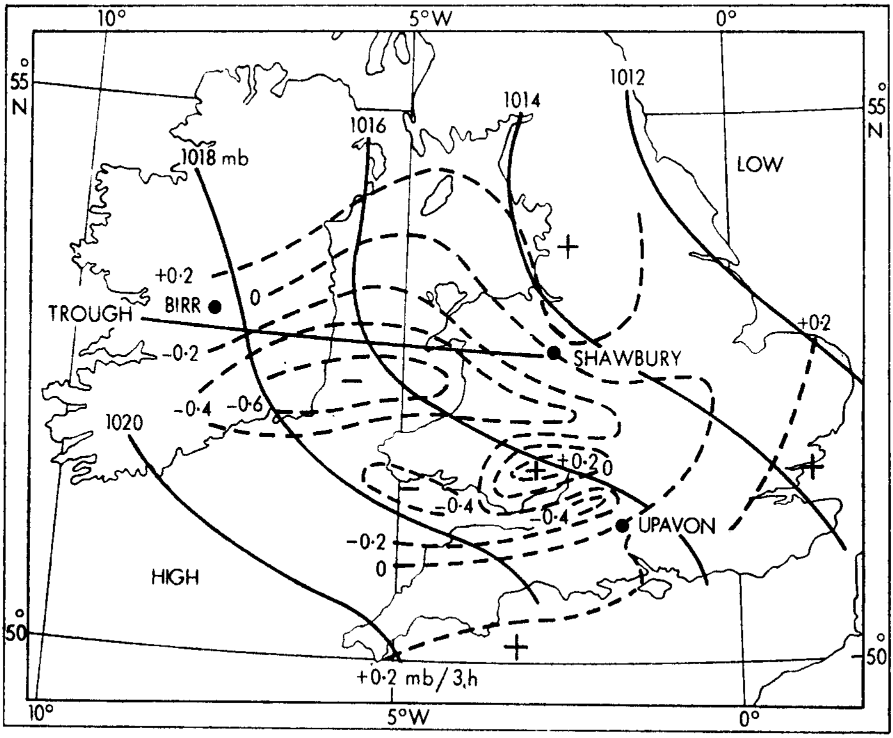


FIGURE I—SYNOPTIC PATTERN ON 6 MARCH 1970 AT 06 GMT

+ rising barometer — falling barometer
———— isobars - - - - - isallobars at intervals of 0·2 mb/3 h

This is shown by the observations from Little Rissington some 35 nautical miles (approximately 65 km) due north of Upavon, and well protected by the Welsh mountains (Table I).

TABLE I—HOURLY OBSERVATIONS AT LITTLE RISSINGTON ON 6 MARCH 1970

Time (GMT)	07	08	09	10	11	12
Wind (deg/kt)	290/08	250/07	270/08	280/08	280/11	280/09
Weather	Nil	Light snow shower	Recent snow shower	Nil	Nil	Nil

Table II gives the observations for Upavon on Salisbury Plain. A snow shower commenced at 0830 GMT some 35 nautical miles ahead of the trough. Snow or snow showers continued with varying intensity until 1230 GMT. With the passage of the trough the surface wind veered to 330° and the precipitation stopped.

TABLE II—HOURLY OBSERVATIONS AT UPAVON ON 6 MARCH 1970

Time (GMT)	08	09	10	11	12	13
Wind (deg/kt)	290/02	320/08	300/05	320/05	290/05	310/08
Weather	Nil	Moderate snow shower	Snow grains	Slight snow	Moderate snow	Recent snow

The reason for this relatively prolonged fall of snow and snow showers can be seen from the 09 GMT chart (Figure 2). The pressure falls on the trough

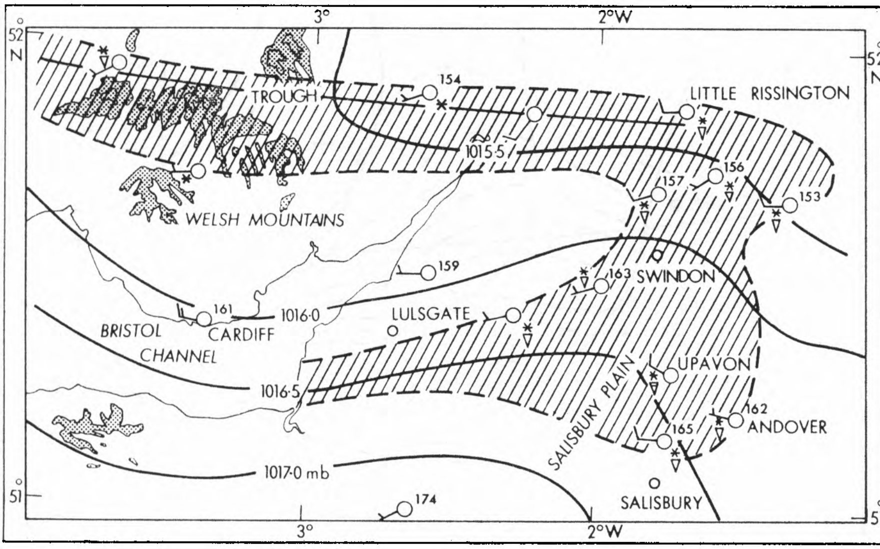
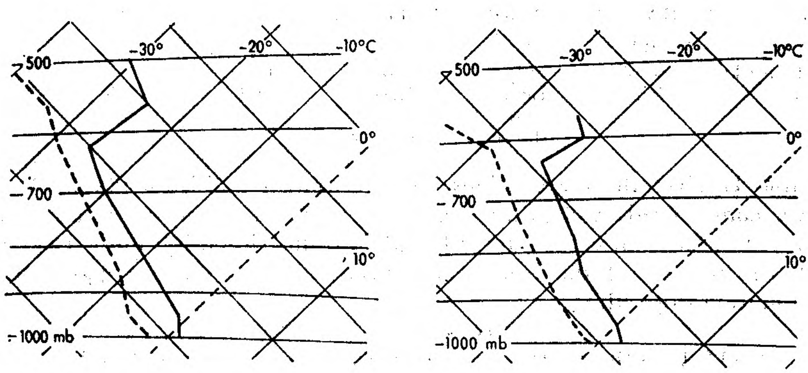


FIGURE 2—SYNOPTIC PATTERN ON 6 MARCH 1970 AT 09 GMT

The hatched area represents the area affected by snow or snow showers. Ground above 400 m is shown stippled.

and over the Bristol Channel had combined to back the gradient wind ahead of the trough until it flowed along the Bristol Channel straight to Salisbury Plain. At this time an aircraft reported cumulus cloud tops at 12 000 ft (about 3700 m) over Salisbury Plain. As can be seen from Figure 3, the 06 GMT



(a) Larkhill 09 GMT *(b)* Aberporth 06 GMT

FIGURE 3—RADIOSONDE ASCENTS FOR 6 MARCH 1970

.———. Dry-bulb temperature .– – – –. Dew-point temperature

Aberporth radiosonde ascent and the 09 GMT Larkhill radiosonde ascent were both unstable with respect to the sea temperatures in the Bristol Channel of 6–8°C, up to heights of 12 000 – 14 000 ft (3700 – 4300 m). Thus an almost continuous stream of snow showers were affecting Salisbury Plain until the trough moved south of the Bristol Channel and the gradient wind veered north-west.

The area affected is best described as a pear-shaped zone centred along the isobar for 1016.5 mb at 09 GMT (Figure 2), extending almost to Swindon in the north, Andover in the east, and Salisbury in the south, although one or two showers did reach the Southampton area.

The persistence of the showers was long enough to cause a considerable number of inquiries from the general public at the Main Meteorological Office at Upavon during the morning. Fortunately most of the snow melted on roads during the showers, and any snow that was left after the passage of the trough soon thawed.

REVIEW

Air pollutants, meteorology, and plant injury, WMO Technical Note No. 96, by E. I. Mukammal (Chairman), C. S. Brandt, R. Neuwirth, D. H. Pack and W. C. Swinbank. 210 mm × 275 mm, pp. x + 73, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1968. Price: Sw. Fr. 10.–.

This WMO *Technical Note* has been published at a time when environmental problems have suddenly become a part of political consciousness on an international scale. In the scientific context of its authors, and most readers, it is a literature review of the broad and complex subject of the interactions between plants and pollutants of their environment. At the same time the note is a statement by an authoritative international body of the present knowledge, and lack of knowledge, in the field, as well as the prospects for forecasting and control of pollutants, and should be reading matter for political advisers on environmental problems. The authors have faced a difficult task simply because of the range of topics covered and as a consequence their work shows some disparity in the level of treatment between sections. Chapter 4, on the physiology of injury by pollutants, and Chapter 5, which catalogues the symptoms of injury of plant species by major pollutants *and* other possible causes of similar symptoms, are probably of greatest practical value. Chapter 7, on sampling methods and Chapter 8, which considers control methods, are also useful reviews of the fields concerned. The major criticisms must be of Chapter 6. It seems inappropriate in a publication of this level to reprint five pages (sections 6.1 – 6.4) of a general discussion of air pollution meteorology, however good in its original context.* This must surely be familiar ground to most readers of the note, and the original journal is easily accessible to others. Similarly the mathematical treatment of turbulent exchange at the air–crop interface (section 6.7) is presented adequately in many quite

* PACK, D. H.; Meteorology of air pollution. *Science, Washington*, **146**, 1964, pp. 1119–1128.

elementary textbooks, and it should hardly warrant more than a note on the limitations of its validity. This space could surely have been more usefully employed to present a separate discussion of the difficult problem of the deposition of pollutants on vegetation and other surfaces. In particular I am surprised that no reference is made to the more recent papers on deposition by A. C. Chamberlain (e.g. in *Proc. R. Soc., London*, A, 1966, **290**, pp. 236–265 and **296**, pp. 45–70. In a publication of this nature omissions are inevitable, but do not detract from the value of this attempt to tie together the threads of this vitally important and fascinating subject.

J. A. CLARK

NOTES AND NEWS

551·575·1:551·578·46

Shallow fog over a snow surface

At Machrihanish, Kintyre, Argyll, shallow fog, with visibility not more than 500 yd, started to form at 0730 GMT on 15 February 1970 over a snow surface and persisted until 1115 GMT reaching a height of 2–4 metres (see Plate IV). Visibility above the fog was 20 miles or more. Snow of a fine dry texture had fallen for about nine hours during the night to give an average depth of 7 cm with considerable drifting. The snowfall ceased at 0620 GMT and the sky cleared about 07 GMT. During the next few hours the wind was calm or very light and the sky was almost cloudless. Air temperature in the screen fell rapidly from −0·8°C at 07 to −7·1°C at 09 GMT with an absolute minimum reading of −8·0°C.

Time GMT	06	07	08	09	10	11	12
				degrees Celsius			
Dry bulb	+0·1	−0·8	−3·5	−7·1	−4·0	−1·8	0·0
Ice bulb	0·0	−1·2	−3·5	−7·1	−4·0	−2·1	−0·9

V. C. SANDERS

OBITUARY

It is with regret that we have to record the death on 27 May 1970 of Mr W. H. Betts, Radio (Meteorological) Technician.

HONOUR

The following honour was announced in the Queen's Birthday Honours List 1970 :

I.S.O.

Mr A. F. Jenkinson, Head of Flood Investigation Section, Meteorological Office, Bracknell.

CORRECTIONS

Meteorological Magazine, June 1970, p. 158.

In equation (1) the final term on the left-hand side should read $\frac{\partial^2\psi}{\partial x^2}$.

In equation (2) for the term $(l^2 + k^2)$ read $(l^2 - k^2)$.

In the fourth line of the fourth paragraph for 'gets' read 'sets'.

THE METEOROLOGICAL MAGAZINE

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CONTENTS

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551.521.1

ESTIMATION OF SOLAR RADIATION RECEIPT FROM SUNSHINE DURATION AT WINNIPEG

By H. L. DRIEDGER* and A. J. W. CATCHPOLE†

Summary. Seasonal changes in the relationship between solar radiation receipt and sunshine duration are examined in detail. The seasonal régimes of the linear regression coefficients support the view that this relationship is dependent upon the effects of multiple reflection of solar radiation between snow-covered surfaces and cloud bases.

Introduction. Ångström's pioneer analysis of the empirical relationship between daily solar radiation receipt on a horizontal surface at ground level Q and daily sunshine duration n yielded:

$$Q = Q_0[a' + (1{\cdot}00 - a')\, n/N]$$

where Q_0 = total daily solar radiation receipt on a horizontal surface at ground level on a clear day, N = maximum possible daily duration of sunshine and a' = mean value of Q/Q_0 on completely overcast days.[1]

The major subsequent modifications of this equation have involved:

(i) development of the linear relationship :

$$Q = Q_0\, (a + bn/N)$$

in which a and b are regression coefficients;

(ii) replacement of Q_0 in this relationship by Q_a which evaluates the receipt of solar radiation on a horizontal surface at the top of the atmosphere. This procedure permits the application of the method in areas lacking observations of Q.

These developments have confirmed that there are significant spatial and temporal variations in the magnitudes of these coefficients.

Black *et alii*[2] obtained values of b varying irregularly between 0·29 and 0·63, and values of a varying irregularly between 0·19 and 0·40, among stations distributed over 50 degrees of latitude. In tropical areas the temporal variations of a and b are so irregular as to prohibit the identification of

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seasonal régimes.[3,4] However, in higher latitudes these temporal variations are more regular. In Canada, Mateer identified values of a and b typical of the snow season, of the snow-free season, and of the transitional seasons.[5] Mateer suggested that these seasonal variations are attributable to the effects of either rime deposition on the glass sphere of the sunshine recorder or the multiple reflection of solar radiation between snow-covered ground surfaces and cloud bases.

This paper contributes to the study of seasonal variations in the magnitudes of a and b. The analysis is applied in seven stages, each of which is based upon the sub-division of the year into periods of different and particular duration. The study is applied to data observed at Winnipeg, Canada.

Data. The data were observed during the 18-year period January 1950 to December 1967, at a synoptic meteorological station located at Winnipeg International Airport. The station is situated on the flat prairie surface within the airfield and is relatively free from obstructions to the receipt of solar radiation. The site has remained unchanged during the years under investigation.

Throughout this 18-year period the solar radiation receipt was observed by Eppley 180° pyrheliometers. On receipt of advice from the Canadian Meteorological Branch, the following corrections were applied to the radiation data observed during this period:

(i) The present instrument was installed in July 1956. The calibration factor of its predecessor is thought to have been incorrect by 5 per cent. All data observed prior to 7 July 1956 were therefore reduced by this percentage.

(ii) The data observed prior to January 1958 were corrected for ambient air temperature effects since this correction had not been applied to the published data.

(iii) The data observed between 5 February 1957 and 31 March 1957 were adjusted by factors incorporating corrections both for ambient air temperature and for the change in radiation scale from the Smithsonian Scale (1913) to the International Pyrheliometric Scale (1956).

The sunshine data were derived from a Campbell-Stokes sunshine recorder. This instrument is insensitive to direct solar radiation of intensities less than 0·2 to 0·4 langley/min (1 langley/min = 69·78 mW/cm^2); 1 langley = 1 cal/cm^2. It is considered by the United Kingdom Meteorological Office that this instrument does not record sunshine when the solar elevation is less than 3°.[6] Thus, the apparent length of the day is less than its actual length. In this paper N is defined as the period during which the elevation of the sun above the horizon exceeds 3°.

Method. The pronounced seasonal changes of Q necessitate that the dependent variable in the regression analysis be expressed in relative terms. This can be achieved by expressing Q as a fraction of either Q_0 or Q_a. The advantage of the latter procedure is that Q_a can be evaluated at all locations. In contrast, Q_0 can only be obtained by extrapolation from measured values of Q using a method similar to that employed by Sellers for this purpose.[7]

A preliminary investigation indicated that, at Winnipeg, the relationship between Q/Q_0 and n/N is closer than that between Q/Q_a and n/N.[8] Monthly mean daily sunshine durations and monthly mean daily solar radiation receipts were utilized in a study of the annual linear regression between these variables. It was observed that the annual coefficient of determination r^2 between Q/Q_0 and n/N ($r^2 = 0{\cdot}66$) was substantially greater than that between Q/Q_a and n/N ($r^2 = 0{\cdot}35$). For this reason, Q will be expressed as a fraction of Q_0 in the present analysis.

There are precedents for using a wide range of seasonal sub-divisions of the year for the estimation of Q from n. The monthly sub-division has been used most frequently for this purpose, but the analysis has also been applied to daily data grouped into periods of less than a month.[9] Any choice of period length is arbitrary and, in the interests of objectivity, the analysis is here applied to daily data grouped into periods of 5, 7, 11, 15, 19, 25 and 29 days' duration.

In order to emphasize seasonal trends and suppress the effects of short-term irregularities, overlapping periods were used throughout the analysis. For example, the first of the 5-day periods includes 1–5 January, and the second of these includes 2–6 January. Consequently, 365 daily estimates of a and b are obtained in each of the seven stages of the analysis. The estimated regression coefficients of a particular day are derived from the data observed in the period centred upon that day.

Results. The results are presented in Figure 1, which illustrates the seasonal variations in a and b obtained in each stage of the analysis. Corresponding values of a and b represent the linear prediction equations which describe the relationship between Q/Q_0 and n/N. In all cases the seasonal changes of a are inversely related to those of b, since the former attains its minimum values in summer at which time the latter attains its maximum values. These seasonal régimes can be approximated by the equations :

$$a = 0{\cdot}50187 - 0{\cdot}0020752x + 0{\cdot}00000483x^2$$
$$b = 0{\cdot}35526 + 0{\cdot}0032518x - 0{\cdot}00000796x^2$$

where x = any day of the year from 1 to 365. These equations are based upon the regression coefficients derived from the 5-day periods (Figure 2).

In all cases the seasonal régimes of a and b are disturbed by relatively short-term irregularities which usually decrease in prominence as the duration of the period of analysis increases. The forms of the curves in Figure 1 indicate that pronounced irregularities occur in early spring and late summer. Early spring is characterized by a relatively abrupt divergence between the curves of a and b. In late summer the values of b range between a secondary minimum in mid-August and the primary maximum in mid-September.

The significance of the irregularities detected by the 5-day analysis was tested statistically. These tests indicate that a exceeds its predicted values by an amount significant at the 95 per cent level of confidence during the period 1–21 March (Figure 2). Comparably significant departures of b from its predicted values occur during the periods 13–20 August and 14–26 September. The fitting of a parabolic curve to the observed values of a and b produces a lack of conformity between 31 December and 1 January, but it is considered that the parabolic curve fulfils the limited function of this part of the analysis.

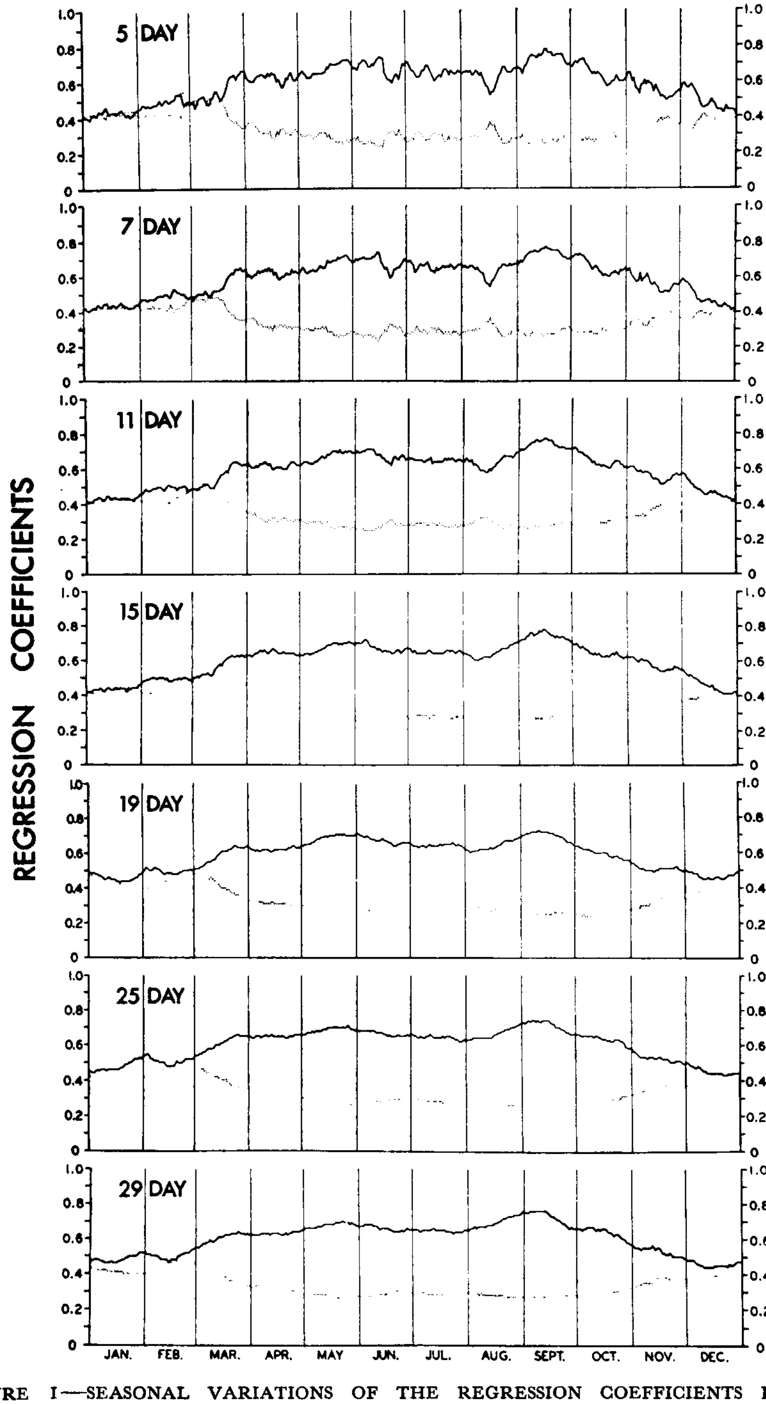

FIGURE 1—SEASONAL VARIATIONS OF THE REGRESSION COEFFICIENTS IN THE EQUATION $Q = Q_0\,(a + bn/N)$ DIFFERENTIATED ACCORDING TO PERIOD LENGTH. WINNIPEG INTERNATIONAL AIRPORT 1950–67

.... a ——— b

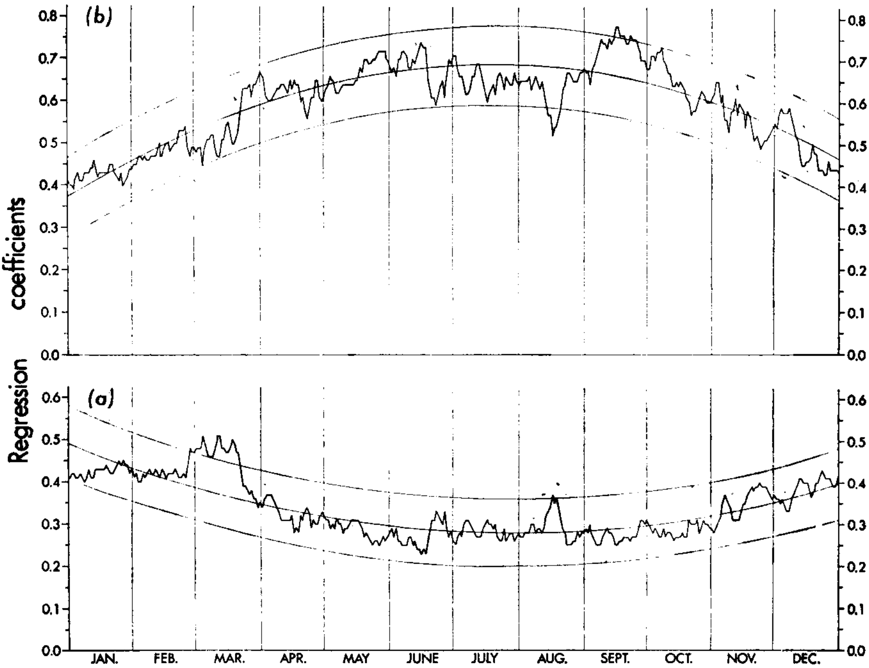

FIGURE 2—SEASONAL VARIATIONS OF THE ACTUAL AND PREDICTED REGRESSION COEFFICIENTS IN THE EQUATION $Q = Q_0\ (a + bn/N)$, DERIVED FROM 5-DAY PERIOD LENGTH. WINNIPEG INTERNATIONAL AIRPORT 1950–67

In the upper diagram *(b)* the irregular curve = actual b; the inner smooth curve = predicted b obtained by using the equation given in the text; the outer curves = 95 per cent confidence intervals.

In the lower diagram *(a)* the irregular curve = actual a; the inner smooth curve = predicted a obtained by using the equation given in the text; the outer curves = 95 per cent confidence intervals.

It is noteworthy that the March and August irregularities appear to be most clearly manifest in the short-period analyses, whereas the September irregularity apparently increases in prominence with increasing period length.

Discussion. A comprehensive discussion of these results is prohibited by the complexity of the relationship between solar radiation and sunshine duration. Daily duration of sunshine is a function of cloud conditions, and the attenuation of solar radiation by cloud depends upon a wide range of controls including solar zenith angle, and the amount, form, height, density and distribution of cloud.[10] The result is a relationship between Q/Q_0 and n/N so nebulous that its use is restricted to the prediction of mean solar radiation receipts rather than to the prediction of receipts on particular days.

Similarly, the distinctive seasonal régimes of a and b cannot with certainty be attributed to the effects of specific factors. In high latitudes particularly, seasonal changes in cloud conditions, concentrations of artificial and natural pollutants, water vapour concentration, midday solar elevation, etc., probably affect the régimes of *a* and *b*. Nevertheless, the general form of these seasonal régimes is consistent with Mateer's view that the periodic development and decay of snow cover may significantly affect the relationship between sunshine duration and solar radiation receipt. The magnitude of each of the regression coefficients might be modified by the effects of multiple reflection between cloud bases and snow-covered surfaces. The coefficient *a* evaluates the receipt of solar radiation on days lacking bright sunshine and it can be approximated to, although not exactly equated with, the solar radiation received on totally overcast days. The multiple reflection process may, therefore, increase the magnitude of *a* in winter. The coefficient *b* evaluates the rate of change in Q/Q_0 per unit change in n/N. Any process which elevates the receipt of solar radiation on sunless days may, in this linear relationship, tend to reduce the magnitude of *b*. In this event, multiple reflection may reduce *b* in winter.

The behaviour of *a* in late winter and spring strongly supports the view that its magnitude is influenced by the multiple reflection process because the period of abrupt decrease of *a* immediately precedes the median date of the spring thaw at Winnipeg. Figure 3 illustrates the duration of snow cover at Winnipeg using data observed between 1950 and 1967. The upper part of this diagram indicates the durations of snow cover during individual winters within this period. Depicted are the periods of discontinuous snow cover of at least a trace (1), the periods of continuous snow cover of at least a trace (2), and the periods of continuous cover of at least 12·5 centimetres (5 inches) of snow (3). The lower part of the figure indicates the median dates of specific events (B), their earliest arrival and latest departure dates (A), and their latest arrival and earliest departure dates (C). Attention is directed to the snow depth of 12·5 centimetres because this has been shown to be critical in terms of the albedo of snow surfaces.[11] With snow depths of less than 12·5 centimetres albedo is a direct function of depth, but albedo remains relatively constant when depths exceed 12·5 centimetres.

The absence of a comparably abrupt change in *a* in association with the median date of snow development may be attributable to the fact that this development occurs near the winter solstice when the absolute receipt of solar radiation is low.

Acknowledgements. The authors acknowledge the assistance of D. H. Gallagher, Director of the Planetarium, Manitoba Museum of Man and Nature, who evaluated the periods of time during which the solar elevation is less than 3° above the horizon at Winnipeg. Financial support for this research was provided by the National Research Council of Canada.

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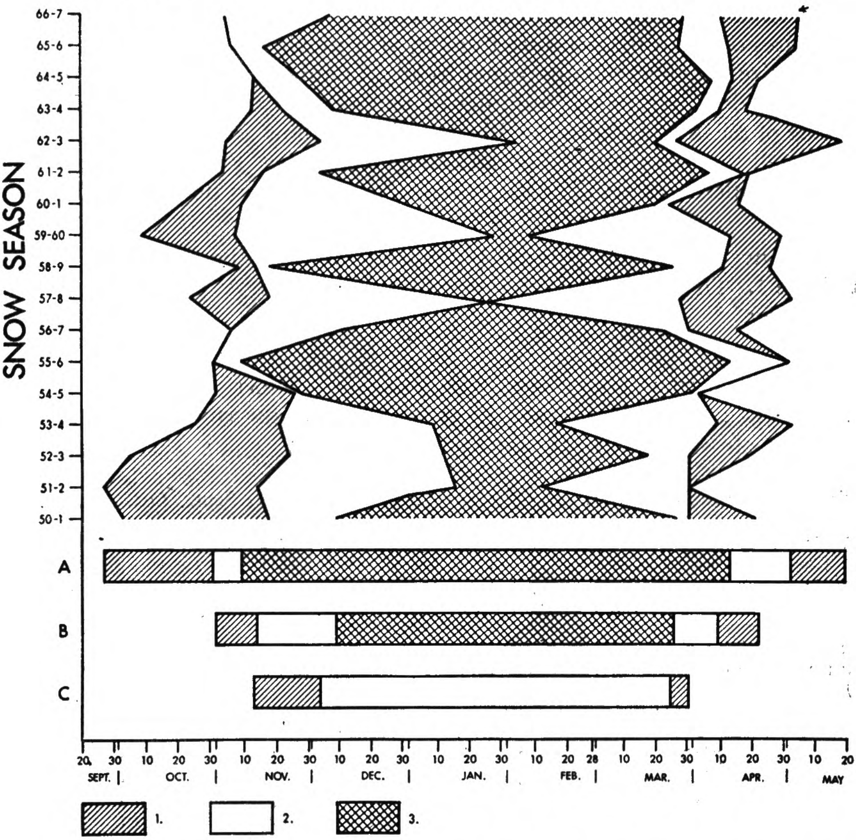

FIGURE 3—DURATION OF SNOW COVER AT WINNIPEG INTERNATIONAL AIRPORT SEPTEMBER 1950 TO MAY 1967

A = Earliest arrival and latest departure dates of specific events.
B = Median dates of specific events.
C = Latest arrival and earliest departure dates of specific events.
Hatched areas (1) = Periods of discontinuous snow cover of at least a trace.
White areas (2) = Periods of continuous snow cover of at least a trace.
Cross-hatched areas (3) = Periods of continuous cover of at least 12·5 cm of snow.
The dates of the snow seasons are abbreviated, e.g. 1966–67 appears as 66–7.
The diagram is taken from CATCHPOLE, A. J. W.; The solar control of diurnal temperature variation at Winnipeg. *Can. Geographer, Toronto*, **13**, 1969, p.p. 255–268.

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A NOTE ON CENTRAL ENGLAND TEMPERATURES IN QUINTILES

By R. MURRAY

Summary. Monthly and seasonal mean temperatures for central England for the period 1873–1968 were assigned to quintiles by ranking (A) departures from 25-year moving averages and (B) actual temperatures. The quintiles to which the temperatures were assigned by the two methods were found to differ by not more than one quintile on over 99 and 97 per cent of occasions for monthly temperatures and seasonal temperatures respectively. Larger differences, of two quintiles, occurred mostly in October for monthly means and in autumn and spring for seasonal means.

In several papers (e.g. Murray[1]) the quintiles of mean temperature over central England[2] for months or seasons have been based on the ranking of the departures of mean temperature from 25-year moving averages, in an attempt to minimize the effect of long-period trends of temperature. For some purposes it may be desirable to use quintiles of temperature derived from the simple ranking of mean temperatures without trying to allow for long-period changes. Let us call the two methods 'A' and 'B' respectively. Then it is of interest to see what differences result in the allocation of quintiles derived in these two ways.

For convenience, the quintile boundaries used in the 'B' case are given in Table I. The method of obtaining quintiles in the 'A' case has been given by Murray.[1,3]

TABLE I—QUINTILE BOUNDARIES OF MEAN TEMPERATURES OVER CENTRAL ENGLAND FOR *(a)* MONTHS AND *(b)* SEASONS, BASED ON THE PERIOD DECEMBER 1873 TO NOVEMBER 1963

(a) Months

Quintile	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees	*Celsius*					
5/4>	5·3	5·8	6·8	9·0	12·2	15·2	17·1	16·4	14·4	10·6	7·4	5·8
4/3>	4·3	4·8	6·1	8·3	11·5	14·5	16·2	15·8	13·7	10·1	6·7	4·9
3/2>	3·6	3·8	5·2	7·7	10·9	14·1	15·5	15·3	13·0	9·5	6·1	4·0
2/1>	2·3	2·7	4·2	7·1	10·3	13·6	15·1	14·6	12·5	8·8	5·3	2·9
Mean temperature	3·6	4·0	5·5	8·0	11·2	14·2	15·9	15·5	13·4	9·7	6·3	4·3

(b) Seasons

Quintile	Winter	Spring	Summer	Autumn
		degrees	*Celsius*	
5/4>	5·2	8·9	15·8	10·5
4/3>	4·5	8·4	15·5	10·1
3/2>	4·0	8·1	15·1	9·7
2/1>	3·0	7·5	14·6	9·1
Mean temperature	4·0	8·2	15·2	9·8

Note. In January quintile 4 refers to mean monthly temperatures $> 4·3°$ and $< 5·3°$C.

The frequencies of the difference between the 'A' and 'B' quintiles each month for the period from December 1873 to November 1968, based on quintile boundaries derived from 1873 to 1963, are presented in Table II.

Table II shows that the same quintile number was allocated by 'A' and 'B' on about 72 per cent of the months and that the two methods differed by not more than one quintile on 99·6 per cent of occasions. Exact correspondence

TABLE II—OCCASIONS WITH SPECIFIED DIFFERENCES IN QUINTILES DERIVED BY 'A' AND 'B' METHODS EACH MONTH

	Differences A–B (quintiles)						
	−3	−2	−1	0	1	2	3
December	0	0	12	69	13	1	0
January	0	0	13	67	15	0	0
February	0	0	11	72	12	0	0
March	0	0	8	73	14	0	0
April	0	0	21	60	14	0	0
May	0	0	16	66	13	0	0
June	0	0	8	74	13	0	0
July	0	0	12	76	7	0	0
August	0	0	15	67	13	0	0
September	0	0	11	75	9	0	0
October	0	2	25	57	10	1	0
November	0	0	15	67	13	0	0
Total	0	2	167	823	146	2	0

was least in October (57 cases) and April (60 cases). However, it may be said that serious discrepancies between the quintile specification of months according to the 'A' and 'B' procedures are generally very small. Three of the four biggest differences (± 2) occurred in October.

Examination of the basic data shows clearly that the incidence of positive or negative differences between 'A' and 'B' is markedly concentrated in different epochs. This is not surprising because of the well-known long-period temperature variations, which are not in phase each month. For instance, the mean January temperature was at a maximum in the 1920s and 1930s but a cooling trend began around 1940. In July the mean temperature was lower in the 1920s than in the 1940s but a cooling trend has set in since about 1960. In April the mean temperature was lower by about 1 degC in the first 25 years of this century compared with the following 25 years, and now a cooling trend appears to have set in during the 1960s. On the other hand, in October the mean temperature was at its lowest in the 1880s and in the most recent decade it has steadily risen. Such long-period changes inevitably affect the sign of the differences between the 'A' and 'B' quintiles. In January positive differences (i.e. A − B positive) occurred mostly before 1920 and after 1952, in April entirely between 1901 and 1939, in July between 1897 and 1942 (mainly in the 1920s and 1930s) and in October mostly between 1888 and 1912.

The seasonal quintiles have also been examined for the two methods 'A' and 'B' and the results are presented in Table III.

TABLE III—OCCASIONS WITH SPECIFIED DIFFERENCES IN QUINTILES DERIVED BY 'A' AND 'B' METHODS EACH SEASON

	Differences A–B (quintiles)						
	−3	−2	−1	0	1	2	3
Winter	0	0	9	63	23	0	0
Spring	0	4	15	67	9	0	0
Summer	0	0	10	70	15	0	0
Autumn	0	6	20	56	13	0	0
Total	0	10	54	256	60	0	0

From Table III it is seen that the same quintiles (i.e. $A - B = O$) applied on 67 per cent of the seasons. No cases with $|A - B| > 1$ occurred in winter and summer; however, in spring and autumn there were 10 cases where the

'A' procedure specified quintiles which were two less than those indicated by the 'B' method. Thus the two methods differed by not more than one quintile on 97·4 per cent of occasions. It appears that serious discrepancies between quintiles specified by the two methods are likely at times in autumn and spring.

The positive and negative differences are not randomly scattered throughout the period but differences of the same sign tend to be concentrated in certain epochs. The differences were all positive before 1920(17) and after 1950(6) in winter, all positive before 1911(9) in spring, mostly positive before 1933 in summer, and mostly positive before 1936 in autumn. Except in winter as just mentioned, all differences were negative after 1935. The largest negative difference of -2 occurred after 1952 in spring (namely in 1953, 1963, 1966 and 1967) and autumn (namely in 1954, 1955, 1960, 1961, 1963 and 1964).

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AN ALGORITHM DEPENDING ON THE PHYSICAL INTERPRETATION OF THE LAPLACIAN

By R. DIXON

Summary. An algorithm is presented which has its genesis in Maxwell's physical interpretation of the Laplacian. Two examples illustrating different applications of the algorithm are given: (i) the removal of a gross irregularity from a height field, and (ii) the intensification of the contour pattern of a height field.

Kirk[1] has recently recalled the physical interpretation given to the Laplacian by Maxwell,[2] who showed that the value of the Laplacian of a function at a point is a measure of the difference between the value of the function at the point and the average value of the function over a small surrounding neighbourhood. In fact

$$\frac{d^2}{24}\,(\nabla^2\varphi) = \varphi_m - \varphi_0, \qquad \ldots (1)$$

where φ is a scalar function, d is a small measure of distance, and the suffix o indicates the value taken at the point in question.

Now the Laplacian is itself a scalar, and equation (1) remains true if $\varphi = \nabla^2 F$ where F is some other scalar. We then have

$$\frac{d^2}{24}\,(\nabla^4 F)_0 = (\nabla^2 F)_m - (\nabla^2 F)_0\,. \qquad \ldots (2)$$

Thus the Laplacian of the Laplacian, known as the biharmonic, is a measure of the difference between the value of the Laplacian at a point and its average value over a small surrounding neighbourhood. The form (2) is given a particular significance for meteorologists by virtue of the fact that the geostrophic vorticity is, save for a factor, given by the Laplacian of the geopotential height field.

This gives rise to the possibility of achieving certain desired adjustments to a geopotential height field by a process having a prescribed effect upon the vorticity field. If the grid points in the neighbourhood of a given grid point o are locally numbered in traditional fashion

$$\begin{array}{ccccc} & & 10 & & \\ & 6 & 2 & 5 & \\ 11 & 3 & 0 & 1 & 9 \\ & 7 & 4 & 8 & \\ & & 12 & & \end{array}$$

and the height at each grid point h_0 is replaced in turn by a new height h_0' such that

$$h_0' = a(h_1 + h_2 + h_3 + h_4) + bh_0, \qquad \ldots (3)$$

where a and b are constants, then it may be shown that the new geostrophic vorticity field ζ_0' is related to the old geostrophic vorticity field ζ_0 by

$$\zeta_0' = [1 + (4a + b - 1)]\zeta_0 + ad^2(\nabla^4 h)_0, \qquad \ldots (4)$$

where $\nabla^4 h$ is a finite-difference analogue of the biharmonic $\nabla^4 h$. Thus the modified vorticity is a multiple of the original vorticity plus an adjustment depending on the local anomaly of the vorticity relative to its average value over the immediate neighbourhood.

If it is not intended to alter the general level of the h field, then the condition

$$4a + b - 1 = 0 \qquad \ldots (5)$$

must be observed. Putting

$$a = \frac{1-k}{4} \quad \text{and} \quad b = k$$

equation (4) becomes

$$\zeta_0' = \zeta_0 + \tfrac{1}{4}(1-k)d^2(\nabla^4 h)_0 \qquad \ldots (6)$$

and it is seen that putting $k < 1$ will decrease the local vorticity anomaly and effect a smoothing of the h field, whilst putting $k > 1$ will enhance the local vorticity anomaly and thereby intensify the h field pattern.

Example 1. Figure 1 shows a section of the 200-mb operational analysis at 00 GMT on 23 March 1967. The obviously wrong grid-point values were adjusted by a recursive application of equation (3), with a and b determined by $k = 0$, to give the result shown in Figure 2. It is seen that, using this technique, the computer arrived at an adjusted h field which is very close to the one which would be obtained by a subjective adjustment.

It is not, of course, being argued that this is the only way to deal with this particular problem. A Shuman type filter with suitable parameter values would doubtless accomplish a similar result as far as the h field is concerned. The point here is simply that the adjustment depends directly on equation (1) for its effectiveness.

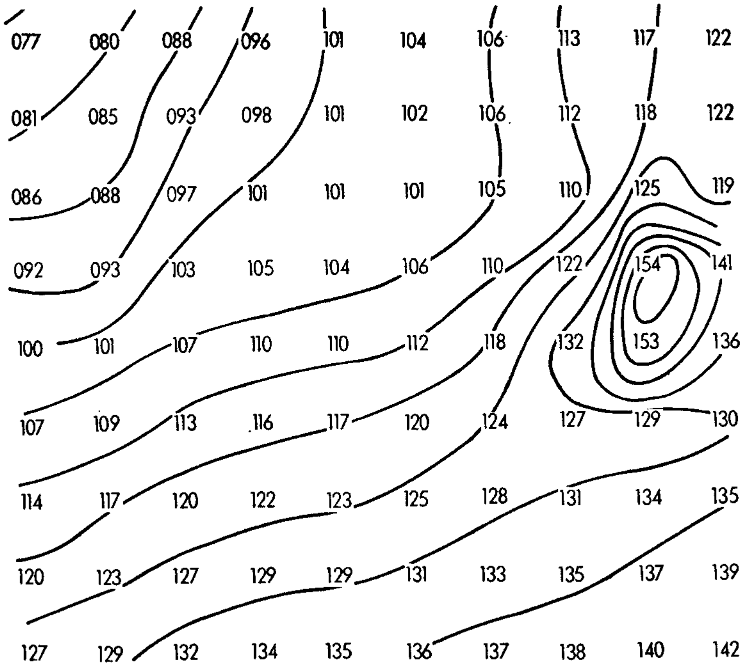

FIGURE 1—SECTION OF THE OPERATIONAL 200-mb ANALYSIS FOR 00 GMT, 23 MARCH 1967

Grid-point and isopleth values in geopotential decametres.

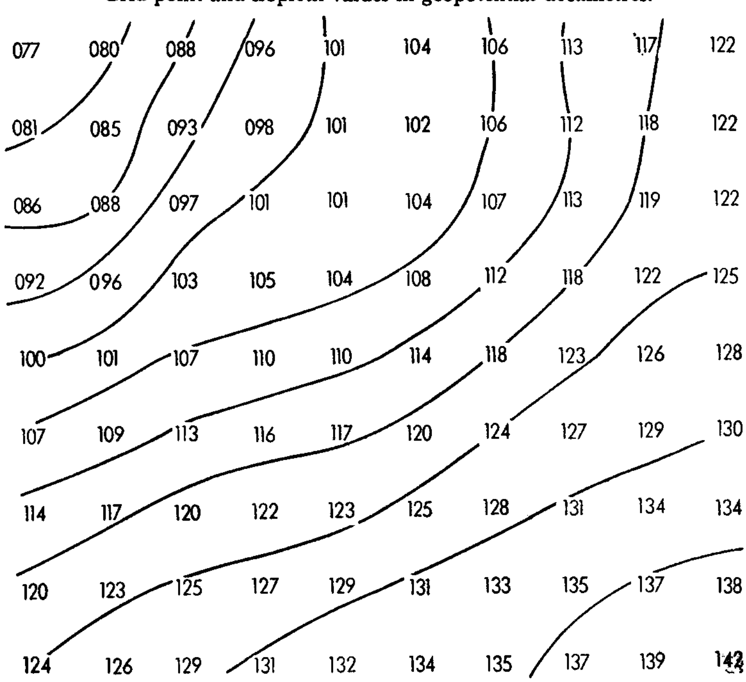

FIGURE 2—THE 200-mb ANALYSIS FOR 00 GMT, 23 MARCH 1967 AS ADJUSTED BY THE ALGORITHM

Example 2. When a set of grid-point geopotential height values are produced by some analysis process depending on smoothing scans or polynomial approximation there is an inevitable loss of intensity in the pattern of the field. Again, if an analysed field is subjected to a numerical forecasting process which is dependent on finite-difference technology a similar loss of intensity will occur. It seems intuitively obvious that this loss effect will be greatest in those regions where the departure of the intensity of the field from linearity is greatest. This being the case an application of equation (3) with a and b determined by a $k > 1$ can be expected to restore the lost intensity.

Figure 3 shows the 200-mb analysis for 00 GMT on 24 June 1969 together with the geostrophic isotachs. Figures 4 and 5 show the result of applying equation (3) with a and b determined by $k = 2$, and $k = 3$ respectively. The progressive intensification of the contour pattern is clearly discernible to the eye and is confirmed by the isotachs.

Finally, it may be noticed that although what has been done in these two examples is essentially the adjustment (equation (4)) of the vorticity field, in fact only equation (3) was used in the computations. Neither the old and new vorticities nor the biharmonic were calculated. This illustrates what has become a commonplace of numerical analysis, namely that a computer algorithm need bear little resemblance to the algebra it is effecting.

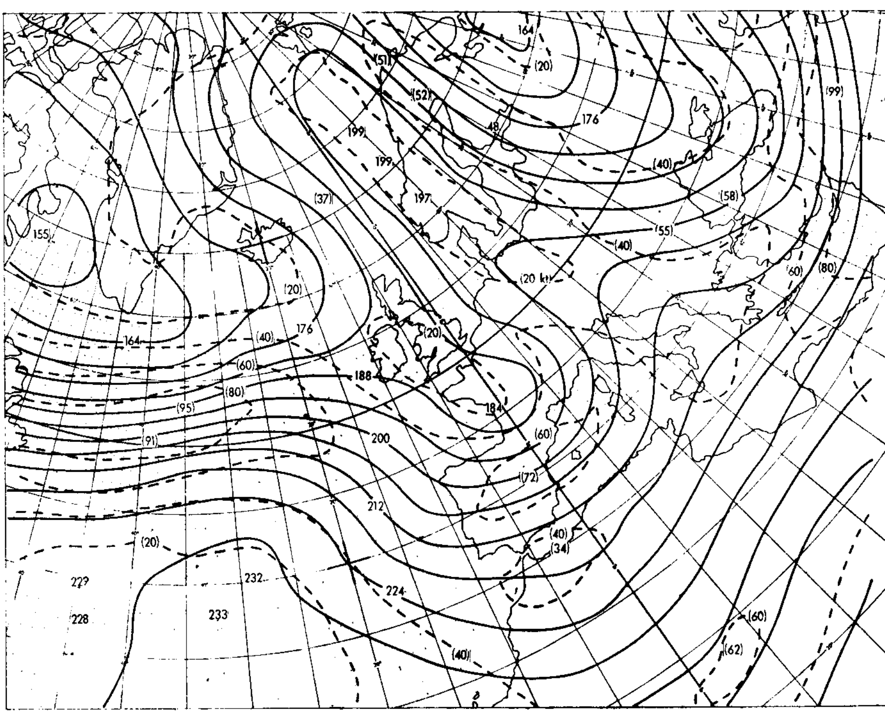

FIGURE 3—200-mb CONTOURS FOR 00 GMT, 24 JUNE 1969 AS OBTAINED BY THE OPERATIONAL ANALYSIS SYSTEM. GEOSTROPHIC ISOTACHS ARE ALSO SHOWN

——— Contours at intervals of 6 geopotential decametres.

– – – Isotachs at intervals of 20 knots (isotach values in brackets).

Wind speeds are given in knots in accordance with WMO recommendations (1 knot≈0·5 m/s).

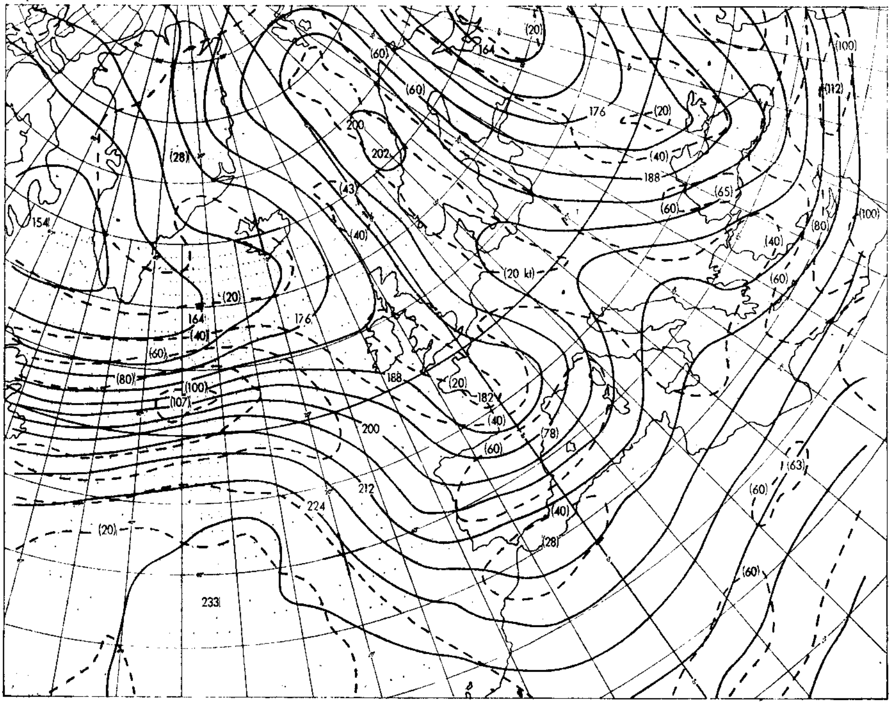

FIGURE 4—200-mb CONTOURS FOR 00 GMT, 24 JUNE 1969 WITH THE PATTERN INTENSIFIED BY APPLICATION OF THE ALGORITHM WITH $k = 2$

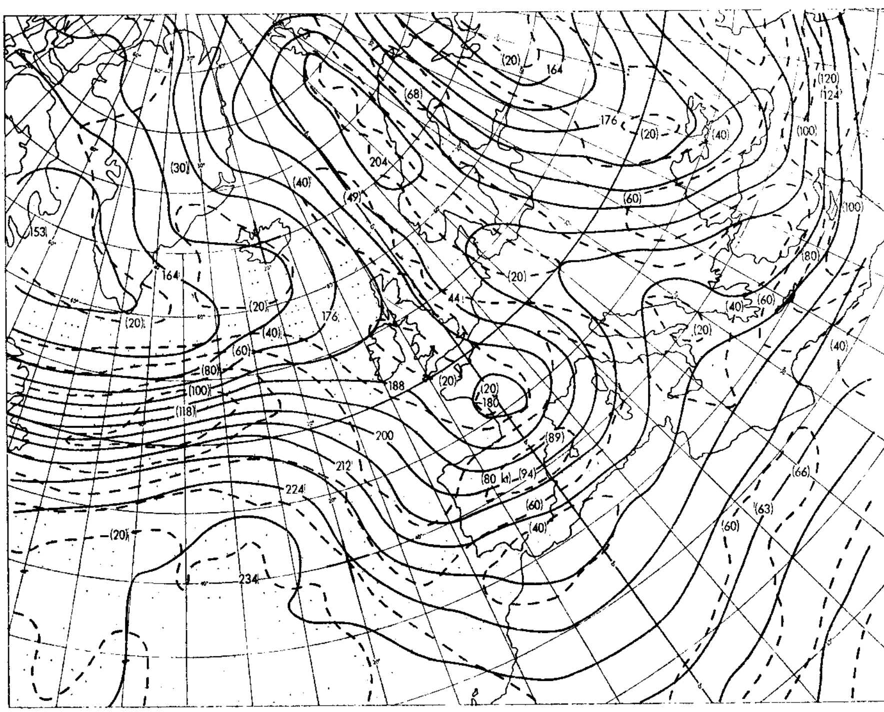

FIGURE 5—200-mb CONTOURS FOR 00 GMT, 24 JUNE 1969 WITH THE PATTERN INTENSIFIED BY APPLICATION OF THE ALGORITHM WITH $k = 3$

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551.578.45:625.1

A RAILWAY PROBLEM DURING THE HEAVY SNOWFALL OF 4 MARCH 1970

By G. E. PARREY

Summary. On 4 March 1970 a small depression moved south-east across the country and brought a heavy snowfall to the Midlands and south-east England. Train services on the electrified main line into London (Euston) were disrupted because the weight of snow and ice brought down the locomotive pantographs and prevented contact with the overhead line. As this was the first time the difficulty had been encountered in five years of operation since electrification, the prevailing meteorological conditions were investigated in order that both forecasters and British Railways might be alive to the problem in future. A possible explanation of the difficulty experienced is proposed.

On 4 March 1970 a small depression moved south-east across England and heavy falls of snow occurred, chiefly on the north-eastern side of the track of the depression. At 06 GMT the depression was centred just south of Chester, at 09 GMT a little north of Reading and by 12 GMT the centre was over mid-Channel south of Beachy Head (see Figure 1 for place names and Figures 2 and 3 for synoptic situation). Heavy delay was caused to trains on the electrified route into London (Euston) from the Midlands by the pantographs on the electric locomotives failing to make contact with the overhead line equipment. The pantographs thrust upwards with considerable force but the weight of snow and ice was sufficient to overcome this upward thrust and to prevent contact being made. A feature of the occurrence was that, although moderate or heavy snow was falling over some part or other of the line between Crewe and Euston from about 03 GMT to 15 GMT, the difficulty with the pantographs was only experienced between about 0930 and 1300 GMT when successive southbound trains were brought to a standstill between Bletchley and Euston. Little or no pantograph trouble was experienced in other sections of the line, or with northbound trains in the same section. Plate I shows a pantograph.

Hourly weather and temperatures at four Meteorological Office stations are given, for relevant times, in Table I. The stations : Shawbury (Shropshire), 235 feet (72 m) above MSL; Birmingham Airport, 319 feet (97 m); Cardington (Bedfordshire), 93 feet (28 m) and Northolt (Middlesex), 108 feet (33 m), were chosen as being the nearest hourly-reporting stations to the main line. The recorded temperatures are taken at 4 feet (1·2 m) above ground level in standard thermometer screens. On this particular occasion there was no inversion of temperature near the ground and ambient temperatures at pantograph level would be only a fraction of a degree lower than those in the screen.

TABLE I—WEATHER AND TEMPERATURES AT SHAWBURY, BIRMINGHAM AIRPORT, CARDINGTON AND NORTHOLT ON 4 MARCH 1970

Time GMT	Shawbury		Birmingham Airport		Cardington		Northolt	
	Weather	Air temp. °C	Weather	Air temp. °C	Weather	Air temp. °C	Weather	Air temp. °C
00	s_0s_0	0·4	c	0·1				
01	s_0s_0	0·5	s_0	−0·2				
02	s_0s_0	0·3	s_0s_0	−0·2				
03	ss	0·4	s_0s_0	−0·1	Stations closed overnight			
04	ss	0·4	ss	0·0				
05	ss	0·4	ss	−0·1				
06	ss	0·4	SS	0·0				
07	ss	0·4	SS	0·0	ss	−0·5	s_0s_0	0·0
08	c	0·3	ss	−0·3	ss	−0·5	ss	0·4
09	s_0	0·4	s_0s_0	−0·4	SS	−0·3	ss	0·5
10	c	0·0	ss	−0·4	ss	0·0	s_0s_0	0·4
11	c	−0·3	ss	−0·7	ss	0·3	rs	1·0
12			s_0s_0	−0·5	ss	0·4	rd	1·6
13			s_0s_0	−0·4	ss	0·3	rs	1·4
14			c	−0·1	ss	0·3	ss	0·9
15					ss	0·1	SS	0·1
16					s_0s_0	0·0	s_0s_0	0·3

For an explanation of the Beaufort letters used in this table see *Observer's handbook*, third edition, London, HMSO, 1969, pp. 67–71.

Associated with the depression was a tongue of slightly milder air which had the effect of bringing temperatures near the ground up to a little above freezing-point and so increasing the liquid water content of the falling snow. The temporary rise of temperature as the depression passed each of the four stations is well illustrated in the table. At Shawbury the maximum temperature was probably reached at about 05 GMT, at Birmingham between 06 and 07 and at Cardington and Northolt between 11 and 13 GMT. The Northolt reports also show a temporary change from snow to rain. Other factors complicating the distribution of above-zero and below-zero temperatures were (i) the normal tendency for temperatures to rise during the day and, possibly, (ii) the subtle effect of altitude over the Northamptonshire uplands and the Chiltern Hills.

The suggested sequence of events which led to the halting of the trains is as follows :

Between 08 and 13 GMT screen temperatures in the Birmingham area were 0·3 degC or more below freezing-point. Pantograph temperatures on south-bound trains travelling towards Bletchley at this time would be a degree or two below freezing-point. Snowflakes containing little or no liquid water would be blown clear by the rush of air. South of Bletchley, however, after 09 GMT air temperatures were beginning to rise a little above freezing-point and in consequence snowflakes would contain an increasing proportion of liquid water. From the Northolt reports of rain and drizzle one may also deduce that somewhere on the London side of Bletchley separate water droplets began to fall with the snow. This water and wet snow would freeze on contact with the still sub-zero pantographs until eventually the weight of accretion brought the equipment down from contact with the overhead line. The fact that temperatures south of Bletchley were only a little above

To face page 300

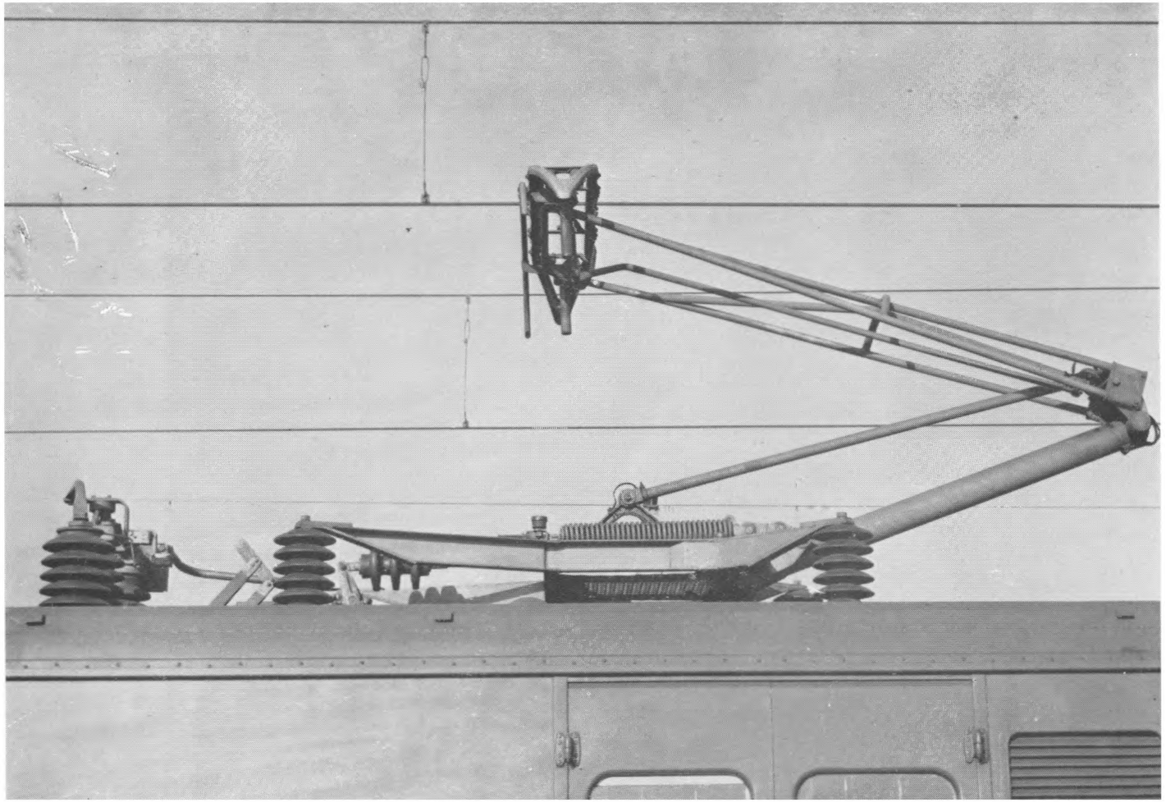

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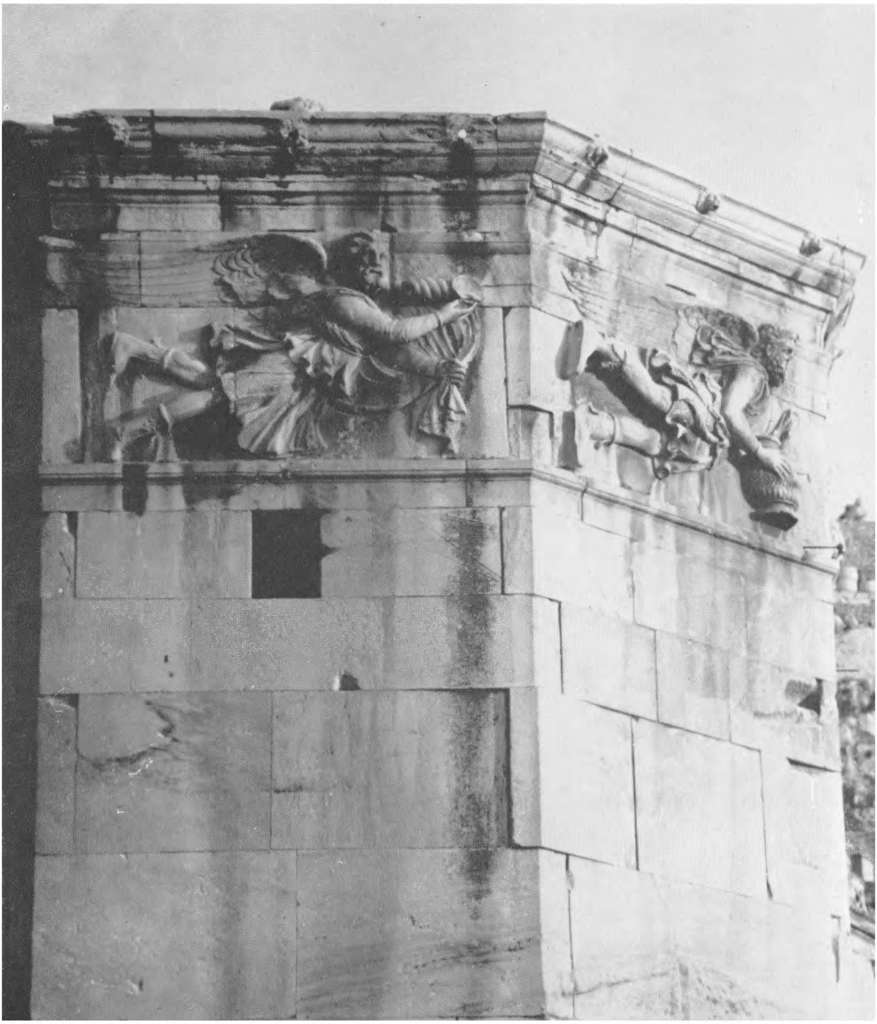
PLATE I—PANTOGRAPH AND OVERHEAD CONDUCTORS
(See page 299).

Photograph by R. K. Pilsbury

PLATE II—THE TOWER OF THE WINDS IN ATHENS

The tower, which was built in about the second century BC, carries on its sides the names of the winds associated with the eight compass points and also symbolic figures which represent the character of the winds.

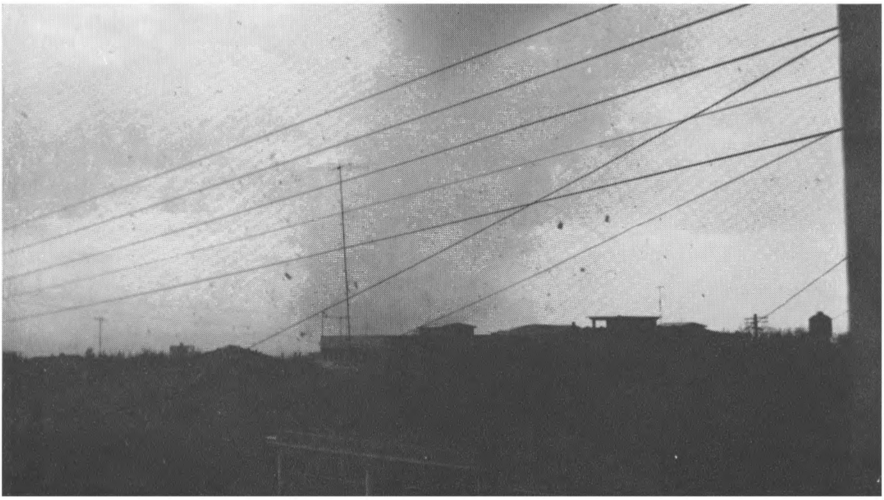


Photograph by R. K. Pilsbury

PLATE III—DETAILED VIEW OF TWO OF THE SYMBOLIC FIGURES ON THE TOWER OF THE WINDS IN ATHENS

The left-hand figure is Boreas (north or north-north-east)—an old man very warmly clothed holding a conch shell. The right-hand figure is Skiron (north-west) — an old man holding a large inverted jar, which may be a brazen fire pot. (See SHAW, SIR NAPIER; Manual of Meteorology, Volume I. London Cambridge University Press, 1932, p. 80.)

PLATE IV—WATERSPOUTS APPROACHING LIMASSOL ON THE AFTERNOON OF 22 DECEMBER 1969



Photographs by courtesy of Sgt. Pownall, RAF

PLATE V—PASSAGE OVER LAND OF TORNADO OVER LIMASSOL ORIGINATING FROM A WATERSPOUT SHOWN ON PLATE IV

Note dust and flying debris which indicate the persistence of the system over land.

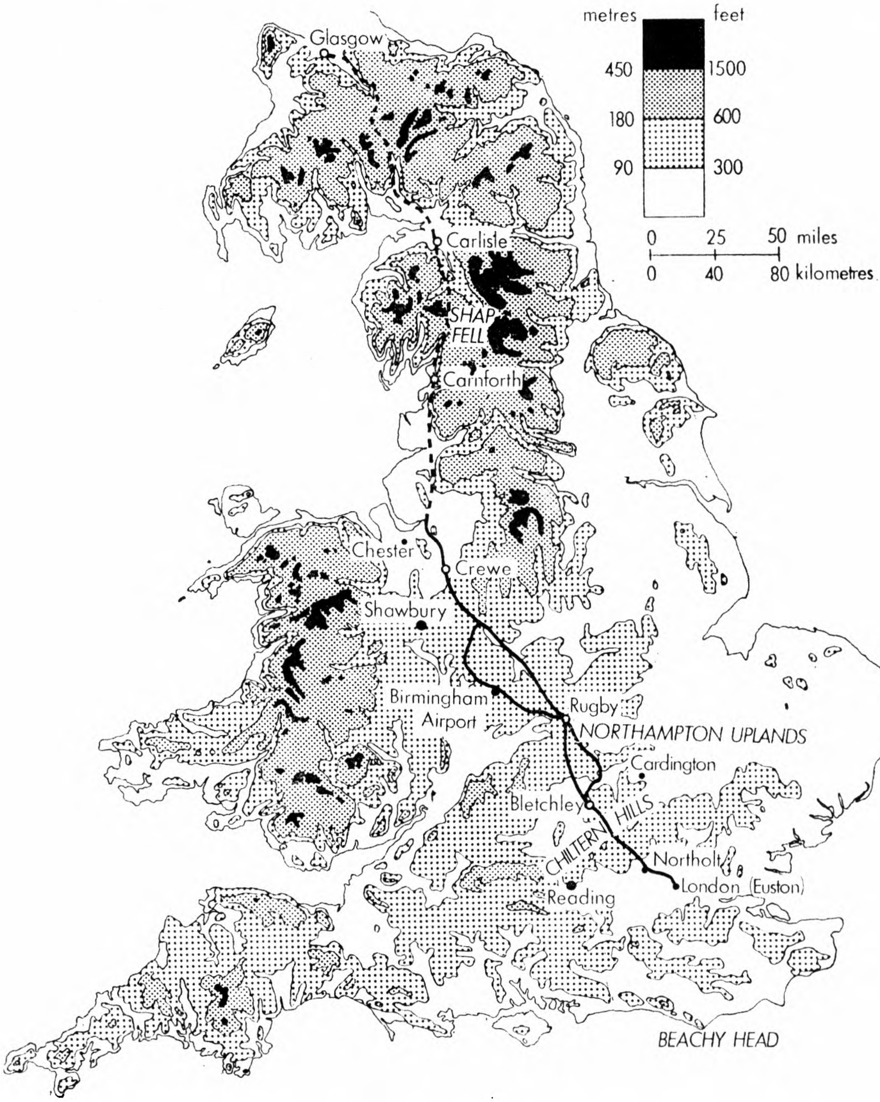


FIGURE 1—MAP SHOWING THE LOCATION OF THE ELECTRIFIED RAILWAY LINE AND ITS PROPOSED NORTHWARD EXTENSION, AND OF PLACES MENTIONED IN THE TEXT

freezing-point is significant; if they had been higher, the pantographs would have been more likely to acquire above-zero temperatures before a large ice accretion had collected. Points in support of this theory are as follows :

(i) Trouble did not occur prior to 09 GMT when temperatures at Cardington were below freezing-point.

(ii) Trouble did not affect northbound trains in the Euston–Bletchley area because they were running from higher towards lower temperatures.

(iii) Trouble did not affect northbound trains between Birmingham and Crewe because at the times when temperatures were favourable for accretion (between 01 and 03 and between 08 and 10 GMT), the snow was only slight during the first period and had become intermittent in the second period, and was dry during both periods.

Two awkward questions remain :

(i) Why were southbound trains not similarly affected between 07 and 09 GMT in the London area where temperatures were just beginning to rise above freezing-point while a little further north they were below zero?

(ii) The possible effect of altitude on air temperature near the ground has already been mentioned; is there any evidence to show what this was and is it justifiable to use temperatures at Cardington in the argument when this station is some 100 to 300 feet (30 to 100 m) below the general level of the line?

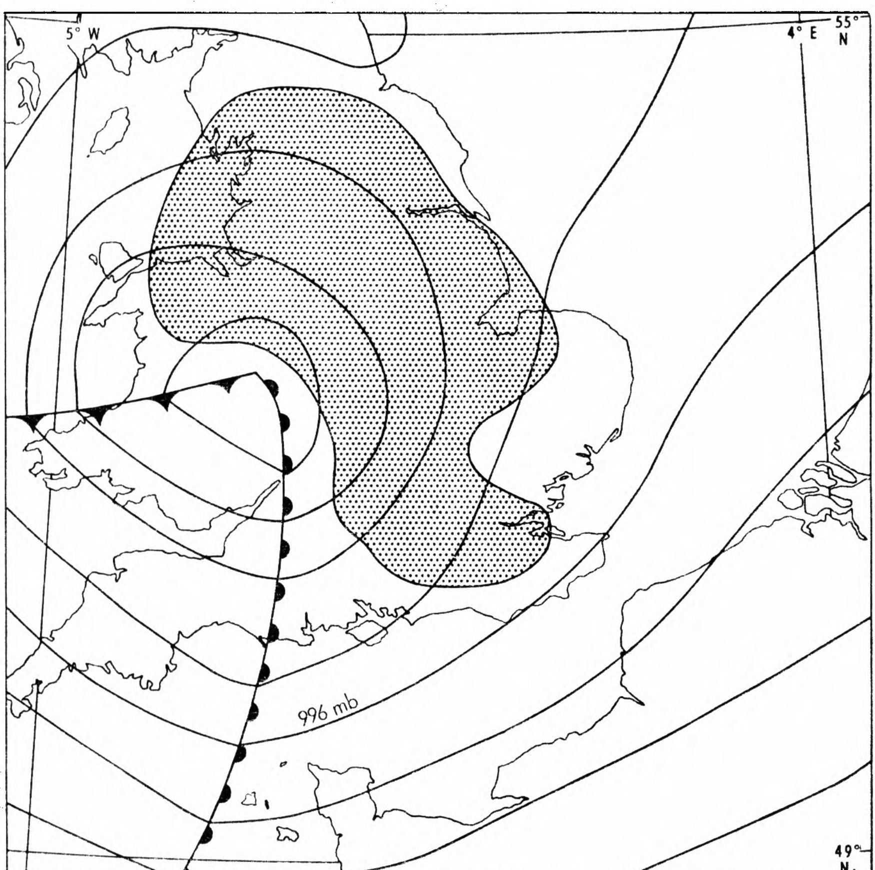


FIGURE 2—SYNOPTIC SITUATION AT 06 GMT ON 4 MARCH 1970

Isobars are at intervals of 2 millibars. The stippled area shows the extensive belt of snow. Some drizzle or sleet occurred near the edge of the snow belt.

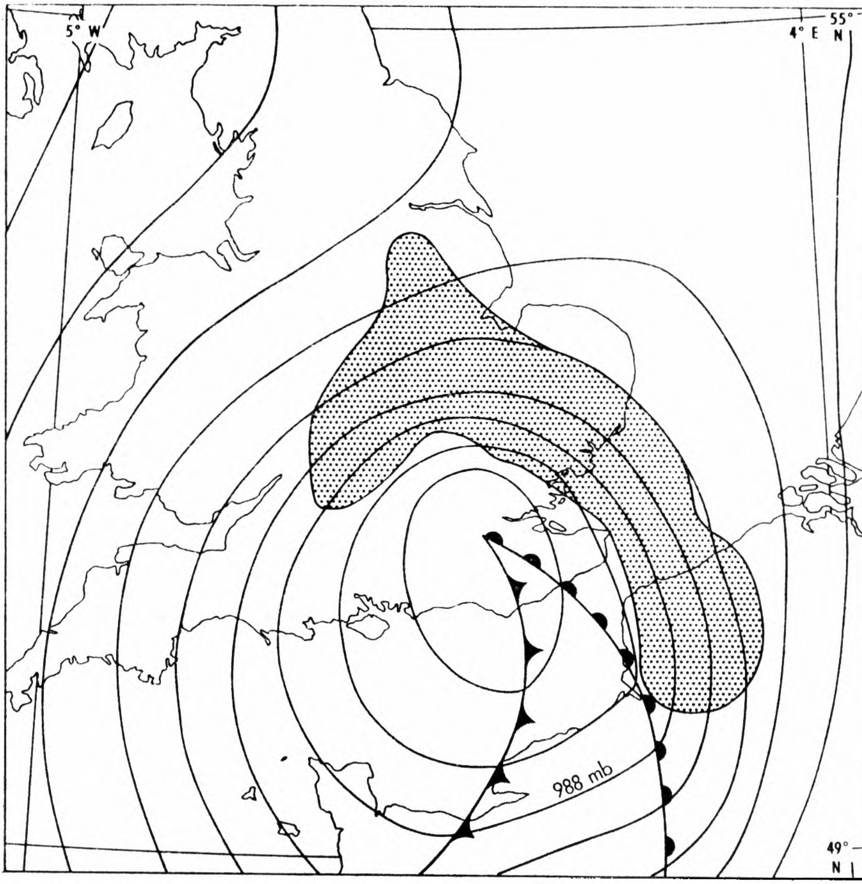


FIGURE 3—SYNOPTIC SITUATION AT 12 GMT ON 4 MARCH 1970

Isobars are at intervals of 2 millibars. The stippled area shows the extensive belt of snow. Some drizzle or sleet occurred near the edge of the snow belt.

A possible clue to question (i) lies in the change from snow to sleet* and then to rain and drizzle at Northolt between 10 and 13 before snow returned by 14 GMT. This clearly indicates a temporary increase in the liquid water content of the precipitation south of Cardington — probably due to slight warming aloft as well as near the ground — at precisely the period when serious accretion occurred. Presumably the liquid content between 07 and 09 GMT was insufficient to give trouble. With regard to question (ii), simultaneous temperature readings at a much larger network of stations in the area have been inspected and differences that can be attributed to altitude are less than 1 degC.

Discussion. The foregoing demonstrates how finely balanced the weather and, particularly, the temperature distribution was on this occasion, and, by implication, how rare the recurrence of similar situations in this part of the

* In the United Kingdom the term sleet is used to denote precipitation of snow and rain (or drizzle) together or of snow melting as it falls, but it has no agreed international meaning.

country might be. Information from British Railways indicates that this is the first time this particular trouble has occurred to any serious extent during the five years since electrification of this line. To predict the same combination of circumstances would be extremely difficult. However, electrification from north of Crewe to Glasgow, using the same overhead system, has now been sanctioned and it may well be that a similar icing problem will be encountered more frequently in north-west England and southern Scotland. High-speed trains, after encountering snow and below-freezing temperatures over Shap Fell (about 900 ft (275 m) above MSL) for example may, on a number of occasions each winter, run into wet snow, sleet or rain at lower levels on the route to Carnforth or Carlisle, both of which are near sea level. If air temperatures at the lower levels are only a degree or so above freezing-point, the cold pantographs may well rapidly acquire an accretion of ice before the equipment has time to attain a temperature above freezing-point. Similar situations could also be expected after crossing the Scottish hills.

551.510.52:551.515.5:551.524.73

STRUCTURE OF THE TROPOSPHERE OVER GAN

By D. W. DENT and B. H. PREEDY

Summary. Analysis of upper air data from Gan and other tropical stations shows that mean monthly temperature variations are very small throughout the troposphere in the areas considered.

Measurement of stability by means of indices reveals no useful relationship between instability and rainfall, though humidity is the most sensitive element in differentiating between wet and dry days.

Introduction. Despite the fact that most rain in the tropics falls from large cumulonimbus clouds, forecasters have found that upper air temperature soundings provide little or no useful aid for solving the problem of forecasting showers or thunderstorms.

The purpose of this report is :

(i) to present mean tropical soundings and their seasonal variability in the temperature structure, and

(ii) to examine the relationship between stability and rainfall or thunderstorms.

Source of data. This type of investigation has been carried out for various parts of the tropics by several authors, including Harris and Ho[1] who studied convective activity and stability for continental south-east Asia. However, the Indian Ocean region appears to have received little attention in this context. Because of its equatorial position and of its being a small island more than 500 miles (800 km) from the nearest land mass, Gan(0° 41′S, 73° 09′E) was chosen for a detailed analysis. The data are therefore considered representative of the atmosphere over the equatorial Indian Ocean.

Processing of data. Upper air data for a number of stations are stored on magnetic tape at Bracknell. Temperature, humidity mixing ratio, wind speed and wind direction are recorded for a number of standard levels. Calculations were performed for a five-year period (1960–64), for each month of the year for Gan. One radiosonde temperature and humidity sounding made at 12 GMT (17 local zone time) was available for each day.

It was necessary to classify each day as either 'wet' (rainfall at Gan being at least 1 mm in 24 hours) or 'non-wet', less accurately 'dry' (rainfall at Gan being less than 1 mm). The use of this definition is unsatisfactory in that the data from one rain-gauge is being used to represent conditions in an area around the station. The Harris and Ho method of using a radar index to define convective days is more representative of the local environment, but could not be applied to Gan as radar pictures were not available for a long period.

The following were calculated :

(i) Mean monthly ascents for all standard pressure levels up to 100 mb.

(ii) Mean ascents for wet days and dry days for January, April, July and October.

(iii) Mean ascents for days on which thunder was reported and for days on which thunder was not reported at Gan.

(iv) the instability of each temperature sounding as measured by the following instability indices :

(a) Boyden's[2] index (I) is given by

$$I = Z - T_{700} - 200$$

where Z = 1000 – 700-mb thickness (decametres)

T_{700} = 700-mb temperature (°C);

(b) Rackliff's[3] index (ΔT) is given by

$$\Delta T = \theta_{w900} - T_{500}$$

where θ_{w900} = 900-mb wet-bulb potential temperature (°C)

T_{500} = 500-mb temperature (°C);

(c) Jefferson's[4] index (T) is given by

$$T = 1{\cdot}6\ \theta_{w900} - T_{500} - \tfrac{1}{2}Td_{700} - 8$$

where Td_{700} = 700-mb dew-point depression (degC).

These indices were designed for temperate latitude environments and no attempt is made to justify the suitability of their use in the tropics. They were selected so that variations in stability could be investigated.

(v) A moisture-deficit index for each sounding as defined by

$$M = \tfrac{1}{2}d_{500} + d_{600} + d_{700} + \tfrac{3}{4}d_{800} + \tfrac{1}{2}d_{850} + \tfrac{1}{4}d_{900}$$

where $d_{500} = x_{s500} - x_{500}$ etc.,

where x_{s500} = saturated humidity mixing ratio at 500 mb (g/kg)

x_{500} = humidity mixing ratio at 500 mb (g/kg).

This index represents the dryness of the troposphere from 900 mb to 500 mb by integrating the moisture deficit between these levels, as suggested by Johnson and Mörth.[5]

Results.

(i) *Variations of mean monthly temperature.* These are remarkably small (see Figure 1) showing variations not greater than 1 degC in the lower troposphere (900 mb to 500 mb) and not exceeding 2 degC throughout the entire troposphere. In May and June there is a temperature fall of 0·5 degC in the lower troposphere increasing to 2 degC at 200 mb. This coincides with the onset of the south-east monsoon at Gan. However, at 100 mb there is a large temperature rise of 6·6 degC between April and August preceding a corresponding fall during the following three months. These changes are closely linked with the height of the tropopause and the position of the thermal

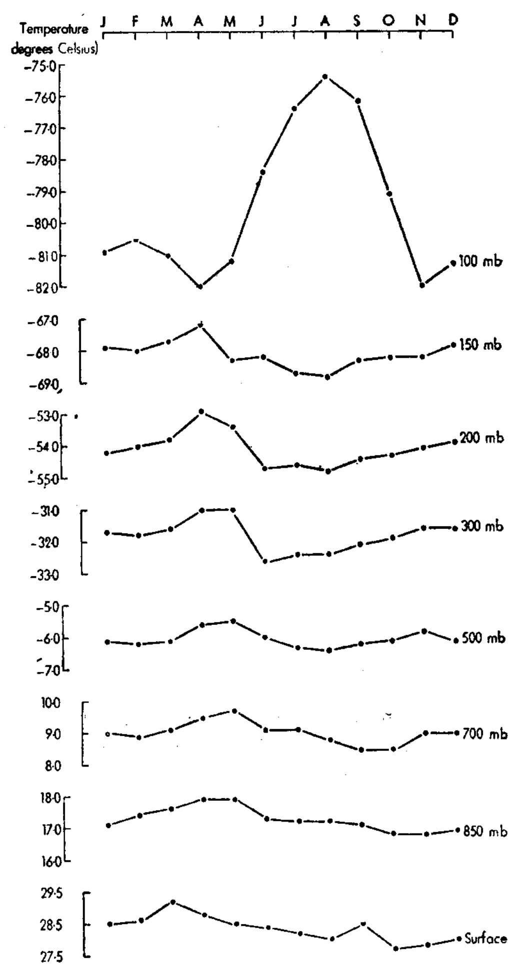


FIGURE 1—MEAN MONTHLY TEMPERATURES AT GAN (1960–64)

equator. The mean ascents, of which October (see Figure 2) is a typical example, show conditional instability from the surface to 500 mb and a near saturated-adiabatic lapse rate above.

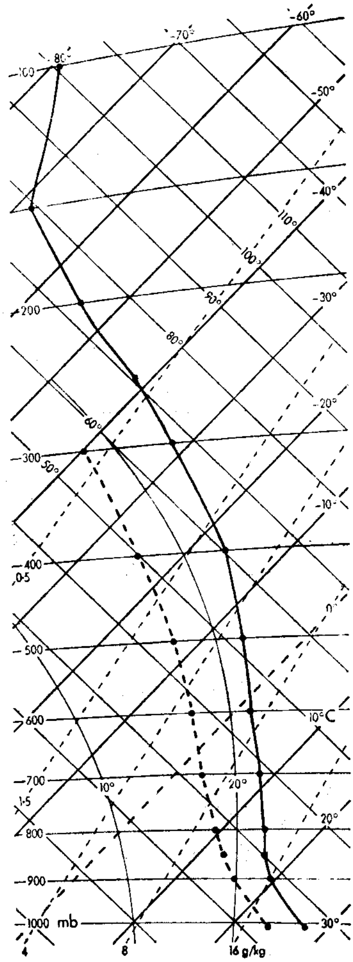


FIGURE 2—MEAN MONTHLY ASCENT FOR OCTOBER AT GAN (1960–64)
·———· Dry-bulb temperature ·– – – –· Dew-point temperature

(ii) *Variations of temperature within each month.* Standard deviations of temperature for the levels from 900 mb to 500 mb are less than 1·25 degC (see Figure 3). There is a minimum value of standard deviation in all months at 900 mb with an absolute minimum of 0·66 degC in January at this level. These values are consistently smaller than those indicated by Goldie, Moore and Austin[6] for this region.

(iii) *Mean stability indices.* The mean monthly values of Boyden's index are not less than 95·9 in all months. This contrasts with the thunderstorm threshold value of 94 suggested by Boyden for temperate latitudes which was surpassed at Gan on 97 per cent of occasions throughout the five-year period.

Pressure (mb)	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC.
100	2·76	3·17	3·08	2·66	3·25	3·15	3·39	3·32	3·54	2·89	3·12	3·06
150	2·46	2·95	2·36	2·32	2·46	2·10	1·98	2·30	2·68	2·24	2·17	2·49
200	2·08	2·27	1·79	2·08	1·83	1·98	1·50	1·63	1·87	1·71	1·64	1·98
250	1·70	1·84	1·59	1·91	1·58	1·68	1·41	1·48	1·54	1·50	1·42	1·68
300	1·57	1·52	1·34	1·50	1·45	1·52	1·32	1·27	1·26	1·33	1·26	1·46
400	1·42	1·28	1·32	1·08	1·07	1·24	1·28	1·58	1·16	1·09	1·01	1·08
500	1·08	1·05	1·23	0·88	0·97	1·20	1·16	1·09	0·99	0·89	0·97	1·03
600	1·04	1·05	1·15	0·98	1·05	1·18	1·11	1·00	1·08	0·99	0·92	1·11
700	1·03	1·11	1·02	1·00	1·06	1·12	1·07	1·24	0·85	1·01	0·90	1·03
800	0·98	1·09	0·95	0·86	1·06	1·09	0·95	0·94	0·96	0·89	1·01	0·99
850	0·78	1·05	0·88	0·82	0·89	0·98	0·83	0·85	0·80	0·74	0·85	0·83
900	0·66	0·83	0·79	0·80	0·81	0·84	0·74	0·69	0·69	0·71	0·72	0·77
Surface	1·13	1·33	1·33	1·54	1·37	1·09	1·28	1·57	1·24	1·33	1·29	1·36

FIGURE 3—STANDARD DEVIATIONS OF MONTHLY MEAN TEMPERATURES AT GAN IN DEGREES CELSIUS

The mean monthly values of Jefferson's index vary from 27·6 to 29·3 and are very close to the thunderstorm threshold value of 28 quoted by the author. However, this is not necessarily the appropriate value to use in the tropics.

The mean values of Rackliff's index, on the other hand, are always below the suggested thunderstorm threshold of 30.

The significant differences in the mean values of Jefferson's and Rackliff's indices may be explained by the additional moisture parameter included in Jefferson's index.

(iv) *Relation between stability and indices.* A comparison of mean monthly soundings for wet and dry days shows a consistent temperature difference. In each season, the mean sounding for wet days indicates an upper troposphere warmer than the dry days by about 1 degC on average (see Figure 4). This would be expected from the release of latent heat in deep convection. Below the 500-mb level the air on wet days is cooler and moister than on dry days. This is essentially the result found by Harris and Ho using Saigon data. Although it was not possible to separate diurnal temperature variations as done by Harris and Ho, a statistical analysis by Preedy[7] shows that the nocturnal bias of rainfall at Gan is slight. Calculations on data for a four-year period indicate that 54 per cent of the total rain at Gan falls by night.

Comparison of the instability indices points to a slight decrease in stability on wet days in the mean (see Table I). Values of Boyden's index for wet days in January, April and July show a slight increase over the mean values. Similarly the Rackliff and Jefferson mean indices on wet days suggest a less

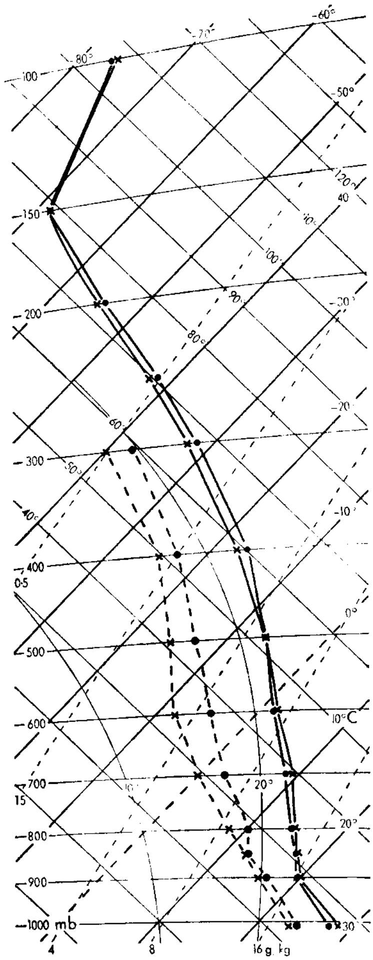


FIGURE 4—MEAN MONTHLY ASCENTS FOR WET AND DRY DAYS AT GAN (JULY 1960–64)

. ——— . Wet days dry-bulb temperature	x ——— x Dry days dry-bulb temperature
. – – – . Wet days dew-point temperature	x – – – x Dry days dew-point temperature

stable atmosphere on wet days than the mean. Although these variations from the mean are statistically significant, they are of no practical value (see Figure 5).

The moisture-deficit index clearly indicates a large increase in moisture content on wet days. This implies that the large variations in the Rackliff and Jefferson indices compared with Boyden's are mainly due to the inclusion of moisture parameters. Humidity is plainly the most sensitive element in differentiating between wet and dry days.

Mean thunder-day calculations were based on small samples because of the infrequent occurrence of thunder at Gan.[7] Nevertheless, the mean soundings for thunder days show a variation in stability which is similar to that for wet days. This is not surprising since most thunder days were also wet ones.

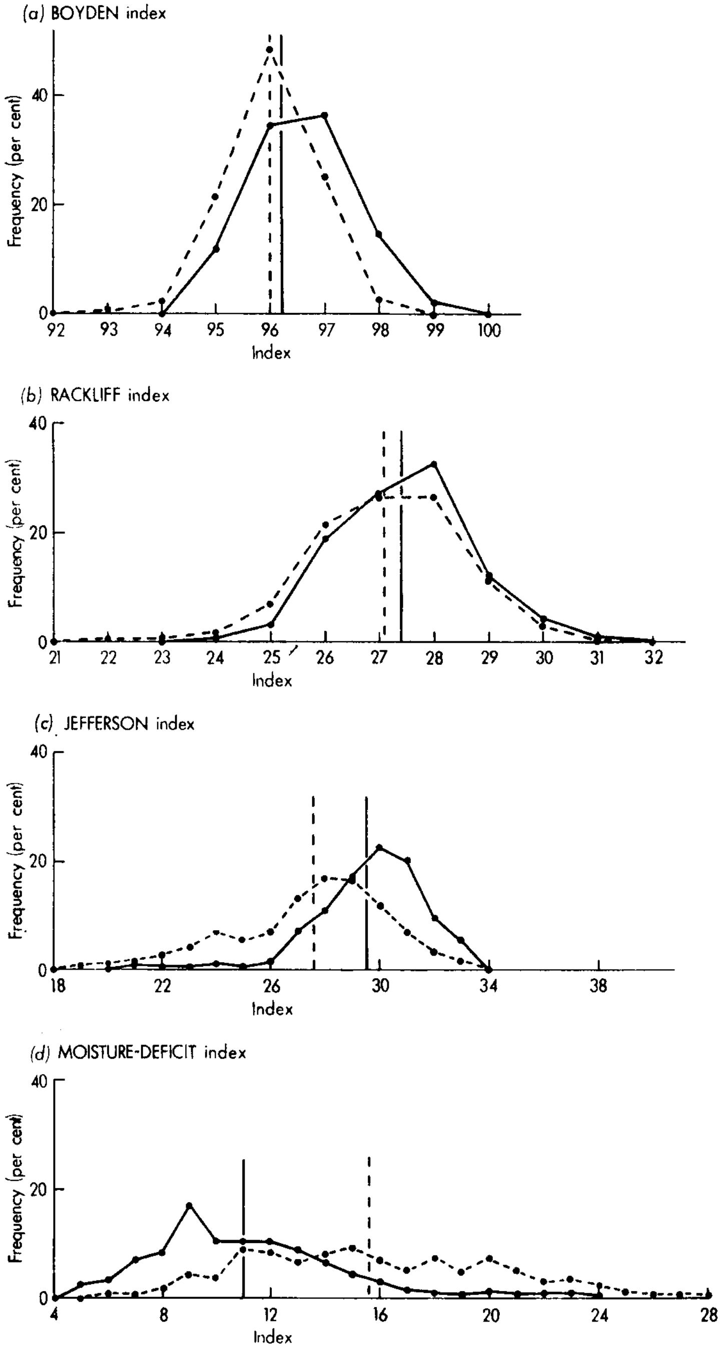


FIGURE 5—FREQUENCY OF INDEX VALUES ON WET AND DRY DAYS AT GAN (JANUARY, APRIL, JULY AND OCTOBER)

——— Wet days   - - - Dry days

Mean of distribution shown by vertical line.

TABLE I—INSTABILITY INDICES AT GAN

	January	April	July	October
BOYDEN (94)				
Mean monthly	96·0	96·3	96·1	96·1
Mean wet days	96·1	96·4	96·3	96·1
Mean dry days	95·9	96·2	96·0	96·1
Mean thunder days	96·5	96·0	96·1	95·8
Mean non-thunder days	95·9	96·3	96·1	96·1
RACKLIFF (30)				
Mean monthly	27·1	27·5	27·5	27·0
Mean wet days	27·4	27·6	27·7	27·2
Mean dry days	26·9	27·3	27·4	26·7
Mean thunder days	28·5	28·4	28·3	28·0
Mean non-thunder days	27·0	27·4	27·4	26·9
JEFFERSON (28)				
Mean monthly	28·2	29·3	27·6	28·4
Mean wet days	29·4	30·2	29·2	29·2
Mean dry days	27·6	28·5	27·0	27·3
Mean thunder days	30·1	31·0	30·1	30·6
Mean non-thunder days	28·1	29·2	27·5	28·3
MOISTURE-DEFICIT				
Mean monthly	13·7	13·3	15·7	12·2
Mean wet days	11·1	11·1	12·0	10·5
Mean dry days	15·0	15·2	17·0	14·4
Mean thunder days	11·9	10·2	12·0	8·5
Mean non-thunder days	13·8	13·5	15·8	12·3

Numbers in brackets after index names indicate thunderstorm threshold values for temperate latitudes.

The Rackliff and Jefferson indices on thunder days suggest a decrease in stability over wet days. The wet-day and thunder-day means of Jefferson's index were about the threshold value of 28. On the other hand, the means of Rackliff's index were below threshold.

(v) *Day-to-day variations.* The next step was to investigate the variations of the indices on a day-to-day basis. An attempt was made to use the moisture-deficit index as an indicator for rainfall in the 24 hours following the sounding. By selecting a suitable critical value, a forecast of rain or no-rain was made according to whether the moisture-deficit index was below or above this value. This is basically a persistence method using humidity content as parameter. The results on average over the five-year period were no better than those obtained for a forecast by persistence of type (that is, predicting a rain day to follow a rain day and a dry day to follow a dry one).

The frequency distributions (see Figure 5) show that none of the indices are capable of satisfactorily discriminating between a wet and a dry day.

(vi) *Comparison with other tropical stations.* The data from several tropical upper air stations for January, April, July and October were analysed to provide a comparison with the Gan results. Five-year means were calculated for Aden and Nairobi. Seychelles data were available for a period of 16 months and Christmas Island data for three years.

At Aden (12° 50′N, 45° 02′E), seasonal variations in temperature in the lower troposphere were much greater than at Gan (see Figure 6). This result would be expected from continental influences.

At Nairobi (01° 18′S, 36° 45′E), the seasonal variations were larger than those at Gan and were confined to a shallow surface layer.

Throughout the troposphere, data for Seychelles (04° 37′S, 55° 27′E) exhibited a slightly larger seasonal variation than did data for Gan, but the variation did not exceed 3 degC below the 150-mb level.

Data for Christmas Island (01° 59′N, 157° 29′W) showed remarkably small variations of temperature throughout the seasons. It is apparent that the stations nearest to the equator experience the smallest seasonal variations in temperature.

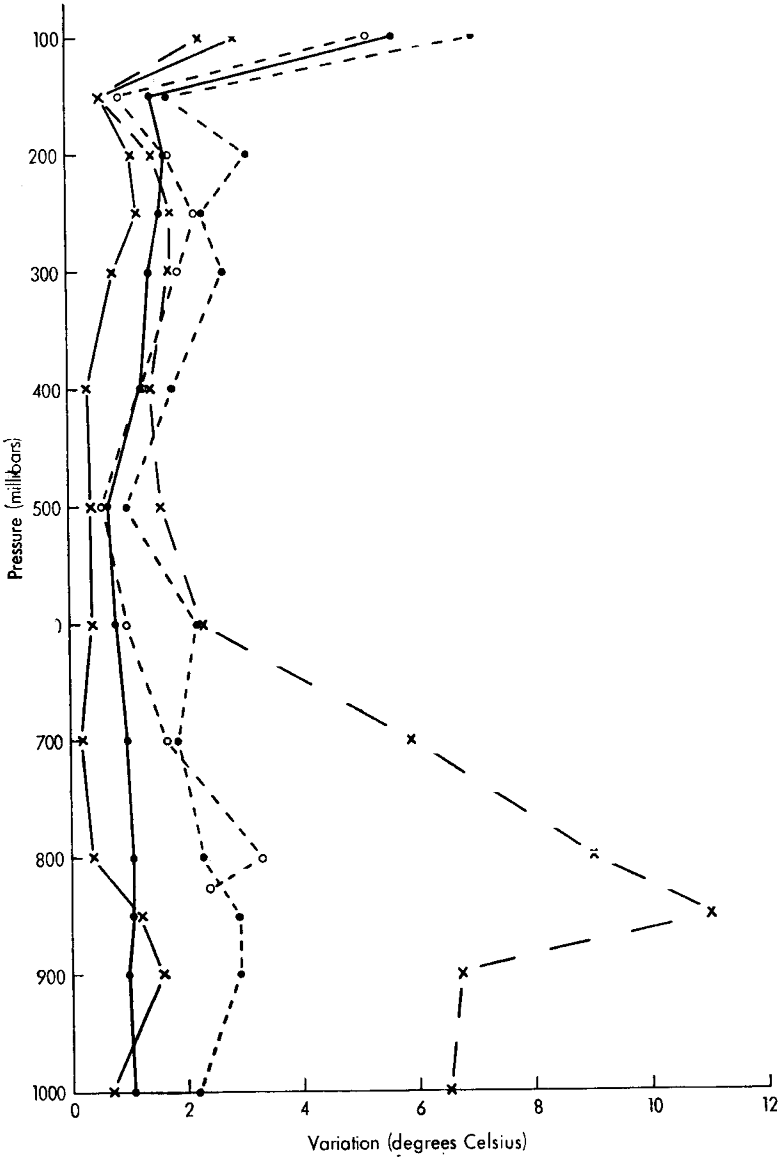


FIGURE 6—RANGE OF MEAN SEASONAL TEMPERATURE

x — — —· x Aden x ——— x Christmas Island · — — — · Seychelles · ——— · Gan o — — — o Nairobi

Indices for wet and dry days at Seychelles and Christmas Island behaved in a similar manner to those at Gan, with a small variation in Boyden's index and rather larger variations in the Jefferson, Rackliff and moisture-deficit indices. The mean soundings were also similar, with cooling in the lower troposphere and warming in the upper troposphere on wet days.

Discussion. The results confirm that temperature variations in the tropics are small, particularly in oceanic environments near to the equator. Mean ascents show that the atmosphere is conditionally unstable in the lower troposphere on both wet and dry days, and support the hypothesis that increases or decreases in convective activity are synoptically controlled.

Instability and moisture-deficit indices are unsuitable as tools for forecasting rainfall in the tropics, although there are significant differences between the mean index values for wet and for dry days. However, the predominant element giving rise to these differences is the moisture content, and variations in stability are small. Warming in the upper troposphere on wet days is accompanied by slight cooling in the lower layers.

There is evidence to suggest that the tropical atmosphere exhibits greater instability in association with thunderstorm activity than is present in non-thundery wet situations, but the differences are so marginal as to be of no value in forecasting.

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NOTES AND NEWS

Retirement of Mr S. E. Virgo, O.B.E.

Mr Sidney Eustace Virgo joined the Meteorological Office at the start of the Second World War as a Forecaster II early in 1940. During the next three years he served at Bicester, HQ No. 15 Group Royal Air Force (Liverpool), Swinderby and Gloucester, finally settling for a spell at Prestwick.

In 1943 Mr Virgo was commissioned Flight Lieutenant in the Meteorological Branch of the RAFVR and after a time in Dorval near Montreal he returned again to Prestwick.

Following his promotion to Squadron Leader he served in Trinidad for nearly three years from 1945 to 1948. In 1948 he was posted, as a Principal Scientific Officer, to London Airport on the senior forecasters' roster and then in 1949 became Senior Meteorological Officer at HQ No. 18 Group, Pitreavie, where he stayed for three years. Following a further three years as Senior Meteorological Officer, Prestwick, he became Chief Meteorological Officer 2nd Tactical Air Force, Germany, until September 1958 when he returned to become Chief Meteorological Officer HQ Bomber Command. In this post he was promoted to Senior Principal Scientific Officer in June 1960 and remained as Chief Meteorological Officer Bomber Command RAF, later Strike Command, until he retired from his senior grade in May 1969. In 1968 he was appointed an Officer of the Order of the British Empire in the New Year Honours List.

During more than 10 years at High Wycombe Sidney Virgo impressed his personality throughout his wide field of subsidiary stations and staff. Very well liked by all, he showed his qualities of leadership in the very considerable amount of investigational work carried out and published by the staff at his stations.

A regular contributor to technical journals over the years, his subjects ranged from föhn winds in Switzerland, weather at Piarco, Trinidad, and instability over Scotland to much work on the forecasting of night minimum temperatures.

After retirement from his senior post, Mr Virgo accepted a disestablished post as Senior Scientific Officer at the Meteorological Office Training School, and finally left the Office on 31 August 1970.

Without doubt a 'character' who will be missed from our ranks; we wish him and Mrs Virgo many years of happy retirement.

V.R.C.

REVIEWS

Clouds and weather, by R. K. Pilsbury. 215×205 mm, pp. 90, *illus.*, B. T. Batsford Ltd, 4 Fitzhardinge Street, London W1, 1969. Price: 25*s*.

The author is known to most meteorologists for the cloud photographs which have appeared above his name in a variety of meteorological texts and journals. This book is in large measure a vehicle for the publication of a selection of 107 of his photographs; they are in black and white and are reproduced, each with its explanatory note, two to a page.

These photographs comprise the latter two-thirds of the book and they are preceded by a general account, in six short chapters, of cloud nomenclature and methods of cloud formation. The treatment is aimed at the level of the layman, follows fairly conventional lines and is generally sound. The author's wording is not, however, always as unambiguous as would be wished and there must be reservations about the helpfulness or accuracy of a few of the statements which he makes: as, for example, 'the forming of steam' (from a boiling kettle) 'is similar to the forming of cloud and fog'; or, in illustration of condensation by mixing of two air masses of different temperature, as occurring 'when warmer, moist air drifts in from the sea and is cooled by contact with the cold ground and with the cooler air over the land'. Again, though the appropriate choice of units in a text of this kind presents particular difficulties, the author is surely unduly indiscriminate in the way in which he uses °F at some times and °C at others (for lapse rates as well as for surface conditions).

The main value of this book lies, in fact, in the plates, which have been well chosen to illustrate the genera, species and varieties of the international cloud classification. Their reproduction is good and the author gives a careful explanation of the particular classification which he allots. It does seem a pity, however, that he did not take the opportunity to add the place and date and a brief reference to the prevailing synoptic situation in each case, and thereby inject additional life and meaning to the clouds.

D. H. McINTOSH

Hydrological forecasting. WMO Technical Note No. 92 (Proceedings of the WMO/Unesco Symposium on Hydrological Forecasting, Australia 1967). 270 mm × 210 mm, pp. xvi+325, *illus.*, Geneva, WMO, 1969 (supplier HMSO, London). Price: £6.

The World Meterorological Organization has included in its admirable series of *Technical Notes,* the Proceedings of the WMO/Unesco Symposium on Hydrological Forecasting which was held in Surfers' Paradise, Queensland, Australia, in 1967. In his comprehensive keynote address, Max A. Kohler gave the principal theme of the Symposium as the 'forecasting, especially for shorter time-intervals, of rainfall floods'. He outlined the problem areas of data acquisition and transmission, and pointed to the rapid developments in forecasting procedures using atmospheric and catchment models. In the future, reliable quantitative precipitation forecasts would constitute the data input to improve catchment models with, as a consequence, much more accurate river-flow forecasts.

The Proceedings contain 30 papers grouped into six parts. Part 1 contains three general review papers, Part 2 four papers on the forecasting of precipitation, Part 3 three papers on data acquisition and instrumentation, Part 4 ten papers on forecasting techniques, Part 5 four papers on operational aspects of forecasting and Part 6 six papers presented by title only at the Symposium.

The subject matter of hydrological forecasting may be considered under three headings: the forecasting of precipitation from the atmosphere, the forecasting of high discharges and flood peaks along a river course, and the interaction between the atmospheric and land phases of the hydrological cycle. The review papers by Popov and Philip cover the last two topics in masterly fashion but it is unfortunate that the paper from Smagorinsky is merely a one-page summary of a previous paper in the *Monthly Weather Review* and does little justice to the too expansive title: 'The hydrological cycle — its physical basis and its predictability'.

In Part 2 some readers might again be disappointed by another one-page presentation of results by Smagorinsky from the American nine-level hemispheric model. 'Researches in India on objective precipitation assessment' and two valuable contributions by Hill on the hydrologically important cyclonic disturbances in the upper troposphere over Australia and New Zealand are welcome contributions.

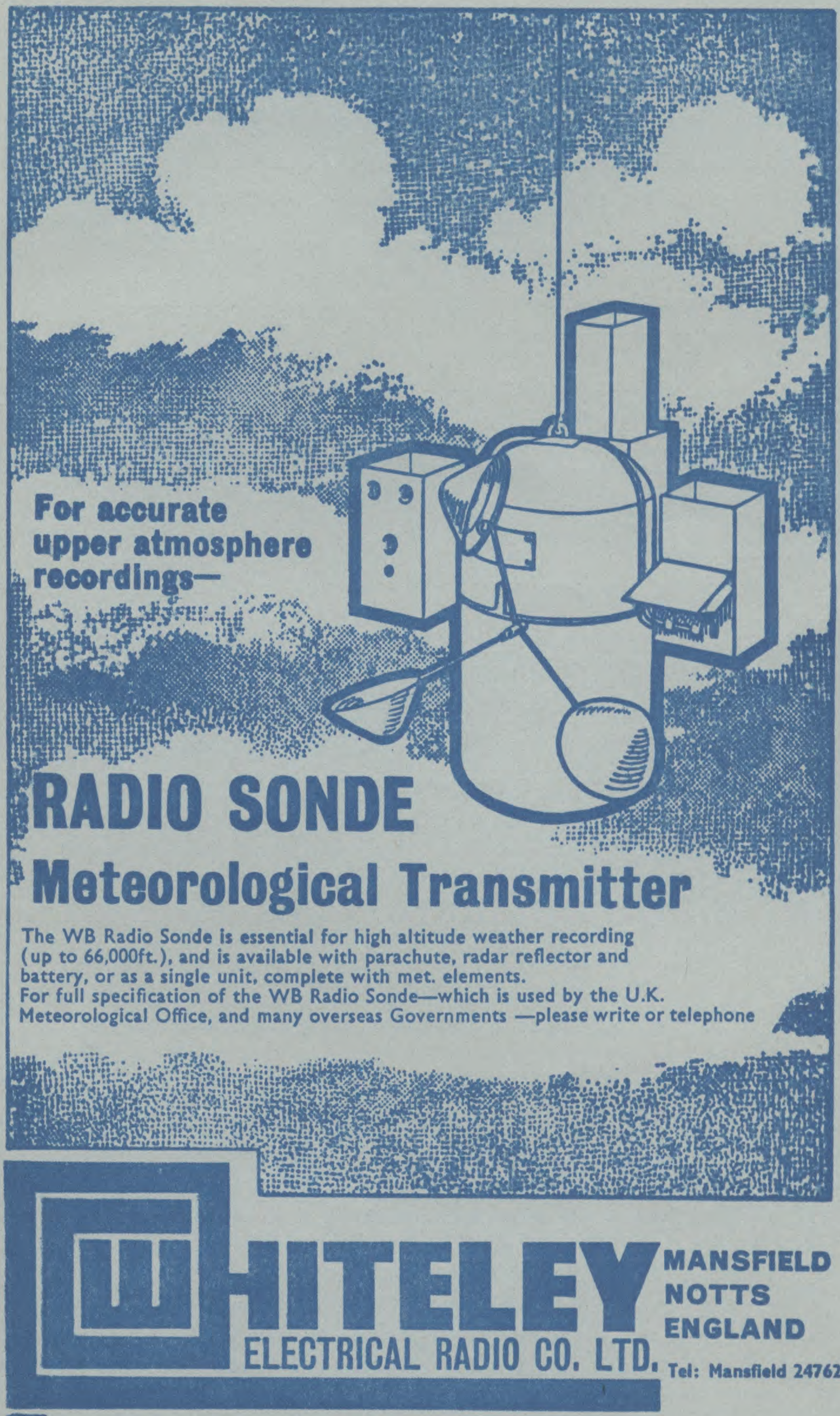
In data acquisition, the future value of observations from satellites is outlined by Rainbird, while Alexander develops mathematical models for the areal rainfall from significant storms.

The largest section, entitled 'Forecasting techniques', is mainly concerned with surface hydrology. In a very good paper on the 'Application of conceptual catchment models to river forecasting', Nordenson describes a selection of conceptual models developed in the United States and highlights the problems of adapting general-purpose models to forecasting where updating of input data and changing catchment conditions is necessary as flood discharges develop. A fuller explanation of the Stanford Watershed Model IV is reported by Crawford who stresses both the difficulties encountered with timing and volume errors in simulating the flood hydrograph and also the particular dangers of errors in the input data from mistaken observations. A paper by Nash and Sutcliffe (J. V.), misleadingly entitled 'Flood-wave formation', reviews the methodology and philosophy of catchment modelling and describes research in progress at the Institute of Hydrology. Further examples of work on models are given by Denisov, Bell, Gartsman and Lylo, and Burakov. There are also descriptions of the forecasting methods used in Korea, Venezuela (the Orinoco River) and on the Latrobe River of South Victoria.

On the operational aspects of forecasting, there are two general papers covering applications of discharge and water-level forecasts and the organization of flood warnings. The functioning of two major control schemes in Australia (Lake Burley Griffin in Canberra and the multi-purpose Somerset Dam in the Brisbane River catchment) conclude the presented papers.

In this rapidly developing subject, the delay in this publication is to be regretted. Many additional floods since 1967 have added to experience. Nevertheless, several of the contributions to the Symposium still merit detailed study and it is to be hoped that future international conferences on this subject will attract more than one paper from the United Kingdom.

E. M. SHAW and T. O'DONNELL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NOTICES

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WEATHER, CLIMATE AND PLANT DISEASE*

By W. H. HOGG

Summary. The development of two plant diseases is described in relation to the weather. Potato blight, *Phytophthora infestans,* can be carried over from the previous season. It spreads rapidly in warm, humid weather and the warning system operated by the Plant Pathology Laboratory and the Meteorological Office is described. On average, the relative durations of potato blight weather at Plymouth, Bristol and Abingdon are 9:3:1.

The relationships between weather and black rust of wheat, *Puccinia graminis* f. sp. *tritici,* are more complicated, as the disease cannot occur unless spores are brought into this country by the wind. The use of trajectories suggests that in years when the disease appears early the spores originate in southern Europe or North Africa; in years when it appears late the spores may arrive from France. There is no warning system for the disease and the role of the meteorologist in any future scheme is discussed.

Introduction. The object of this paper is to discuss the meteorological factors concerning the occurrence and spread of two plant diseases which occur in south-west England, potato blight and black rust of wheat. From a meteorological standpoint the chief way in which these differ is in the availability of the pathogen. For potato blight it is normally present and the development of the disease awaits only the occurrence of favourable weather; for black rust of wheat it has to be imported from outside the British Isles and the possibility of spore transport is a major factor in relation to the disease. The forecasting of these diseases on meteorological grounds is also discussed. For potato blight, a workable scheme has been in operation for many years, but at present there is no warning system for black rust.

Potato blight, *Phytophthora infestans.* The dependence of outbreaks of potato blight epidemics on the weather has long been recognized and Beaumont[1] investigated this in some detail at Seale-Hayne Agricultural College. Blight appears in the crop as a result of infected tubers which may have survived in or on the ground from the previous season, or which may have been unwittingly planted. The fungus invades aerial shoots from these tubers to form foci from which the disease spreads to neighbouring plants. There are, therefore, normally ample supplies of the pathogen and the timing of the spread and the intensity of the epidemic is largely determined by the weather.

As with many plant diseases the two most important weather variables are temperature and humidity. The rate of growth of the fungus depends on

* Paper presented at the meeting of the British Association for the Advancement of Science, Section M, at Exeter on 10 September 1969.

temperature, and infection requires a film of moisture on the leaf; the longer this film persists, the greater the opportunity for infection. There are obvious difficulties in making routine inspections of potato crops to determine whether the leaves are wet and this possibility is estimated from atmospheric humidity. For the Netherlands, van Everdingen[2] established that four conditions had to be met before outbreaks of blight occurred; these involved measurement or observation of dew, temperature, cloud amount and rainfall. Beaumont tested these in the south-west of England, simplified them and finally defined a critical period as one of 48 hours when :

(i) Temperature does not fall below 10°C, and

(ii) relative humidity does not fall below 75 per cent.

His examination of the south Devon weather records for July and August over 10 years showed that critical periods occurred in 7 years and that in each of these years the first critical period was followed by blight within 22 days; in 4 of the seasons, blight followed within 15 days; and in the 3 years without critical periods there were only slight attacks of blight.

Since 1950 Beaumont periods have been used as the basis of a warning system for England and Wales, with the modification that the criteria need be met on only 46 out of 48 hourly observations. The warnings use hourly observation of air temperature and humidity from some 40 synoptic stations of the Meteorological Office, and the Plant Pathology Laboratory of the Ministry of Agriculture, Fisheries and Food maintains an operations chart, an example of which is given in Figure 1. Clearly, the success of such a service depends on close co-operation between meteorologists and plant pathologists.

The operations charts for a period of years can be used to give a general picture of the likelihood of weather favourable to the general spread of potato blight. Table I shows this for four meteorological stations in south-west England and for Abingdon in Berkshire. The values represent the number of hours of Beaumont periods during June, July and August; in other words, the total number of hours with temperature $\geqslant 10$°C and relative humidity $\geqslant 75$ per cent provided that these occur during or immediately following periods of 48 hours, at least 46 of which satisfy these criteria; a Beaumont period is terminated when the criteria are not reached for 3 consecutive hourly observations.

TABLE I—HOURS OF BEAUMONT PERIODS, JUNE–AUGUST 1959–68

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	Mean
St Mawgan (near Newquay)	535	1073	633	865	1212	1270	1226	576	1293	1010	969
Plymouth	575	792	450	776	1298	1215	1379	830	1207	792	931
Exeter	381	341	6	336	599	261	350	142	242	332	299
Bristol	329	388	49	53	369	204	456	228	331	307	271
Abingdon (Berks.)	63	67	0	0	153	61	153	251	88	165	100

The chance of potato blight weather varies considerably over the West Country. As would be expected, places exposed to the moist winds off the Atlantic have far more of this weather than other parts. Exeter has lower humidities than places further west, because of its inland position in the lee of Dartmoor. It is not surprising that the values in the table are very little higher than those for Bristol. Naturally, inland places further east are still

POTATO BLIGHT FORECASTING 1965

WARNINGS & FIRST RECORDS

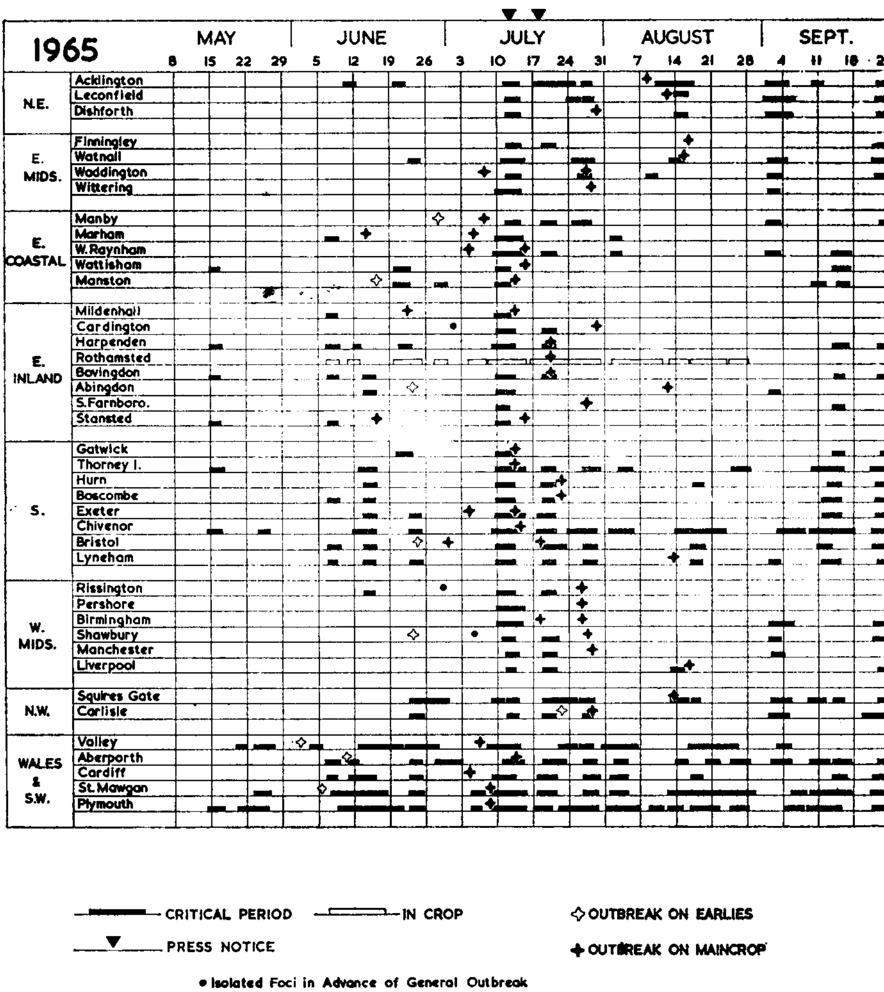

FIGURE 1—EXAMPLE OF AN OPERATIONS CHART

less likely to experience this weather and the average for Abingdon is only 100 hours. In practical terms, potato blight in the more humid parts of the West Country occurs with such regularity that a warning system is of limited use. Many farmers prefer to spray on a routine basis, confident that only occasionally will their efforts be wasted.

The potato blight warning system has on the whole proved a useful tool but it is worth considering whether it could be improved in any way. The objection is often raised that the records of temperature and humidity upon which the scheme rests are standard meteorological observations. They are taken in a thermometer screen over a grass surface at a height of about 4 feet

(1·2 m), often on an airfield, and are therefore not relevant to what may happen in a potato crop. While no doubt there are differences of micro-climate between different potato fields, the standard observations are used only as an indicator of what is likely to happen within the crop and there is no suggestion that temperature and humidity are the same as in the screen. A further point is that meteorologists should attempt to forecast the arrival of the damp warm weather of the Beaumont periods and give more time for spraying. In Ireland, Bourke[3] has identified three synoptic situations favourable for blight development :

(i) Open warm sectors of maritime tropical air, particularly when a sequence of waves is involved, bringing warm moist air with some rainfall.

(ii) Stagnant or slow-moving depressions giving long periods of wet overcast weather.

(iii) Active fronts which are more or less stationary and give long periods of wet overcast weather.

It is broadly true that similar reasoning could be applied in the west of Great Britain, but its use in the east is doubtful. The weather situations which hinder blight development can be somewhat more easily identified and Bourke gives the following as the most important :

(i) An anticyclone or a ridge of high pressure with dry sunny weather.

(ii) A direct breakthrough of cold air from northerly latitudes following a depression. Although the weather may be showery the intervening bright periods are not favourable to the spread of infection.

In the Netherlands, also, efforts are being made to predict the infection date as, from a purely practical standpoint, spraying should be done before this, since most fungicides lack any curative action (de Weille[4]). On the basis of laboratory work and field work the criteria over a period of 18 hours have been closely defined in weather terms and synoptic models have been adopted as the basis for predictive warnings.

This approach in countries to the east and west of Great Britain is interesting and may point the way to future development here. However, one must not forget that forecasting the weather will introduce a further element of uncertainty, and that reliability is the main aim.

Black rust of wheat, *Puccinia graminis* f. sp. *tritici*. In many ways our second example contrasts very much with the first. Unlike potato blight it is not a frequent disease in the British Isles and it is not economically important here, although it can be of great importance in the major wheat growing areas of the world, where it is largely controlled by breeding varieties of wheat which are not susceptible to the disease. In spite of this, serious epidemics can occur and we in Great Britain cannot rely on an indefinite immunity. Although it is difficult to control the disease other than by breeding, some progress is now being made with chemical controls. If any warning system were possible it might, within a few years, be possible to act on it. Perhaps the most fundamental way in which these diseases differ lies in the fact that black rust of wheat, unlike potato blight, is not normally capable of completing its life cycle within the British Isles and therefore it cannot occur unless a supply of inoculum is brought into the country. The only exception is that barberry may act as an alternate host allowing the disease to over-winter, and this has led to small outbreaks in Ireland (Prendergast[5]). Normally wind is the agent which transports the pathogen but many other meteorological factors are concerned with the whole process of development of the crops and disease and transport of the inoculum.

The complete life cycle of the disease does not concern us here and our interest is confined to the uredospores which may infect the crop. We shall consider the ways in which weather and climate act to determine what happens in the source area where the disease affects the local wheat crop, the ways in which the uredospores are liberated and transported from the crop to the higher layers of the atmosphere, how they are transported horizontally in the air, sometimes for long distances, how they are deposited on the wheat crop of the target area and what weather is favourable at that time to infection and, possibly, the establishment of an epidemic. Most of our attention will be directed to the question of horizontal transport of spores but a short generalized description of all the stages is given, based on Figure 2.

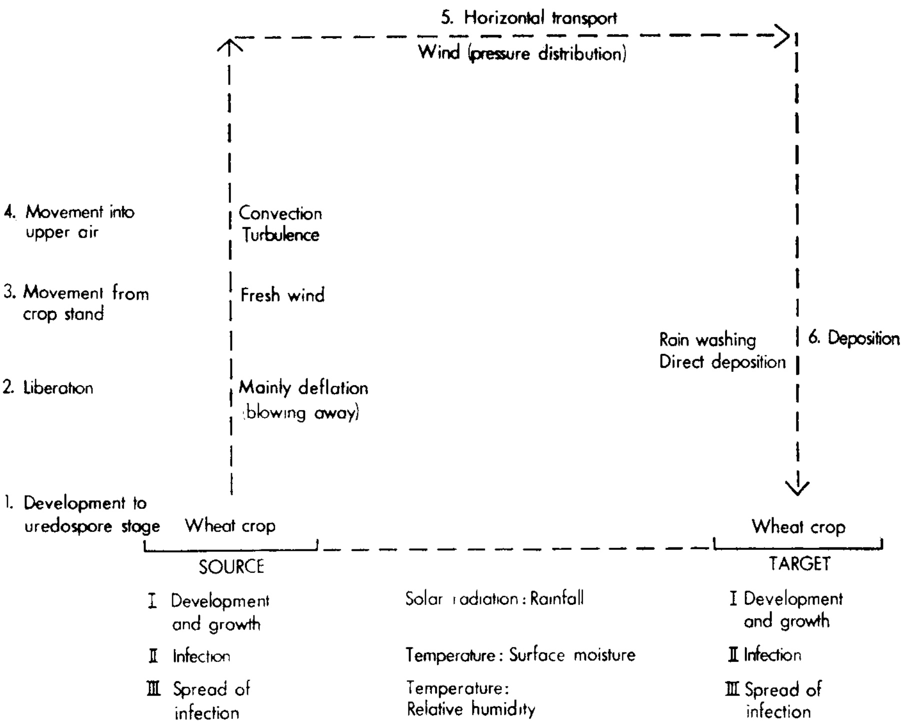

FIGURE 2—WEATHER FACTORS AND THE EPIDEMIOLOGY OF BLACK RUST OF WHEAT

It is convenient to think of a source area for the disease and a target area to which the pathogen is transported, the British Isles. Even if only the uredospore stage of the rust is considered there is a very complicated interaction between events in the source and target areas. In general terms, infection in this country depends on the phenology of the crop in both areas, the phenology of the rust in the source area and the possibility of spore transport followed by deposition and suitable weather in the target area.

The state of the crop in the source area is important in relation to the period of time for which it is exposed to infection; for example, a late crop will be at risk for a longer than normal period. This will depend fundamentally upon the weather factors of solar radiation and rainfall, though husbandry is also important. Uredospores over-winter in the source areas and infection there depends upon temperature and surface moisture. The spread of the infection is most rapid when humidity is high (temperature also needs to be high, but this is likely) and if the infection develops there will be an abundant supply of uredospores.

As a result of sporulation, the uredospores remain in place on the plant and form a dense mass of powder with little cohesion in the dry state and before dissemination they must be liberated (Zadoks[6]). Liberation is mainly achieved by deflation or shaking of the plant, though raindrop collision has already been cited as another possibility (Hirst and Stedman[7]). The next stage is movement from the crop stand and this is accomplished by the turbulent motion resulting from a fresh surface wind. At this stage horizontal motion will also increase in importance but the spores are unlikely to have a long path until they are carried higher into the atmosphere, a process assisted by larger-scale turbulence resulting from wind or convection. The horizontal transport is the result of wind at spore level and is dependent on the pressure distribution, i.e. the shape and the spacing of the isobars.

Before infection can result in the target area the spores must land on the plant, a process known as deposition. The spores are subject to gravity but sedimentation by this process alone is important only in still air, a somewhat rare occurrence. Other processes involved include turbulent deposition, direct interception or impaction, which is due to the fact that the spores cannot follow the streamlines of the air round the plants so that some of them are in collision with it. Probably the most important mechanism is rain-washing, by which the spores are brought down in the drops and the air is effectively cleansed. For infection to occur, the crop in the target area must be at a suitable stage of growth and the spread of infection will depend on local weather. The sequence of events will thus be similar to that in the source area, which may be many hundred miles and several degrees of latitude distant.

To return to the question of horizontal transport over long distances, any warning system must depend on a knowledge of source areas, so that a watch may be kept on winds from these areas. In continental areas the spread of disease over great distances can be well estimated from spore catches, the visible effects on the crop and the winds which blow between source and target areas. Such studies led to an understanding of the spread in North America, from Mexico and Texas northwards into the Prairie Provinces of Canada in spring and summer, followed by a reverse direction of movement in autumn (Stakman and Harrar[8]). For the British Isles this method is not possible because of the sea barriers between source and target areas and less direct methods msut be used.

Horizontal movement of the air is determined by the rotation of the earth and the distribution of atmospheric pressure, which can be represented on maps by isobars. In the lowest layers of the atmosphere, surface friction affects the speed and direction of wind but above about 600 m these effects may be ignored and a reasonable approximation to airflow may be derived from the direction and spacing of isobars. In general terms the wind is parallel to the isobars and speeds increase as the isobars are more closely spaced. Estimates of what is known as the geostrophic wind may be obtained without tedious calculation by using specially constructed scales but these estimates are based on certain assumptions which may not always be realized; they are, however, sufficiently close to the true wind to be acceptable as a substitute.

Pressure charts can provide an instantaneous picture of wind over the area and the lines of airflow derived from such charts are known as streamlines. The pressure patterns are, however, subject to change and displacement and they cannot therefore be used to indicate possible sources of spores except over short periods of time during which only minor changes occur in pressure distribution. It is therefore necessary to regard the pressure charts as valid only for short periods (normally the interval between successive charts). By estimating the movement of air towards the target area on a succession of charts, it is possible to indicate likely source areas and the trajectories between the source and target areas. Because any estimates of wind relate to geostrophic rather than true wind, the trajectories are only approximate and best designated as geostrophic trajectories. One interesting result which stems from the approximation inherent in the use of geostrophic trajectories is that in certain circumstances the trajectory from a possible source area for spores could reach the target area somewhat ahead of the moving air, and therefore before the spores are deposited.

For this work, spore counts were available from the Hirst spore trap at Cardiff (Hirst[9]), also from gravity slides both at Cardiff and at the Bishop Rock Lighthouse, in the Isles of Scilly. For the days on which spores were caught geostrophic trajectories were constructed reaching a target area at Plymouth. They were estimated from surface weather charts, which gave trajectories at about 600 m and also from upper air charts for the pressure levels 700 and 500 mb which gave trajectories respectively for about 3000 m and 5600 m, but only the lowest ones will be discussed here. Full results are given elsewhere (Hogg[10]); here, these may be summarized by saying that there was a close connection between spore deposition in this country and geostrophic trajectories from southerly or south-easterly directions. In years such as 1955 when the disease was observed early, the spores are more likely to have come direct from Spain or Portugal; in years when it appeared late the inoculum may have originated in France. The trajectories for 1955 are shown in Figure 3. There were spore catches on 26 May (Spanish trajectory) and on 31 May and 1 June (French trajectory) but these did not apparently lead to any infection and the main catches were on 6 June and 17/18 June, by which time the infection was probably established so that later catches were not important. The trajectory for the 6th was from southern Spain and the state of the crops at this time of the year support the idea that the uredospores were picked up from Spain.

In many ways the 1956 trajectories were interesting, particularly in that catches in June and early July occurred when trajectories at all levels were from the Atlantic. The number of spores caught was small and may not

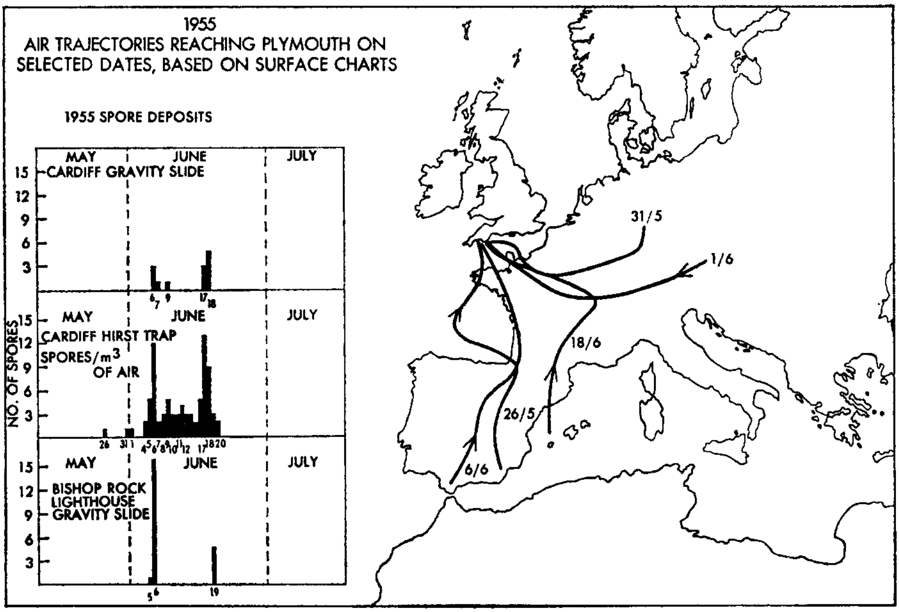

FIGURE 3—TRAJECTORIES AND SPORE COUNTS FOR MAY AND JUNE 1955

have led to infection but it raises the possibility of transatlantic transfer of spores. Some support is given to this possibility by the fact that a reasonable trajectory has been found for a moth which landed in Wales in 1954 (Hirst and Hurst[11]) but there is as yet no evidence that the disease has reached us from north America.

Finally, the validity of the results obtained from geostrophic trajectories may be demonstrated from some catches of *Puccinia graminis* uredospores made in London. An estimate of the total daily catch is given on Figure 4 (the figures are not absolute as they are derived from the addition of concentrations at various times of day, but it is clear that there are marked differences during the period). Relevant trajectories are also given on Figure 4 and it is apparent that the large catches occur with trajectories from the continent and small ones with Atlantic trajectories. Only one is doubtful, trajectory 5, for midnight on 9/10 July, which may have come from north Germany but which cannot be tracked beyond this because of the very weak pressure gradient associated with an area of high pressure. It is not certain whether north Germany should be regarded as the source, for the air may have travelled southwards along the North Sea as shown by the arrow and then turned south-westwards into the British Isles.

There is no warning system for black rust of wheat and, until recently, there was little point in devising one because no control measures existed. There are still no controls for use on a field scale but recent work on chemicals seems to be more hopeful. It may well be true that the present economic effect of the disease in this country does not justify the expenditure of much effort, but meteorologists and plant pathologists are very much concerned with what goes on in other countries and, if any warning system is possible, there can be little doubt that we should be involved at least in relation to the mainland of Europe.

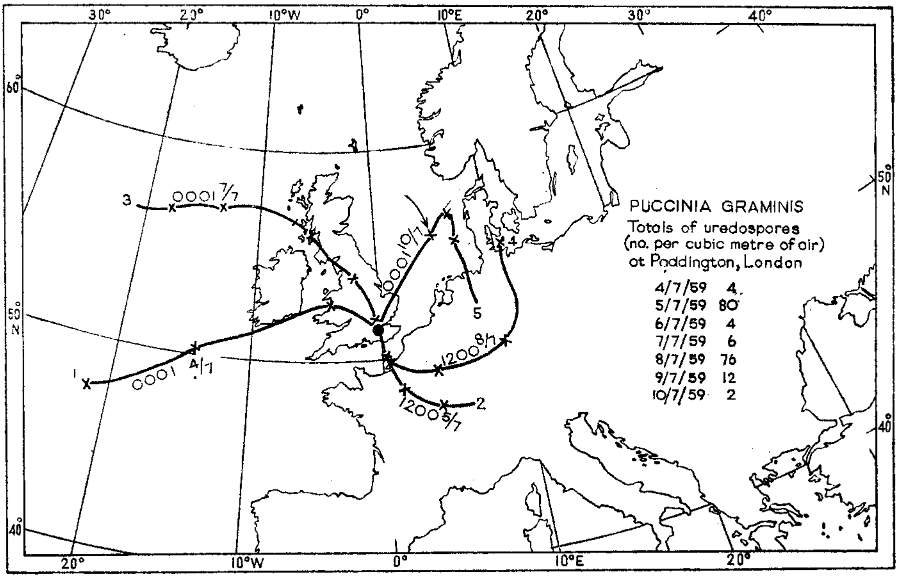

FIGURE 4—TRAJECTORIES AND SPORE COUNTS FOR JULY 1959

The trajectories are numbered from 1 to 5, and the time and date of the arrival of the air sample over London are noted for each. Crosses show estimated positions of the air samples at intervals of 12 hours.

It is evident that no warning system could be based on meteorological factors alone and that both wheat phenology and rust phenology would have to be considered. In addition, the possibility of airborne transport of spores will need to be studied, and observation of spore clouds may provide a good means of forecasting outbreaks and epidemics of black rust in much of Europe. Traps such as the Hirst spore trap could be used, possibly supplemented by a wider distribution of simpler apparatus to help define the spread of spores. In view of the probable origin of some spores in North Africa, spore trapping along the northern shores of the Mediterranean is desirable. The role of the meteorologist here would be to provide a background against which these biological observations may be set. A series of spore trappings becomes much more meaningful when studied in relation to trajectories based on surface and upper air charts which could form a basis for the extrapolation of spore data to areas without sampling. Also, a routine programme of trajectory plotting could give indications of the possibility of spore transport before the time-consuming examination of the slides had been finished. Even a recognition of the synoptic situations which give a high probability of transport from source areas to wheat growing areas could be very valuable at certain stages of rust and wheat phenology.

Provided that the spores are present in the air and are deposited on to plants in the right state for infection, the possibility of spore germination depends on weather and the main criteria are fairly high temperatures with free water on the plant surface. Generalizing from Zadoks[6] the optimum temperature can be taken as ranging from 20 to 29°C for different stages of the infection process and bright weather is probably the most suitable with little cloud and dew-formation during radiation nights. As a slow evaporation of dew after sunrise is an advantage, high humidity is favourable.

However, these are optimal conditions and epidemics occur and spread in a suboptimal environment and one problem remaining is the definition of the limits which if surpassed will give a high probability of the disease, provided that the uredospores have been transported from a source area in sufficient quantity.

Acknowledgements. My thanks are due to the Director, Plant Pathology Laboratory, for permission to use Figure 1.

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551.501.5:551.515.81

A NOTE ON THE USE OF THE UPPER WIND HODOGRAPH

By A. E. PARKER

Summary. The average wind field for eight warm fronts which gave rain was used to calculate total divergence and vertical motion at various heights and distances from the surface warm front. It is shown both theoretically and practically that the wind components towards the cold air and normal to a rainy warm front increase with height above the frontal surface. Data for the average wind field were used to construct typical upper wind hodographs at various distances from the surface warm front. Finally an interesting example of an inactive warm front is examined.

Introduction. In a previous paper* the present writer discussed the different types of wind hodographs from upper wind soundings made in the vicinity of active and inactive fronts. A forecasting rule was derived that a

* PARKER, A. E.; Relation between upper wind structure and rainfall at fronts. *Met. Mag., London*, **78**, 1949, pp. 247–258.

warm front will be active (i.e. produce rain) if the wind component normal to the front and towards the cold air increases markedly with height above the frontal surface. In the present paper a theoretical derivation of this rule is given. The mean wind fields for eight warm fronts giving rain are also examined in order to calculate the vertical motion in the neighbourhood of an average active warm front.

A theoretical estimate of the cross-frontal flow at an average active warm front. If pressure p is used as the height co-ordinate, the vertical motion $(\mathrm{d}p/\mathrm{d}t)$ in the atmosphere may be obtained by integrating the equation of continuity, in the form

$$\frac{\partial}{\partial p}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\right) = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

over the height range p_1 to p_2 to give

$$\left[\frac{\mathrm{d}p}{\mathrm{d}t}\right]_{p_1}^{p_2} = -\int_{p_1}^{p_2}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)\mathrm{d}p, \qquad \ldots (1)$$

where u and v are isobaric wind components in the directions x and y, normal to and parallel to the front, respectively, these axes being embedded in a constant-pressure surface and depicted in Figure 1. Component u is positive towards the cold air and component v is positive towards low pressure. The

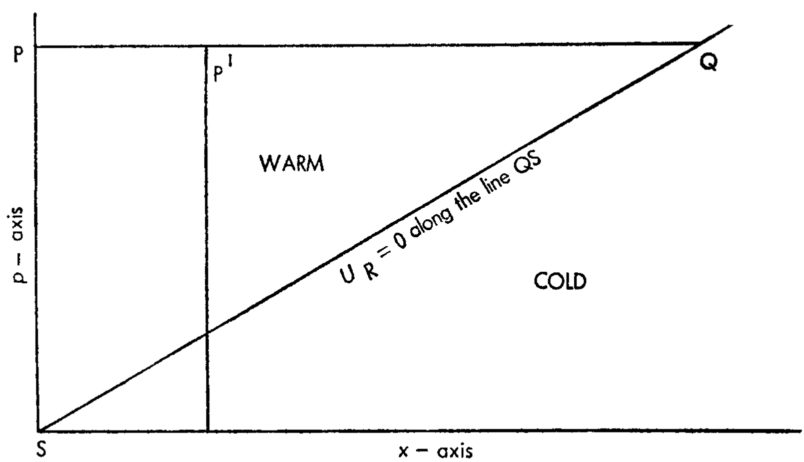

FIGURE 1—VERTICAL CROSS-SECTION THROUGH A WARM FRONT

The y-axis is directed into the paper. At P the velocity relative to the warm front and in the x-direction is u_1.

right-hand side of equation (1) is not an easy quantity to deal with and a practising forecaster needs something which will indicate positive or negative vertical motion almost at a glance. If for the moment the term $\partial v/\partial y$ in equation (1) is ignored, the vertical motion is given by

$$\left[\frac{\mathrm{d}p}{\mathrm{d}t}\right]_{10} - \left[\frac{\mathrm{d}p}{\mathrm{d}t}\right]_{2} = -\int_{2}^{10}\frac{\partial u}{\partial x}\,\mathrm{d}p, \qquad \ldots (2)$$

in which suffix 10 denotes 1000 mb, and suffix 2 a level of lower pressure.

Since $(dp/dt)_{10}$ may be taken as zero,

$$\left[\frac{dp}{dt}\right]_2 = \int_2^{10} \frac{\partial u}{\partial x}\, dp.$$

Now refer to Figure 1 which depicts a vertical cross-section of winds relative to a warm front, i.e. the speed of the front has been subtracted from all the u components. If $(dp/dt)_2$ is not to be zero then $\partial u/\partial x$ cannot be zero, and the larger $\partial u/\partial x$ is (for an active front it will be negative) the larger dp/dt becomes. Let the u component relative to the front be u_R.

Since u_R is zero at S and Q the velocity u_2 at P can be written

$$\int_S^P \frac{\partial u}{\partial p}\, dp \text{ or as } - \int_Q^P \frac{\partial u}{\partial x}\, dx,$$

and it follows that $-\partial u/\partial p$ cannot be zero and for an active front u_R must increase with decrease of pressure, i.e. u_R must increase with height, a result which is really obvious from Figure 1.

Estimation of the value of u_R at some height to produce a given vertical motion at that height. It will be of interest to make an estimate of the cross-frontal flow to be expected at an average active warm front in order to see if it would be apparent on a wind hodograph. As wind speeds were measured in knots, horizontal distances have been quoted in nautical miles so that horizontal divergence appears in knots/n. mile. (Conversion to SI units may be made by using the relationships 1 knot $\approx$ 0·5 m/s; 1 n. mile $\approx$ 1850 m; 1 mb = 10^2 N/m^2.)

If dp/dt is 35 mb/h at the point P′ in Figure 1 at a height of 465 mb and 50 n. miles from the surface front, then from equation (2)

$$-35 = (\partial u/\partial x)_m 535$$

where $(\partial u/\partial x)_m$ is the mean value of $\partial u/\partial x$ over the pressure layer 1000 to 465 mb, i.e. 535 mb. Therefore

$$(\partial u/\partial x)_m = -35/535 = -0{\cdot}065 \text{ knots/n. mile.}$$

If the distance P′Q is 300 n. miles and if $\partial u/\partial x$ over this distance has a mean value similar to $(\partial u/\partial x)_m$ then u_R at 465 mb will be 0·065 × 300 = 20 knots. In practice $\partial v/\partial y$ is not zero but positive and so u_R must be larger than 20 knots to give the assumed upward motion of 35 mb/h. The foregoing estimate of cross-frontal flow is of course rather crude but it does suggest that the cross-frontal flow at an active warm front will be appreciable and easily apparent on an upper wind hodograph.

Average values of u_R from eight warm fronts. Some data have recently been made available which may here be taken as representative of an average active warm front. Figure 2 (personal communication from M. K. Miles), is a vertical cross-section giving mean values of u_R from eight well-marked warm fronts with rain. These fronts were chosen as clearly defined fronts which were located conveniently in relation to available radiosonde ascents. The mean cross-section was prepared in the hope that it would bring out some of the features of the wind fields common to the individual warm fronts. The velocity u_R was obtained by subtracting the speed of the front from all the values of u, to give the flow relative to the front. The zero isotach of u_R may be taken to define the front for the purpose of this paper and has a slope of about 1 in 110. The strong convergence along and above the front is apparent, i.e. there are large negative values of $\partial u/\partial x$. The calculations made in the previous section apply to a vertical section 50 n. miles from the surface front (i.e. at P′ in Figure 1) where the value of u_R from Figure 2 is 27 knots, i.e. larger than 20 knots, as suggested in the previous section. The value of dp/dt at 465 mb and 50 n. miles from the surface front in Figure 2 was estimated as 35 mb/h. The strong cross-frontal flow is apparent at a glance from Figure 2.

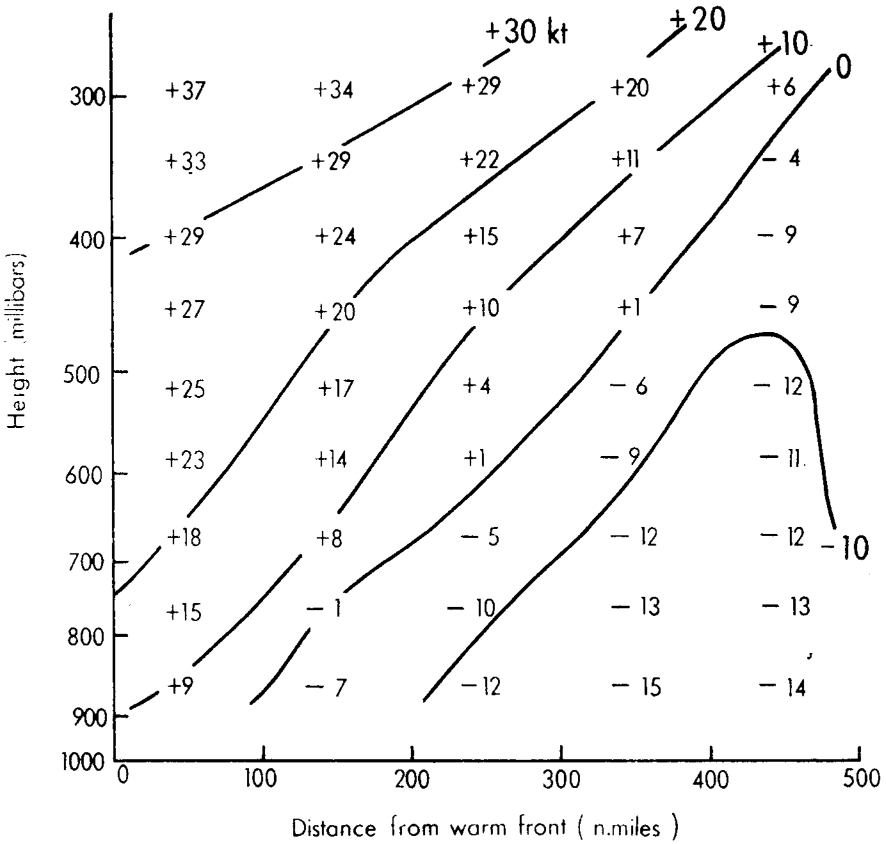

FIGURE 2—AVERAGE FOR EIGHT WARM FRONTS OF RELATIVE WIND u_R IN KNOTS

The vertical motion at an average active warm front. From Miles's data in Figure 2 and the data for $\partial v/\partial y$ in Table I (also a personal communication from Miles), the total divergence was calculated at various pressure levels and distances from the surface front and the results are given in Figure 3. Interpolations and extrapolations were used to obtain values of $\partial v/\partial y$ not given in Table I. At 100 n. miles from the surface front there is convergence from 1000 to 455 mb with increasing divergence at pressures less than 465 mb. The convergence in the lower levels of the troposphere decreases with distance from the front and at 400 n. miles there is divergence from 1000 to about 525 mb and convergence at lower pressures.

TABLE I—VALUES OF $\partial v/\partial y$ FOR AN AVERAGE ACTIVE WARM FRONT

Pressure	$\partial v/\partial y$
mb	*knots/100 n. mile*
850	7
700	9·5
500	6
400	7
300	8·5

Note : According to Miles the above values are practically constant over several hundred nautical miles at right-angles to the front.

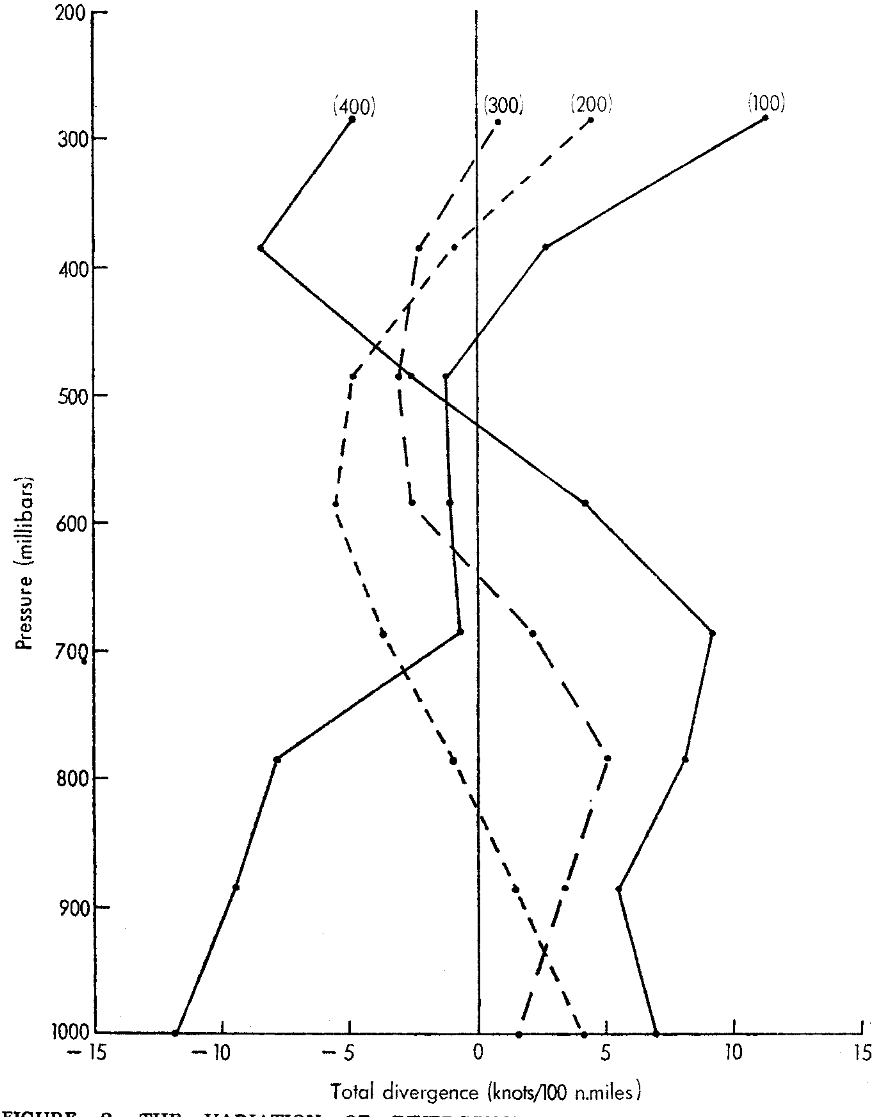

FIGURE 3—THE VARIATION OF DIVERGENCE WITH PRESSURE AT VARIOUS DISTANCES FROM THE SURFACE WARM FRONT FOR AN AVERAGE ACTIVE WARM FRONT

The numbers in brackets indicate the distance from the surface warm front in nautical miles.

The divergence values given in Figure 3 were integrated with respect to pressure using the simple trapezoidal rule to give (dp/dt – pressure) profiles which are given in Figure 4. At 100 n. miles from the front dp/dt is negative for all pressures less than 1000 mb. There is subsidence from 1000 to 655 mb at 200 n. miles from the front with upward motion for pressures less than 655 mb. The strong subsidence at 500 mb and 400 n. miles from the front is noteworthy and is due to high-level convergence.

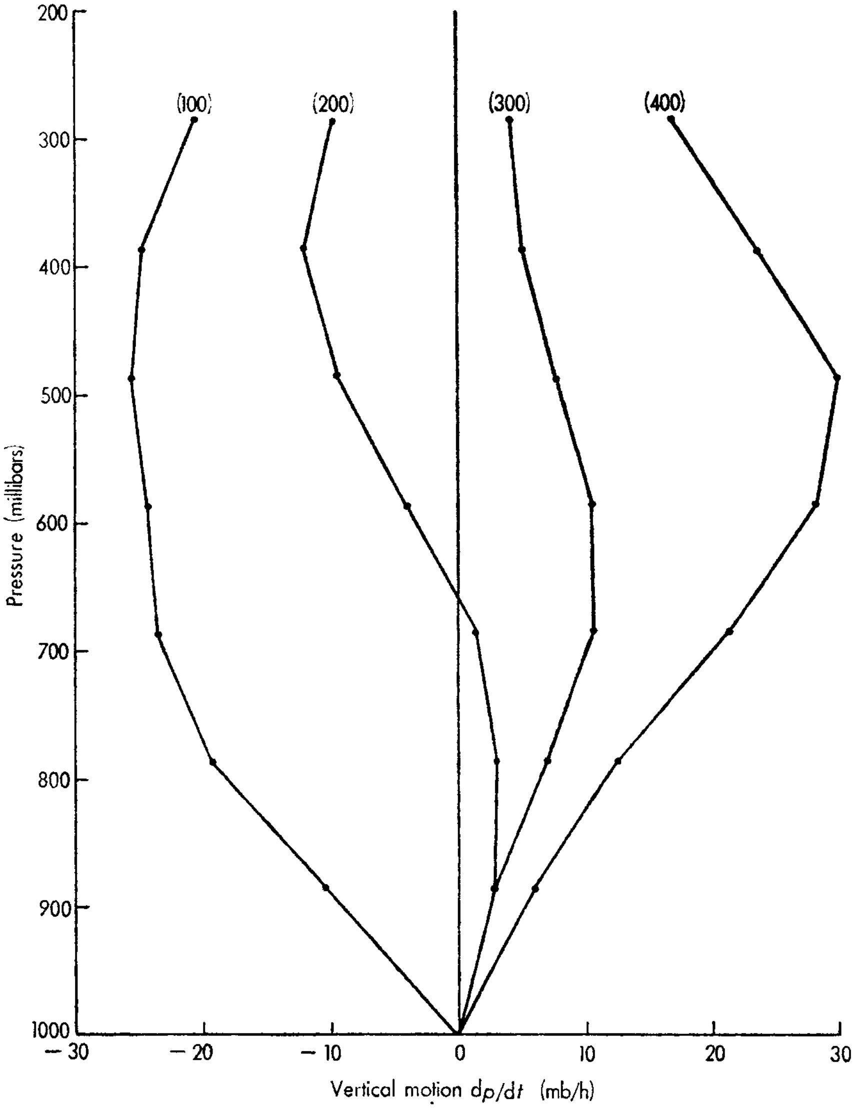

FIGURE 4—THE VARIATION OF VERTICAL MOTION WITH PRESSURE AT VARIOUS DISTANCES FROM THE SURFACE FRONT FOR AN AVERAGE ACTIVE WARM FRONT

Finally the results given in Figure 4 were used to produce the cross-section of vertical motion shown in Figure 5. This cross-section is of great interest

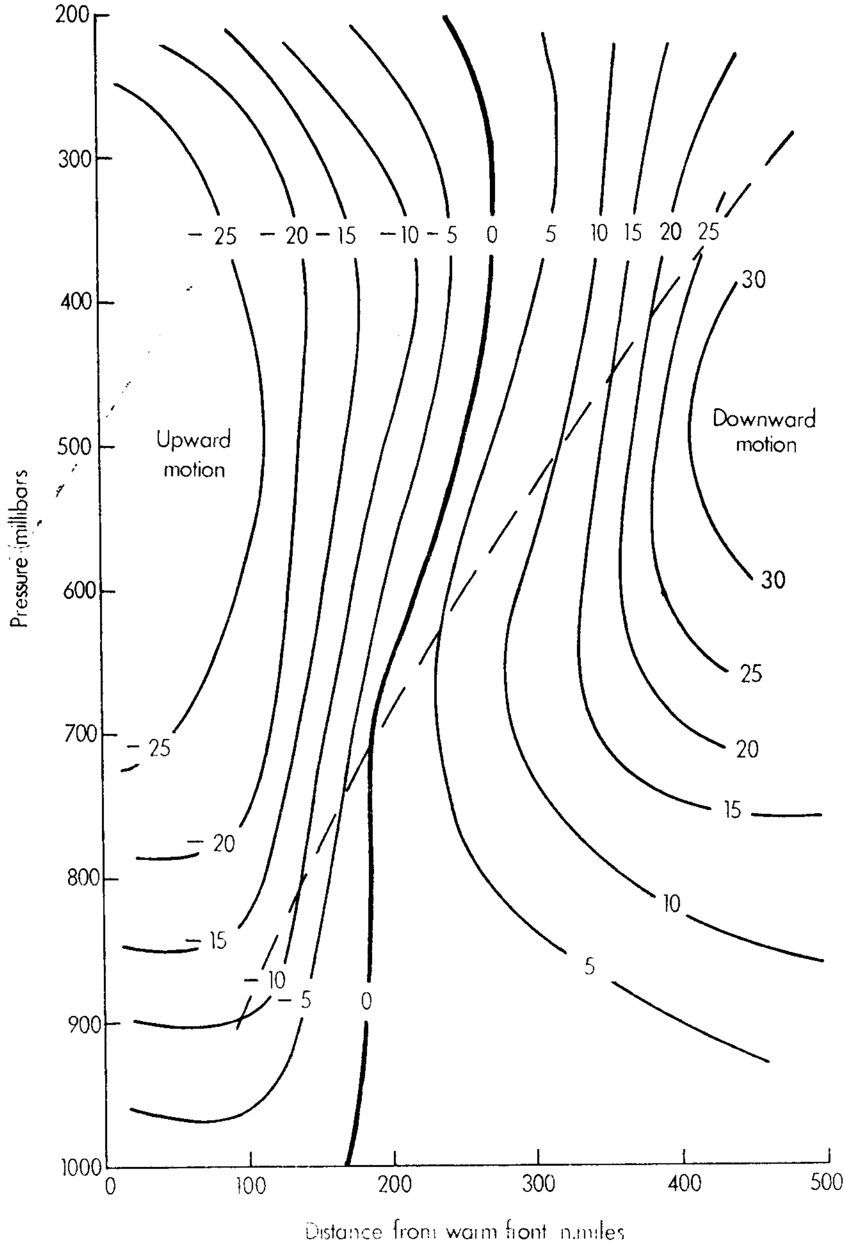

FIGURE 5—AVERAGE FOR EIGHT WARM FRONTS OF THE CALCULATED VERTICAL MOTION

Isopleths give vertical motion in millibars per hour. The pecked line gives the position of the zero isopleth of u_R as given in Figure 2 and may be taken to represent the slope of the front.

as it illustrates a number of characteristics of warm fronts which have been observed in practice. Firstly note the position of the zero isopleth of d*p*/d*t*. It does not lie along the front. At first sight one might be tempted to expect no frontal cloud to the right of this isopleth but this would not be so as cloud formed to the left of this line could be advected to the right of it and then be dissipated by subsidence. It follows that the slope of the frontal cloud is greater than the slope of the front, a fact which has been observed from an analysis of aircraft observations. Secondly the front itself is subsiding to the right of the isopleth delineating zero vertical motion and so must be ill-defined in this region. To the left of this isopleth the air has upward motion and this also applies to the air below the front which is possibly somewhat surprising. The convergence and vertical motion serve to keep the front quite sharp to the left of the zero isopleth of d*p*/d*t*.

Upper wind hodographs at various distances from the surface front for an average active warm front. The data given in Figure 2 and values of *v* (obtained from a personal communication from M. K. Miles but not reproduced here) were used to construct upper wind hodographs for positions at various distances from the surface front and on the cold side of it. The results are given in Figure 6 in which wind components have been plotted, since Miles gave the data in this way. The strong cross-frontal flow at 50 n. miles from the surface front should be noted and in particular at 300 mb the air was moving 37 knots faster than the front. However it does not always follow that there is upward motion if the wind component normal

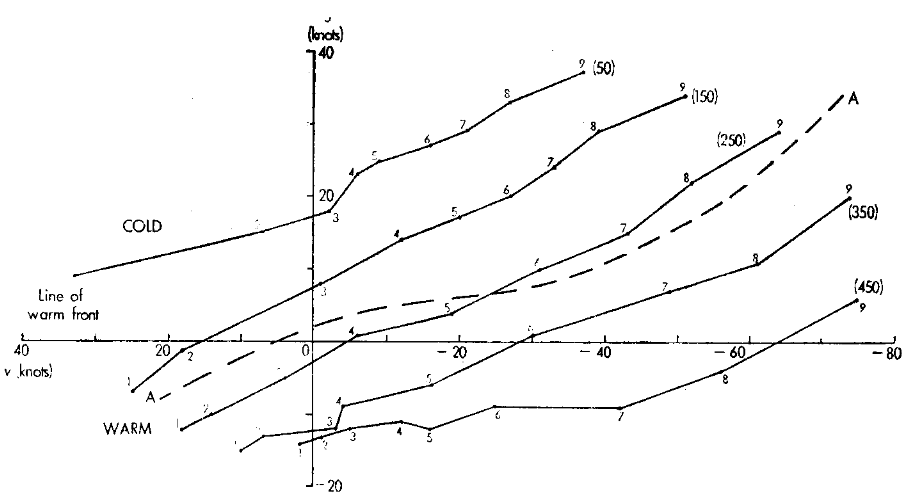

FIGURE 6—UPPER WIND COMPONENTS RELATIVE TO THE FRONT AT VARIOUS DISTANCES FROM THE SURFACE FRONT

The numbers in brackets at the end of each line indicate the distance in nautical miles from the surface warm front. The pecked line AA represents the *u*, *v* values corresponding to the heights and positions, with respect to the front, of the zero isopleth of d*p*/d*t* in Figure 5. The values were obtained from Figure 2 and corresponding data for *v*; d*p*/d*t* is negative on the cold side of the pecked line.

Heights in millibars for the plots numbered 1–9 :

Plot	1	2	3	4	5	6	7	8	9
Height *(mb)*	900	795	700	615	540	465	410	355	300

to the front is greater than the speed of the front. For example at 350 n. miles from the front and at a height of 300 mb the u_R component from Figure 6 is 20 knots (i.e. 20 knots faster than the front) but Figure 5 shows that the air was subsiding at this level. Nevertheless one would be justified in concluding from this rather large cross-frontal flow of 20 knots that there would be upward motion nearer the front and thus that it would be active. This follows since the u_R components increase progressively as the front is approached.

At this point it may be instructive to restate the prognostic criterion for the activity of a moving warm front. A moving warm front will be active if the u components increase appreciably with height through the frontal surface, an average value for the rate of increase required being shown by Figure 6 in which the pecked line corresponds to no vertical motion. A warm front will be inactive if the u components above the frontal surface do not increase with height faster than a certain value which is determined of course by the values of $\partial v/\partial y$.

An example of an inactive warm front. Rather a lot of attention has been devoted to active warm fronts in the previous sections so it should be interesting and instructive to examine the wind structure of an inactive warm front. Table II gives the upper air sounding for Camborne at 12 GMT on 26 March 1968. The winds for the 12 GMT sounding have been plotted on a diagram in Figure 7 which gives the components normal to and parallel to the warm front. At the time of the sounding the warm front was approaching Camborne from about west-north-west and it was estimated that the base of the warm air over Camborne was at about 799 mb but its exact height is not important for the present analysis. The fact that it was a warm front with a large temperature discontinuity is confirmed by the direction of the wind shear above 799 mb and by the magnitude of the wind shear of about 74 knots from 799 to 300 mb.

From 799 to 640 mb the u component of wind decreases with height, which represents downward motion. Consequently subsided (dry) air would be expected at 700 mb and this is confirmed since the depression of the dew-point was 22 degC at 700 mb and was probably even greater at 640 mb. The u component of wind increased from 640 to 500 mb so the relative humidity

TABLE II—UPPER AIR DATA FOR CAMBORNE AT 12 GMT, 26 MARCH 1968

Pressure *mb*	Wind *degrees/knots*	Dry bulb *°C*	Dew-point depression *degC*
(Surface)	230/12	10·6	4·2
1000		7·6	6
850	245/23	− 1·2	8
799	250/27		
717	260/17		
700	275/10	− 6·2	22
640	360/08		
574	330/13		
510	320/15		
500	320/15	− 19·4	10
449	350/18		
400	340/30	− 32·1	9
300	005/58		
239	015/76		

at 500 mb would be expected to be higher than that at 640 mb, a point confirmed by the dew-point depression of 10 degC at 500 mb. The *u* components in the layer 400–300 mb were greater than the speed of the front but no upward motion would have been expected owing to the strong subsidence lower down. The absence of frontal cloud on this front was confirmed by an aircraft from the Meteorological Research Flight which investigated it.

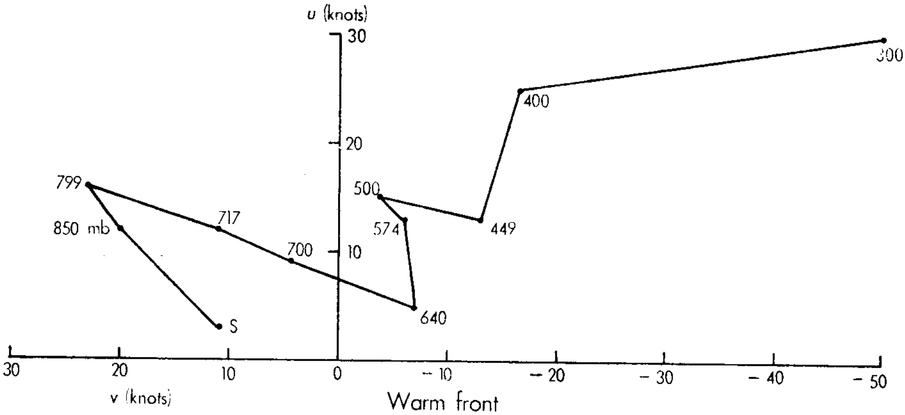

FIGURE 7—WIND COMPONENTS, NORMAL TO AND PARALLEL TO THE FRONT, DERIVED FROM THE CAMBORNE SOUNDING AT 12 GMT, 26 MARCH 1968

S indicates the surface wind and the other heights are in millibars.

Some remarks on wind structure at cold fronts. Some instructive examples of the wind structure on cold fronts were given in the 1949 paper. Three types of cold front occur in practice and are as follows :

(i) The most frequent active cold front in which the wind shear vectors remain approximately parallel to the front but with no large cross-frontal component.

(ii) The katafront in which the *u* components, in the warm air above the frontal surface, increase rapidly with height and are greater than the speed of the front.

(iii) The anafront in which the *u* components in the warm air above the frontal surface decrease with height and are considerably less than the speed of the front.

The weather which occurs with types (ii) and (iii) is what would be expected from the characteristics of the *u* components but there is comparatively little cross-frontal flow with type (i). Since the term $\partial u/\partial x$ seems small the vertical motion must stem from fairly large negative values of $\partial v/\partial y$. An analysis of examples of this type of front on the lines of the analysis carried out by Miles would be very valuable and enable the values of $\partial u/\partial x$ and $\partial v/\partial y$ to be obtained.

Final remarks. The main conclusions to be drawn from the results presented in this paper are summarized below.

(i) At an active warm front the vertical motion is due entirely to convergence towards the front which is manifested by an increase with height of the u wind component above the frontal surface — a most useful prognostic tool. However owing to the positive value of $\partial v/\partial y$ the u component must exceed a certain value before upward motion occurs.

(ii) In the upper portions of an average active front there is subsidence while upward motion occurs in the lower parts. From this it follows that the lower parts of the front remain sharp but the upper parts become diffuse and acquire the properties of a subsidence inversion.

(iii) The zero isopleth of $\mathrm{d}p/\mathrm{d}t$ does not lie along the frontal surface. This means that the frontal cloud has a steeper slope than the front itself and implies that a single observer would tend to overestimate his distance from a surface warm front if he based his estimate on the height of the leading edge of cirrus cloud.

The writer has found the variation of u component with height a most useful prognostic tool and it is most valuable when considering the onset or otherwise of activity at stationary fronts; but caution should be used in the neighbourhood of occlusions.

Finally the writer feels that in spite of sophisticated atmospheric models and the use of large computers there should still be a place in the forecaster's repertoire for the use of the upper wind hodograph which is so quick and easy to apply.

Acknowledgement. The writer would like to thank Mr M. K. Miles for making his data for eight warm fronts available for this study.

551.515.4

A SUDDEN SQUALL AT SHARJAH, TRUCIAL STATES

By H. DOUGLAS

Summary. On 17 January 1970 at Sharjah there was a noteworthy squall at about 21 GMT in which the wind gusted to 47 knots and the temperature fell by about 8 degC. Instrumental records of surface conditions and a time cross-section of upper air ascents in the area are presented and discussed. The instability which gave rise to the squall is attributed to the overrunning of air with a high wet-bulb potential temperature by a high-level trough. The peak wind observed was found to be in good agreement with the value which would have been forecast by application of the technique due to Fawbush and Miller.

A good example of the wind squall and fall of temperature often associated with well-developed cumulonimbus clouds was recorded at Sharjah, Trucial States, at about 21 GMT on 17 January 1970 and is illustrated in Figures 1 and 2.

The anemograph record (Figure 1) shows that the squall, in which the wind gusted to 47 knots (24 m/s), occurred in a period of otherwise light winds. The sudden onset of the north-westerly surface wind is seen to have occurred some three hours later.

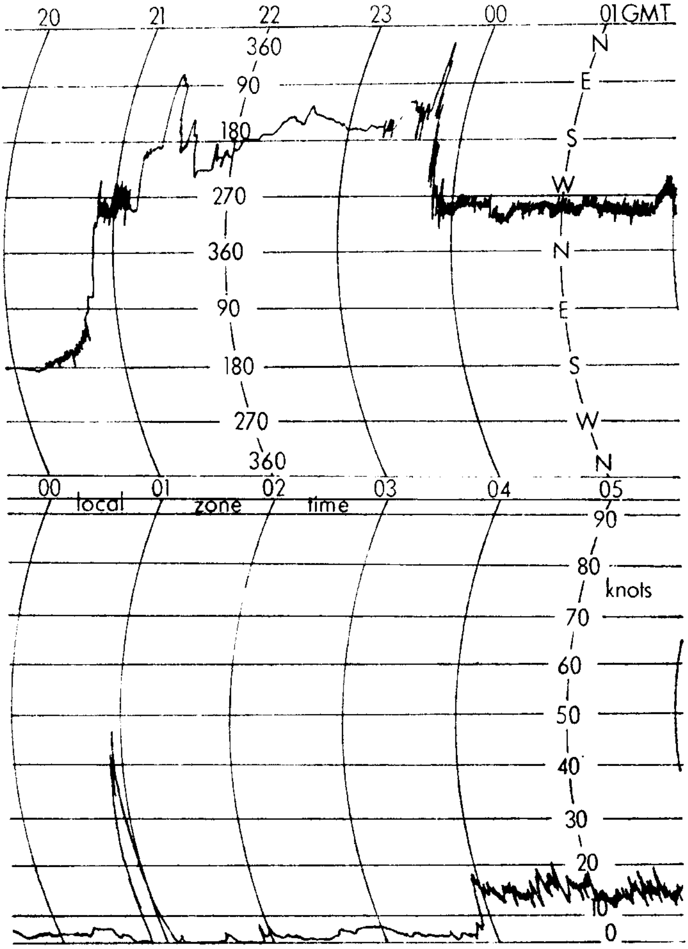

FIGURE 1—DIAGRAMMATIC REPRESENTATION OF THE ANEMOGRAPH RECORD AT SHARJAH 17–18 JANUARY 1970

Times are shown in GMT and in local zone time (GMT + 4 hours).

The thermograph record (Figure 2) shows a rather unsteady fall of temperature during the afternoon and evening prior to the onset of the squall, when a rapid fall of some eight degrees took place. After the squall the temperature rose a little, and with the arrival of the north-westerly wind recovered to about 18°C, rising further after dawn. The temporary drop in temperature on the 18th between 06 and 08 GMT (10 and 12 local time zone) was associated with a further veer of the surface wind.

The synoptic situation at 12 GMT on the 17th is shown in Figure 3. The depression over south-east Arabia moved from the eastern Mediterranean

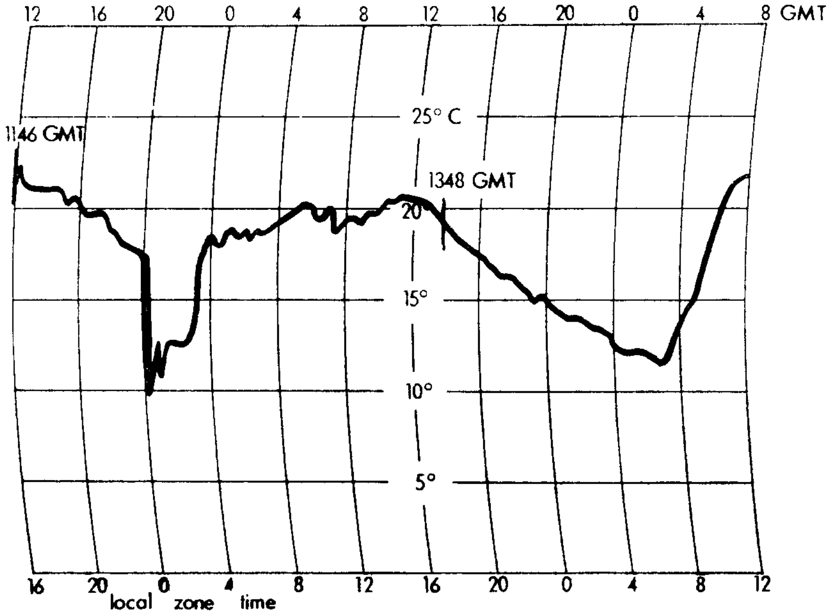

FIGURE 2—THERMOGRAPH RECORD AT SHARJAH 17–19 JANUARY 1970

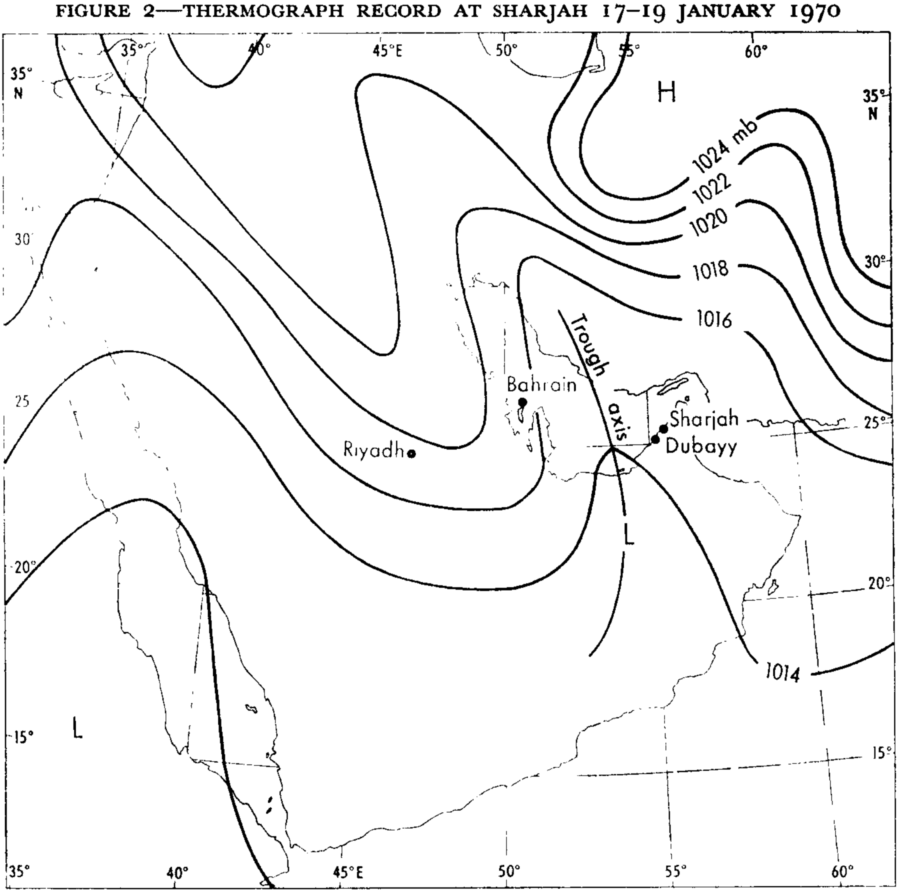

FIGURE 3—SYNOPTIC SITUATION AT 12 GMT 17 JANUARY 1970

on the 14th, across southern Syria, then turned south-east into Arabia and passed between Riyadh and Bahrain. It subsequently continued east across southern Oman into the north Arabian Sea. Its movement was associated with that of a trough in the strong flow at high levels.

This synoptic situation is similar to that associated with the more severe storm of 23 November 1957 described by Murray and Coulthard;[1] in particular, the surface low-pressure area on both of these occasions passed to the south of Sharjah.

A detailed mesoscale analysis of the situation is not possible owing to the scarcity of observations in the area. (The Meteorological Office at Sharjah does not maintain a full observing watch and indeed was closed at the time of the storm — another, rather unfortunate, similarity between this occasion and the one described by Murray and Coulthard.)

A time cross-section of the radiosonde ascents made at Bahrain (Figure 4), however, reveals that the orientation of the trough axis was not uniform with height. The veer of wind at high levels occurred at the same time as that at low levels, but the veer at middle levels occurred later. No precipitation was reported at Bahrain during the passage of the trough but outbreaks of rain and thunderstorms developed as it moved eastwards. One of these thunderstorms gave the squall at Sharjah and the 15 mm of rain recorded overnight was attributed to this storm. By contrast, although lightning was seen at Dubayy Airport, 8 miles (13 km) to the south, no rain fell there nor were any strong gusts experienced.

An examination of the wet-bulb potential temperatures (WBPT) shows that the lowest WBPTs in the upper troposphere were associated with the axis of the upper trough, and that the highest WBPTs in the lowest layers were found ahead of the surface trough.

The surface low passing to the south of Sharjah would serve to delay the onset of the surface north-westerlies and thus maintain air with a high WBPT at low levels. The overrunning of this air by the unimpeded high-level trough axis with its low WBPTs is thought to have produced the unstable situation in which the storm occurred.

Fawbush and Miller[2] have described a technique for forecasting the peak winds in non-frontal thunderstorms. They associated the strength of the peak winds with the difference between the surface air temperature ahead of the storm and the temperature of the 'downdraught' when it reaches the surface. They found that an estimate of the 'downdraught' temperature at the surface was given by the WBPT at the level at which the wet-bulb temperature was 0°C.

The Bahrain ascent for the 17th at 00 GMT (Figure 5) has been taken as being fairly representative of conditions at Sharjah at the time of the storm, although the air at Sharjah probably had a higher WBPT at low levels and a lower WBPT at high levels than this ascent indicates. The wet-bulb temperature is 0°C at 780 mb, giving a WPBT of 11°C. This compares well with the 'downdraught' lowest temperature of 10°C recorded on the thermograph and confirmed by the minimum-thermometer reading of 9·7°C.

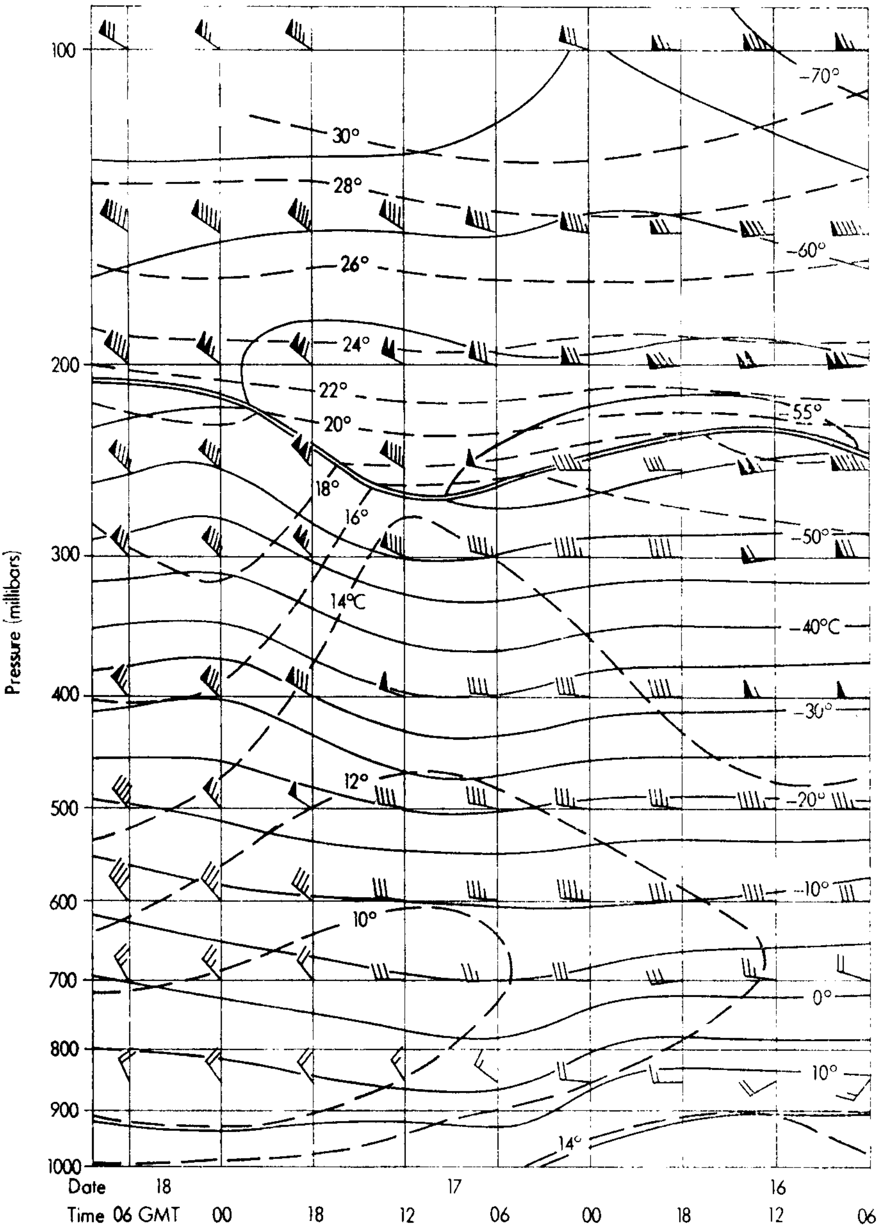

FIGURE 4—TIME CROSS-SECTION THROUGH THE UPPER AIR SOUNDINGS AT BAHRAIN 06 GMT 16TH TO 06 GMT 18TH JANUARY 1970

═══════ tropopause ——————— isotherms

- - - - isopleths of wet-bulb potential temperature below 350 mb, potential temperature above 350 mb

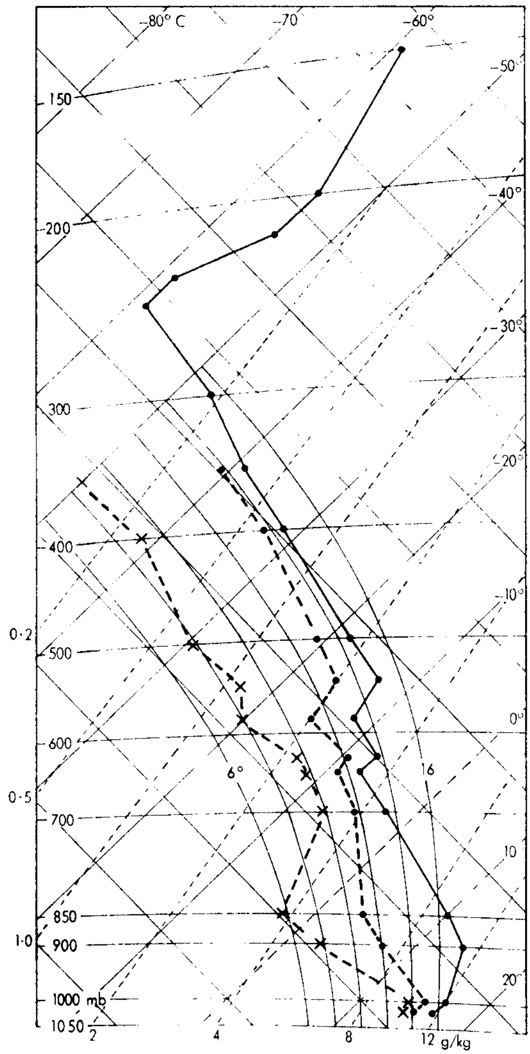

FIGURE 5—UPPER AIR SOUNDING AT BAHRAIN 00 GMT 17 JANUARY 1970

· ———— · dry-bulb temperature   · – – – · wet-bulb temperature

x – – – x dew-point temperature

Applying the recorded temperature difference of 8 degC to the graph given by Fawbush and Miller[2] (Figure 6), a forecast peak wind speed of 50 knots is obtained, in excellent agreement with observation.

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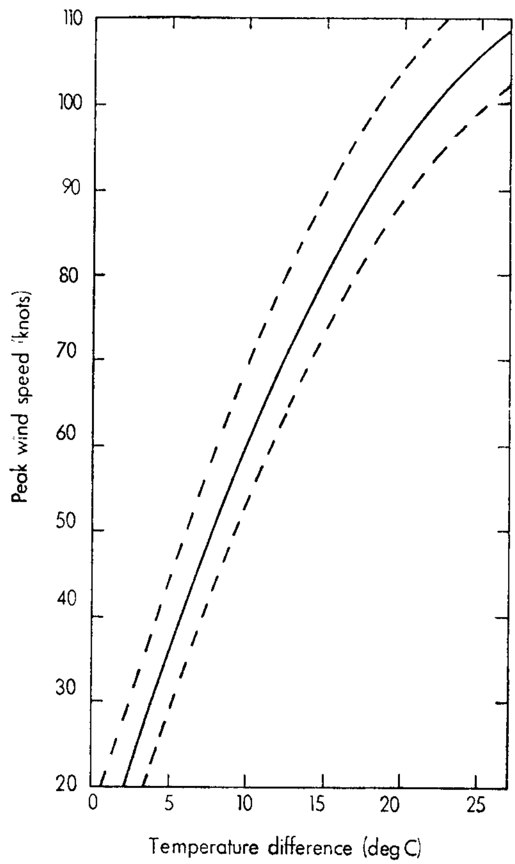

FIGURE 6—PEAK GUSTS AND TEMPERATURE DIFFERENCES IN THUNDERSTORMS IN THE UNITED STATES OF AMERICA

Abscissa is temperature just prior to the thunderstorm minus temperature immediately after the downrush.

——— regression curve   – – – standard error of estimate

(After Fawbush and Miller[2])

551.509.325

FORECASTING THE TIME OF FOG CLEARANCE*

By V. L. PATTERSON and J. CRABTREE

Summary. A published method of forecasting the time of clearance of fog by solar radiation was tested at Mildenhall. The method was combined with a means of allowing for wind speed and wind direction. The combined method was found to give better overall results than a method taking into account only solar radiation as a clearance mechanism.

Introduction. Kennington[1] described a method of forecasting the time of clearance of radiation fog. The method requires an estimate to be made of the amount of solar energy required to establish a saturated adiabatic lapse rate from the surface to the fog top, an allowance being made for the

* This paper is a shortened and slightly amended version of a report,[5] of the same title, by SSgt V. L. Patterson, USAF. It is published with the permission of the Air Weather Service, United States Air Force, who also provided the data for the tests carried out in 1968.

energy needed to evaporate the fog droplets. Barthram[2] produced a set of diagrams which provide a quick and convenient way of calculating the forecast clearance time. Heffer[3] carried out a test of the method at a number of stations, using the Cardington BALTHUM ascents to provide information on the depth of the fog. Atkins[4] showed how a reasonable estimate of the depth of fog could be made, using surface data only.

The problem at Mildenhall was to forecast the time of clearance of fog by a method requiring only data available by 06 GMT. This ruled out the data from the 06 GMT BALTHUM ascent, and it was decided to test the Kennington–Barthram–Atkins method.

Test of the Kennington–Barthram–Atkins method. The data under test comprised 76 occasions when there were less than four oktas of cloud above 1000 ft (300 m), neglecting cirrus, from a selection of winter months (October to March) in 1959 and during 1962–65. For operational reasons, the upper limit of visibility in fog was taken to be 0·5 nautical mile (927 m), instead of the usual 1000 m, but this probably has little effect on the results because the clearance process, once started, is normally quite rapid. The method requires a knowledge of the temperature at dawn, T_1, and an estimate of the temperature, T_2, at which the fog may be expected to clear. In the present tests, T_1 was taken as the temperature at 06 GMT if dawn occurred later than that time. The clearance temperature was assumed to be given by the formula used by Atkins[4]

$$T_2 = T_d + 2 \text{ degC},$$

where T_d is the dew-point temperature when the fog is formed. If $T_1 > T_d + 2$, T_2 was taken to be $T_1 + 1$ degC.

On 12 of the 76 occasions, when the forecast clearance temperature was 0°C or below, the clearance times were erratic; on only two such occasions was the forecast time of clearance correct to within one hour. When the forecast clearance temperature was above freezing-point, the forecast clearance time was correct to within an hour on 30 occasions out of 64 (i.e. 47 per cent), the percentage of correct forecasts being greater when the sky was obscured (21 occasions out of 38, 55 per cent) than when the sky was not obscured (9 occasions out of 26, 35 per cent). On 10 occasions the fog cleared before sunrise.

The forecast clearance temperature was compared with the actual clearance temperature; the difference was 1·5 degC or less on 80 per cent of occasions, the maximum difference being 5 degC. An attempt was made to improve the forecasting of the clearance temperature by means of an analysis of the distribution of fog and temperature on the 03 GMT and 06 GMT charts. The area upwind was studied, and the clearance temperature was taken to be higher than any within the foggy area but lower than any temperature outside this area. On the whole, this approach was no more successful than that in which the clearance temperature was estimated by adding 2 degC to the value of T_d. However, on the eight occasions when $T_1 > T_d + 2$ degC, the forecast obtained from the surface chart analysis was closer to the actual clearance temperature than was $T_1 + 1$ degC.

The actual fog clearance temperatures were used to test Barthram's diagrams and also Atkins's rules for estimating the thickness of the fog. The results were correct (within 30 minutes) on 55 per cent of occasions; Atkins's rules appear to be reasonably satisfactory.

The Kennington–Barthram–Atkins technique showed a marked improvement over the use of climatological data; the most likely time of clearance would have given a good estimate of the clearance time (within one hour) on only 27 per cent of occasions.

The pressure diagram. The method described above provides reasonably accurate forecasts of the time of fog clearance when insolation is the main clearance mechanism. Other factors, however, often have some effect on the clearance time. Previous studies at Mildenhall by Edwards[6] had shown that the surface wind speed and direction were important factors in determining whether or not fog would clear by 12 GMT. These studies had led to the introduction of a pressure-grid diagram (Figure 1), in which the abscissa was the mean-sea-level pressure difference at 06 GMT between Wittering and Wattisham, and the ordinate was that between Cardington and West Raynham. The distances between Wittering and Wattisham and between Cardington and West Raynham are approximately equal and the

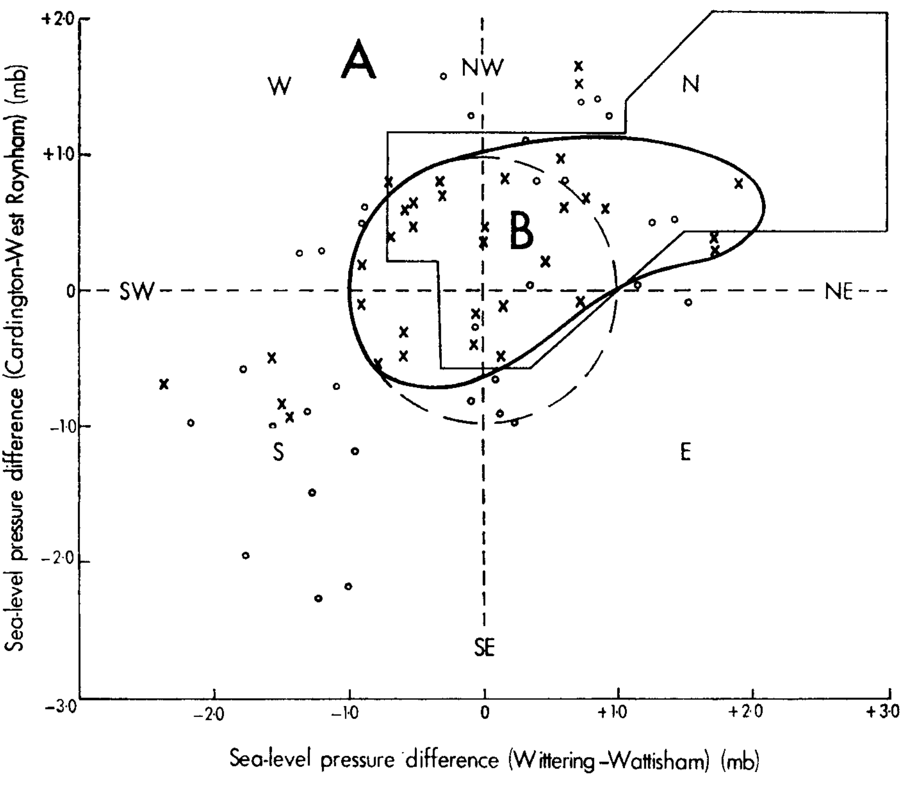

FIGURE 1—PRESSURE-GRID DIAGRAM

lines joining these pairs of stations are approximately at right angles. If the point fell within the area enclosed by the light lines, the fog was forecast not to clear by 12 GMT; if outside, the fog was expected to clear by that time. In practice it was found that a fog at any time of the day tended to clear in one hour to a visibility of 0·5 nautical mile or more, if the pressure differences were such that the point representing the fog fell outside the area enclosed by the light lines, i.e. if geostrophic winds exceeded the strength represented by the light lines.

However, the forecasting problem under consideration is rather different from that for which the diagram was devised, and the diagram had to be modified. This was done by plotting fog on the diagram in two ways. The pressure difference at the time of an initial observation of fog was plotted in the form of a small circle if the fog cleared within 2 hours, and in the form of a cross if the fog did not clear in 2 hours. The data were obtained from the same period as was used in the test of the Kennington–Barthram–Atkins method but no limitations were made on cloud cover or time of day. A line was drawn, the heavy line of Figure 1, to provide optimum separation of area A, containing mostly circles, from area B, containing mostly crosses. For points within area A, it was found that the fog usually cleared within about one hour, and the following forecasting rules were derived :

(i) If the plot lies outside the heavy line, i.e. in A, forecast clearance within one hour of the time of observation.

(ii) If the plot lies inside the heavy line, i.e. in B, solar radiation will be the major factor determining clearance time, and the Kennington–Barthram–Atkins method should be used.

A test on independent data for 1966 showed the usefulness of the above rules, but too few cases were available to enable firm conclusions to be drawn: the first rule proved useful at night, when the second method is not applicable. A further independent test was carried out during the period September 1967 to February 1968; out of 21 occasions, the time of fog clearance was forecast to within one hour on 62 per cent of occasions, compared with 47 per cent for the earlier tests using only the Kennington–Barthram–Atkins method.

Physical basis of the pressure-grid diagram. The diagram is, in essence, an approximate representation of the pressure gradient, and hence of the geostrophic wind or wind in the free atmosphere. If the wind is light, i.e. if the plot of pressure differences on Figure 1 lies close to the origin, solar radiation is the main fog-clearance mechanism. As the wind increases and the plot moves away from the origin, turbulent mixing becomes more effective until, when the point reaches a certain distance from the origin, it is sufficient to clear the fog fairly quickly. Ideally, the critical distance from the origin would be the same for all wind directions, and the line dividing the two areas would be a circle. (In Figure 1 the dashed circle represents a geostrophic wind speed of 13 kt.) However, differences in the properties of the air masses associated with different wind directions, and variations of topography, etc., are likely to have some effect, and the critical distance may vary with wind direction, as it apparently does at Mildenhall.

Conclusions. It has been shown that the pressure-grid diagram, giving an approximate measure of the wind in the free atmosphere, can provide a useful aid to the forecaster by enabling him to decide whether solar radiation will be the major factor in effecting fog clearance, or whether turbulent mixing will be strong enough to play an important part. The principles of the method should be readily applicable at other stations, but the areas A and B will, of course, be different from those at Mildenhall, and will need to be determined for each station on the basis of its own observations. If analysed charts are available for the required times of observation, an equivalent method would be to plot on the diagram a vector representing the geostrophic wind, instead of the pressure differences between pairs of stations.

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551.509.324.2

ADVECTION OF RAIN BELTS WITH THE 700-mb WIND

By W. E. SAUNDERS

This note reports the results of tests of a method of forecasting the speed of movement of rain belts which is due to McElmurry.*

From an examination of some 200 cases, McElmurry found that the wind at the 700-mb level is the most useful one to use for the advection of a rain area. The movement of a rain belt was found to be so nearly that of the 700-mb wind component normal to the leading edge of the precipitation that no adjustments were required. The investigation was restricted to rain belts approaching the Midlands from between west and south. McElmurry also proposed a method of dealing with those occasions when a blocking patterns exists which causes a rain area to decelerate or even to retrogress.

In the test now described, McElmurry's method was used at two airfield meteorological offices in eastern England, Stradishall and Cranwell. The work was carried out between January 1965 and October 1967. The number of blocking occasions was too small to warrant any conclusions being reached. The cases used in the test described here were therefore only those in which there were no signs of blocking. They were all in fact mobile situations, with the normal wind components varying widely between 9 and 43 knots. As

* MCELMURRY, T. M.; Forecasting rain with low stratus in the Midlands of England. *Bull. Am. met. Soc., Lancaster, Pa*, **42**, 1961, pp. 817–822.

soon as a rain belt spreading from between west and south had reached a position over Ireland, Wales and south-west England, such that the leading edge of the rain could be clearly defined, the normal 700-mb wind component was used to forecast the time of arrival of continuous rain at the selected stations. The results were later checked against the stations' observations.

The number of occasions tested was 85. The forecasts were made, on average, $7\frac{3}{4}$ hours before the actual time of arrival of the rain. The average error was 57 minutes. On 74 per cent of occasions the forecast was correct to within one hour, while 88 per cent were correct to within two hours. Differences in accuracy between the two stations were negligible. Errors were sufficiently evenly distributed to confirm McElmurry's statement that no adjustments are required.

At Stradishall the work was carried out by Mr R. G. Surman. At Cranwell the tests were carried out by the duty forecaster and a number of individuals co-operated. These forecasters are thanked for their efforts.

REVIEW

Weather economics, by J. A. Taylor (editor). 235 mm × 155 mm, pp. 126, *illus.*, Pergamon Press Ltd, Headington Hill Hall, Oxford, 1970. Price: 60*s*.

This is a report of eight papers and the discussion thereon at the eleventh of an annual series of symposia held at the University College of Wales, Aberystwyth. This 1968 meeting courageously attempted to study the complex relation of meteorological conditions to industry and agriculture from the economic point of view. As admitted by the Editor in the Introduction 'meteorology and economics make strange bed-fellows', but he makes a strong case for the need to assess the hazards of weather and climate in economic as well as physical terms. The title of the book may be a little misleading as the material relates mainly to 'weather-sensitive' industries such as farming and forestry.

Certainly the opening chapter entitled 'The cost of British weather' embraces many examples of the adverse financial effect of meteorological factors on industrial as well as agricultural efficiency — but it would be nice to see figures showing the other side of the picture! Chapter 2 consists of a detailed survey of the economic effect of weather on farm organization and management and highlights the need for the farmer to have adequate and reliable weather advice. The following chapter deals mainly with the relationship between weather and the planning and carrying out of farming operations; in particular, it discusses the value of extended forecasts directed especially to the farmer. By means of examples involving frost, irrigation and degree-day data, Chapter 4 illustrates how climatological data may be used for planning purposes. Then follows a short chapter in which the possibility is considered of measuring the effect of weather variations on the availability of farm labour. Chapter 6 is essentially a regional study which indicates the range of environments for early potato production in Pembrokeshire and the possible extent to which various environmental factors can be expressed in financial terms. In the next chapter the effects of meteorological conditions on forestry planning and practice are examined; it deals especially with 'wind-throw' and fire losses. Finally, in Chapter 8 there is a discussion, with an operational example, of the application of cost-benefit studies in the interpretation of weather forecasts specifically for agriculture and industry; it emphasizes the importance of taking into account the effect of local geography. The book concludes with an edited report of the discussions at the symposium plus an 'economic postscript' which deals with the problem of the extent to which expenditure on insurance or providing physical protection against adverse weather is really worth while.

It is obvious from this book that the subject of weather economics calls for close collaboration between all concerned — meteorologists, geographers, biologists, economists and, of course, the 'entrepreneurs'. To assess and dovetail all the many factors involved is by no means easy; but to all those who are working on, or interested in, the subject, this book is recommended as a guide to what can be achieved and as a spur to further efforts.

R. G. VERYARD

OBITUARY

It is with regret that we have to record the death of Mr A. G. Holgate (Signals Officer) on 11 August 1970.

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NOTICES

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

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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COMPARISON OF METHODS OF FORECASTING NIGHT MINIMUM TEMPERATURES ON CONCRETE ROAD SURFACES

By G. E. PARREY, W. G. RITCHIE and S. E. VIRGO, O.B.E.

Summary. Three methods of forecasting night minimum temperatures at the surfaces of concrete roads were examined and possible improvements considered. A regression-equation method which gives the forecast concrete minimum temperature as a function of the air temperature and dew-point at 12 GMT the previous day was improved by making an adjustment for cloud amount during the night. Satisfactory improvements were not obtained for the other two methods considered which derive the forecast concrete minimum temperature from a combination of a forecast of the air minimum temperature with a forecast of the difference between the air minimum temperature and the concrete minimum temperature. The methods were applied over periods independent of the original data, and successful results were obtained at two independent road surfaces. The mean errors and standard deviations of the errors are given. The methods depending on forecast of air temperature give better results than the direct regression method unless there are large errors in forecasting air temperature.

Introduction. First reports on two experiments concerned with night minimum temperatures at the surfaces of concrete roads have already appeared in this magazine; Parrey[1] has reported on a road at Watnall and Ritchie[2] has reported on one at Wyton. Both experiments are continuing and, as time goes on, more data are accumulating. Since the practical application is to forecasting temperatures of 0°C or below on roads or runways, this paper will be concerned only with the months October to April inclusive.

In both experiments ordinary minimum thermometers are used with their bulbs resting on the surfaces of the roads. Other reports on minimum temperatures at or near concrete surfaces have also been published, for example by Johnson and Davies[3] and by Hay.[4] In these experiments temperatures were measured by other means, but as it is not yet known whether results obtained by the various methods are strictly comparable, this paper will confine itself to a discussion of the Wyton and Watnall results.

There are two ways of attacking the problem of forecasting night minimum temperatures over concrete. One is to forecast the concrete minimum temperature directly by means of a regression equation from observations made in a thermometer screen. The other is to forecast first the air minimum temperature by one of the recognized methods and then as a second step to derive the concrete minimum temperature from it.

The direct regression method. For the first method, the direct method, data from Watnall for the period October 1967–April 1968 were examined and occasions when a front passed between 12 GMT and 06 GMT next morning were rejected. From the remaining 147 cases the following correlation coefficients were obtained :

between M_R and T_{12} 0·75
between M_R and D_{12} 0·81,

where M_R is the minimum temperature at the surface of the concrete road,
T_{12} is the dry-bulb temperature at 12 GMT
and D_{12} is the dew-point temperature at 12 GMT.

These correlation coefficients suggested that a useful regression equation could be set up and the following equation was obtained by the method of least squares[5] :

$$M_R = 0{\cdot}59T_{12} + 0{\cdot}69D_{12} - 4{\cdot}6,$$

where temperatures are in degrees Celsius.

Values derived from this equation were tabulated for Watnall in Table I for ready use. Differences between forecasts obtained from this equation and observed minimum temperatures were calculated and an attempt was made to construct a correction table to make some allowance for the effects of cloud amount and wind speed. There was no apparent relation with wind speed and the residuals were very widely scattered in relation to cloud amount. The best that could be done was to add the small correction table to the main Table I. (Presumably the reason why no relation with wind speed was found is that wind direction is important; if the wind blows along the concrete road, the fetch is over concrete; but if it blows across the road, the fetch is over grass.)

TABLE I—TABLE FOR OBTAINING NIGHT MINIMUM TEMPERATURE AT WATNALL AT THE SURFACE OF CONCRETE FROM AIR TEMPERATURE AND DEW-POINT TEMPERATURE AT 12 GMT ON THE PREVIOUS DAY

Air temperature T_{12}	Dew-point temperature D_{12}(°C)													
	−7	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	
°C							degrees Celsius							
2	−8·3	−7·6	−6·9	−6·2	−5·5	−4·8	−4·1	−3·4	−2·7	−2·0				
3	−7·7	−7·0	−6·3	−5·6	−4·9	−4·2	−3·5	−2·8	−2·1	−1·5	−0·8			
4	−7·1	−6·4	−5·7	−5·0	−4·3	−3·6	−2·9	−2·2	−1·6	−0·9	−0·2	0·5		
5	−6·5	−5·8	−5·1	−4·4	−3·7	−3·0	−2·3	−1·7	−1·0	−0·3	0·4	1·1	1·8	
6	−5·9	−5·2	−4·5	−3·8	−3·1	−2·4	−1·8	−1·1	−0·4	0·3	1·0	1·7	2·4	3·1
7	−5·3	−4·6	−3·9	−3·2	−2·5	−1·9	−1·2	−0·5	0·2	0·9	1·6	2·3	3·0	3·7
8		−4·0	−3·3	−2·6	−2·0	−1·3	−0·6	0·1	0·8	1·5	2·2	2·9	3·6	4.3
9			−2·7	−2·1	−1·4	−0·7	0·0	0·7	1·4	2·1	2·8	3·5	4·2	4·9
10				−1·5	−0·8	−0·1	0·6	1·3	2·0	2·7	3·4	4·1	4·8	5·4
11					−0·2	0·5	1·2	1·9	2·6	3·3	4·0	4·7	5·3	6·0
12						1·1	1·8	2·5	3·2	3·9	4·6	5·2	5·9	6·6
13							2·4	3·1	3·8	4·5	5·1	5·8	6·5	7·2

Correction (δ) to be added for mean cloud amount during the night:

Mean cloud amount (oktas)	0	1	2	3	4	5	6	7	8
δ (degC)	−1·2	−0 7	0·0	0·0	+0·3	+0·6	+0·9	+1·1	+1·3

The next step was to test this equation on samples of data obtained from two separate winters at Watnall and three separate winters at Wyton. In every case the cloud correction produced a marginal improvement in the standard deviation of the errors, but moved the mean a little further from zero; this is not surprising since the basic equation was derived by the method of least squares.

The winter of 1969–70 was one of those for which data from Watnall were used. October 1969 contained many warm days in a range not represented in the data used for deriving the equation, so a recalculation of the data for this winter was carried out by rejecting occasions when D_{12} was greater than 10°C. This was deemed permissible as forecasting temperatures of 0°C or below on roads is unlikely to be a problem for a forecaster in these circumstances, and moreover the regression may not be strictly linear at these extreme values. Table II shows the improvement which resulted.

TABLE II—EFFECT OF REJECTING OCCASIONS WHEN D_{12} WAS GREATER THAN 10°C IN THE APPLICATION OF THE DIRECT REGRESSION METHOD TO WATNALL DATA FOR THE PERIOD OCTOBER 1969–APRIL 1970

		Number of observations	Mean error	Standard deviation
			degrees Celsius	
Without cloud correction :	All cases	110	+0·60	3·54
	Rejecting $D_{12}>10$°C	96	−0·04	2·83
With cloud correction :	All cases	110	+1·03	3·43
	Rejecting $D_{12}>10$°C	96	+0·29	2·66

Analysis of variance showed that the three samples of data consisting of errors in forecasts of minimum temperatures at Wyton all came from the same population. Data for all three winters were then lumped together to obtain the best estimates of the mean and standard deviation of this population. Analysis of variance also showed that the data for two winters at Watnall were themselves samples of one population and the mean and standard deviation were calculated for this population. In short, there was no year-to-year variation at either place. Student's *t*-test was now applied to these two resultant populations and it was found that these two populations were themselves samples of a common population. The whole process was then repeated with allowance for cloud cover and this process again yielded resultant populations for Wyton and Watnall which were themselves samples of a common population (though not the same population as the first which contained no correction for cloud cover). The 5 per cent level of significance was used as the criterion and, as stated above, occasions when D_{12} was greater than 10°C were rejected.

It is a noteworthy result that the errors in forecasts of minimum temperatures on two roads over 60 miles apart are samples of the same two populations (with and without cloud cover respectively); but as later work[6] showed that there are differences between the results for other places in the same part of England by this method, this particular result may be no more than a coincidence. Throughout this paper the error is reckoned as the forecast value minus the observed value, and the best estimates of the mean error and standard deviation for each of the two populations are as follows :

	Without cloud correction	With cloud correction
Mean error	−0·14 degC	+0·38 degC
Standard deviation	2·56 degC	2·42 degC

Total number of cases 554.

The reduction in standard deviation is the maximum which can be expected from applying the cloud correction because cloud amounts were assessed from the *Daily register* after the event and are therefore not subject to any forecasting errors.

Because Parrey and Ritchie had shown that the depression of the minimum temperatures at the surface of a concrete road below that of the air in the screen is closely related to the hours of darkness, an attempt was made to introduce a further modification into the direct regression equation to take the duration of darkness into account. It was unsuccessful. Perhaps an equation might have been set up to derive M_R in terms of three quantities instead of two (duration of darkness perhaps being the third) but an equation of this kind cannot be tabulated for ready use on the forecast bench, and the figures given above therefore probably represent the best that can be achieved by direct regression.

Indirect methods. (i) *Parrey's method.* Two methods have been proposed for deriving a forecast of the minimum temperature over a concrete road (M_R) from a forecast of the minimum air temperature (M_A) in the thermometer screen. From data for the winter 1967–68 Parrey[1] derived the linear regression equation :

$$M_A - M_R = 0{\cdot}28t - 2{\cdot}9,$$

where t is the time between sunset and sunrise in hours and temperatures are in degrees Celsius. With the aid of the *Nautical Almanac* this equation can be tabulated for ready use for any given latitude. Table III shows the tabulation for 53°N. This method was not tested on the road at Watnall but it was tested on data for three successive winters at Wyton. As this was done in retrospect, actual values of M_A were used. Analysis of variance showed that data for all three winters could be regarded as samples of the same population and the following results were obtained for all occasions :

number of occasions	618
mean error	$-0{\cdot}04$ degC
standard deviation σ_1	$1{\cdot}02$ degC

The errors were normally distributed.

To obtain the total error it is necessary to take into account the errors in forecasting air minimum temperatures. Steele, Stroud and Virgo[7] have given figures for clear and cloudy nights separately for the period October 1967–March 1968. When compounded the mean error is $-1{\cdot}10$ degC and the standard deviation $\sigma_2 = 2{\cdot}79$ degC. By adding the errors and adding the variances we may obtain an estimate of the errors involved in the whole process. The figures are :

mean error	$-1{\cdot}14$ degC
standard deviation	$\sqrt{(\sigma_1^2 + \sigma_2^2)} = 2{\cdot}97$ degC.

(ii) *Ritchie's method.* Instead of a regression equation Ritchie[2] expressed the quantity $M_A - M_R$ for each day of the year October 1967–September 1968 as a simple sine curve of the form

$$M_A - M_R = 0{\cdot}48 + 1{\cdot}22 \sin(\theta + \varphi),$$

TABLE III—TABULATION OF $(M_A - M_R)$ FOR PARREY'S METHOD

Duration between sunset and sunrise from	to	$M_A - M_R$	Dates	
h min.	*h min.*	*degC*		
9 06	9 26	−0·3	26–30 Apr.	
9 27	9 48	−0·2	20–25 Apr.	
9 49	10 09	−0·1	14–19 Apr.	
10 10	10 31	0·0	9–13 Apr.	
10 32	10 53	+0·1	4–8 Apr.	
10 54	11 15	+0·2	29 Mar.–3 Apr.	
11 16	11 37	+0·3	24–28 Mar.	
11 38	11 59	+0·4	19–23 Mar.	
12 00	12 20	+0·5	14–18 Mar.	
12 21	12 40	+0·6	9–13 Mar.	1–5 Oct.
12 41	13 03	+0·7	4–8 Mar.	6–10 Oct.
13 04	13 24	+0·8	27 Feb.–3 Mar.	11–16 Oct.
13 25	13 45	+0·9	21–26 Feb.	17–21 Oct.
13 46	14 06	+1·0	16–20 Feb.	22–26 Oct.
14 07	14 27	+1·1	10–15 Feb.	27–31 Oct.
14 28	14 49	+1·2	4–9 Feb.	1–6 Nov.
14 50	15 10	+1·3	29 Jan.–3 Feb.	7–12 Nov.
15 11	15 32	+1·4	22–28 Jan.	13–19 Nov.
15 33	15 54	+1·5	15–21 Jan.	20–27 Nov.
15 55	16 15	+1·6	8–14 Jan.	28 Nov.–8 Dec.
16 16	16 36	+1·7	9 Dec.–7 Jan.	

The durations on the left-hand side of the table are derived from the equation $M_A - M_R = 0{\cdot}28t - 2{\cdot}9$ where t is duration in hours. The corresponding dates on the right-hand side are appropriate to latitude 53°N. The quantity in the middle column must be subtracted from M_A to obtain M_R.

where θ is the day as an angle (365 days = 360°) and φ is a phase angle. When a harmonic analysis was performed on the data for another year, October 1968–September 1969, it was found that the numerical constants were the same as before to two places of decimals and the only difference was in the phase angle (due presumably to a late spring or early autumn or some such difference between the years). This curve, with the value of the phase angle obtained for the year October 1967–September 1968, was taken as the basis for further study. The actual points for the year October 1967–September 1968 are scattered about this curve and an attempt was made to reduce the scatter by making allowances for wind speed and cloud amount. This was unsuccessful, so the best forecast of the depression of M_R below M_A by this method remains that derived from the curve itself. Values of this quantity were tabulated for 10-day intervals and are given in Table IV.

TABLE IV—TABULATION OF $(M_A - M_R)$ FROM RITCHIE'S CURVE

Days of month	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
				degrees Celsius			
1–10	+0·8	+1·3	+1·7	+1·7	+1·4	+1·1	+0·5
11–20	+1·0	+1·4	+1·7	+1·6	+1·3	+0·9	+0·2
21–31	+1·2	+1·5	+1·7	+1·5	+1·2	+0·7	0·0

This table was then used to obtain values of $M_A - M_R$ for two winters at Watnall and three at Wyton and the errors calculated. They are summarized in Table V. As Student's t-test gives strong grounds for believing that the data for the two places are samples of the same population, the averages are also given at the foot of the table. These averages are very similar to the only comparable figures available from the use of Parrey's method, namely

TABLE V—ERRORS IN $(M_A - M_R)$ BY RITCHIE'S METHOD

Place	Number of winters	Total number of occasions	Mean error	S.D.
			degrees Celsius	
Wyton	3	560	−0·09	1·08
Watnall	2	279	+0·08	1·09
Mean			0·00	1·09

those for Wyton (see page 352). When the two sets of figures were compared by means of the *t*-test, a value of $t = 0{\cdot}7$ was obtained. As the critical value of t at the 5 per cent level is 1·96, it may be accepted that both sets of figures refer to samples of the same population. This was to be expected as Parrey's equation and Ritchie's curve are simply different ways of expressing the dependence of $M_A - M_R$ upon the length of the cooling period.

Combined with the data for errors in forecasting M_A given by Steele, Stroud and Virgo (mean error − 1·10 degC, σ_2 2·79 degC) the figures for the whole process for Wyton are :

mean error − 1·09 degC
standard deviation 3·00 degC.

For Watnall for 1969–70 the mean error in forecasting M_A is − 0·21 degC and the standard deviation is 1·99 degC, irrespective of whether occasions when D_{12} was greater than 10°C are included or not. The mean error of $M_A - M_R$ was zero with σ 1·09 degC so that for the whole process for Watnall the figures are :

mean error − 0·21 degC
standard deviation 2·27 degC.

Discussion. To clarify the discussion the essential figures have been gathered together in Tables VI and VII. For Wyton the direct regression

TABLE VI—COMPARISON OF ERRORS IN FORECASTING M_R

Method	Source of observations	Mean error	σ
		degC	
Direct regression with cloud correction and rejecting $D_{12} > 10$°C	Wyton and Watnall combined	+0·38	2·42
Parrey's method	Wyton	− 1·14	2·97
Ritchie's method	Wyton	− 1·09	3·00
Ritchie's method	Watnall	− 0·21	2·27

TABLE VII—COMPARISON OF ERRORS IN FORECASTING $(M_A - M_R)$

Method	Source of observations	Mean error	S.D.
		degC	
Parrey's	Wyton	− 0·04	1·02
Ritchie's	Wyton and Watnall combined	0·00	1·09

method gives better results, possibly because the large errors in forecasting M_A at Wyton are masked to some extent in the direct regression equation. At Watnall, however, where the errors in forecasting M_A are much lower, Parrey's and Ritchie's methods give better results. For forecasting $M_A - M_R$ it is immaterial whether Parrey's or Ritchie's method is used.

The agreement between the results for the two roads over 60 miles apart is remarkable and while it would be unwise to conclude that the tabulations used in these two roads are of widespread application, it may be assumed that these results show the order of accuracy attainable, and it is hoped that other investigators will be encouraged to try similar experiments on roads elsewhere.

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551.509.323

MAXIMUM TEMPERATURE ON CLEAR DAYS

By G. A. INGLIS

Summary. An account is given of some further developments of Gold's technique for forecasting maximum day temperature. The *isothermal method* is a variation of Johnston's method in which the geometrical work is reduced; in the *oblique method* a set of parallel oblique straight lines is substituted for the isothermals; the *saturated-adiabatic method* makes use of a 'mean' saturated adiabatic instead of a 'mean' isothermal. In the *thickness method* the maximum temperature in summer is obtained from a table of 1000–850-mb thickness values.

The isothermal method. Gold's[1] method of estimating maximum day temperatures was modified by Johnston[2] and this in turn was slightly amended following a suggestion by Jefferson.[3] Johnston made use of assessments (denoted here by p_1) made by Gold of the depth of the layer which is changed from an isothermal to a dry adiabatic by solar heating on clear days (Table I). The term 'depth' is used instead of 'thickness' which is used in a different sense later on. The curve does not really become a dry adiabatic, the lapse rate next to the surface being much steeper in the typical case, but Gold's figures give good results in practice. As in all the tephigram methods the ascent used is that for 00 GMT.

TABLE I—DEPTH OF LAYER (p_1) WHICH IS CHANGED BY HEATING FROM AN ISOTHERMAL TO A DRY ADIABATIC, AND ASSOCIATED RISE IN TEMPERATURE (r_1)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
p_1(mb)	60	80	95	110	120	125	120	110	100	85	60	50
r_1(degC)	5	6·5	8·5	9·5	10·5	11	10·5	10	9	7	5	4·5

In Johnston's method (Figure 1) the isobars p_0 and p_0–p_1 are drawn, corresponding to the pressures at the surface and the top of the layer. The isothermal II′ is drawn to make equal areas between it and the environment curve, IE the boundary of the upper area being a dry adiabatic. The point F where the dry adiabatic meets the surface isobar gives the forecast maximum temperature.

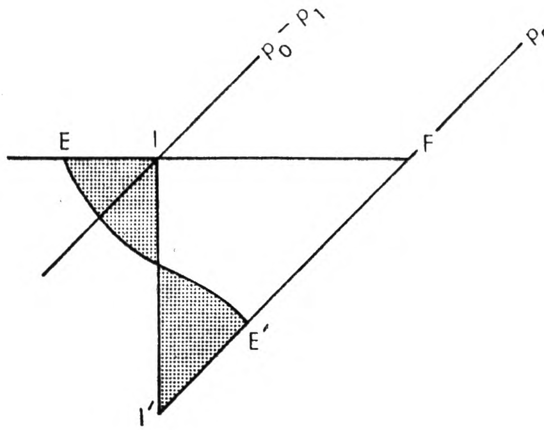

FIGURE 1—JOHNSTON'S METHOD

Gold also made assessments of the rise in temperature (r_1) corresponding to the change from an isothermal to a dry adiabatic; in Table I these have been converted to Celsius to the nearest 0·5 degC. The values of p_1 and r_1, can easily be verified by drawing on the tephigram a set of triangles FII′ for each month.

If we know the value of r_1 it is not necessary to draw IF. If instead we note the temperature at I′ we can add to this the appropriate rise from Table I. This gives an alternative method in which part of the geometry is replaced by arithmetic, and it is considered to be somewhat easier and more accurate.

Procedure. Draw the isobars p_0 and $p_0 - p_1$ (Figure 2). Draw the isothermal II′ to make equal areas between it and the environment curve, IE the boundary of the upper area being a dry adiabatic. To the temperature at I′ add the rise (r_1) from Table I to get the forecast maximum temperature. As in Johnston's method it is helpful to use a transparent scale with two lines at right angles.

Johnston says that the midnight environment curve is to be modified so as to approximate to conditions at dawn. But since modification of the curve is difficult and the change in area is usually insignificant it may be better to leave the curve unaltered.

The oblique method. Johnston's method has two advantages over Gold's; it is independent of the scale of the tephigram and the areas to be estimated are relatively small because the midnight environment curve is often nearly isothermal. But this is not always so; in fact on the average the curve is

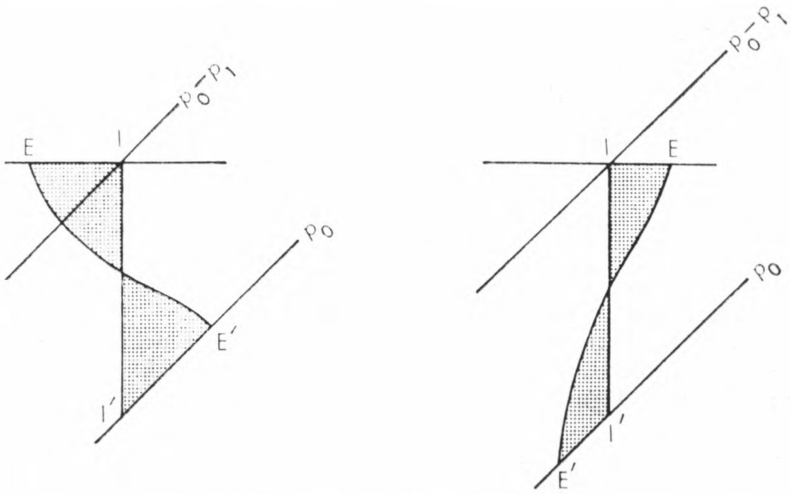

FIGURE 2—THE ISOTHERMAL METHOD

closer to the saturated adiabatic and often nearly coincides with it. It would be useful to have a technique based on estimating a 'mean' saturated adiabatic instead of a 'mean' isothermal. It was found that Johnston's technique for the isothermals can be adapted to any other set of lines; but the saturated adiabatics are not suitable for use with a scale because they vary in slope. (The curvature is negligible.) Therefore another method — the oblique method — was devised which makes use of a set of parallel straight lines inclined at an angle to the isothermals.

It is necessary to make assessments of the depth of the layer which is changed by heating from an oblique to a dry adiabatic and the corresponding rise in temperature. This could be done graphically as in Figure 3. For any month let I′F be the mean surface isobar (say 1020 mb), and let F correspond to the

FIGURE 3—GRAPHICAL METHOD OF ASSESSING VALUES OF p_2, r_2, p_3, r_3 AND DIAGRAM FOR OBTAINING FORMULAE FOR p_2 AND r_2

mean daily maximum temperature for, say, southern England. Subtract r_1 from the maximum temperature to get the point I′ and let the isothermal and the dry adiabatic meet at I. Draw the oblique OO′ at the required angle of inclination α so that ORI and O′RI′ are equal in area. Then FO′ will give the rise in temperature r_2, and the difference in pressure between O and the surface will give the depth of the layer p_2.

It is easier however and just as accurate in practice to calculate the values. If the surface isobar is assumed to be a straight line inclined at an angle of 45° to the isothermals then by geometry

$$\frac{r_2}{r_1} = \frac{\text{O}'\text{F}}{\text{I}'\text{F}} = \frac{1}{\sqrt{(1 + \tan\alpha)}} \;.$$

But $r_1 p_1 = r_2 p_2$ since area II′F = area OO′F, therefore

$$\frac{p_2}{p_1} = \sqrt{(1 + \tan\alpha)} \;.$$

These formulae were used to calculate, for an angle of inclination α of 45°, the values in Table II, and the values were then used to make the transparent scale illustrated in Figure 4. (not exact).

TABLE II—DEPTH OF LAYER (p_2) WHICH IS CHANGED BY HEATING FROM AN OBLIQUE AT 45° TO A DRY ADIABATIC, AND ASSOCIATED RISE IN TEMPERATURE (r_2)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
p_2(mb)	85	115	135	155	170	175	170	155	140	120	85	70
r_2(degC)	3·5	4·5	6	6·5	7·5	8	7·5	7	6·5	5	3·5	3

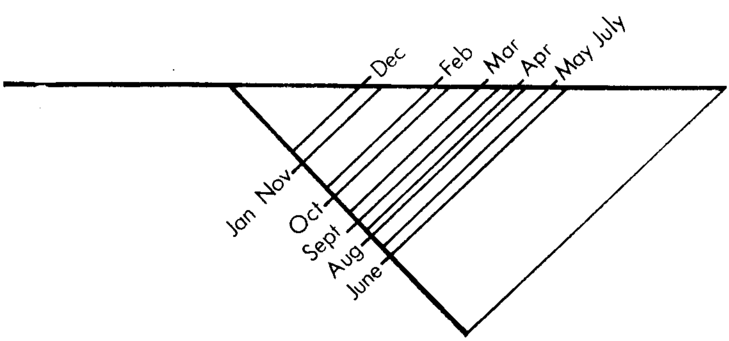

FIGURE 4—SCALE FOR USE IN OBLIQUE METHOD

Procedure. The scale is used as follows (Figure 5). Lay the thin line corresponding to the month along the surface isobar. Adjust the position of the heavy oblique line OO′ so that equal areas are enclosed between it and the environment curve, the upper and lower boundaries being the dry adiabatic and the surface isobar. Note the temperature at O′ and add r_2 to get the forecast maximum temperature, which can also be read at F.

The dimensions of the scale depend on those of the tephigram. Figure 4 is ¾ the scale suitable for the tephigram currently in use, i.e. Metform 2810. Alternatively a scale consisting simply of two lines OO′ and OF inclined at an angle of 45° can be used. The procedure would then be to subtract p_2 from the surface pressure and adjust the position of OO′ so that the point O lies on the isobar $p_0 - p_2$ and OO′ intercepts equal areas between it and the environment curve as above. The temperature at O′ on the surface isobar is then read and the value of r_2 added.

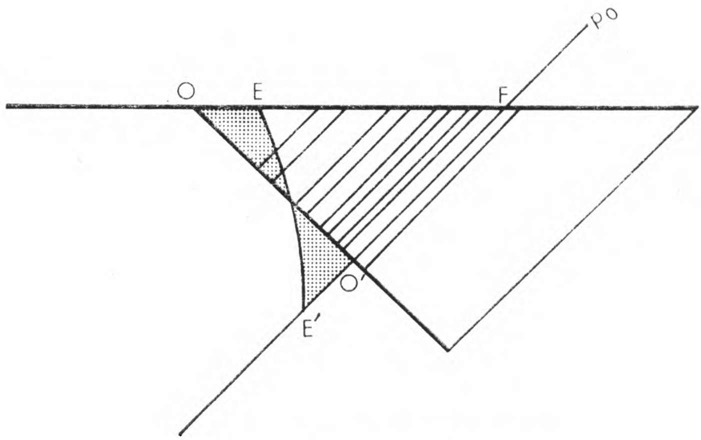

FIGURE 5—METHOD OF USING SCALE

The saturated-adiabatic method. This method is for use without a scale. The necessary table of assessments of values of depth and rise in temperature could be made graphically by a construction similar to that in Figure 3, OO′ being in this case replaced by a saturated adiabatic SS′. But since the curvature of the saturated adiabatics is negligible they can be treated as straight lines, so that the method becomes a modification of the oblique method, in which the slope of the oblique varies from month to month. The values of the angle of slope in Table III were based on mean monthly values of the 1000–850-mb thickness for south-east England but a similar result can be got by drawing on the tephigram a set of saturated adiabatics through the points corresponding to the mean daily surface temperatures. From these values Table IV was calculated using the formulae for the oblique method.

TABLE III—MEAN INCLINATION TO THE ISOTHERMAL OF THE SATURATED ADIABATICS IN THE 'HEATED LAYER'

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					angular degrees						
58	58	57	55	51	47	45	45	49	51	55	57

TABLE IV—DEPTH OF LAYER (p_3) WHICH IS CHANGED BY HEATING FROM A SATURATED ADIABATIC TO A DRY ADIABATIC, AND ASSOCIATED RISE IN TEMPERATURE (r_3)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
p_3(mb)	100	130	150	170	180	180	170	155	145	125	95	80
r_3(degC)	3	4	5	6	7	7·5	7·5	7	6	5	3	3

Procedure. Draw the surface isobar p_0 and the upper isobar $p_0 - p_3$ (Figure 6). Draw a saturated adiabatic SS′ making equal intercepts with the environment curve, SE the boundary of the upper area being a dry adiabatic. To the temperature at S′ add r_3 to get the forecast maximum temperature. The latter can also be read at the intersection of the dry adiabatic and surface isobar. In drawing the saturated adiabatic the curvature can be disregarded.

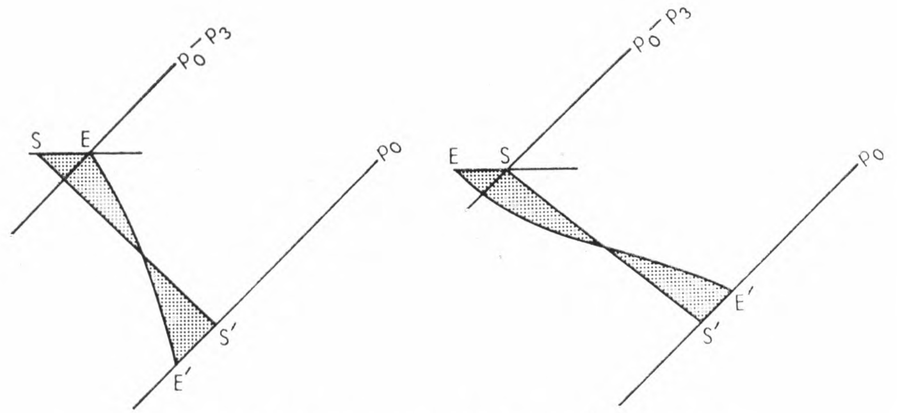

FIGURE 6—THE SATURATED ADIABATIC METHOD

The 1000–850-mb thickness method. In the methods described above we see that the maximum temperature can be regarded as consisting of two parts — the 'mean' temperature in a layer of the atmosphere next to the surface, which is a characteristic of the air mass, plus a constant which depends on the month. But the mean temperature of the layer between two pressure levels can also be measured by its thickness in geopotential metres, and in the summer months it happens that the layer examined to find the Gold maximum is very nearly the same as the 1000–850-mb layer at 00 GMT.

The areas equated in the isothermal method are not exactly the same as those equated in calculating the 1000–850-mb thickness; if they were the same then the thickness value, from a suitable table, would give the Gold maximum exactly. Actually two curves with different profiles but with the same thickness and same surface pressure have Gold maxima which differ by an amount which is usually less than 1 degC. If, in order to make a suitable table, we assume an average value of the lapse rate then the thickness value can be used to give an estimate of maximum temperature very close to the Gold maximum.

The average value of the lapse rate was assumed to be three-quarters of the saturated adiabatic and from the Radio Sounding Diagram (Metform 2813A) Table V was prepared, an allowance being made for an assumed mean relative

TABLE V—VALUES OF 1000–850-mb THICKNESS AND ASSOCIATED SURFACE TEMPERATURE (AT 1020 mb) ASSUMING THREE-QUARTERS OF SATURATED ADIABATIC LAPSE RATE AND 75 PER CENT RELATIVE HUMIDITY

Thickness (gpm)	1280	1290	1300	1310	1320	1330	1340	1350	1360	1370	1380	1390
Temperature (°C)	−0·5	1·4	3·3	5·2	7·1	9·0	10·9	12·7	14·5	16·3	18·2	20·0

humidity of 75 per cent. (The tephigram is not suitable for calculating values of the 1000–850-mb thickness.) Table VI was then prepared by proportional parts from Tables I and IV, and Tables V and VI were combined in Table VII. To avoid the need for interpolation the maximum temperatures corresponding to each geopotential metre have been worked out for August in Table VIII, which can also be used for the other months if a small correction is applied.

TABLE VI—RISE IN TEMPERATURE ASSOCIATED WITH CHANGE BY HEATING FROM A CURVE WITH THREE-QUARTERS OF THE SATURATED ADIABATIC LAPSE RATE TO A DRY ADIABATIC

	April	May	June	July	August	September
Rise (degC)	6·9	8·0	8·5	8·3	7·8	6·8

TABLE VII—VALUES OF GOLD MAXIMA FROM 1000–850-mb THICKNESS, ASSUMING THREE-QUARTERS OF SATURATED ADIABATIC LAPSE RATE AND 75 PER CENT RELATIVE HUMIDITY

Thickness	April	May	June	July	August	September
gpm			*degrees Celsius*			
1280	6·4	7·5	8·0	7·8	7·3	6·3
1290	8·3	9·4	9·9	9·7	9·2	8·2
1300	10·2	11·3	11·8	11·6	11·1	10·1
1310	12·1	13·2	13·7	13·5	13·0	12·0
1320	14·0	15·1	15·6	15·4	14·9	13·9
1330	15·9	17·0	17·5	17·3	16·8	15·8
1340	17·8	18·9	19·4	19·2	18·7	17·7
1350	19·6	20·7	21·2	21·0	20·5	19·5
1360	21·4	22·5	23·0	22·8	22·3	21·3
1370	23·2	24·3	24·8	24·6	24·1	23·1
1380	25·1	26·2	26·7	26·5	26·0	25·0
1390	26·9	28·0	28·5	28·3	27·8	26·8

TABLE VIII—1000–850-mb THICKNESS VALUES AND CORRESPONDING GOLD MAXIMA FOR AUGUST

Thickness	0	1	2	3	4	5	6	7	8	9
gpm					*degrees Celsius*					
1280	7·3	7·5	7·7	7·9	8·1	8·3	8·4	8·6	8·8	9·0
1290	9·2	9·4	9·6	9·8	10·0	10·1	10·3	10·5	10·7	10·9
1300	11·1	11·3	11·5	11·7	11·9	12·1	12·2	12·4	12·6	12·8
1310	13·0	13·2	13·4	13·6	13·8	13·9	14·1	14·3	14·5	14·7
1320	14·9	15·1	15·3	15·5	15·7	15·9	16·0	16·2	16·4	16·6
1330	16·8	17·0	17·2	17·4	17·6	17·7	17·9	18·1	18·3	18·5
1340	18·7	18·9	19·1	19·2	19·4	19·6	19·8	20·0	20·1	20·3
1350	20·5	20·7	20·9	21·0	21·2	21·4	21·6	21·8	21·9	22·1
1360	22·3	22·5	22·7	22·8	23·0	23·2	23·4	23·6	23·7	23·9
1370	24·1	24·3	24·5	24·7	24·9	25·1	25·2	25·4	25·6	25·8
1380	26·0	26·2	26·4	26·5	26·7	26·9	27·1	27·3	27·4	27·6
1390	27·8	28·0	28·2	28·3	28·5	28·7	28·9	29·1	29·2	29·4

	April	May	June	July	September
Correction (degC)	−0·9	+0·2	+0·7	+0·5	−1·0

The meaning of Table VIII is that, for example, in the month of August a curve with a thickness of 1335 gpm, a surface pressure of 1020 mb, a relative humidity of 75 per cent and a lapse rate three-quarters of the saturated adiabatic will have a Gold maximum of 17·7°C exactly. If with the same surface pressure and relative humidity the lapse rate is really isothermal, then Table VIII will overestimate the Gold maximum by an amount between 0·7 and 1·0 degC. If the lapse rate is really a saturated adiabatic then the table will underestimate the Gold maximum by about 0·2 degC.

Differences also arise from variations in surface pressure; 1020 mb was taken as the mean surface pressure on sunny days (i.e. slightly higher than the mean pressure for all days), and strictly speaking, a correction of about 0·1 degC should be added or subtracted for every 2 mb above or below 1020 mb; but this correction is usually small and was disregarded in the test. Other differences may arise from variations in humidity and from irregularities in the shape of the curve near 850 mb.

Test. A test of the method was carried out using data for the months April to September 1966–69. Days with 40 per cent or more of possible sunshine and no precipitation between 09 and 15 GMT were selected. The upper air ascent for 00 GMT at Aughton was used to forecast the maximum temperature by (i) one of the tephigram methods and (ii) the thickness method. (Aughton was used because plotted ascents from southern England were not available.) The forecast maxima were compared with the reported maxima at one or more of the stations Ringway (334), Shawbury (414), Birmingham (534) and Watnall (354). If more than one of these qualified as 'sunny' the mean was taken.

TABLE IX—COMPARISON OF TEPHIGRAM AND 1000–500-mb THICKNESS METHODS AS PREDICTORS OF MAXIMUM TEMPERATURE USING DATA FOR AUGHTON 1966–69

	Number of observations	Root-mean-square error	
		Tephigram method	Thickness method
		degC	*degC*
April	32	1·67	1·56
May	29	1·39	1·44
June	43	1·65	1·66
July	45	1·94	1·82
August	28	1·55	1·68
September	27	1·13	1·10
Apr.–Sept.	204	1·62	1·59

The results are shown in Table IX. It will be observed that there is no difference in accuracy between the two methods and hence in the summer months the thickness method could be used instead of the tephigram methods with equally good results. Although the method was fully tested only for the six summer months it is thought that it may be useful for some other months such as March and October. All that is necessary is to add these months to the list of corrections in Table VIII.

The thickness method has several advantages. Firstly, there is no need to plot and examine the tephigram; secondly, a central office can obtain a forecast very quickly for a large area, e.g. north-west Europe, by plotting the thickness values on a chart; thirdly, the method can be used by inexperienced staff as it simply involves a subtraction followed by reference to a table.

Regression technique. The direct way to establish a relationship between thickness and maximum temperature would be by means of a regression equation, using the same type of data as in the test above. It would have to be done separately for each month, except that the midsummer months could be grouped together. The result would be entirely independent of Gold's figures and might be the best method if sufficiently large samples were taken.

Comments. During the past two years the tephigram methods described above have been found to be easy and accurate. The curve is usually nearer to the saturated adiabatic than to the isothermal and is often so close to it that the areas involved are almost nil in which case the estimation can be done by eye alone. The reduction in geometrical work makes the methods more suitable for use with FAX copies of the tephigram than the older methods. The thickness method provides a quick and accurate estimate of the maximum temperature without reference to the tephigram.

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DEW-POINT TEMPERATURE AS A SNOW PREDICTOR

By B. J. BOOTH

Summary. Winter observations made at Upavon were analysed to see if there is any correlation between the dew-point temperature and the type of precipitation occurring at the time of the observation, which might allow the dew-point to be used as a snow predictor. A relationship was found and an empirical formula is suggested for use by the practising forecaster.

Introduction. Many, if not all, of the snow predictors now in use resort to the use of upper air data. The various methods have been summarized by Boyden.[1]

The use of upper air data creates three basic problems:

(i) Which ascent or ascents are applicable to a particular area?

(ii) The ascents are only available at 12-hourly intervals, and may substantially change in any 12-hour period.

(iii) Most of the radiosonde stations are close to the sea, and in the lower levels may not be representative of a particular air mass.

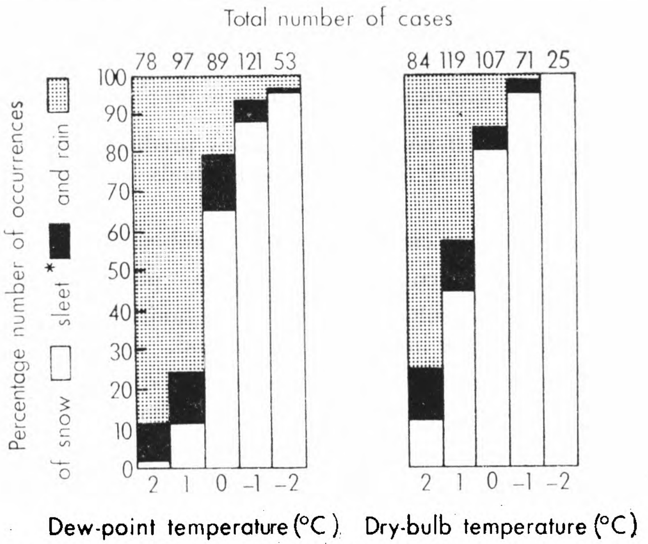
Boyden in his paper finds that the surface air temperature is an unreliable snow predictor. What is needed is an element which is readily available hour by hour, easily measured, and reasonably conservative. With this in mind an analysis was made of the full synoptic observations at Upavon, to see if it would be feasible to use the dew-point temperature as a snow predictor. Upavon is an exposed station some 580 ft (177 m) above mean sea level, and about 35 nautical miles (65 km) from the south coast. Full synoptic observations are made at 09, 12, 15 and 21 GMT. Temperature observations are not available in the form of a continuous record.

The data. The dry-bulb temperature, dew-point temperature and type of precipitation were extracted from the Upavon observations on all occasions when precipitation was occurring at the time of the observation, or had occurred during the previous hour, for the winter months of the years 1950 to 1969 inclusive. No note was made of the intensity or duration of the precipitation. Winter in this case was defined as the months December, January and February.

Results. An analysis was made of the dry-bulb temperature and associated precipitation so that a comparison could be made of the methods of forecasting snow using dry-bulb temperature and dew-point temperature. Scatter diagrams were then prepared, in which the type of precipitation was plotted against (i) the dew-point temperature and (ii) the dry-bulb temperature.

It was noted that snow never fell with a dew-point $\geqslant 3°C$ and rain never occurred with a dew-point $\leqslant -3°C$.

In the dew-point diagram the type of precipitation showed a marked change from rain to snow at about 0°C. Boundaries were then marked on the diagram such that 2°C embraced values between 2·4°C and 1·6°C inclusive, 1°C embraced 1·5°C to 0·5°C, etc., i.e. the approximations used when coding synoptic reports. The percentage numbers of occasions on which snow fell for each temperature were then calculated. Snow was classified as all types of freezing precipitation (excluding hail and sleet*). Occasions of sleet were also noted and are shown in the histograms, Figures 1*(a)*, 1*(b)*, 2*(a)*, 2*(b)*. Freezing rain or drizzle was also included as snow, but this only occurred on 9 occasions in the 20 years.



(a) With varying dew-point temperature. *(b)* With varying dry-bulb temperature.

FIGURE 1—HISTOGRAMS SHOWING THE FREQUENCY OF OCCURRENCE OF DIFFERENT TYPES OF NON-SHOWERY PRECIPITATION

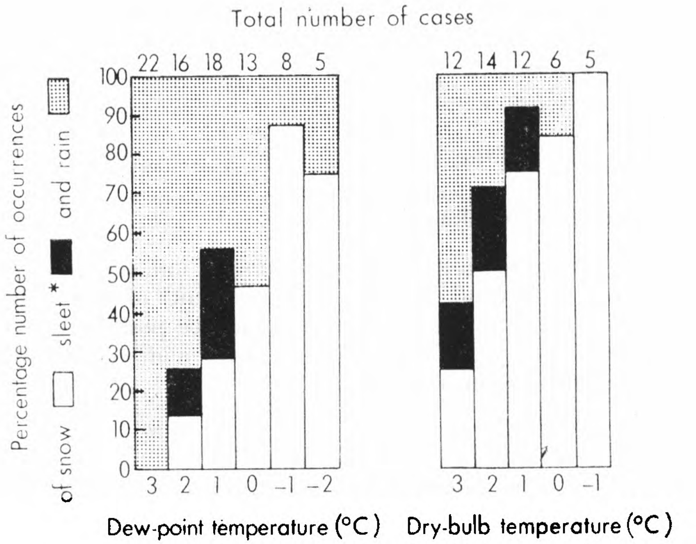
* Sleet : see footnote.

The histogram in Figure 1*(a)* shows a marked increase in the frequency of snow when the dew-point changes from 1°C to 0°C. The solid black area of each column shows the percentage number of occurrences of sleet. The total number of occasions examined was 438.

An analysis of the dry-bulb temperatures and type of precipitation gave the histogram in Figure 1*(b)*. The increase of frequency of snow occurrences is a much steadier process. Total number of cases examined was 406.

Separate diagrams were produced for occasions when showers occurred. Although the size of the sample was small, the results, as shown by the histograms, Figures 2*(a)* and 2*(b)*, show a similar pattern to the results previously noted. Here however the increased frequency of snow showers occurs with a dew-point of minus 1°C. Smith,[2] in a recent paper, also noted that a dew-point of 0°C was the critical value for the change from rain to snow.

* In the United Kingdom the term sleet is used to denote precipitation of snow and rain (or drizzle) together or of snow melting as it falls, but it has no agreed international meaning.



(a) With varying dew-point temperature. *(b)* With varying dry-bulb temperature.

FIGURE 2—HISTOGRAMS SHOWING THE FREQUENCY OF OCCURRENCE OF DIFFERENT TYPES OF SHOWERY PRECIPITATION

* Sleet : see footnote on page 364.

As there seemed to be a marked increase in the frequency of non-showery snow with a dew-point of 0°C a further analysis was made to see if a more accurate forecast of snow or rain/drizzle could be made, taking into account the dew-point depression. A scatter diagram was made with the dew-point as the abscissa and the air temperature as the ordinate. The type of precipitation was plotted at the intersection of each value of dew-point and air temperature. The results are summarized in Tables I, II and III.

TABLE I—SLEET* : FREQUENCY OF OCCURRENCES

Dew-point depression	Dew-point in degrees Celsius				
	−2	−1	0	1	2
degC			*per cent*		
3	0	16			
2	0	4	40		
1	0	4	25	15	
0	—	3	5	13	10

* Sleet : see footnote on page 364.

TABLE II—RAIN : FREQUENCY OF OCCURRENCES

Dew-point depression	Dew-point in degrees Celsius				
	−2	−1	0	1	2
degC			*per cent*		
3	0	33			
2	12	11	20		
1	0	8	29	77	
0	—	0	18	72	87

TABLE III—SNOW : FREQUENCY OF OCCURRENCES

Dew-point depression *degC*	Dew-point in degrees Celsius −2	−1	0 *per cent*	1	2
3	100(18)	51(6)			
2	88(8)	85(26)	40(5)		
1	100(24)	88(47)	46(28)	8(26)	
0	—	97(38)	77(56)	15(54)	3(30)

Numbers in brackets represent total number of occasions examined for each dew-point and dew-point depression.

It can be seen from these tables that (i) snow is unlikely with a dew-point $\geqslant 1\,^\circ$C; (ii) there is a good chance (> 50 per cent) of snow with negative dew-points even though the air temperature may be positive; (iii) there is a moderate chance (30–50 per cent) of snow with a dew-point of 0°C even with a dew-point depression of 1 degC.

The process was repeated for showery situations. Unfortunately the sample was not large enough to produce any conclusive results.

Examination of Table III suggests that there is a relationship between dew-points $\leqslant 0\,^\circ$C (DP) and dew-point depressions (DPD) which gives the boundary between snow and precipitation other than snow. This is :

$$\text{DPD} = [(-2\times\text{DP}) + 1]\ \text{degC},$$

i.e. if DPD $\leqslant [(-2 \times \text{DP}) + 1]$ degC, then there is a good (> 50 per cent) chance of snow.

Table IV gives the values of dew-point and dew-point depression required for > 50 per cent chance of snow using the above relationship. These values are easily obtainable from hourly synoptic reports.

TABLE IV—VALUES OF DEW-POINT AND DEW-POINT DEPRESSION FOR PROBABILITY OF SNOW > 50 PER CENT

Dew-point in degrees Celsius	0	−1	−2	−3	−4
Dew-point depression in degrees Celsius equal to or less than	1	3	5	7	9

Result of check on independent data. Using Table IV and adding the rider 'no snow with dew-points 0°C', the method was tested on independent data for March 1950–69. Although the frequency of snow and sleet is declining in March, it is still, at Upavon, as high as in December. The results are summarized in Table V*(a)*.

TABLE V*(a)*—NON-SHOWERY PRECIPITATION

Forecasts of rain	Correct forecasts	Forecasts of snow	Correct forecasts
49	37(76 per cent)	46	41(89 per cent)

5 of the incorrect forecasts were due to sleet. 1 of the incorrect forecasts was due to sleet.

TABLE V*(b)*—SHOWERY PRECIPITATION

Forecasts of rain	Correct forecasts	Forecasts of snow	Correct forecasts
18	14(78 per cent)	25	23(92 per cent)

Table V*(b)* gives the results for showery precipitation. Here, however, the criterion used was simply a forecast of snow with a dew-point $\leqslant -1\,^\circ$C. This cruder criterion was used mainly because of the lack of conclusive data as previously mentioned.

Discussion. As the analysis of dew-points and dew-point depressions was made without reference to the intensity or duration of precipitation, no conclusion could be made about the rate of increase or decrease of the dew-point during precipitation. One would expect a change of dew-point with the approach of a different air mass, and it is possible to follow the change of dew-points and dew-point depressions on a normal working chart. It is then possible to decide, particularly in the case of an approaching warm front in winter, when precipitation falling as snow will turn to rain.

Lumb[3] states that snow can extend down to the 1·5°C wet-bulb level; unfortunately surface wet-bulb temperatures are not plotted on synoptic charts. If the figures in Table IV are plotted on a tephigram and the wet-bulb temperatures calculated, it will be seen that they lie between 0·5°C and 1·5°C. Thus by using the criteria in Table IV we now have a method of estimating, hour by hour, from the synoptic charts the change in wet-bulb temperature at the surface. Lumb[4] shows how prolonged moderate or heavy precipitation can also cause a change of dew-point.

The figures in Table IV were calculated for occasions when precipitation was occurring. It is felt, however, that in situations where precipitation is expected to occur, if the conditions of Table IV are fulfilled, then it would be reasonable to forecast the precipitation as snow.

Table VI gives the 2×2 contingency table comparing forecasts of rain or snow with the actual occurrences of rain and snow for the test forecasts on the March data. The chi-square value (with Yates's correction) is also shown.

TABLE VI—NUMBER OF FORECASTS OF SNOW OR RAIN AT UPAVON COMPARED WITH THE TYPE OF PRECIPITATION THAT ACTUALLY OCCURRED

	Rain forecast	Snow forecast	Totals
Rain occurred	37	5	42
Snow occurred	12	41	53
Totals	49	46	95

The chi-square value is 37·6, which is significant at the 0·1 per cent level.

The results of the test, Table V, are encouraging; however it would be interesting to see if similar results would be obtained from a low-level inland site, and a coastal site.

The object of this paper was to see if there was a correlation between the type of precipitation and dew-point temperature; this would seem to be the case with the dew-point of 0°C being the critical value for non-showery precipitation and -1°C for showery precipitation.

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MOUNTAIN LEE WAVES IN THE VALE OF YORK

By G. F. RUDDOCK

Following publication of Casswell's simplified method of forecasting lee-wave conditions,[1] a number of aircraft reports were received at Linton-on-Ouse during frequent westerly spells in the period June 1966 to December 1967. These westerly spells frequently produce wave conditions over the Vale of York, because of flow over the Pennines.

Examination of the reports, together with ground observations of wave-type clouds, suggested that, broadly speaking, Casswell's method worked fairly well in regard to maximum vertical velocities. However, the investigation drew attention to two important variations from Casswell's findings :

(i) Casswell quoted 20 kt* as the likely lower limit of wind speed at the mountain crest for wave formation. In this area the incidence of wave clouds, or of waves reported by aircraft, is quite common with wind speeds down to about 15 kt. This is in agreement with the statement in WMO *Technical Note* No. 34, page 119, that the minimum speed for wave formation is about 7 m/s for small mountains.

(ii) Casswell's method involves smoothing the environment temperature curve between 1000 and 700 mb, and between 700 and 300 mb. This has the disadvantage of smoothing through inversions, which may be major discontinuities. Theory strongly points to the height of maximum vertical velocity being at the inversion level (see for example Corby,[2] para. 19). The examination of aircraft reports leads to the same conclusion. It follows that the height of the maximum vertical velocity, as deduced by Casswell's method, is open to doubt if it differs widely from the base of the stable layer.

A comparison was made for 57 occasions (all suitable for mountain waves) between the height of maximum vertical velocity as deduced from Casswell and the height of the base of the isothermal or inversion layer, as taken from the representative tephigram.

This gave the following results :

Number of occasions with base of stable layer below 10 000 ft*	49
Number of occasions when Casswell method gave height of maximum vertical velocity within 1000 ft of the base of the stable layer	14 (28·6 per cent)
Number of occasions when Casswell method gave height of maximum vertical velocity more than 1000 ft above the base of the stable layer	32 (65·3 per cent)
Number of occasions when Casswell method gave height of maximum vertical velocity more than 1000 ft below the base of the stable layer	3 (6·1 per cent)

If the maximum vertical velocity occurs at the base of the stable layer then the Casswell method will give too high a level on a substantial number of occasions presumably because of the smoothing used in the procedure. Thus the height of inversion, or of base of isothermal, should be used to forecast the height of maximum vertical velocity, rather than the theoretical value. In practice, the nearer the stable layer to the mountain top, the more important this becomes. Light aircraft with maximum power lift of 1000 to

* 1kt ≈ 0·5 m/s; 1000 ft ≈ 300 m; 1000 ft/min ≈ 5 m/s.

1500 ft/min have insufficient power to overcome downdraughts of 1200 to 1500 ft/min and these are not uncommon in waves due to the Pennines.

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REVIEWS

Atmospheric tides, by Sydney Chapman and Richard S. Lindzen. 240 mm × 165 mm, pp. ix + 200, *illus.*, D. Reidel Publishing Company, 419–421 Singel, PO Box 17, Dordrecht, Holland, 1970. Price : Dfl. 38.

This monograph must be one of the last of the great contributions made by Professor Sydney Chapman to our knowledge of the upper atmosphere. It was with deep regret that the members of a Symposium of the American Meteorological Society on 'The Dynamics of the Mesosphere and Lower Thermosphere' at Boulder, Colorado (*Bull. Amer. met. Soc., Lancaster, Pa*, **51**, 1970, pp. 377–387), learned that because of illness he would not be able to be Chairman of one of the sessions and later that he had died. He was 82. The first of his papers quoted in the references was dated 1913 and the last in 1969 and there were several in each decade between. As all interested in atmospheric physics will know, his contributions were not restricted to the tides. Other subjects such as the ionosphere, the earth's magnetism, ozone photochemistry, solar radiation, the theory of non-uniform gases, etc., etc., have equally benefited from his great insight. His co-author Professor Lindzen of the University of Chicago some 50 years his junior has already established himself as a world authority on tidal and other wave motions in the upper atmosphere. Their joint review of the present state of knowledge of this complicated subject is authoritative and must become a standard reference book for many years.

Attempts to explain theoretically the magnitudes and phases of the observed tides in the ocean and in the atmosphere have been made by outstanding physicists and mathematicians for almost the last three centuries and a short discussion of the contributions due to such scientists as Newton, Laplace, Kelvin, Rayleigh, Lamb, Taylor and many others are included in the introductory first chapter which also gives a clear account of the fundamental concepts and outstanding problems. It is known that the gravitational pull of the moon is greater than that of the sun and hence in the ocean the lunar tides are greater than the solar. In the atmosphere, however, the lunar tide measured by barometers is comparatively small and hence it appears that the thermal drive due to the sun must play a dominant role. Observations show also that the semidiurnal barometric solar tide is unexpectedly great compared with the diurnal component although the thermal forcing for the latter is clearly the greater. Earlier explanations in terms of a natural resonance of the atmosphere have now been rejected in favour of increased efficiency of coupling between the semidiurnal forcing terms and their induced motions.

The second and third chapters (labelled 2S and 2L) deal respectively with the solar and the lunar daily atmospheric oscillations as revealed by meteorological data. Near the surface the details are not easy to extract. The necessary harmonic analyses require careful statistical techniques and the detailed results are described at some length. At higher levels the tidal components become successively larger until above 100 km they dominate the general circulation of the atmosphere. The rapidity of the wind changes and their magnitudes and phases at different times and locations raise severe practical problems as regards methods of measurement and theoretical questions regarding wave propagation, forcing functions and dissipation mechanisms.

The final chapter (3) sets out in detail the present position on the quantitative theory of tides. The basis as in all dynamical studies of atmospheric motions rests on the equations of motion and the continuity and thermodynamic equations and the analytical solutions of their linearized forms with the tidal constraints are given in full. The subject, however, is complex and the Hough functions which arise in the solutions have in practice to be evaluated numerically using electronic computers. Recent computations are presented in some detail, compared with observations and outstanding problems discussed.

The division of labour between the two authors was broadly that Professor Chapman wrote most of Chapters 1, 2S and 2L except the sections dealing specifically with recent upper atmosphere observations and modern theoretical calculations while Chapter 3 was written by Professor Lindzen. Even if it had not been stated in the Preface this could have been deduced directly. In his section Chapman sets out his procedures in great detail while Lindzen prefers to assume that his readers do not need quite so much guidance. This may be a disadvantage as many students may be deterred by the difficulty of the theoretical aspects in some sections, leaving these to the specialists. In particular it might have been preferable to include more detailed explanations in Chapter 3 possibly with the inclusion of examples of the procedures involved.

The subject is still moving rapidly due, to a large extent, to further work by Lindzen himself and no doubt in a few years a second edition will be called for. The sections covered by Chapman, however, will need little revision and until that time this edition will remain the major basic text and statement of all that was known about this subject in early 1970. The book is attractively set out and clearly illustrated but a few minor errors were noted presumably due to insufficient proof reading.

R. J. MURGATROYD, O.B.E.

Statistische Auswertung geophysikalischer und meteorologischer Daten, by J. Taubenheim. 230 mm × 165 mm, pp. 386, *illus.* Geest & Portig K.-G., Sternwartenstrasse 8, Leipzig, 1969, Price : DM 61.

The application of statistical methods to geophysical data has been surprisingly unsystematic, considering the number, variety and quality of the data and there is a need for an authoritative and comprehensive account of the tools of the statistician's trade which is sympathetic to the geophysical medium. Professor Taubenheim's book goes a long way towards satisfying this need by providing a well-balanced and well-illustrated account, first of the standard statistical concepts and methods and then of subjects such as time series analysis, power spectrum analysis and filtering which are relatively more important in geophysical work than they are elsewhere. The illustrations are nearly all drawn from meteorology or other geophysical sciences and the depth of the theoretical treatment is enough to serve the needs of most professional meteorologists without being violently excessive. The treatment does not generally extend to the statistical aspects of methods, such as principal component analysis or stepwise multiple regression, which can only be exploited by computer, nor to subjects such as the statistical control of errors in data, which have become increasingly important in the era of computerized research.

Some statistical tests such as Kolnogoroff's and Wilcoxon's are included which are not usually found in comparable accounts, and the general impression is of clarity and thoroughness, and of the collection in one place of material which is hard to find elsewhere. The bibliography is good and the index excellent. Altogether a book to be recommended, and this reviewer at any rate hopes that it will appear before long in English translation.

J. M. CRADDOCK

Meteorological data catalogue. International Indian Ocean Expedition Meteorological Monographs, Number 3, by James R. Nicholson. 210 mm × 280 mm, pp. 59, *illus.*, East-West Center Press, Honolulu, Hawaii, 1969. Price: $7.50.

This monograph is the third in a series covering the meteorological work of the International Indian Ocean Expedition (IIOE) between 1959 and 1965. The author, an Environmental Science Services Administration (ESSA) Weather Bureau research meteorologist assigned to the IIOE, spent the years 1963 and 1964 at the International Meteorological Centre, Bombay, followed by three years at the University of Hawaii where he supervised data handling for this series of monographs, and so can write on the subject with some authority. As implied by its title the monograph is primarily intended to serve as a reference catalogue of data collected in the course of the meteorological and oceanographic research programmes of this expedition, and the reader will soon appreciate how well this purpose has been achieved. In the field of meteorological telecommunications there is material concerned with organization and operational experience, which could have a bearing upon planning for similar large-scale projects in the future within the World Weather Watch. Problems met with in the recording, collection and processing of data are next briefly described, followed by an account of methods of archiving which includes tables giving full details of sorties and observations made by research aircraft over the Indian Ocean, together with a description of instrumentation available on the aircraft and time-lapse films taken on these flights. Another table, summarizing all computer programmes (title, language, purpose, etc.) already written in connection with processing numerous categories of data collected during the IIOE, could be a valuable aid to research workers in these fields.

The monograph concludes with a brief discussion and, arising from experience gained by the author and his colleagues during the IIOE, some suggestions for future procedures for data collection and handling during World Weather Watch. While some valid points are made relating to quality control of data and modification of codes, it seems doubtful whether difficulties involved in revising codes at the international level have been fully appreciated by the writer of this book.

The monograph is lavishly produced and contains a useful set of up-to-date references. Not surprisingly it is rather expensive in relation to its slim dimensions.

R. F. M. HAY

Numerical analysis — the mathematics of computing, Volume 1, by W. A. Watson, T. Philipson and P. J. Oates. 227 mm × 149 mm, pp. xi+224, *illus.*, Edward Arnold (Publishers) Ltd, Woodlands Park Avenue, Woodlands Park, Maidenhead, Berks., 1969. Price: 25*s.* (limp edition).

Those of us who have learned something of numerical analysis as and when it became necessary will welcome the publication of this book. Although designed primarily as a textbook for the special G.C.E. A-level course in numerical analysis, this book will be useful also in other sixth-form courses and in courses of further education. It provides a basic introduction to numerical methods of solving mathematical problems, such as must surely now be regarded as an essential feature of scientific education in schools. An increasing use of books such as this in science sixth forms will do much, I think, to eliminate confusion and apprehension from attitudes to the use of computers in scientific work.

The first three chapters of the book prepare the ground for the remaining six by introducing the reader to hand calculating machines, flow charts, and the sketching of simple functions respectively. I found that the emphasis on hand calculating machines in the opening chapter gave the book a rather dull beginning. The rather tedious details of register setting and crank rotating might perhaps have been better placed in an appendix to the book. By contrast, I felt that the second and third chapters provided clear and attractive introductions to their respective topics.

The rest of the book deals with a series of basic numerical techniques which include iterative methods for the solution of equations, differences, linear interpolation, and numerical integration up to Simpson's rule. Chapter six, dealing with the solution of linear simultaneous equations, is especially useful, I think, introducing as it does such topics as the method of relaxation in a painless way.

Throughout the book clear indication is given of the limitations of the techniques described and of the rounding and other errors involved in various operations. Profitable use is made of worked examples to explain the numerical methods, and a good selection of examples for the student (with answers) is included. Taken as a whole, there is no doubt that this is a useful introductory textbook on numerical analysis, and I look forward to the publication of Volume 2 in due course.

A. J. GADD

Numerical analysis — the mathematics of computing, Volume 2, by W. A. Watson, T. Philipson and P. J. Oates. 227 mm×149 mm, pp. x+166, *illus.*, Edward Arnold (Publishers) Ltd, Woodlands Park Avenue, Woodlands Park, Maidenhead, Berks., 1969. Price: 28*s*. (limp edition).

The first volume of this work gave a useful introduction to some basic concepts of numerical analysis and encouraged one to look forward to the publication of this second volume. In the event, however, I found the second volume rather disappointing. In general one would not quarrel very much with the presentation of individual techniques; the disappointment stems rather from the suspicion that the student who follows through these two volumes may be left with the impression that numerical analysis is a tedious and confusing subject.

Admittedly the authors had no easy task of presentation in this second volume. They are concerned in part with extending and generalizing the material of Volume 1 and in doing so they inevitably become involved with more complex techniques which lack both mathematical elegance and obvious usefulness. Even so, I feel that a more attractive presentation could have been achieved if an overall direction of development of the subject were more apparent. Volume 2 ends with a short chapter on the summation of slowly convergent series which is a complete anticlimax. One is tempted to believe that the fact that the book has three authors may have contributed to a certain lack of coherence from one chapter to another.

More than half of the pages of this second volume are devoted to material which in earlier books on numerical analysis has generally appeared in the chapter headed 'interpolation'. I find it difficult to judge whether or not such an emphasis is justified, but certainly a rather sustained effort is required to remain interested in the various details presented.

As the authors admit, the inclusion of an introductory chapter on the numerical solution of differential equations has the difficulty that the readers of the book in schools may not be in a position to cope with the methods of solution which are most widely used. Some simpler methods are therefore presented, in the hope that an enthusiasm for further study will be stimulated. The authors deal mainly with first-order equations, despite the fact that the simplest numerical process is that for a second-order equation with the first derivative absent. The description given of Fox and Goodwin's method for first-order equations is, I think, unnecessarily daunting, and would have been better introduced by way of the trapezium rule for integration.

One feature of the layout of the printed material deserves comment. The tables, formulae, and numerical examples are printed so boldly that they overshadow the explanatory text and tend to obscure the continuity of the development. I liked the occasional historical references and thought that they could have been usefully extended to give more perspective to the place of numerical analysis in the general pattern of mathematics and physics.

I remain grateful that the attempt has been made to provide an attractive introduction to numerical analysis at sixth-form level, but I feel that there is scope for an improved presentation in the near future.

A. J. GADD

Field guide to snow crystals, by E R. LaChapelle. 210 mm × 150 mm, pp. v + 101, *illus.*, University of Washington Press, Seattle and London, c/o American Universities Publishers Group, 27–29 Whitfield St, London, W1. 1970. Price : 62*s.*

This slim volume consists principally of a collection of 65 very beautiful photographs of snow crystals, each of which is accompanied by a short commentary describing the situation in which the crystals were found and the important physical mechanisms involved in their formation. The photographs have been carefully selected, not so much for their symmetry and beauty, but rather to illustrate clearly the various forms which snow crystals *on the ground* can assume. In this respect the new book differs significantly from the classic collections obtained by Bentley and Humphreys and by Nakaya, who were primarily concerned with the forms of snow crystals as they first fall from the sky.

In the opening chapter, LaChapelle describes very clearly the processes which lead to changes in the structure of precipitated snow when it is lying on the ground. He also gives an account of a new system for classifying snow on the ground which has been proposed by R. A. Sommerfeld and himself. In this scheme three major processes leading to changes in the structure of snow are recognized—equitemperature (destructive) metamorphism, temperature-gradient (constructive) metamorphism and firnification (the process by which snow changes into glacier ice).

The book contains a short section explaining how best to observe and photograph snow crystals with fairly simple equipment, so that the interested reader can experiment for himself.

In short, this book fully lives up to the claim made in its title to be a *field guide* to snow crystals and it will make a handsome addition to the libraries of all who are interested in the fascinating forms of snow crystals.

J. T. BARTLETT

Tropical Indian Ocean clouds, International Indian Ocean Expedition Meteorological Monographs No. 4, by Andrew F. Bunker and Margaret Chaffee. 282 mm × 222 mm, pp. 194, *illus.*, East-West Center Press, Honolulu, Hawaii, 1970. Price: $10.00.

This monograph, the fourth in the series reporting data-gathering activities during the International Indian Ocean Expedition, presents schematic cloud patterns deduced from flights over the Indian Ocean during 1963 and 1964. Cloud data were derived from time-lapse film frames exposed from aircraft at intervals ranging from 2 to 10 seconds. A vast number of photographs were taken but only one frame in every hundred was used in this analysis. The photogrammetric technique employed to determine the distances of cloud from the aircraft, and the heights of bases and tops, is described. The volume is not, however, a collection of cloud photographs as the title might suggest.

Two main sections deal with the south-west and north-east monsoons separately and each section is liberally illustrated with diagrams. There are only 20 pages of text compared with 165 pages of diagrams. There is the surprising total of 346 figures, nearly all of them line drawings; only 23 show actual cloud photographs and of these only 4 were taken from aircraft, the remaining 19 being from satellites. All photographs are of rather poor quality.

The schematic cloud distributions along flight paths are presented in cross-section or map form with the minimum of discussion, and are supported by daily wind maps showing streamline and isotach analyses for the surface and 700-mb levels. These maps, 210 of them, are very much smoothed and do not show the wind data upon which they were based. In some cases the analyses are significantly different from others for the same days published in *Monograph No.* 1 of this series. For example, Figure 125 should be compared with Figure 21 of *Monograph No.* 1, where basic data are reproduced on all the maps and small-scale distortions in the wind field are shown to exist. Such small-scale variations may be more closely related to cloud formations than the broad-scale flow itself, but the authors do not attempt any detailed interpretation of cloud patterns in relation to the wind field.

No legend to the symbols used in depicting clouds appears with the diagrams. The reviewer found it a little distracting to refer back continually to the description of the method of representation given on page 8, and even then some of the schematic forms remained difficult to interpret. Some radiation and temperature measurements are discussed briefly and presented as composite — not daily — data. In particular the temperature data are of little help in studies of the daily cloud structures.

The volume is presented in the same attractive way as the others of the series. The reviewer would have preferred the daily wind-field maps to be adjacent to the appropriate cloud charts instead of being gathered together at the end of each section — but this is a minor criticism. The book is likely to have little general appeal because it is really intended for the research worker interested in the weather of the Indian Ocean, and to him it presents a wealth of information for study and digestion.

J. FINDLATER

HONOUR

The following honour was announced in the Queen's Birthday Honours List 1970 :

B.E.M.

Mr V. Efstathiou, Communications Superintendent, Main Meteorological Office, Episkopi.

AWARDS

WMO Research Prize

We note with pleasure the decision of the Executive Committee of the World Meteorological Organization to award the WMO Prize for 1970 to the following young research workers : Mr F. B. A. Giwa (Nigeria), Mr M. Yamasaki (Japan), Mr P. E. Merilees (Canada) and Mr F. Bretherton (United Kingdom), for research work in various fields of meteorology.

Fifteenth IMO Prize

This prize, which is awarded each year as a token of remembrance of the International Meteorological Organization, which was the non-governmental body preceding WMO, was awarded posthumously to Professor R. Scherhag, Berlin, who died on 31 August 1970.

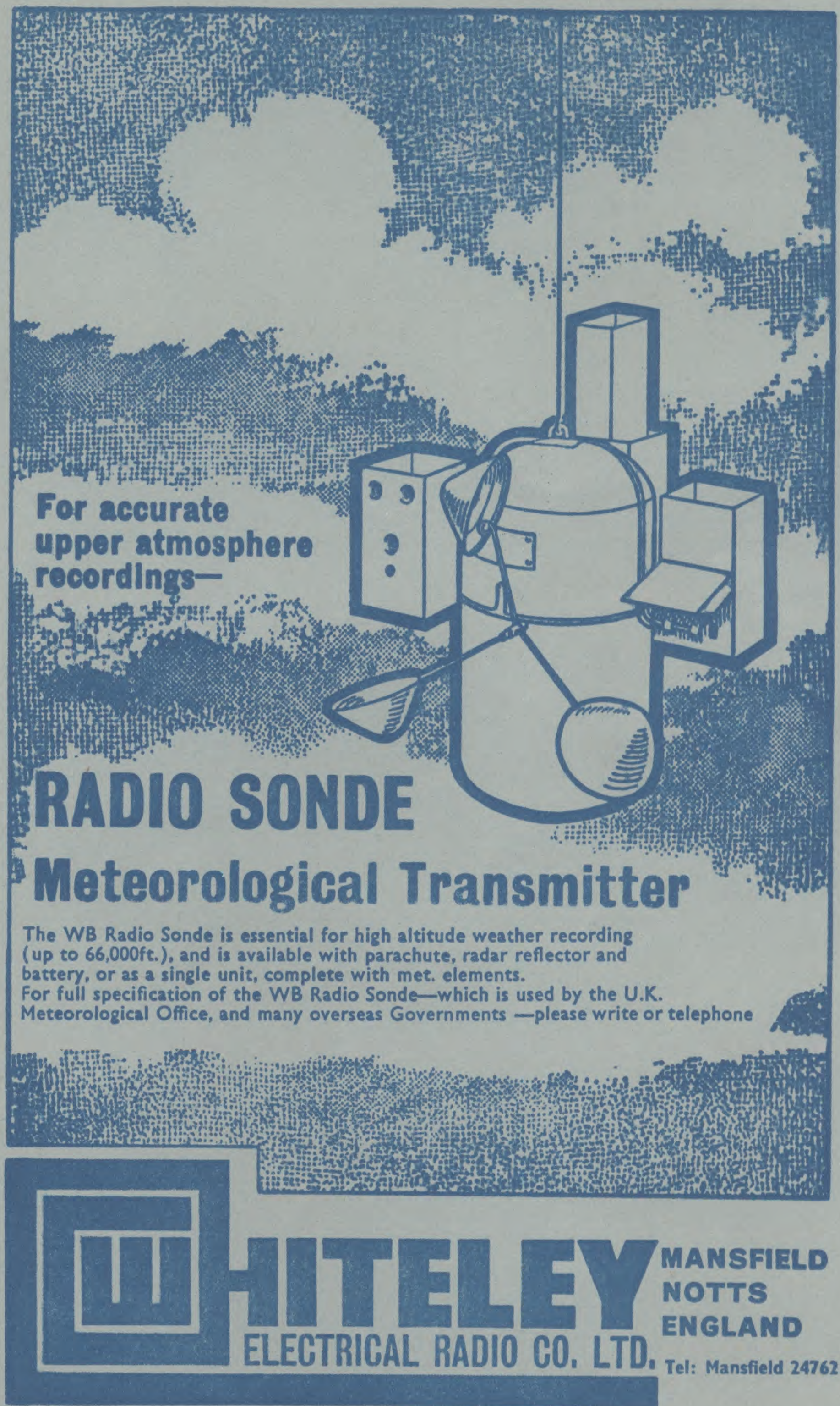
NOTES AND NEWS

Meteorological Magazine : price increase

As from January 1971, the price of an issue of the Meteorological Magazine will be 4*s*. [20 p] and the annual subscription will be £2 14*s*. [£2.70] including postage.

CORRECTION

Meteorological Magazine, September 1970, p. 270. In the second line of the summary and the fourth line of the main text of the article on a heated anemometer, for 'Mount Olympus, Greece, *read* 'Mount Olympus, Cyprus'.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