Met.O.826

METEOROLOGICAL OFFICE

the meteorological magazine

JUNE 1970 No 1175 Vol 99
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.826

THE METEOROLOGICAL MAGAZINE

Vol. 99, No. 1175, June 1970

551.558.21

A COMPUTING AID TO STUDIES OF AIRFLOW OVER MOUNTAINS

By C. E. WALLINGTON*

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

* Director of the Institute of Marine Sciences, University of New South Wales, Kensington, NSW, Australia.

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

$$\frac{\partial^2\psi}{\partial z^2} + \left(\frac{2}{U}\frac{\partial U}{\partial z} - \frac{1}{\theta}\frac{\partial \theta}{\partial z}\right)\frac{\partial\psi}{\partial z} + \left(\frac{g}{U^2\theta}\frac{\partial\theta}{\partial z}\right)\psi + \frac{\partial^2\psi}{\partial z^2} = 0, \quad \ldots (1)$$

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 $f(z)e^{ikx}$, where $f(z)$ 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

$$\frac{\partial^2 f(z)}{\partial z^2} + 2S\frac{\partial f(z)}{\partial z} + (l^2 + k^2)\, f(z) = 0, \quad \ldots (2)$$

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

$$h = \frac{Hb^2}{b^2 + x^2}, \quad \ldots (3)$$

where H is the height of the crest and b is a width parameter, then the solution for the streamline displacement becomes

$$\psi = \text{real part of } Hb \int_{k=0}^{k=\infty} e^{-k(b \pm ix)} \frac{f(z)}{f(0)}\, dk, \quad \ldots (4)$$

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 $f(0) = 0$. 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

$$\psi = \text{real part of } Hb \int e^{-k(b \pm ix)} \frac{f(z)}{f(0)}\, dk -$$

$$- 2\pi Hbe^{-kb} \frac{f(z)}{[\partial f(0)/\partial k]_{k=K}} \sin Kx, \quad \ldots (5)$$

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.

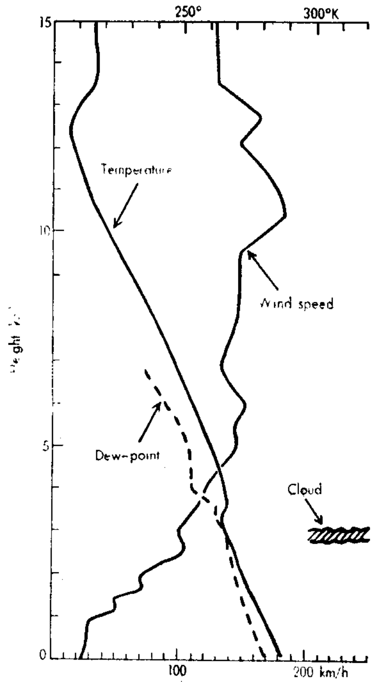


FIGURE 1—PROFILES OF TEMPERATURE, DEW-POINT AND WIND COMPONENT FROM 270° FOR 0950 EST, 17 APRIL 1966 AT HOBART, TASMANIA

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.

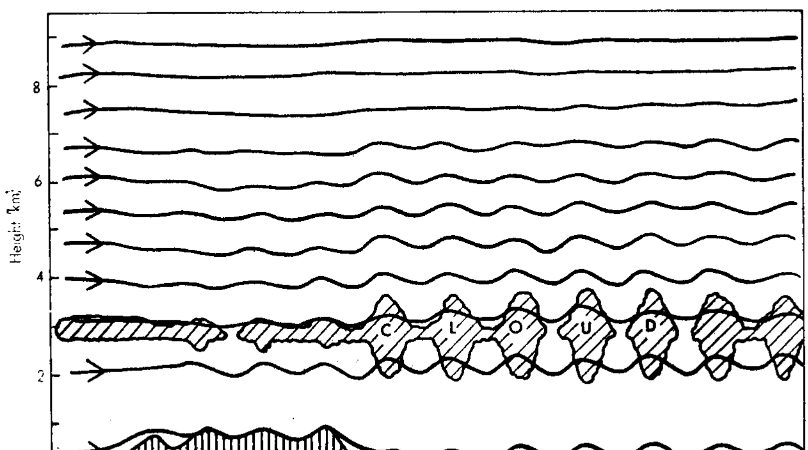


FIGURE 2—COMPUTER-PLOTTED STREAMLINE AND CLOUD PATTERN FOR THE AIRSTREAM REPRESENTED BY THE DATA IN FIGURE 1 FLOWING OVER A HIGH-GROUND WEST-TO-EAST CROSS-SECTION THROUGH HOBART

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.

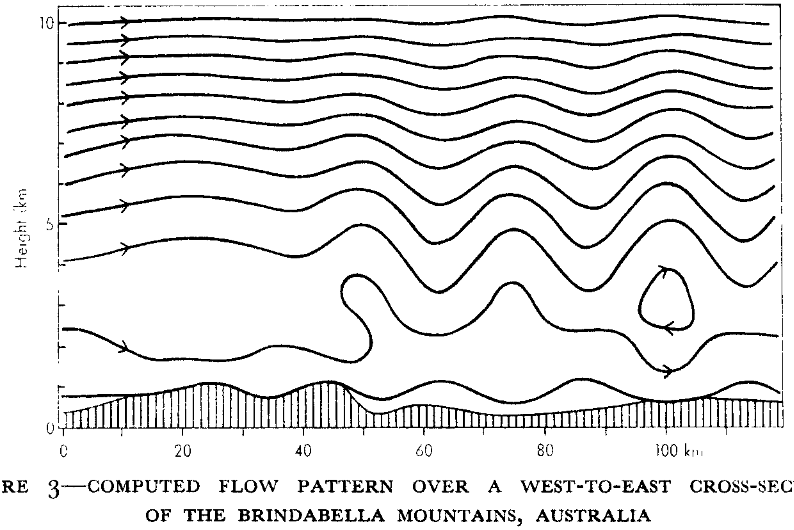


FIGURE 3—COMPUTED FLOW PATTERN OVER A WEST-TO-EAST CROSS-SECTION OF THE BRINDABELLA MOUNTAINS, AUSTRALIA

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;

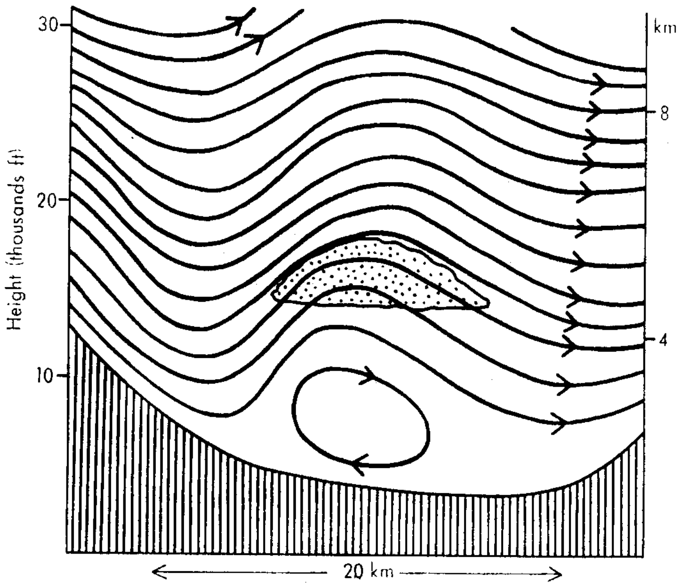


FIGURE 4(*a*)—FLOW PATTERN DEDUCED FROM OBSERVATIONS AND MEASUREMENTS ON 16 FEBRUARY 1952

The observed lee wavelength was 18 km at about the 3-km level.

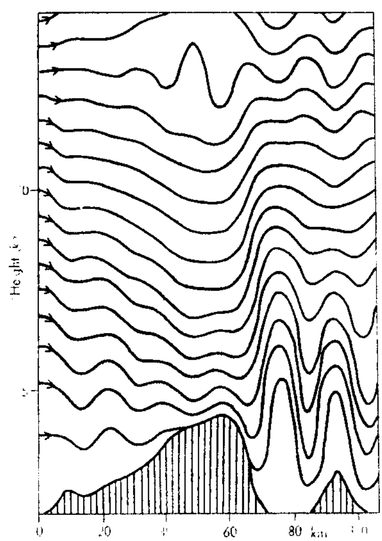


FIGURE 4(*b*)—COMPUTED FLOW PATTERN FOR 16 FEBRUARY 1952

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.

REFERENCES

1. SCORER, R. S.; Theory of waves in the lee of mountains. *Q. Jnl R. met. Soc., London*, **75**, 1949, pp. 41–56.
2. SCORER, R. S.; Theory of airflow over mountains : II — The flow over a ridge. *Q. Jnl R. met. Soc., London*, **79**, 1953, pp. 70–83.
3. CORBY, G. A. and WALLINGTON, C. E.; Airflow over mountains : the lee-wave amplitude. *Q. Jnl R. met. Soc., London*, **82**, 1956, pp. 266–274.
4. WALLINGTON, C. E. and PORTNALL, J.; A numerical study of the wavelength and amplitude of lee waves. *Q. Jnl R. met. Soc., London*, **84**, 1958, pp. 38–45.
5. WALLINGTON, C. E.; A numerical study of the topographical factor in lee-wave amplitudes. *Q. Jnl R. met. Soc., London*, **84**, 1958, pp. 428–433.
6. ANDERSEN, I. I.; Mountain lee wave activity over Tasmania on 17 April 1966. *Aust. met. Mag., Melbourne*, **14**, 1966, pp. 119–131.
7. HOLMBOE, J. and KLIEFORTH, H.; Investigation of mountain lee waves and the air flow over the Sierra Nevada. Los Angeles, University of California, Department of Meteorology, 1957, Final Report, AFCRC Contract No. AF19(604)-728.

551.510.721:551.513:551.557.3

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} cm^2/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 $K = 10^5$ cm^2/s (troposphere) *km*	WIDTH $K = 10^{10}$ cm^2/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 8½ and 9½ 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 8½ to 9½ 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 15½ 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.

REFERENCES

1. PEIRSON, D. H.; Private communication (1969) to be published by the Atomic Energy Research Establishment, Harwell.
2. HEASTIE, H. and STEPHENSON, P. M.; Upper winds over the world. Parts I and II. *Geophys. Mem., London*, **13**, No. 103, 1960.
3. TUCKER, G. B.; Upper winds over the world. Part III. *Geophys. Mem., London*, **13**, No. 105, 1960.
4. FINDLATER, J.; A major low-level air current near the Indian Ocean during the northern summer. *Q. Jnl R. met. Soc., London*, **95**, 1969, pp. 362–380.
5. FINDLATER, J.; Interhemispheric transport of air in the lower troposphere over the western Indian Ocean. *Q. Jnl R. met. Soc., London*, **95**, 1969, pp. 400–403.
6. FINDLATER, J.; Monthly mean airflow at low levels over the western Indian Ocean. To be published as a *Geophysical Memoirs*.
7. BOLIN, B.; The general circulation of the atmosphere as deduced with the aid of tracers. *Tech. Notes Wld met. Org., Geneva*, No. 68 (Meteorological aspects of atmospheric radio-activity), 1965, pp. 27–56.
8. DURST, C. S.; Variation of wind with time and distance. *Geophys. Mem., London*, **12**, No. 93, 1954.
9. KOCHANSKI, A.; Models of vertical correlations of the wind. *Jnl Met., Lancaster, Pa*, **18**, 1961, pp. 151–159.

551.5:06:551.586:63

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.

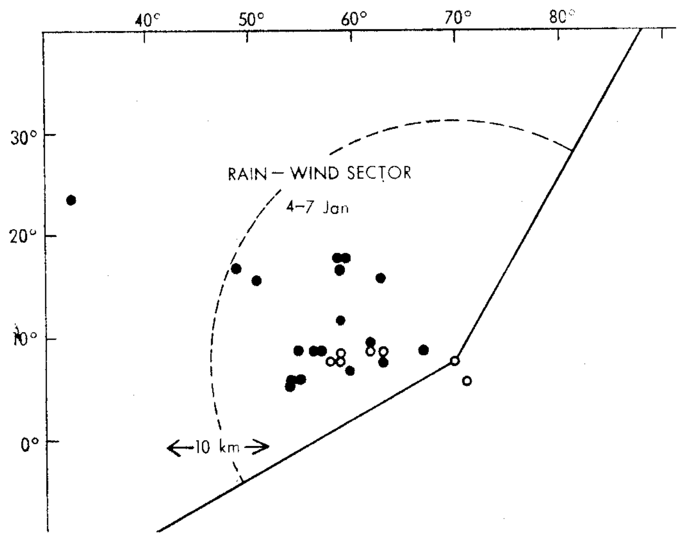


FIGURE 1—SPREAD OF FOOT-AND-MOUTH DISEASE IN HAMPSHIRE IN JANUARY 1967

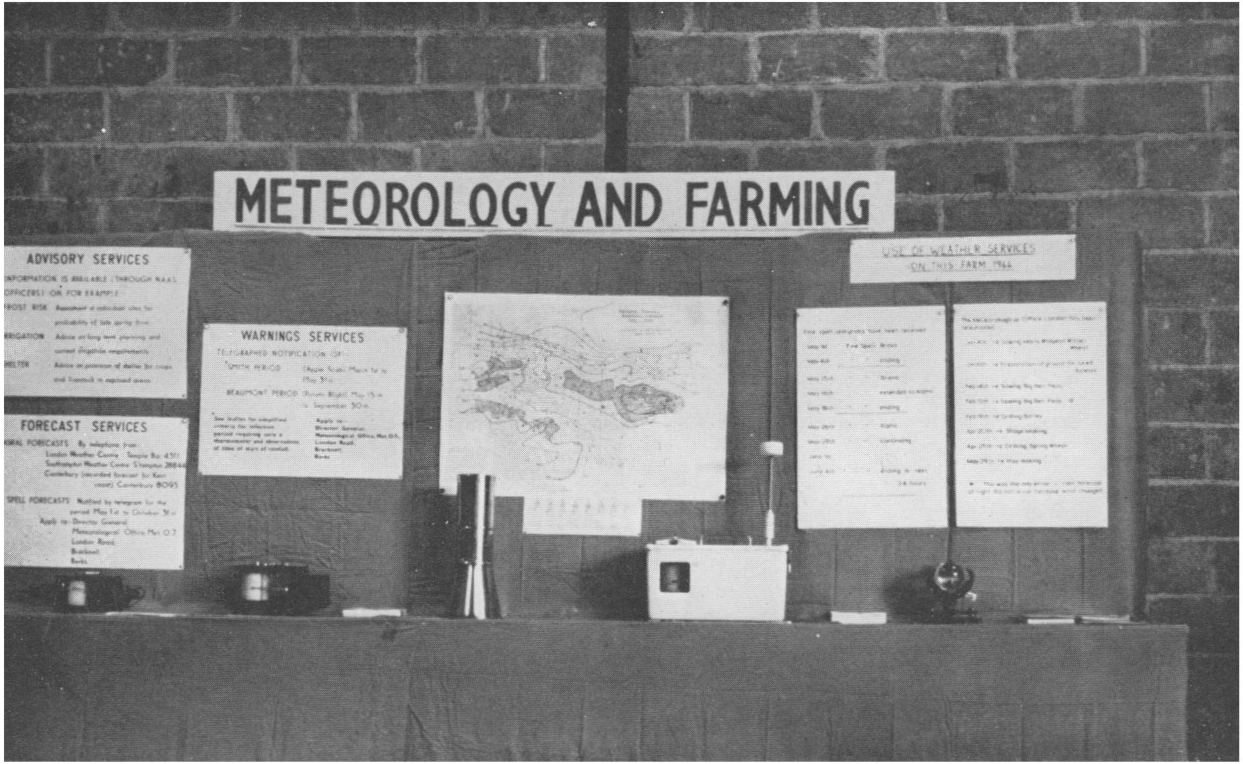
o Sources • Infections from 8–22 January

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.

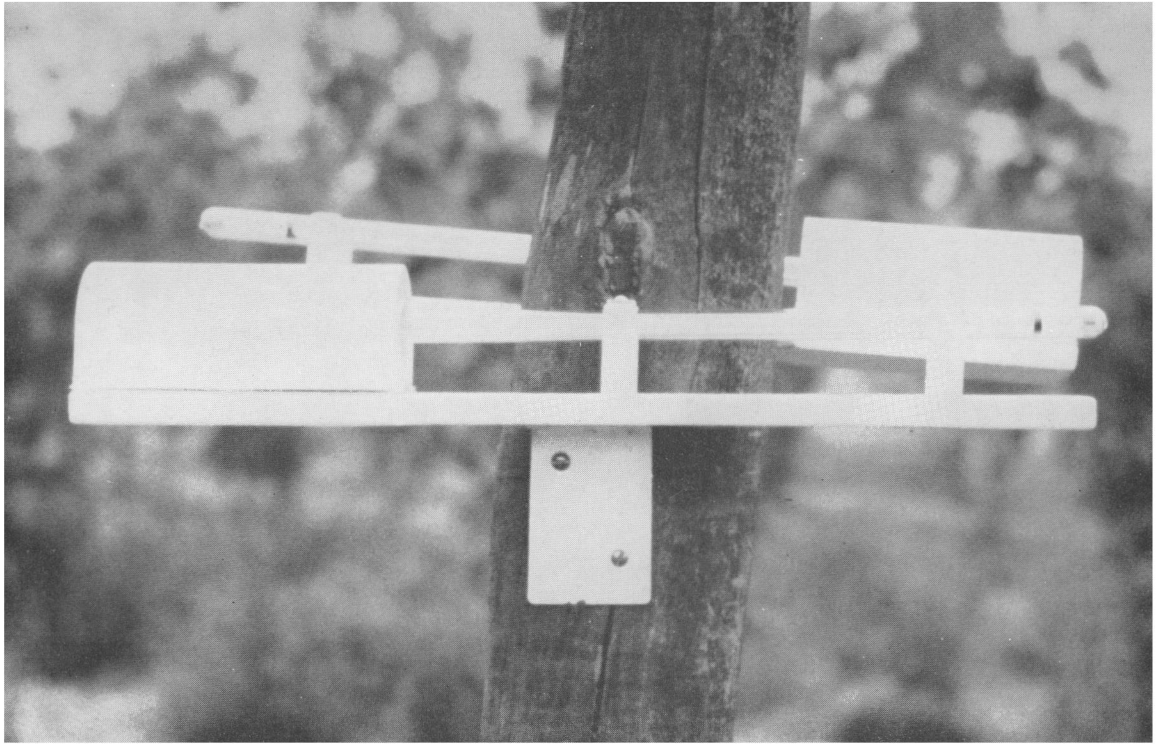
To face page 172



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.

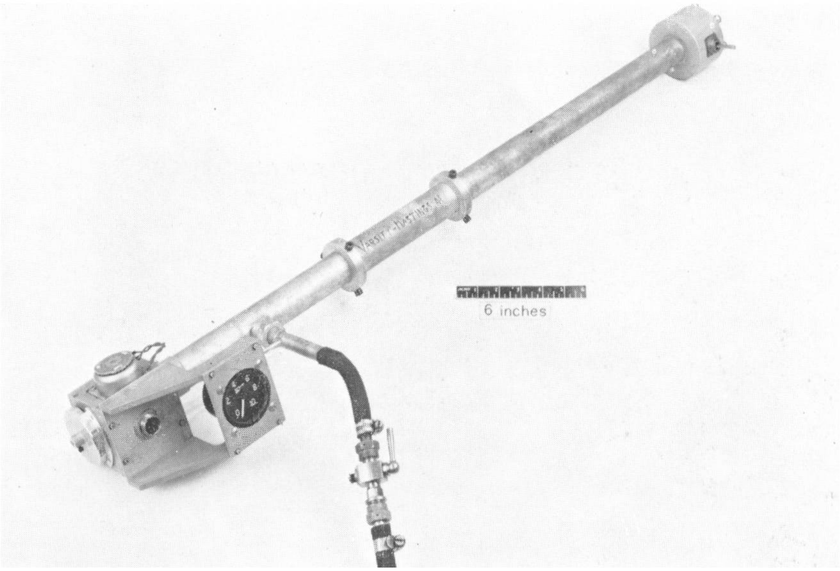
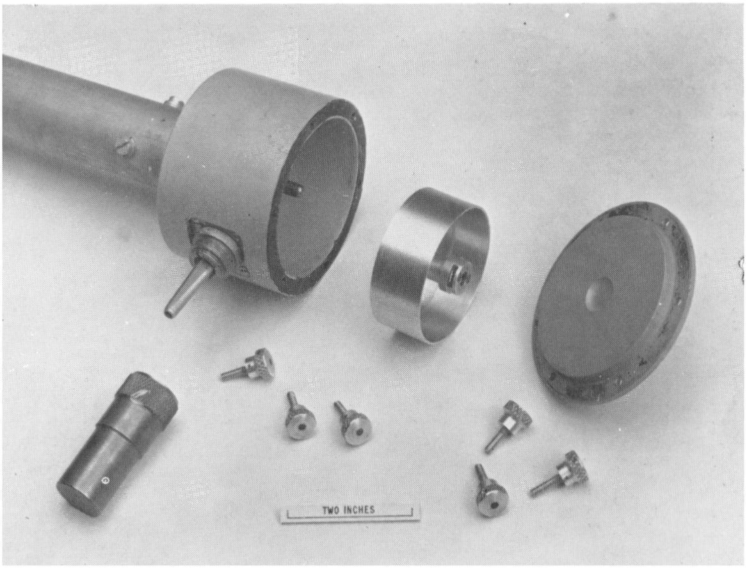


PLATE III(*a*)—IMPACTOR USED FOR SPORE COLLECTION BY AIRCRAFT

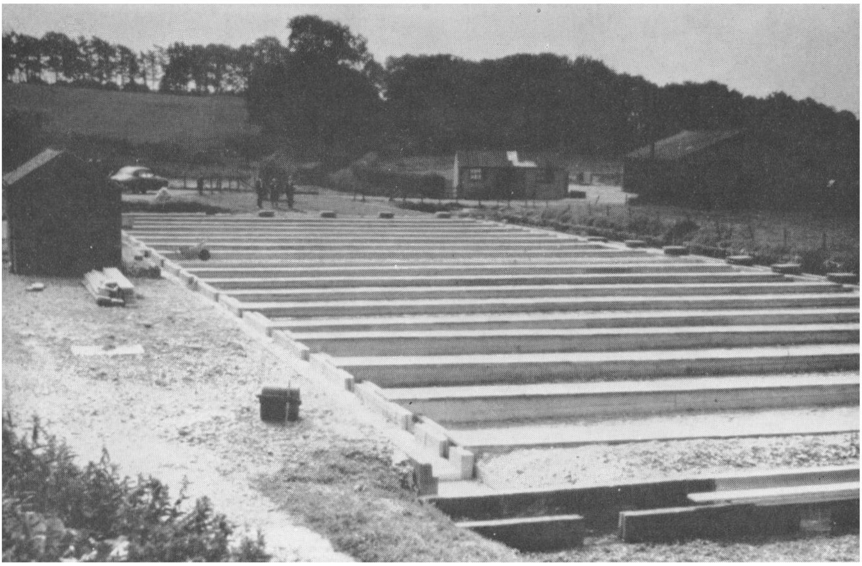
The right half of the instrument projects horizontally out of the aircraft, perpendicular to the side, in free airflow. See page 175.



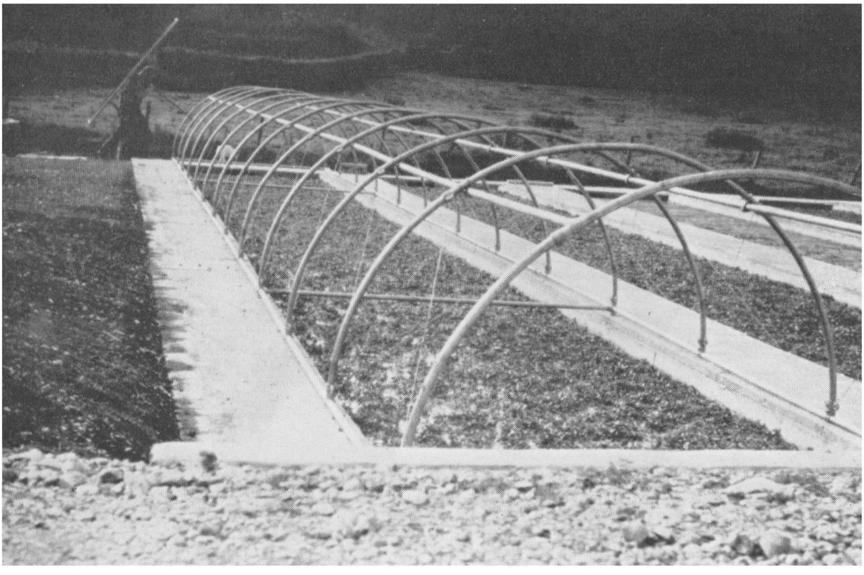
Photographs by courtesy of Royal Aircraft Establishment, Farnborough

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.



(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.

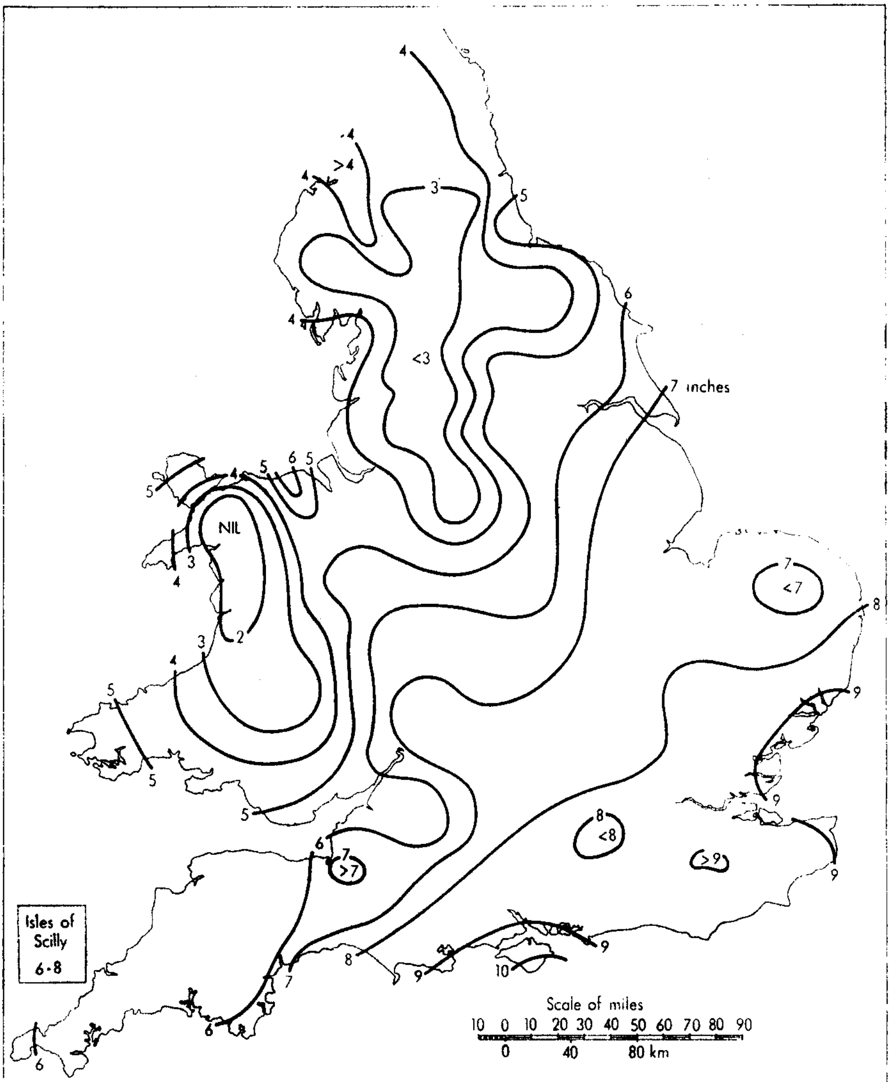


FIGURE 2—IRRIGATION NEED IN 5th DRIEST YEAR IN 20 FOR THE PERIOD MAY TO AUGUST (after Hogg[3])

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.

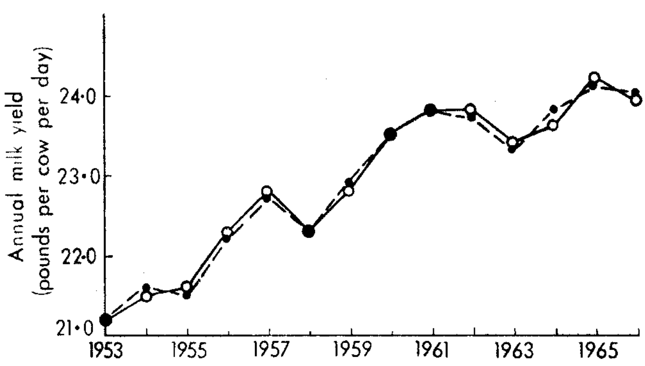


FIGURE 3—FORECASTS OF ANNUAL MILK YIELDS, MADE AT THE END OF JUNE FOR THE YEAR ENDING THE FOLLOWING MARCH

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.

REFERENCES

1. HURST, G. W.; Services to the agricultural community. *Met. Mag., London,* **94**, 1965, pp. 121–126.
2. London, Ministry of Agriculture, Fisheries and Food. Potential transpiration. *Tech. Bull. Minist. Agric. Fish. Fd, London,* No. 16, 1967.
3. HOGG, W. H.; Atlas of long-term irrigation needs for England and Wales. London, Ministry of Agriculture, Fisheries and Food, NAAS, 1967.

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 (≈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.

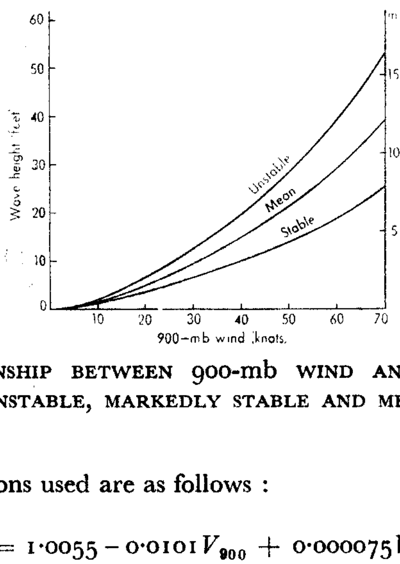


FIGURE 1—RELATIONSHIP BETWEEN 900-mb WIND AND WAVE HEIGHT FOR MARKEDLY UNSTABLE, MARKEDLY STABLE AND MEAN CONDITIONS

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.

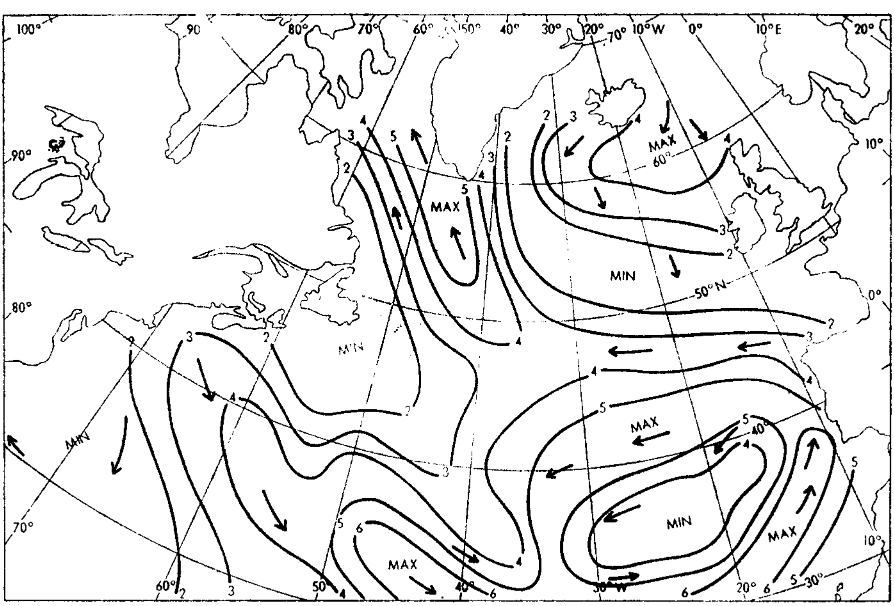


FIGURE 2—COMPUTER WAVE-HEIGHT ANALYSIS, 00 GMT, 3 JANUARY 1970

Wave heights in metres.

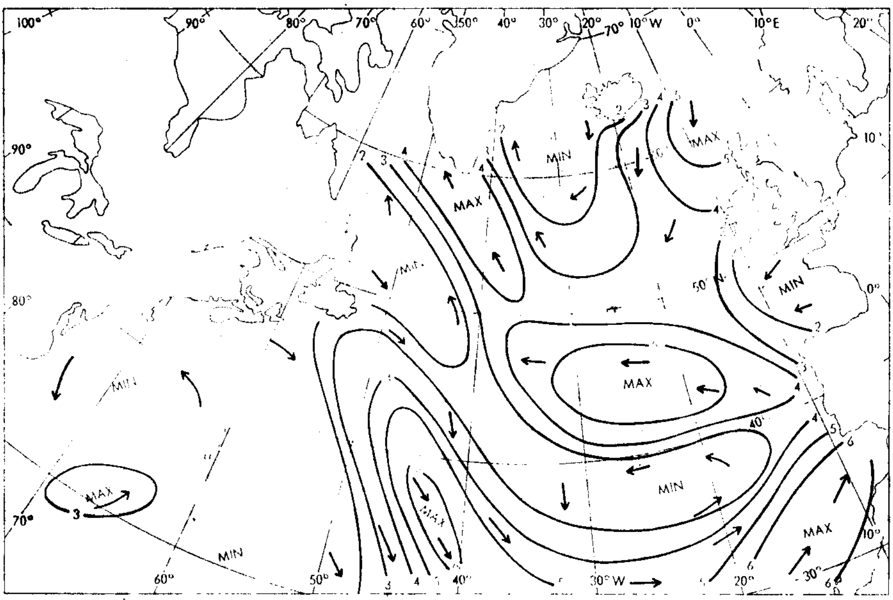


FIGURE 3—24-HOUR FORECAST OF WAVE HEIGHT FOR 00 GMT, 4 JANUARY 1970

Wave heights in metres.

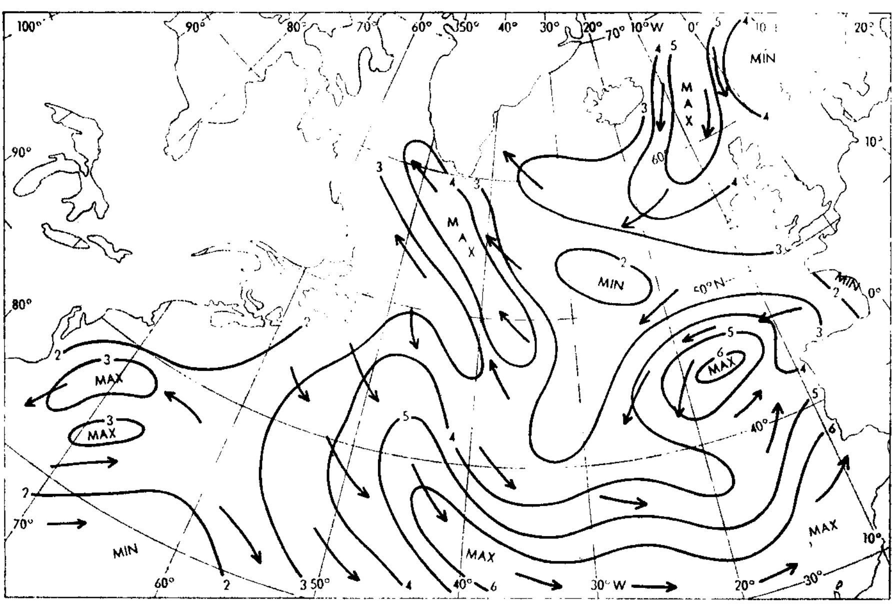


FIGURE 4—COMPUTER WAVE-HEIGHT ANALYSIS, 00 GMT, 4 JANUARY 1970

Wave heights in metres.

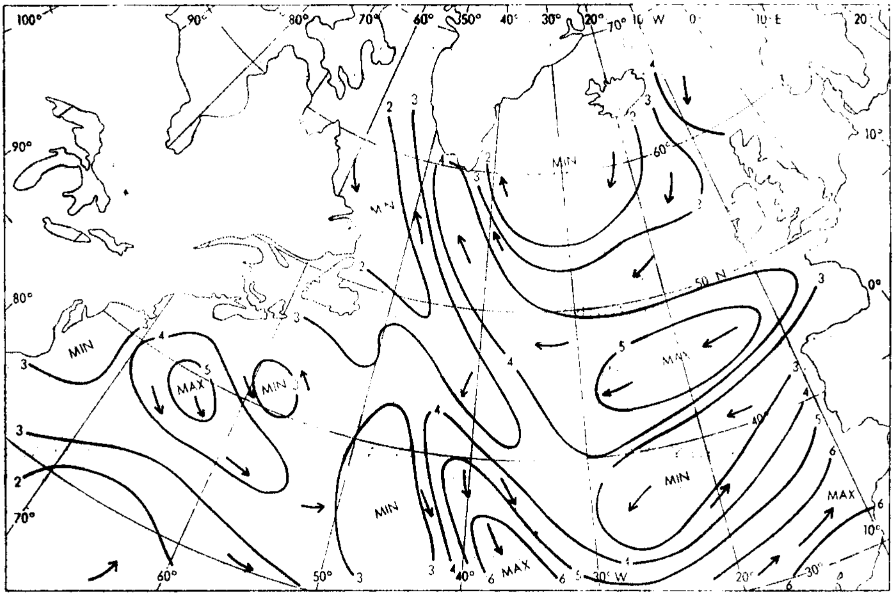


FIGURE 5—48-HOUR FORECAST OF WAVE HEIGHT FOR 00 GMT, 5 JANUARY 1970
Wave heights in metres.

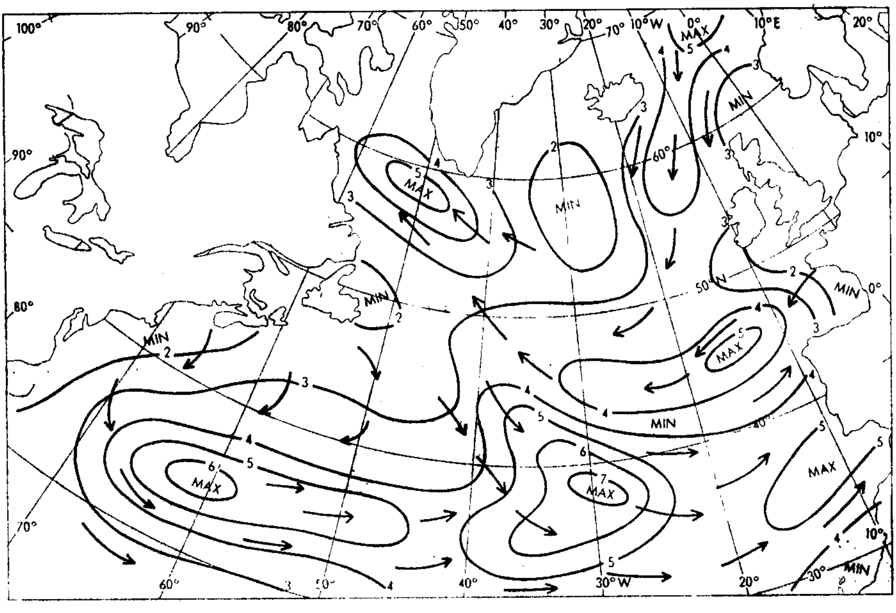


FIGURE 6—COMPUTER WAVE-HEIGHT ANALYSIS, 00 GMT, 5 JANUARY 1970
Wave heights in metres.

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

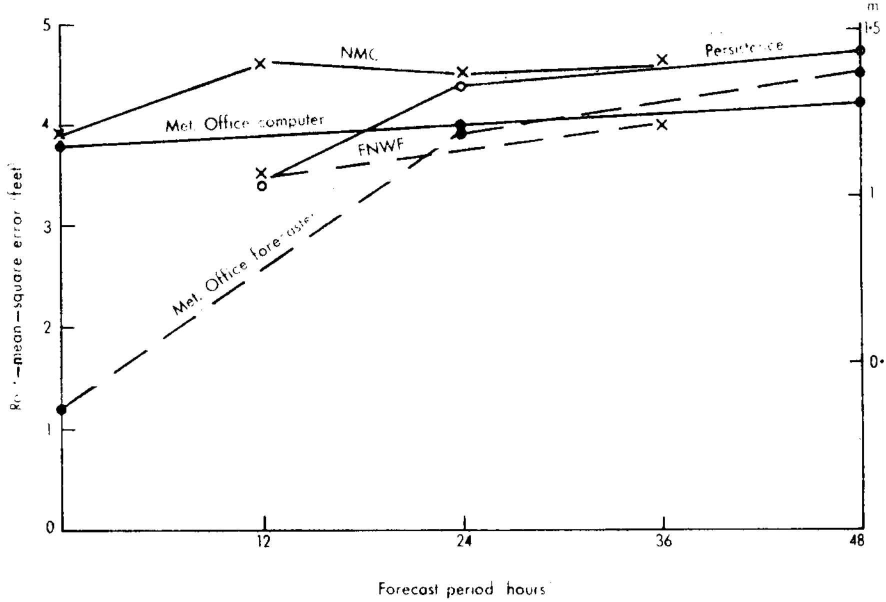


FIGURE 7—ROOT-MEAN-SQUARE ERRORS OF WAVE-HEIGHT ANALYSIS AND FORECASTS IN RELATION TO FORECAST PERIOD

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.

REFERENCES

1. FINDLATER, J., HARROWER, T. N. S., HOWKINS, G. A. and WRIGHT, H. L.; Surface and 900 mb wind relationships. *Scient. Pap. met. Off., London*, No. 23, 1966.
2. SCOTT, J. R.; Some average sea spectra. *Trans. R. Instn nav. Archit., London*, **110**, 1968, pp. 233–245.
3. PORE, N. A. and RICHARDSON, W. S.; Interim report on sea and swell forecasting. Washington, Environmental Science Services Administration, Techniques Development Laboratory, *Weath. Bur. Tech. Memor., Silver Spring, Md*, TDL 13, 1967.

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 Altantic.	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°N45°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.

REFERENCES

1. PATON, J.; Noctilucent clouds over western Europe during 1966. *Met. Mag., London,* **96**, 1967, pp. 187–190.
2. PATON, J.; Noctilucent clouds over western Europe during 1967. *Met. Mag., London,* **97**, 1968, pp. 174–176.
3. PATON, J.; Noctilucent clouds over western Europe during 1968. *Met. Mag., London,* **98**, 1969, pp. 219–222.

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.

THE METEOROLOGICAL MAGAZINE

VOL. 99 NO. 1175 JUNE 1970

CONTENTS

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.

All inquiries relating to the insertion of advertisements in the Meteorological Magazine should be addressed to the Director of Publications, H.M. Stationery Office, Atlantic House, Holborn Viaduct, London E.C.1. (Telephone: 01-248 9876, extn 6098).

The Government accepts no responsibility for any of the statements in the advertisements appearing in this publication, and the inclusion of any particular advertisement is no guarantee that the goods advertised therein have received official approval.

Printed in England by The Bourne Press, Bournemouth, Hants.

and published by

HER MAJESTY'S STATIONERY OFFICE

3s. 6d. [17½p] monthly **Annual subscription £2 7s. [£2·35] including postage**

Dd. 500145 K16 6/70 SBN 11 400075 1