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AIRFLOW OVER BROAD MOUNTAIN RANGES—A STUDY OF FIVE FLIGHTS ACROSS THE WELSH MOUNTAINS

By C. E. WALLINGTON, M.Sc.

A number of theoretical studies of airflow over mountains involve assumptions and approximations which are difficult to test experimentally. Observational and numerical studies, such as that by Wallington and Portnall,[1] have concentrated on the lee-wave characteristics of the flow over flat ground downwind of long mountain ridges, but study of the flow pattern in the immediate neighbourhood of a ridge is beset with more theoretical and observational difficulties than those encountered in lee-wave investigations. However, a recent paper by Corby and Sawyer[2] makes certain deductions regarding the flow, and these deductions become particularly easy to interpret in the study of airflow across a broad mountain ridge. Furthermore, vertical motion on a scale somewhat broader than that of typical lee waves (of wavelengths between about 5 and 30 kilometres) is likely to be detectable through its effect on the temperature field. Therefore, it was decided to attempt a comparison of the computed airflow across a broad mountain range with the vertical motion deduced from temperature measurements made during reconnaissance flights through the flow.

The observational programme.—After paying due regard to operational limitations in the selection of a route for observations in flight, it was decided to make a series of flights across the Welsh Mountains between the points X and Y shown in Figure 1 with a flight pattern of the form illustrated in the Figure. The flights were made when, as far as could be foreseen, a moderate or strong flow from within 25 degrees of west was likely to blow across the Welsh Mountains with little or no change in the airstream wind and temperature structure during the period of the flight. A further aim was to ensure that the airstream was stably stratified at the levels of the traverses.

Deducing the streamlines.—The temperature and frost-point measurements made in flight were converted to true potential and wet-bulb potential temperatures before being plotted on the vertical cross-sections shown in Figures 2(*a*)–(*e*). Isopleths of potential temperature were drawn as straight lines between the appropriate vertical soundings. The vertical displacement of the air at each point on the traverses was then deduced on the assumption of conservation of potential temperature, and streamlines were constructed on the further assumption that within 1500 feet above and below the flight level any vertical variations

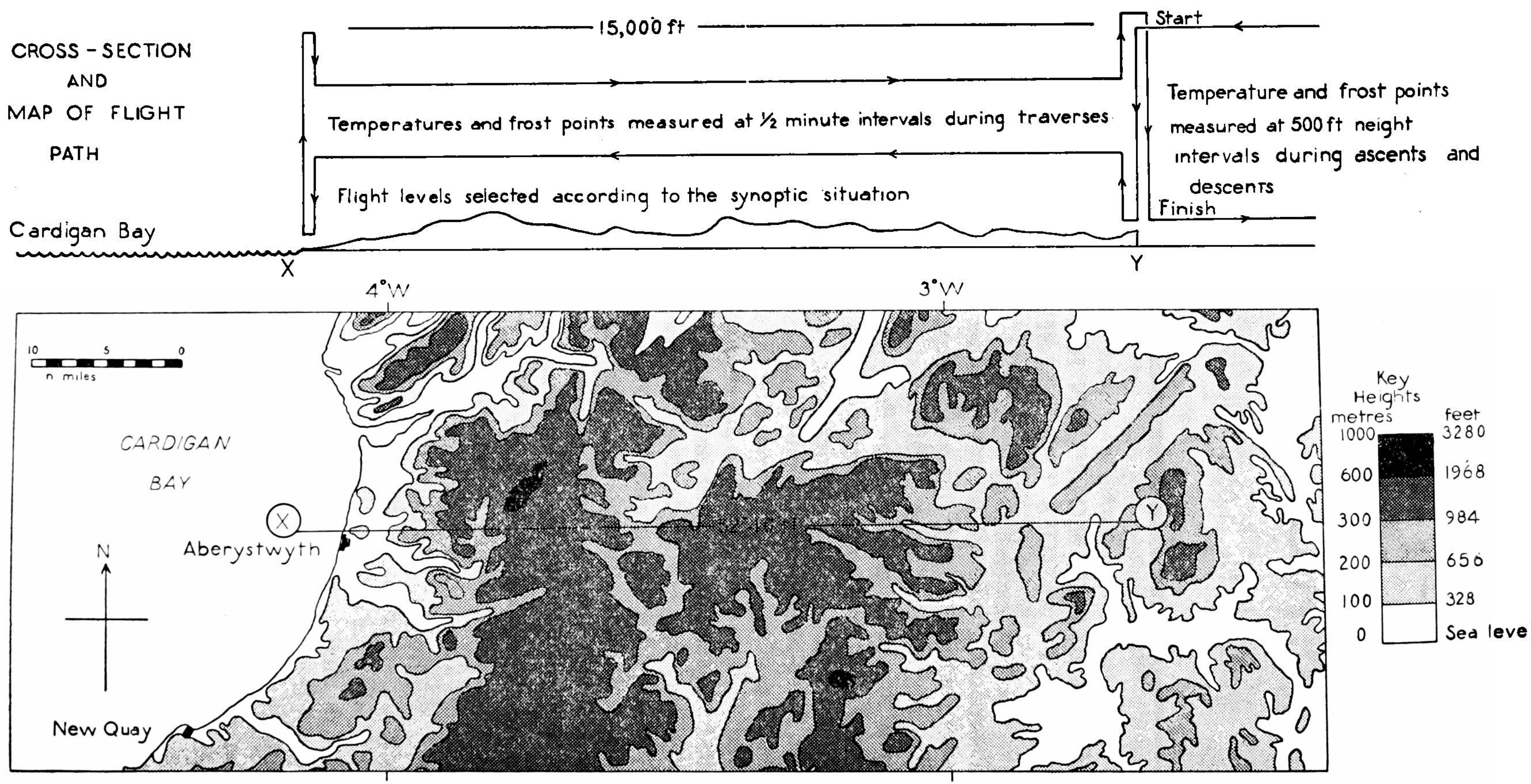

FIGURE I—CROSS-SECTION AND PLAN VIEW OF THE FLIGHTS MADE ACROSS THE WELSH MOUNTAINS

The flight path is indicated by the arrowed lines in the cross-section in streamline displacement would be negligibly small. Wherever possible wet-bulb potential temperatures were used as a check on the potential temperature deductions; usually such a check could not be regarded as accurate since the vertical wet-bulb potential gradients were often weak, but the two sets of temperatures were found to be at least consistent.

Vertical motion (derived from the deduced streamlines and wind speeds obtained by interpolation from the surrounding routine radiosonde observations) appeared to be excessive in places; vertical motion of the air at speeds of about 300 feet per minute normally have noticeable effects on flight conditions, but many of the large vertical speeds deduced from the wind and temperature observations were not positively confirmed by pilots' remarks in the flight logs.

Probably the vertical temperature soundings made over the points X and Y were not truly representative of the initially undisturbed flow, but errors due to the operational difficulties in obtaining soundings farther upstream or downstream take the form of a slight raising, lowering or tilting of a whole streamline between the points X and Y; they do not produce errors in the main undulations in a deduced streamline, and it is reasonable to assume that the deduced flow pattern reveals the broad features of the air motion across the mountains.

Computing the streamlines.—A computing technique devized by Sawyer, and based on his theoretical treatment outlined in the Appendix to this article (page 221), was used to calculate streamline displacements over various mountain ridges of the type specified by equation (1), the airstream data for these calculations being obtained by interpolation between the routine midday radiosonde observations at Liverpool and Camborne. A high-ground profile similar to that of the real topography across the flight route was obtained by a synthesis of the various elementary ridges, and the corresponding two-dimensional flow pattern was determined. The real and synthetic high-ground profiles are illustrated in Figures 2(*a*)–(*e*).

The occasions investigated

(i) *28 November 1957*.—The lower of the deduced streamlines sketched in Figure 2(*a*) shows a slight rise just upstream of the principal mountain ridge followed by a general lowering over the main region of high ground. This lowering appears to be consistent with appreciable breaks in the low cloud which was more extensive at the beginning and end of the traverse. With the natural wavelength ($=2\pi/l$, where l is defined on page 222) structure depicted at the left of the figure it is not surprising that wave clouds were observed, and the indicated decrease of wind with height in such conditions is consistent with the turbulence encountered in flight. The upper deduced streamline shows only a slight lowering over the principal ridge and a somewhat larger fall towards the downstream end of the route. The computed streamlines for this occasion do not agree with the flight observations.

(ii) *5 March 1958*.—As shown in Figure 2(*b*) the shape of the lower deduced streamline is reasonably consistent with the observed cloud structure, but the absence of cloud despite the high humidity of the air sampled during the upper traverse suggests that the marked rise in the deduced upper-level streamline is excessive. The computed streamlines portray large-amplitude waves which are not confirmed by cloud observations or pilots' remarks; nor do they agree with the streamlines deduced from the observed temperatures. The fault is probably due to the assumption of approximately two-dimensional flow being substantially incorrect on this occasion.

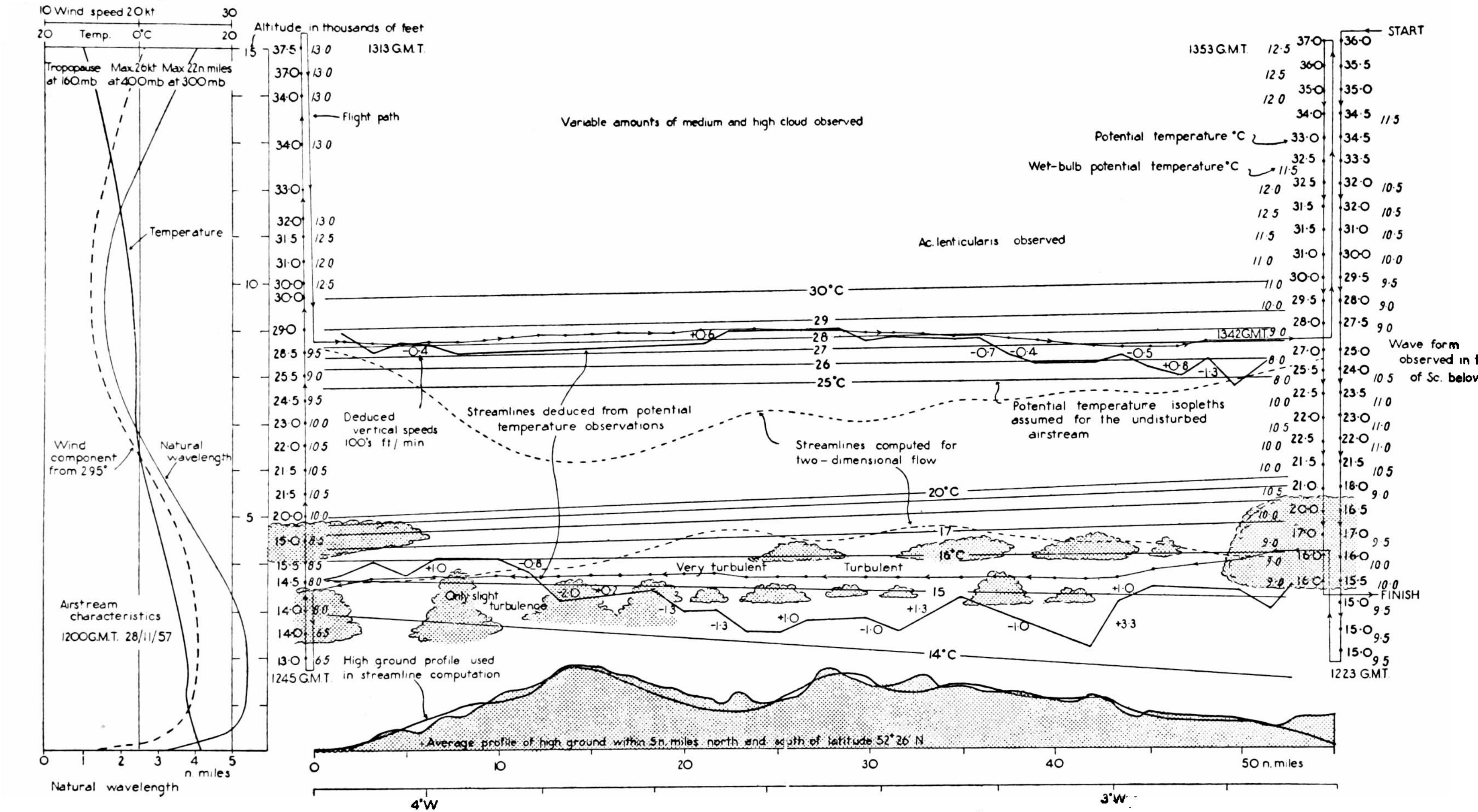

FIGURE 2(*a*)—FLIGHT ACROSS THE WELSH MOUNTAINS, 28 NOVEMBER 1957

The arrowed lines with dots show the flight path, the dots being positions where temperatures and frost points were measured. The potential temperatures and wet-bulb potential temperatures in °C are denoted by large and small numbers respectively adjacent to the observing points on each ascent and descent. Selected potential temperature isopleths assumed for the undisturbed airstream are drawn as straight lines across the diagram.

Streamlines deduced from the potential temperature observations are shown as thick lines while thin broken lines show streamlines computed from the two-dimensional flow theory described in the text. Signed numbers adjacent to sections of the deduced streamlines denote vertical speeds (in hundreds of feet per minute) derived from the deduced streamlines and wind speeds obtained by interpolation from the surrounding radiosonde observations.

The high-ground profile used for the theoretical streamline computation was obtained as a synthesis of various symmetrical ridges of mathematically convenient shapes.

The temperature and wind profiles at the left were obtained by interpolation from the surrounding radiosonde observations while the "natural wavelength" denotes the parameter $2\pi/l$ (l is specified in the Appendix). On all of these five occasions the wind directions at the radiosonde stations used were almost constant with height through much of the troposphere.

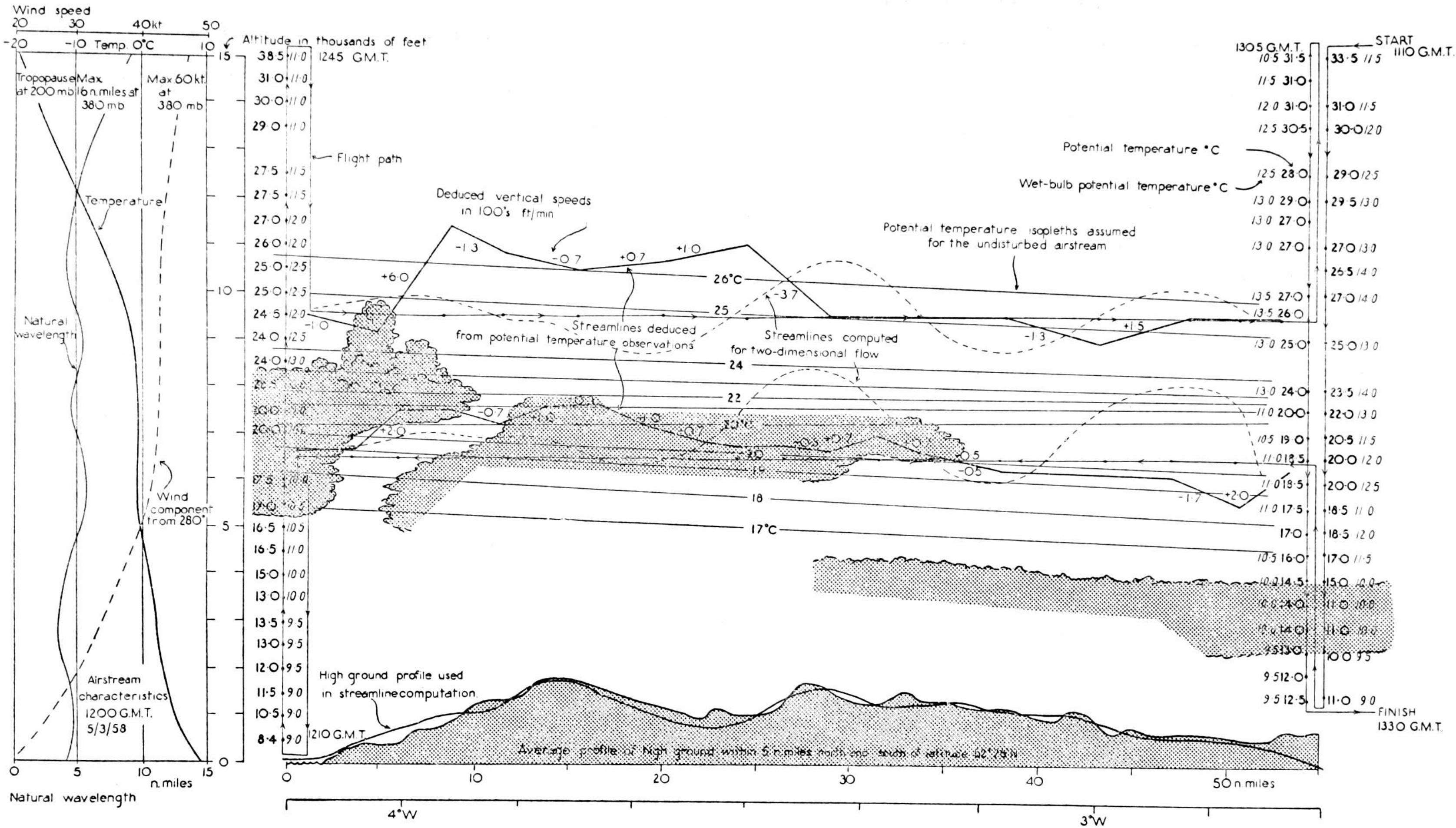

FIGURE 2(*b*)—FLIGHT ACROSS THE WELSH MOUNTAINS, 5 MARCH 1958

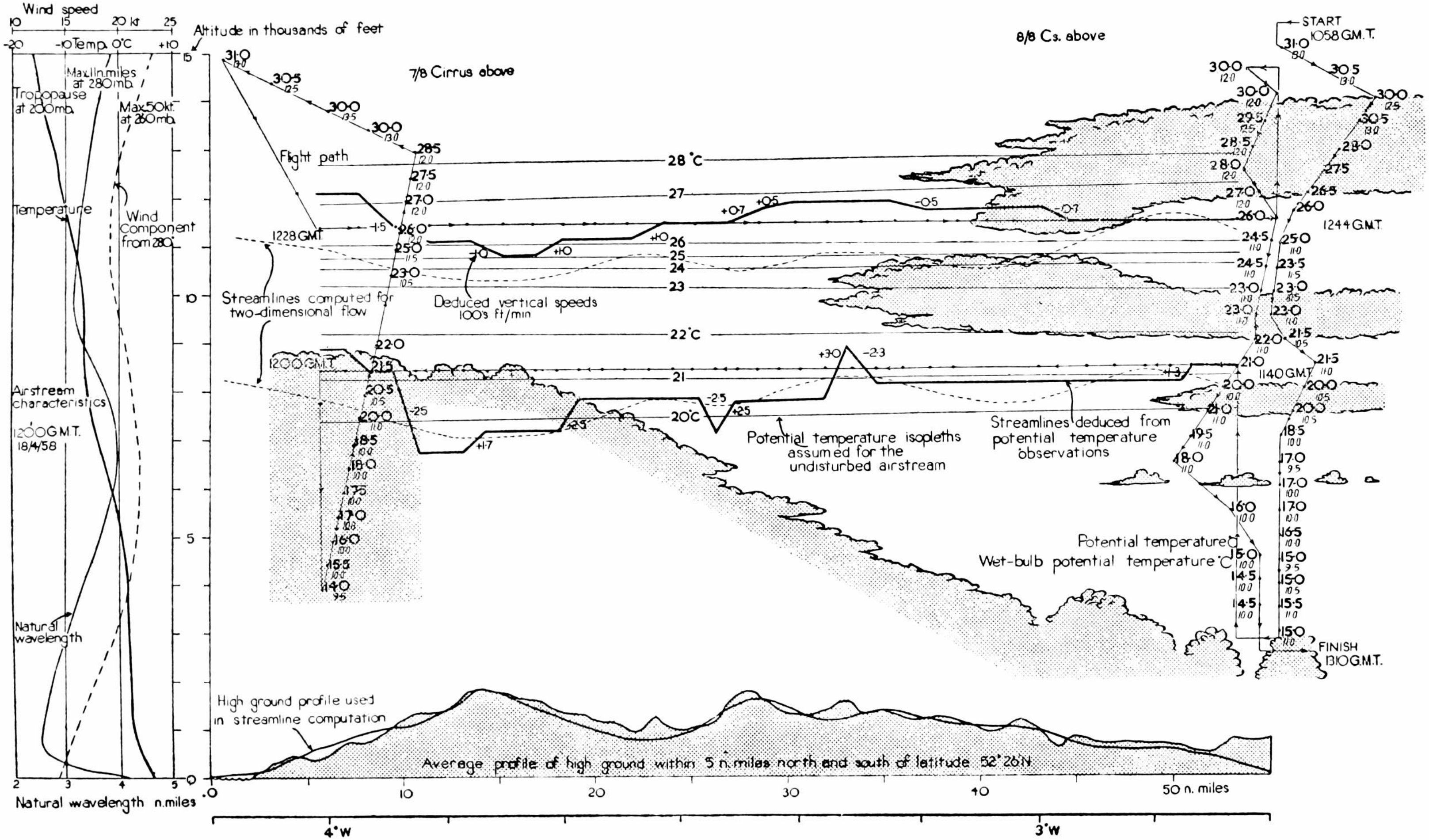

FIGURE 2(*c*)—FLIGHT ACROSS THE WELSH MOUNTAINS, 18 APRIL 1958

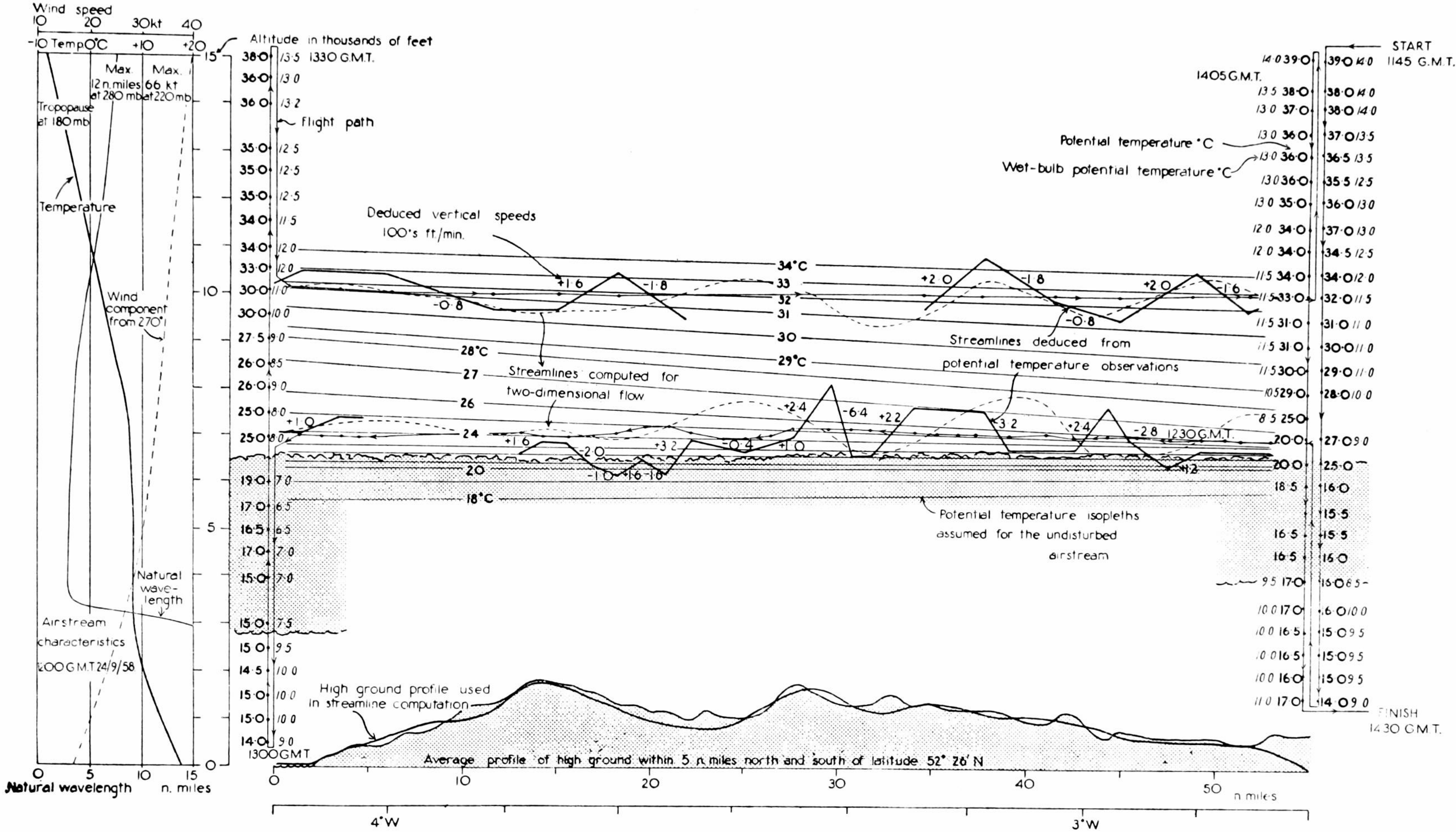

FIGURE 2(*d*)—FLIGHT ACROSS THE WELSH MOUNTAINS, 24 SEPTEMBER 1958

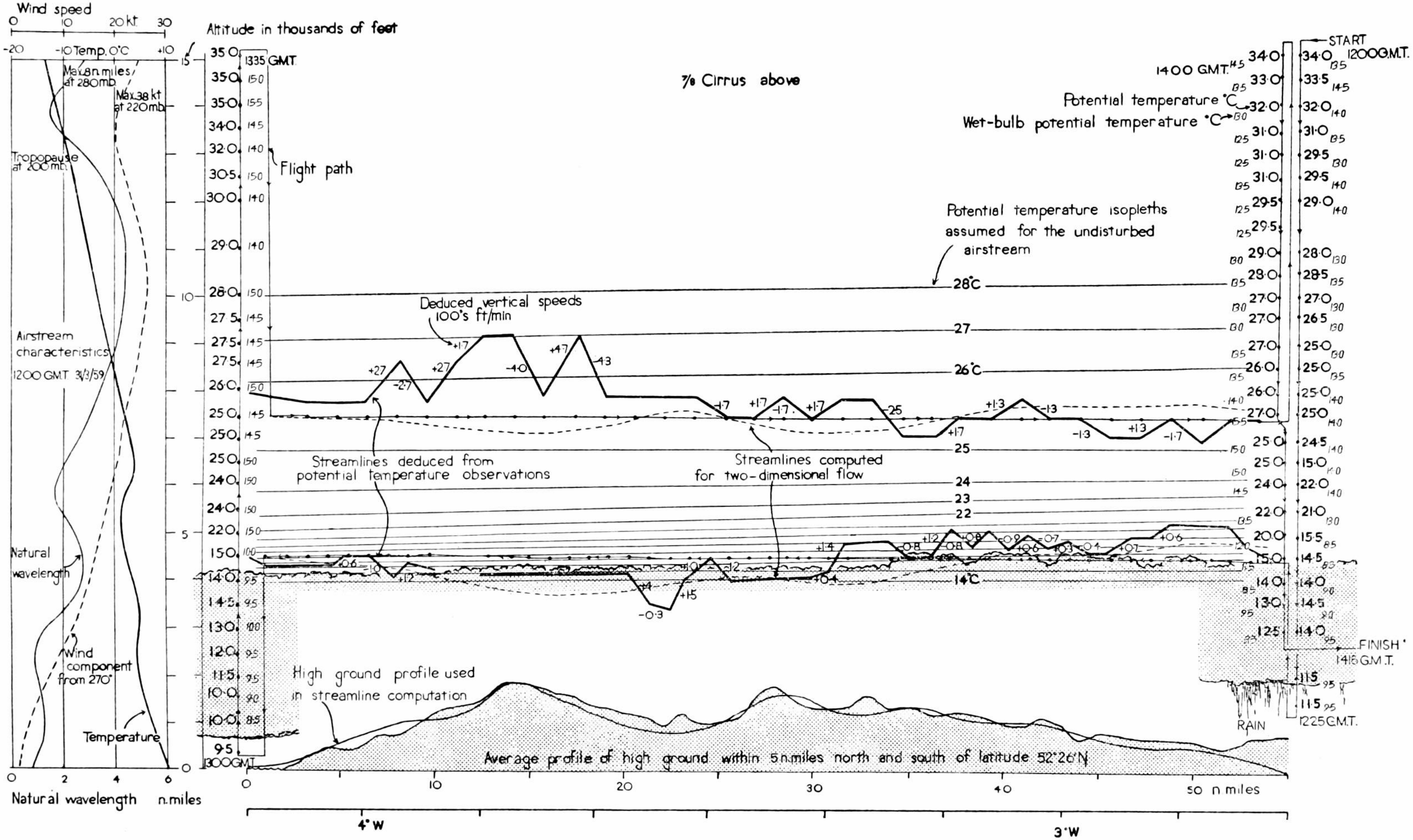

FIGURE 2(*e*)—FLIGHT ACROSS THE WELSH MOUNTAINS, 31 MARCH 1959

(iii) *18 April 1958.*—On this occasion operational difficulties led to some distortion of the intended flight plan and truly vertical soundings over points X and Y were not obtained. But with the flight path as shown in Figure 2(*c*), it was still possible to deduce streamlines from the flight observations.

Allowing for the fact that the general level of a deduced streamline may be slightly incorrect, there is a broad but distinct similarity between the deduced and computed streamlines. Unfortunately the shape of these streamlines at low levels is not confirmed by the cloud structure but the apparent inconsistency is probably due to an advected thickening of the low cloud.

(iv) *24 September 1958.*—Gaps in the deduced streamlines drawn in Figure 2(*d*) are due to temporary operational difficulties, but the observations are sufficient to reveal appreciable similarities between the deduced and computed streamlines.

(v) *31 March 1959.*—Results on this occasion showed reasonable agreement between the deduced and computed streamlines, except for a section of the upper-level flow over the principal mountain ridge. As on a previous occasion the temperature observations suggested a marked rise while the computations produced a lowering of the streamline.

Conclusion.—This investigation is best regarded as a feasibility experiment to determine whether or not the operational method is practical or satisfactory, and although the results may provide material for discussion they must be viewed with considerable caution. There are several inconsistencies between the streamlines deduced from the potential temperatures and the cloud observations. Furthermore, the deduced vertical speeds appear to be excessive in places.

In view of these doubts the flight observations must not be regarded as a satisfactory check of the method of computing the flow over broad mountain ranges, but the calculated streamlines show such apparently excessive undulations that the theory of its application must also be open to considerable doubt.

Despite uncertainties in the details of the deduced streamlines, it is clear, however, that the air does not undergo a simple lifting as it crosses the hills; we find descent over the mountains on some occasions, and indeed theoretical study has called attention to mountain airflow characteristics of this nature, even though the details have not been accurately computed for regions immediately over the rugged terrain selected for this investigation.

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Appendix

The theoretical treatment

In order to make the theoretical problem tractable, it is convenient to treat the problem as two-dimensional in a vertical plane and to linearize the relevant equations, thus treating the problem as one of a disturbance in a uniform flow.

If the two-dimensional ridge is specified by the Fourier integral

$$\zeta_0 = \int_0^\infty F(k) \exp(ikx)\, dk, \qquad \ldots (1)$$

where ζ_0 denotes the height of the mountain ridge at a horizontal distance x from its crest, k is the wave number, and the sign $\mathrel{=\!\!\!\mid}$ means "equals the real part of", then the vertical displacement ζ_z of a streamline at any level z is given by

$$\zeta_z \mathrel{=\!\!\!\mid} \int_0^\infty \psi_k \, l^{ikx} F(k) \, \mathrm{d}k, \qquad \ldots (2)$$

where ψ_k satisfies the equation

$$\frac{\partial^2 \psi_k}{\partial z^2} + (l^2 - k^2)\,\psi_k = 0 \qquad \ldots (3)$$

in which

$$l^2 = \frac{g}{u^2}\frac{1}{\theta}\frac{\partial \theta}{\partial z} - \frac{1}{u}\frac{\partial^2 u}{\partial z^2}, \qquad \ldots (4)$$

θ being the potential temperature, u the wind component across the ridge and g the acceleration due to gravity.

The solution of equation (3) requires the specification of suitable boundary conditions. The lower boundary condition is that the flow must follow the ground profile, but the choice of an appropriate condition to be applied to the upper limit of the integration has been the subject of controversy.

For the case in which l is independent of z, Corby and Sawyer have reasoned that the appropriate solution of equation (3) is

$$\psi_k = C \exp\,(i\,v\,z), \qquad \ldots (5)$$

where C is determined by the lower boundary condition and $v = \sqrt{l^2 - k^2}$, the positive value of the square root being taken if the flow is in the direction of increasing x.

For an individual Fourier component this solution corresponds to sinusoidal streamlines with the troughs and ridges inclined upstream. If the width of the mountain ridge is large compared with $1/l$, then the significant Fourier components have values of k which are small compared with l and the solution of equation (3) is practically independent of k.

The preceding treatment can be extended to an airstream in which l varies with height, by inserting a region with l=a constant above a level which is chosen sufficiently high to leave the solution unaffected in the lower levels. The solution in this upper region of constant l is then known to have the form $\psi_k = C \exp\,(i\,v\,z)$ and the condition

$$\frac{\partial \psi_k}{\partial z} = i\,v\,\psi_k \qquad \ldots (6)$$

can be used as a boundary condition at any level in the region.

If the vertical distribution of wind speed and potential temperature are known, numerical integration can be used to obtain solutions of equation (3) subject to the upper boundary condition of equation (6) and the ground-level condition $\psi_k = F(k)$ for $z = 0$. For a broad mountain ridge v in equation (6) is independent of k and the solution has the same variation with height for all values of k. Thus it is possible to compute the pattern of streamlines for two-dimensional flow of any specified airstream over a broad mountain ridge.

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DUST HAZE IN RELATION TO PRESSURE GRADIENTS

By F. BURNS

Introduction.—During the period November to April, north-easterly winds on the eastern side of the semi-permanent anticyclone over North Africa sometimes carry dust into northern Nigeria, and in the resulting haze, known as Harmattan haze, visibility can be reduced to 100 yards. Hamilton and Archbold[1] associate this dust haze with the post cold frontal conditions which prevail when cold air sweeps southwards behind Mediterranean depressions. They stress the role of strong convective activity in the cold air in lifting dust from the ground.

Forecasters at Kano have found the tracking of cold fronts over the desert to be exceedingly difficult, and of little practical use in forecasting haze. It is general practice to forecast haze for northern Nigeria after it has been reported at one of the few desert stations to the north-east—usually Faya-Largeau (international index number 64:753)—when the surface and low-level winds are from a favourable direction. The forecast then involves estimating its time of arrival in Nigeria and its intensity.

However, because of communication difficulties, vital observations from desert stations are sometimes missing or received corrupt at Kano, and it is consequently desirable to be able to link occasions of occurrence of dust with general synoptic developments. This note presents the results of an investigation into the relation between the presence of dust in the desert and the pressure gradient, which can usually be obtained with reasonable accuracy from synoptic charts.

Pressure gradients and dust at Faya-Largeau.—Dust at Faya-Largeau is often associated with a strong surface pressure gradient across the desert. Figure 1, the chart for 0600 GMT on 13 March 1958, shows a typical example of a favourable pressure pattern. To investigate this association quantitatively, pressure differences between stations Sebha (60:785) and Abechar (64:756) at 0600 GMT for each day of the period 1 December 1957 to 1 April 1958 were extracted and compared with the visibilities reported from Faya-Largeau at main and intermediate synoptic hours (0001, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 GMT) for the same period. For a number of days, pressures were not available from Sebha, and for these days its pressure was estimated from surface pressure charts.

The visibility at Faya-Largeau will be taken to be characterized by the smallest of the visibilities for that day. On the vast majority of occasions this was given by the 0900 GMT observation. Two categories of haze will be considered: "dust haze" when the visibility is less than two kilometres, and "slight haze" when the visibility is between two and ten kilometres.

Table I shows the number of occurrences of haze with specified categories of visibility and pressure difference (Sebha minus Abechar).

It will be seen from this table that on all 22 occasions when dust haze occurred there was a relatively strong pressure gradient across the desert. The pressure difference, Sebha minus Abechar, was invariably greater than 10 millibars on these 22 occasions. On the other hand, there were 21 days when the pressure difference of over 10 millibars gave rise to only slight haze, and a further 22 days when no haze was reported.

TABLE I—OCCURRENCES OF VISIBILITY (IN KILOMETRES) FOR SPECIFIED PRESSURE DIFFERENCES

Pressure difference	Dust haze					Slight haze		
mb	≤0·1	0·2	0·3–0·4	0·5–0·9	1·0–1·9	2·0–5·0	6·0–10·0	>10·0
	number of occurrences							
20·0–18·0	3	2				1		
17·9–16·0	2	1				2	2	2
15·9–14·0		1	2	2	1	3	3	1
13·9–12·0		2				1	5	8
11·9–10·0		1	2	1	2	1	3	11
9·9– 5·0						4	10	36
4·9– 0·0						1	4	28
<0·0								3

If a period in which the pressure difference between Sehba and Abechar is at least 10 millibars on successive days is termed a spell, then the distribution of spell lengths is shown in Table II. Under (*a*) is shown in successive rows, for the various spell lengths, the number of occasions on which dust haze first appeared on the 1st, 2nd, 3rd and 4th day of the spell; similar information for the first occurrence of slight haze is given under (*b*).

TABLE II—DISTRIBUTION OF SPELL LENGTHS

		Spell length in days 1	2	3	4	5	6	7	8
		number of occurrences							
	Total	5	5	4	2	2	2	0	1
(*a*) First occurrence of dust haze	1st day	0	0	2	0	1	0	0	0
	2nd day		3	1	0	0	1	0	1
	3rd day			0	1	1	1	0	0
	4th day				1	0	0	0	0
(*b*) First occurrence of slight haze	1st day	1	1	2	1	1	0	0	0
	2nd day		3	2	1	0	2	0	1
	3rd day			0	0	1	0	0	0

It follows from Table II that if (assuming the absence of present weather reports from Faya-Largeau throughout the period) dust haze were forecast at Faya-Largeau on the second successive day on which a pressure difference of at least 10 millibars existed between Sebha and Abechar, the results in Table III would have been obtained.

TABLE III—FORECASTS OF DUST HAZE AT FAYA-LARGEAU ON SECOND SUCCESSIVE DAY OF PRESSURE DIFFERENCE

	No. of forecasts
Total	16 (15)
Correct both as regards occurrence and the day of occurrence of dust haze	6 (7)
When the occurrence of dust haze preceded the forecast	3 (3)
When the forecast time preceded the dust haze	4 (3)
When no dust haze was reported during the spell	3 (2)

If a pressure difference between Sebha and Abechar of at least 10·5 millibars is required (instead of 10 millibars) then the results for this set of data are slightly improved; the results are shown in brackets.

One use of this method was well illustrated on 22 March 1958. The differences on the 21st and 22nd (10·7 and 12·1 millibars) indicated a strong risk of dust haze at Faya-Largeau on the 22nd. On this day, however, wind and weather observations were not received at Kano from that station from 0001 GMT to

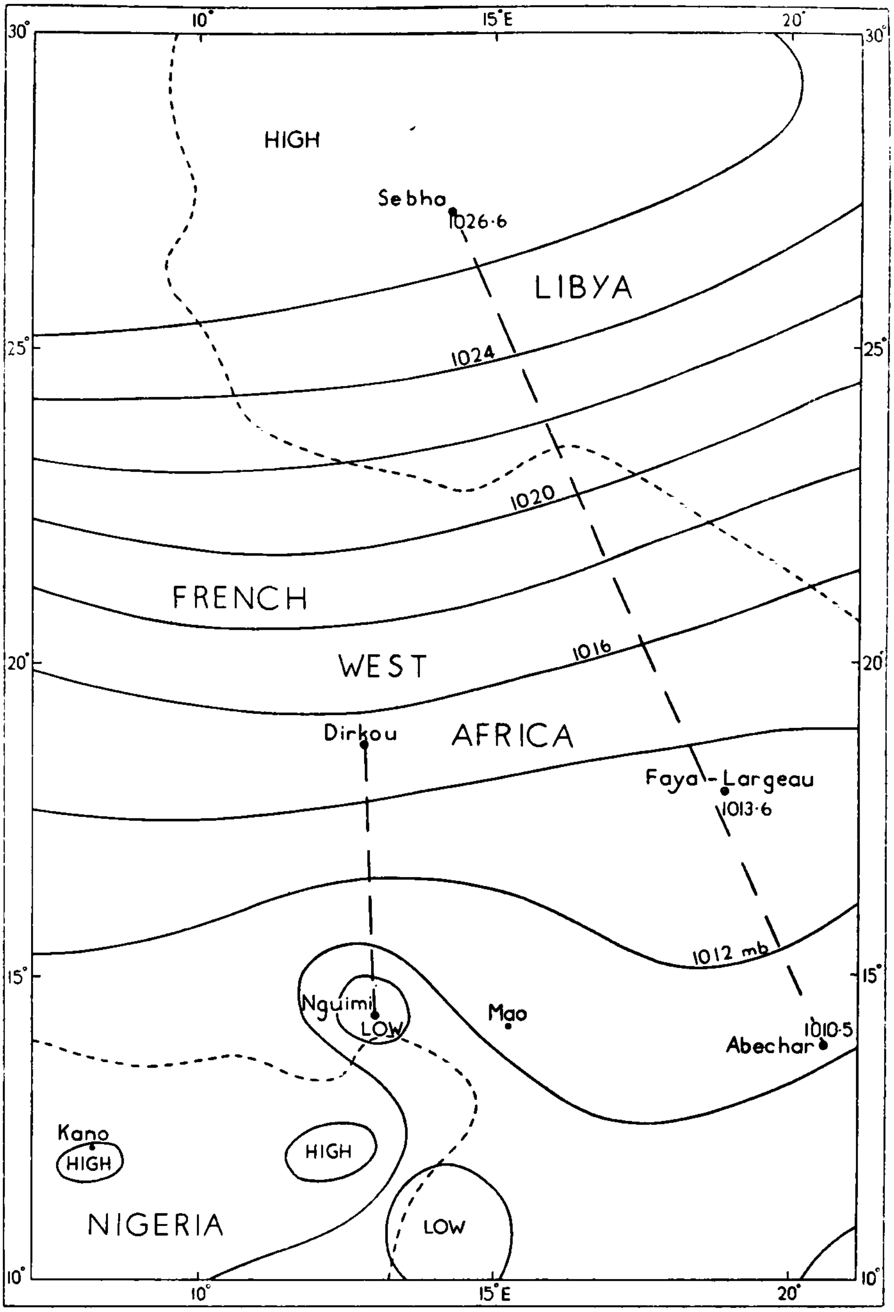

FIGURE 1—SURFACE SYNOPTIC CHART FOR 0600 GMT, 13 MARCH 1958

1200 GMT inclusive. The risk of dust haze at Kano on the morning of the 23rd was, however, put in forecasts on the strength of those differences. Dust haze affected Kano at 0500 GMT on the 23rd and dust haze at Faya-Largeau on the 22nd was later confirmed.

Persistence of haze at Faya-Largeau.—Table IV shows the distribution of visibilities at Faya-Largeau (*a*) on the first day of a spell (all spells included); (*b*) on the second day of a spell (spells of two days or more included); (*c*) on the third day of a spell (spells of three days or more included).

TABLE IV—DISTRIBUTION OF VISIBILITIES AT FAYA-LARGEAU

	Visibility in kilometres							
	0·1	0·2	0·3–0·4	0·5–0·9	1·0–1·9	2·0–5·0	6·0–10·0	>10·0
	number of occasions							
(*a*)	0	1	1	1	0	0	2	16
(*b*)	0	3	2	1	1	3	4	2
(*c*)	3	1	1	1	1	2	2	0

Out of a total of 22 days when a pressure difference of at least 10 millibars existed and yet no haze was reported at Faya-Largeau, 18 were either the first or second day of a spell. It follows that, once haze has occurred, it is likely to persist as long as the pressure gradient remains high. Table I shows that when the pressure difference, Sebha minus Abechar, falls below 10 millibars visibility is likely to improve rapidly.

Arrival of haze in Nigeria.—If haze is reported or suspected in the Faya-Largeau area it will usually affect parts of north Nigeria within 24 hours. Dust haze reports at Faya-Largeau generally precede dust haze in Nigeria, though in Nigeria the dust haze is usually less intense, because of the effect on the dust of gravity, diverging winds aloft and convection. Similarly, slight haze at Faya-Largeau will generally result in slight haze in Nigeria. At the beginning and end of the dry season, however, the winds aloft over north Nigeria may be all southerly and keep the haze in the desert.

Dust haze in the Dirkou-Nguimi region.—Faya-Largeau is about 370 miles from the next station, Mao (64:701), in the direction of Kano, and about 850 miles from Kano itself. Haze often affects Kano within 24 hours of being reported in the Faya-Largeau area; and for this to be possible, dust must be rising in the vast area between Faya-Largeau, Mao and Dirkou (61:017).

On most occasions, dust haze at Kano has been preceded by dust haze at Faya-Largeau. Two instances in the season studied when this was not so were 13 and 17 March 1958, when only slight haze was reported at Faya-Largeau. Visibilities in north Nigeria were good on the 13th, but deteriorated on the 14th; they had improved again on the 17th but deteriorated on the 18th.

In an attempt to find a similar gradient criterion to the west of Faya-Largeau which might account for these unexpected deteriorations, extractions of 0600 GMT surface pressures were made for Dirkou and Nguimi (61:049). These stations were chosen because they lie more or less across the favourable pressure pattern as Figure 1 shows.

It was found that the pressure differences, Dirkou minus Nguimi, on the two dates above were abnormally high, 8·2 and 7·0 millibars respectively. The average value for this difference throughout the season investigated was 3·9 millibars. There were a few other occasions when this pressure difference was 7·0 millibars or more, but these were not enough to formulate a rule.

Conclusion.—It has been shown that in the absence of observations from desert stations, the occasions when dust haze is present can usually be inferred from the surface pressure pattern.

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THE OCCURRENCE AND PREDICTION OF COLD NORTHERLY-TYPE SPELLS OVER THE BRITISH ISLES IN WINTER

By M. K. MILES, M.Sc., and G. G. LEAF, B.Sc.

Summary.—Cold spells of at least two days' duration over the British Isles with winds from the northern quadrant have been defined by reference to the thickness of the layer 1000–500 millibars over southern England. There were 34 such spells in the months November to March, inclusive, during the ten years 1950–59. Of these, 27 were preceded by the occurrence of a "southerly" flow of a certain minimum dimension located on average about 55°–60° longitude upwind. This minimum size of the "southerly" flow appears to be the factor which ensures that the amplifying thermal trough associated with the cold spell remains open for at least 48 hours. The position of surface anticylcones and the location and direction of the flow downwind of the "southerly" have to be taken into account to enable a useful prediction of these cold spells to be made 24 to 48 hours before their onset.

Introduction.—Winter cold spells over the British Isles arise in three ways:

(i) In areas of light winds associated with an almost stationary anticyclone.

(ii) With persistent easterly winds, usually associated at some stage with an anticyclone over Scandinavia.

(iii) With airstreams between north-east and north-west.

The first type is quite rare: it requires a special combination of anticyclone and absence of stratocumulus layer. Occurrences of the second type are estimated to average about two per year, and in November do not bring temperatures appreciably below the normal.

A cold spell defined by the occurrence of low thickness (1000–500 millibars) is more likely to be types (ii) and (iii) than type (i). Accordingly, for the purpose of this study a cold spell was said to have started when the 5280-metre (1000–500 millibar) thickness line moved southwards to reach 50°N within the longitude zone 10°W to 5°E. It was required to remain at or to the south of this latitude on two successive 1200 GMT (1500 GMT before 1957) thickness charts. (For November the 5340-metre line was used instead of that for 5280 metres.) A spell was said to have ended when the defining thickness line moved north of 50°N or out of the longitude zone. For the five months November to March, inclusive, of the ten years 1950–59, 34 spells occurred according to this definition. All cases where the defining thickness line moved into the British Isles from the east were excluded so that these 34 cases represent occurrences of type (iii).

A study of easterlies of at least four days' duration described by Miles[1] revealed 20 in the twelve years 1946–57*. Belasco[2] recorded 118 days of winds between north-east and south-east at Kew during the winter compared with 165 days of winds between north-west and north-east during the years 1931–45. Belasco[2] also states that spells of polar continental air (that is, easterlies) tend to be rather longer than spells with winds between north-west and north-east so that it may be concluded that cold spells from the northern quadrant are considerably more frequent than those from the eastern quadrant in winter.

Distribution and duration of the spells.—Table I shows the distribution by months and the durations of the northerly-type spells.

The frequency of occurrence by months may be a little affected by using the same thickness line (5280 metres) for December to March. The number in December and March may be somewhat less than it should have been had a more appropriate value, say 5310 metres, been used. The smaller number in November than in January and February probably represents a significant difference.

* Several of these easterly spells affected only southern England.

TABLE I—DISTRIBUTION AND DURATION OF NORTHERLY-TYPE COLD SPELLS OVER THE BRITISH ISLES, 1950–59, AND NORMAL THICKNESS AT 50°N, 00°W

	Duration in days 2–3	4–6	7–9	10 or more	Totals	Normal thickness 1000–500 millibars at 50°N, 00°W in metres
November	2	1	0	0	3	5420
December	1	1	2	0	4	5390
January	4	4	3	0	11	5370
February	4	3	1	1	9	5360
March	3	4	0	0	7	5390
Totals	14	13	6	1	34	

Temperature anomaly at Kew during the spells.—The departure of the maximum and minimum temperatures from the monthly means was worked out for Kew. It is common experience that even after an increase of thickness has occurred surface temperatures remain depressed for a further 12 to 24 hours during the winter months. Accordingly the maximum and minimum values for the day after the spell have been included in determining the mean temperature of the spell. In most cases it is clear from the data that the low temperatures do continue for a further day. This should clearly be kept in mind when considering the mean length of the spells.

TABLE II—MEAN TEMPERATURES AND ANOMALIES AT KEW DURING COLD SPELLS, 1950–59

	November max. °F	November min. °F	December max. °F	December min. °F	January max. °F	January min. °F	February max. °F	February min. °F	March max. °F	March min. °F
Mean value	44·3	36·5	38·0	32·2	39·1	30·8	40·7	33·5	42·8	31·9
Mean anomaly	−4·9	−4·2	−6·5	−5·5	−5·0	−6·3	−4·5	−3·0	−7·6	−5·9

The mean values and anomalies for each month are given in Table II, and, for comparison, similar data based on Kew temperatures for the period 1931–45 determined by Belasco[2] for airstreams between north-west and north-east are given in Table III.

TABLE III—MEAN TEMPERATURES AND ANOMALIES AT KEW FOR AIRSTREAMS BETWEEN NORTH-WEST AND NORTH-EAST (AFTER BELASCO)

	November max. °F	November min. °F	December max. °F	December min. °F	January max. °F	January min. °F	February max. °F	February min. °F	March max. °F	March min. °F
Mean value	45·2	36·7	40·7	32·7	38·2	30·7	41·0	32·2	46·5	34·2
Mean anomaly	−4·0	−4·0	−3·8	−5·8	−5·9	−6·4	−4·2	−4·3	−3·9	−3·6

The rather larger anomalies for December and March in Table II are possibly due to one or two less severe spells being eliminated by using the 5280-metre criterion. The small values for February are somewhat surprising. It may be that a thickness value a little less than 5280 metres is more appropriate to this month. The overall mean anomalies of the maximum and minimum temperatures are −5.6° and −5.1°F respectively.

Synoptic evolution associated with the spells.—The spells usually began with the surface airflow over the British Isles veering to a direction between north-west and north-east. This was often associated with the development of a surface anticyclone just west of Iceland as in Figure 1 or the development of a strong anticyclonic col between an anticyclone north of the Azores and one over Greenland. Associated with these developments there was either a deepening depression in the North Sea or marked trough development southwards into Europe.

Almost all of the spells were associated with a moderate or large amplitude contour ridge at 500 millibars over the East Atlantic. Just before the spell began this was most often between 30° and 40°W, moving to about 20°W by the second day of the spell.

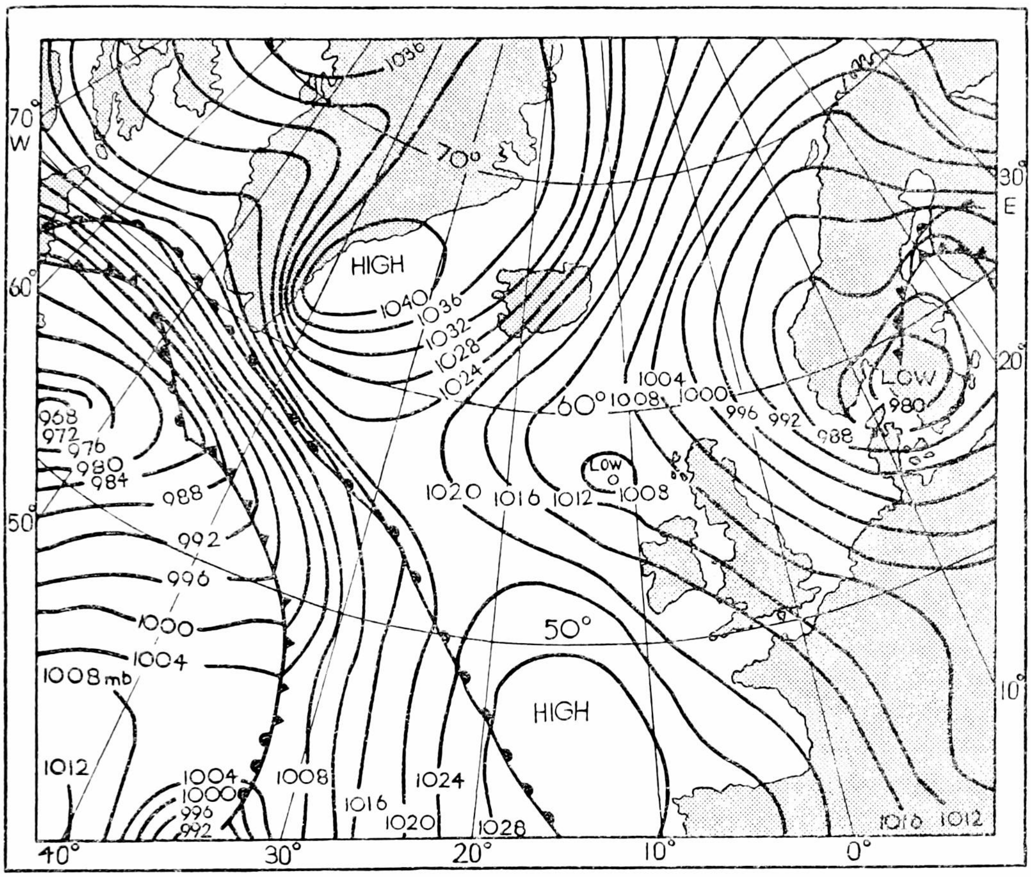

FIGURE I—SURFACE CHART FOR 1200 GMT, 3 JANUARY 1959

Tropospheric flow patterns preceding the spells.—It seemed probable from earlier data on the growth of contour ridges given by Miles[3] that the growth of these ridges would be preceded by the occurrence of predominantly southerly flow some 20°–30° longitude farther west some 24 hours earlier. In fact 27* out of the 34 cold spells were preceded by a flow which had the following characteristics:

(i) Mean direction was between 160° and 220°.

(ii) The mean speed (measured over 400 nautical miles) was at least 40 knots.

(iii) The length was at least 500 nautical miles and the width at least 400 nautical miles.

(iv) The longitude of the centre of the flow was located between the limits 40° and 70°W (modal value about 55°W), and the latitude between 45° and 65°N.

With six of the remaining seven cold spells there was a marked contour confluence at 500 millibars over the Atlantic 24–48 hours before the onset of

*With two of the remaining seven cases there was a "southerly flow" but its length was about 100 nautical miles below the minimum value of 500 nautical miles.

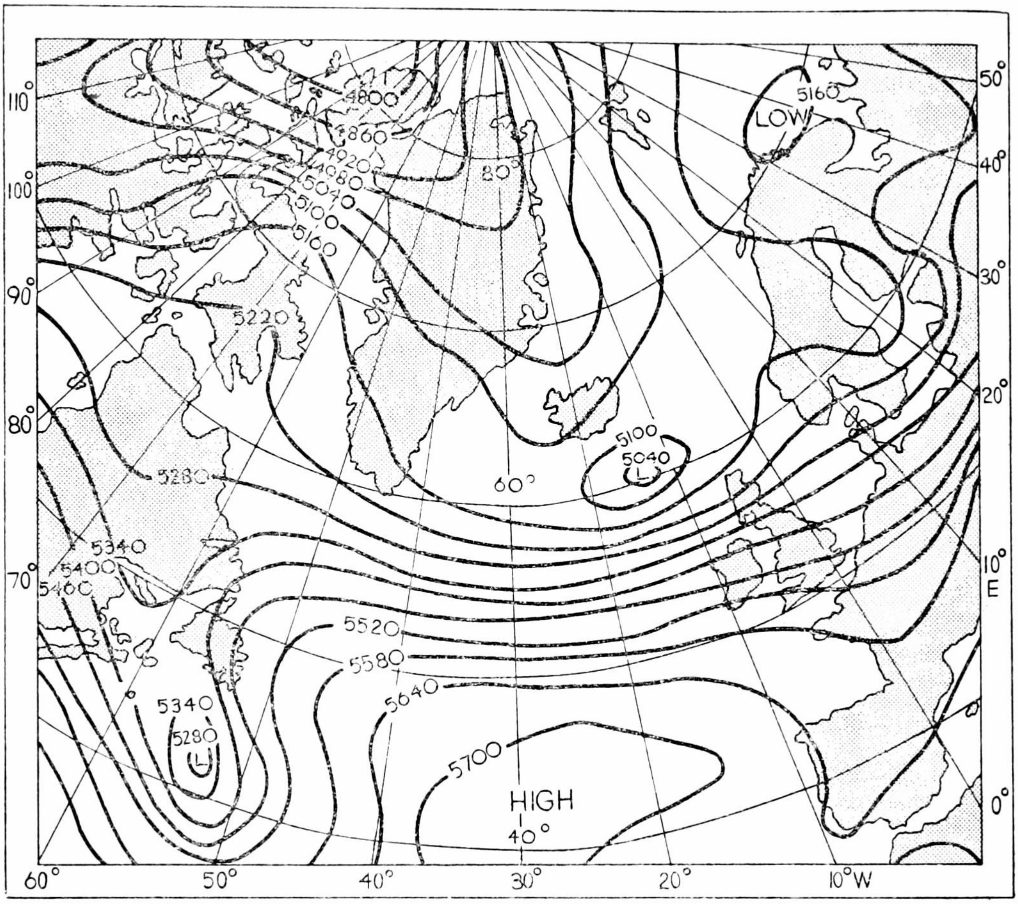

FIGURE 2—500-MILLIBAR CONTOURS FOR ABOUT 1200 GMT, 1 JANUARY 1959

the spell. The entrance to the maximum flow was usually located between longitudes 30° and 45°W, and north of 50°N. The usual evolution involved a substantial rise of contour height in the confluent region leading in about 24 hours to a ridge near or to the east of the initial position of the confluence. There was occasionally a "southerly" current to the west of the confluence and Figure 2 shows a development in which both features were present 48 hours before the onset of a cold spell, shown in Figure 3.

"Southerly" flow in the middle troposphere.—With trough extensions following inflexion points, as described by Miles[3], the amplified trough frequently did not remain open for 48 hours, so that the condition for a cold spell as defined here was not satisfied. It is a reasonable assumption from the results described in the previous section that a certain minimum length and width of the "southerly" ensures the persistence of the cold outbreak.

Accordingly all southerly currents for the ten years 1950–59 satisfying the four criteria in the previous section were studied. There were, besides the 27 already mentioned, 102 others. Out of this total of 129 there were 17 per cent in which the model of ridge growth and trough extension failed entirely and 18 per cent in which the 5280-metre line of the extended thermal trough did not reach as far south as 50°N. Of the 83 per cent where there was some extension about 50 per cent were east of the British Isles and 15 per cent were to the west.

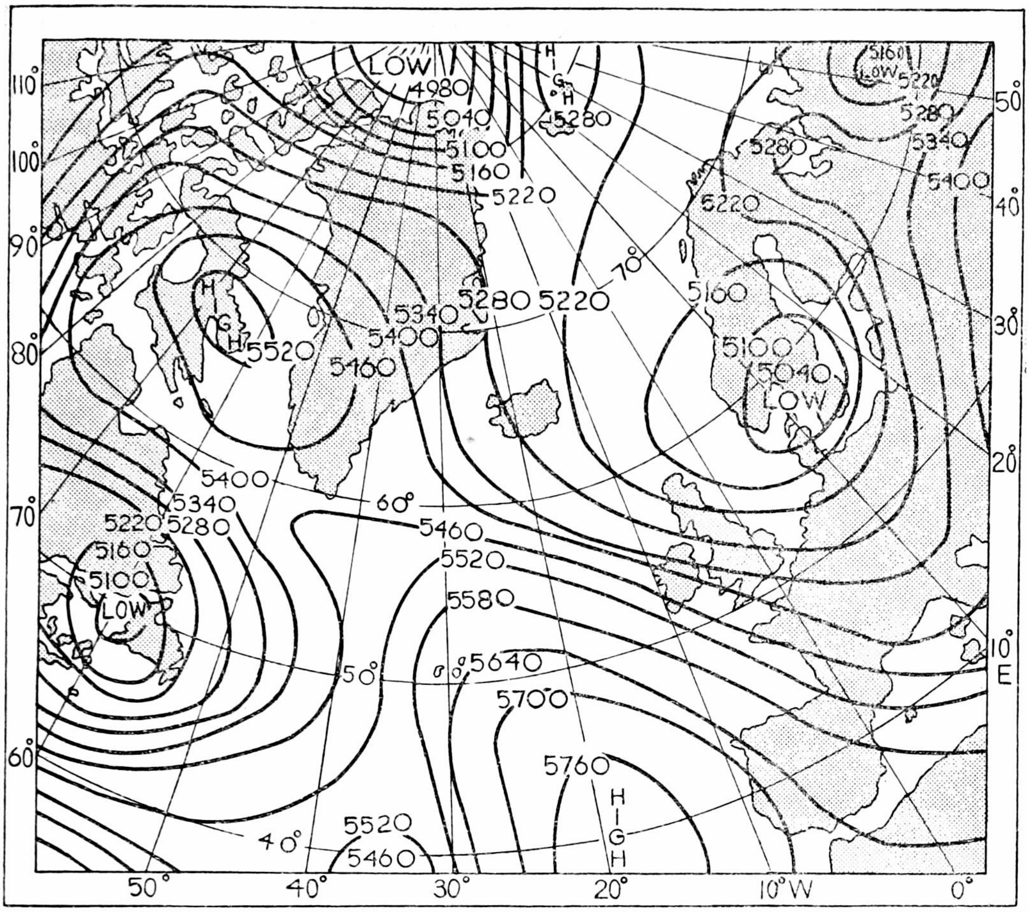

FIGURE 3—500-MILLIBAR CONTOURS FOR ABOUT 1200 GMT, 3 JANUARY 1959

The important question now to be considered concerns the factors which determine the longitude of the cold outbreak, but before doing this it may be useful to indicate three circumstances which were thought to be unfavourable to the working of the model.

They are:

(i) A separation of 35° longitude or less between the two troughs immediately upwind of the southerly.

(ii) A strong west-south-westerly flow to the south-south-west of the southerly.

(iii) A comparable "southerly" flow within about 55° longitude downwind.

Factors determining the location of cold outbreaks following the occurrence of "southerly" flows

(*a*) *The location of surface anticyclones.*—An anticyclone centred in the hatched area shown on Figure 4 when the southerly first appears constitutes a favourable condition for a cold outbreak over the British Isles. Equally an anticyclone in the longitude zone 10°W to 20°E constitutes an unfavourable situation.

Since there was usually an anticyclone some 20° to 30° longitude downwind from the "southerly" flow another one in the zone 10°W to 20°E was often the eastern member of a pair. When the separation of the two cells was less than some 50°–60° longitude the trough between them showed a marked tendency to weaken and move quickly across until it was some 10°–20° longitude to the east of the second cell and then intensify. This almost invariably meant that the cold outbreak was east of the British Isles. However, if the eastern member of the pair was at a lower latitude than the western member (the less common situation) the trough extension occurred either between the two centres or in the zone occupied by the eastern member which had by this time collapsed or moved southwards.

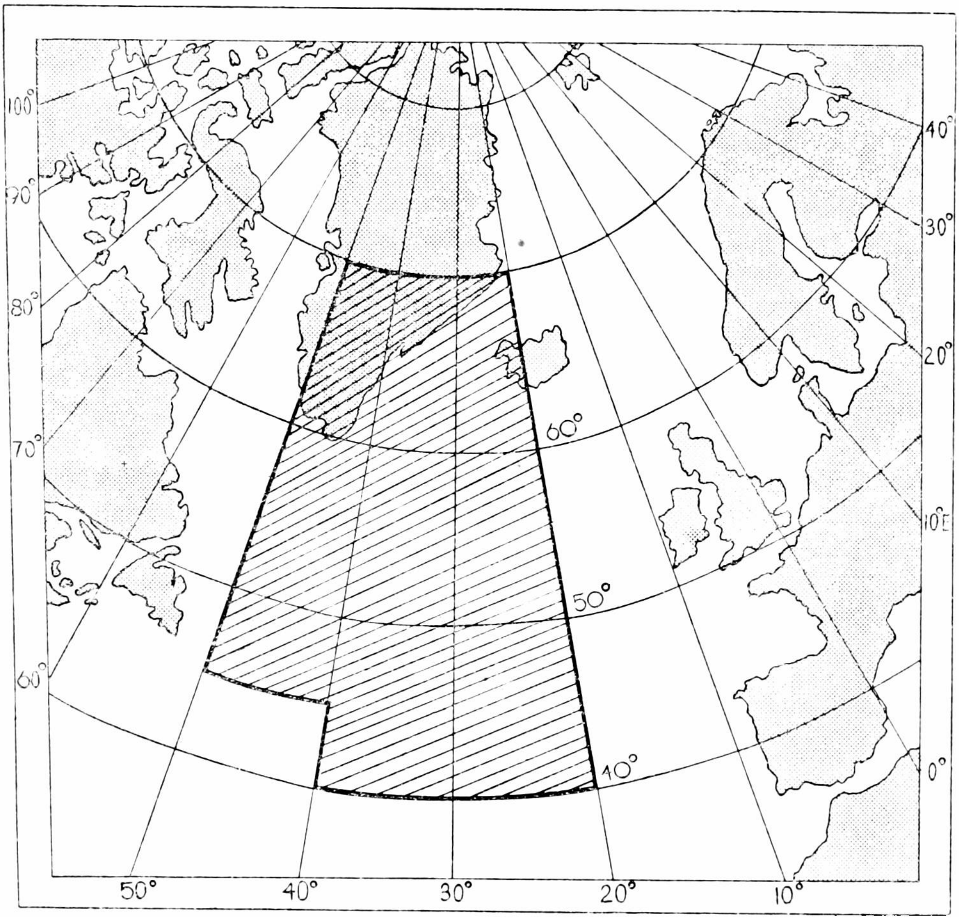

FIGURE 4—MOST FAVOURED AREA FOR ANTICYCLONES ASSOCIATED WITH COLD NORTHERLY SPELLS OVER THE BRITISH ISLES

(*b*) *Tropospheric flow downwind of the southerly.*—As mentioned earlier, the model associated with these spells involves the growth of a tropospheric ridge to the west of the British Isles. It was found that the direction and location of the tropospheric flow downwind of the ridge (or the incipient ridge) had to be taken into account to determine (i) whether there would be a strong cold outbreak and (ii) whether it would be over the British Isles or not.

The centres of the currents at 500 millibars were found to be mostly located between 20° and 40° longitude downwind of the southerly. Measurements of the directions of the flow at the centre at the time of the first appearance of the southerly showed that for the 29 occasions preceding cold spells over the British Isles this was only once less than 270°, and three days elapsed before the cold spell in this case.

Moreover, of thirteen cases when the direction of the flow was 310° or more and it was centred west of 35°W only one was followed by a cold spell over the

British Isles. For directions between 270° and 300° the flow should not be centred appreciably east of 30°W otherwise the cold outbreak is likely to be east of the British Isles.

The direction of the flow also appears to affect the length of the interval between the appearance of the southerly and the onset of the cold spell. Table IV shows the distribution of these intervals for a division of the directions into two classes (the two cases with southerlies about 400 nautical miles long have been included).

TABLE IV—INTERVAL BETWEEN APPEARANCE OF "SOUTHERLY" FLOW AND ONSET OF COLD SPELL OVER THE BRITISH ISLES IN RELATION TO FLOW DOWNWIND OF SOUTHERLY

	Interval in days				
	1	2	3	4	5
	number of cases				
Direction <310°	3	10	2	0	1
Direction ⩾310°	9	4	0	0	0
All cases	12	14	2	0	1

This flow can be thought of as the one which veers during the growth of the ridge and advects cold air southwards, so that with an average rate of veering of about 30° per day, the two-day interval for initial directions of 300° or less is not surprising. Of course, the interval will also depend on the initial latitude of the cold source (that is, 1000–500-millibar thickness lines less than 5280 metres), but this effect has not been examined in this study.

The latitude of the centre of the flow appeared to have some effect on the longitude of the cold outbreak. The higher the latitude the farther eastwards was the outbreak, other factors being equal.

(*c*) *Optimum combination of these factors for cold spells.*—When a southerly has appeared in the defined area, a cold outbreak over the British Isles is most likely when the following four conditions are satisfied:

(i) A surface anticyclone (1020 millibars or more) in the hatched area on Figure 4.

(ii) No other anticyclone within 60° longitude to the east of this one unless it is at a lower latitude.

(iii) The direction of the main flow at 500 millibars downwind of the southerly must be ⩾ 270°.

(iv) If the direction of this flow is greater than 310° then it must not be west of 35°W.

The result of applying these conditions to the 129 cases available is shown in Table V. This promises a fairly useful amount of success in distinguishing cold from not cold, though it might be unsatisfactory for some purposes to miss about 40 per cent of all the cold spells (that is, seven preceded by southerlies and seven which were not).

TABLE V—OCCURRENCE OF COLD SPELLS IN RELATION TO SPECIFIED CONDITIONS

	Cold over British Isles	Cold not over British Isles
	number of cases	
Conditions satisfied for cold spell ...	20	11
Conditions not satisfied	7	91

Forecasting these cold spells.—These northerly-type spells account for more than a half of the severe winter weather over the British Isles and it may be a matter of economic importance to provide a warning of their onset. The results given in this study appear likely to provide at least 24 hours' warning of the occurrence of just over a half of these spells. The likelihood of an indication not being followed by a severe spell would in practice probably be somewhat greater than 35 per cent.

In cases where the model shows no signs of working 24 hours after the appearance of a "southerly" and this still satisfies the conditions, it is possible that a fresh forecast using the current values of the variables might give more accurate results, especially when the anticyclone is outside the prescribed area on the first occasion and the flow downwind of the "southerly" is $<270°$. This has not been done in this study: each "southerly" has been considered only on the day it first appeared east of 75°W.

In eighteen cases there were ridges of high pressure extending south from Greenland. These have been disregarded in the above analysis: in fact five of them preceded cold spells and thirteen did not. They appear not to play a decisive role, though synoptically they would seem to be important elements in this kind of evolution.

Conclusions.—A definition of cold spells in terms of the thickness (1000–500 millibars) over the British Isles fairly effectively covers those where the cold comes in from between north-west and north-east. Four-fifths of these spells followed the occurrence of a predominantly "southerly" flow at 500 millibars centred on average about 55° longitude west of the British Isles. Only a quarter of all "southerlies" of a certain strength and size between longitudes 40° and 75°W gave cold spells over the British Isles (the majority of the cold outbreaks were east of 5°E).

Anticyclones centred between longitudes 50° and 20°W were found to be a second requirement, but there should not be another anticyclone at the same or a higher latitude within 60° longitude to the east of it. A consideration of the direction and position of the main flow downwind of the "southerly" can give some indication of whether the cold outbreak is likely to be west or east of the British Isles, and of the interval before its onset.

The most favourable combination of these factors would have correctly indicated 60 per cent of all cold northerly-type spells over the ten years 1950–59 (inclusive). Sixty-five per cent of the indications of such spells over the British Isles would have been correct. The average interval between the indication and the onset of a cold spell was between 24 and 48 hours.

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WIDESPREAD SEVERE CLEAR-AIR TURBULENCE, 13 NOVEMBER 1958

By J. BRIGGS, B.A.

Introduction.—Unusually numerous and widespread reports of severe clear-air turbulence were received from aircraft flying over Great Britain on 13 November 1958. The turbulence was reported as occurring at various heights between

15,000 and 40,000 feet and affected a wide variety of types of aircraft. The exceptional severity of the turbulence was stressed in some reports, for example:

"turbulence comparable with cumulonimbus turbulence at low levels"

"extensive and severe; pilot never experienced such turbulence in 16 years' flying"

"continuous and violent bumps; difficult to control aircraft and read instruments".

The meteorological situation.—The surface synoptic charts showed a slowly intensifying ridge of high pressure across the country; Figure 1 gives the situation for 1200 GMT. A quasi-stationary front over the southern North Sea was weakening and a warm front approaching Ireland was beginning to slow up.

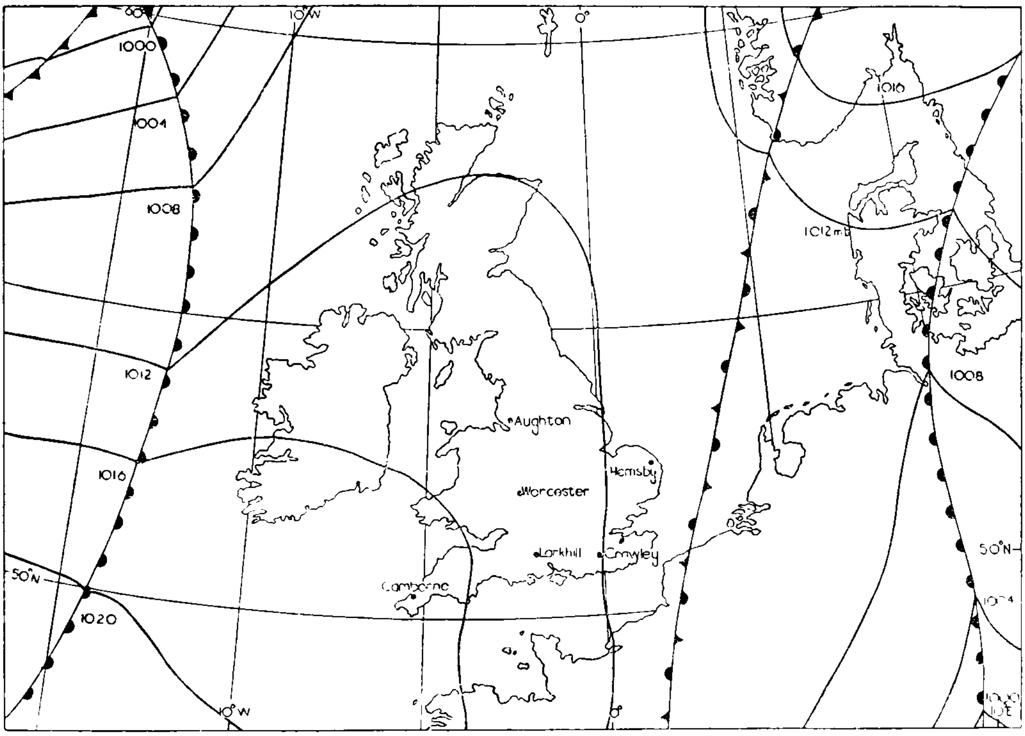

FIGURE 1—SURFACE CHART FOR 1200 GMT, 13 NOVEMBER 1958

At the upper levels strong northerly winds were affecting most of the country but there was a sharp moderation of wind over East Anglia with a quick reversal to southerly winds over the North Sea. Figure 2 shows the 300-millibar chart for 1200 GMT; a northerly jet stream extends from central southern England to north-west Scotland and a very sharp trough has its axis just off East Anglia. At the 700- and 500-millibar levels the trough was farther west and Hemsby was still reporting southerly winds at these heights. In the preceding 12 hours the trough had moved slowly eastwards and had become steadily sharper due to the combined effect of the warm air aloft, which was preceding the surface front over Ireland, and of continued warm air advection from the east over Germany.

Reported occurrences of severe clear-air turbulence are indicated on Figure 2; it will be seen that the majority were over eastern England between 1000 and 1500 GMT. The nearest time for which simultaneous soundings of wind and temperature are available is 1100 GMT; Figure 3 is an east–west cross-section for that time. For a section centred at 52°N it is possible to use the ascents made at around 1100 GMT from Camborne, Liverpool, Larkhill, Crawley and Hemsby; an aircraft ascent made over Worcester at 0850 GMT is also shown on the cross-section. Wind components shown on the section are north to south components of the reported winds. Positions of the turbulence occurrences relevant to the section are indicated by crosses in Figure 3.

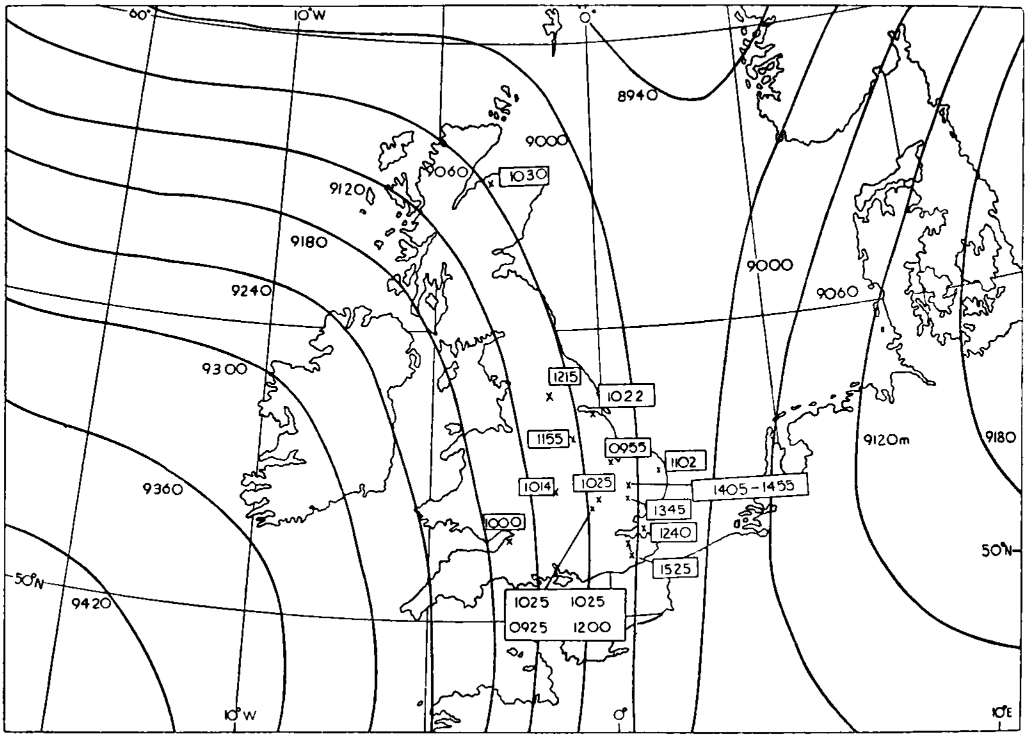

FIGURE 2—300-MILLIBAR CONTOURS FOR 1200 GMT, 13 NOVEMBER 1958

Crosses mark turbulence reports; times are in adjacent boxes.

The axis of the northerly jet stream is seen to lie just to the west of Crawley and just below the 300-millibar level at 1100 GMT. At Hemsby the southerly winds appear below about 320 millibars; extension of the cross-section to the east is limited by lack of data but there are indications that the southerly airstream itself approached "jet stream" magnitude. The most marked feature of the section is the exceptionally strong horizontal shear of wind between the two airstreams. Below the jet axis and on the low pressure side of the axis the shear is of the order of 2.5 knots per nautical mile; this probably exceeds any previously reported horizontal wind shear in the vicinity of the British Isles. A very strong vertical shear of wind is also shown and, in particular, the Crawley wind reports indicate a shear of the order of 14 knots per 1000 feet between 500 and 350 millibars.

Discussion.—Apart from not infrequent cases of bumpiness near the tropopause, Bannon[1] has found that clear-air turbulence is generally associated with pronounced horizontal wind shear and/or with small values of the Richardson number (R_i) which itself depends mainly on large vertical wind shear and small static stability. In general it is not possible to obtain reliable values of R_i as the

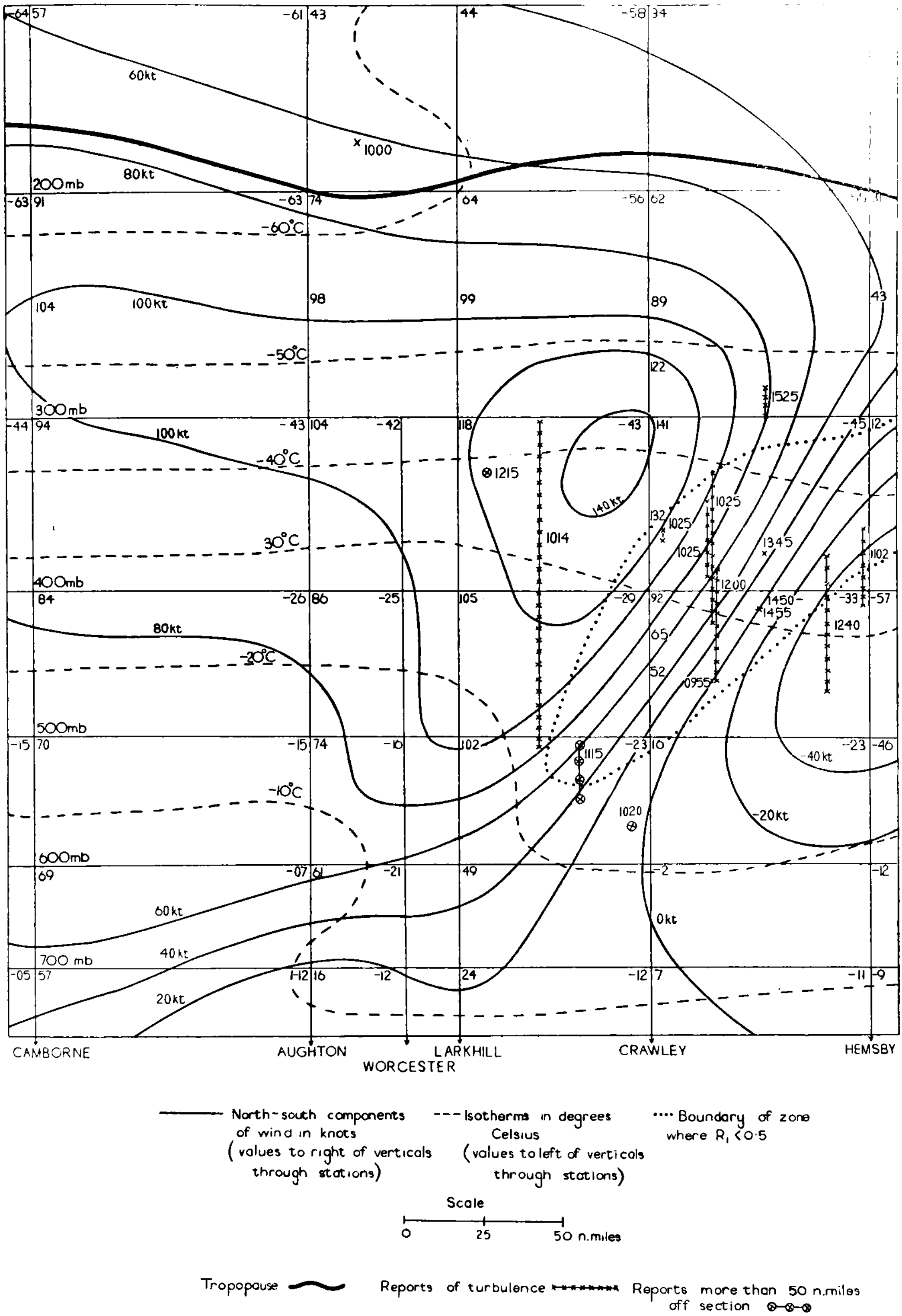

FIGURE 3—EAST–WEST CROSS-SECTION CENTRED AT 52°N FOR 1100 GMT, 13 NOVEMBER 1958

radio-sonde winds are really mean winds over depths of the order of 3000 feet and so vertical shears over shallow layers cannot be obtained. However, in this instance the wind shear, as shown by Hemsby and Crawley, is large over quite a deep layer and it is possible to obtain fairly accurate values of R_i. The variation of R_i with height at Crawley and Hemsby is presented in Table I. Also, using the cross-section, reasonable estimates can be made for the value of R_i in the zone of marked wind shear. On Figure 3 the approximate boundary of the zone within which R_i is 0·5 or less is indicated.

TABLE I—VARIATION OF THE RICHARDSON NUMBER (R_i) WITH HEIGHT, 1100 GMT, 13 NOVEMBER 1958

Height *feet*	Crawley R_i	Hemsby R_i	Height *feet*	Crawley R_i	Hemsby R_i
17,000	7·1	—	25,000	0·45	0·39
18,000	0·50	8·4	26,000	2·0	0·40
19,000	0·25	9·5	27,000	2·0	0·40
20,000	0·26	9·6	28,000	2·1	0·40
21,000	0·89	9·7	29,000	2·1	0·41
22,000	0·18	9·7	30,000	0·70	4·4
23,000	0·13	2·3	31,000	0·71	—
24,000	0·45	0·39	32,000	0·71	—

Radar-wind soundings are available for 1700 GMT though no temperature values are obtained at that time. The 1700 GMT winds for Crawley and Hemsby are given in Table II. Both these ascents show that the zone of strong vertical wind shear has lowered; the strongest shear at Crawley is now between 4200 and 5400 metres and at Hemsby the shearing zone is from 5400 metres to about 9000 metres; these changes are consistent with a displacement of some 50 nautical miles eastward of the shearing zone of Figure 3.

TABLE II—WINDS AT 1700 GMT, 13 NOVEMBER 1958

Height	Crawley Wind		Hemsby Wind	
metres	*degrees*	*knots*	*degrees*	*knots*
900	010	14	350	11
1500	010	12	340	10
3000	070	02	140	03
4200	060	03	190	24
5400	010	64	230	18
7200	010	68	010	35
9000	360	93	360	72
10,500	010	86	360	55
12,000	350	70	350	49

The majority of the occurrences of clear-air turbulence lie inside the zone where R_i is less than 0·5; if due allowance is made for the displacement of this zone with time in line with the movement suggested by the 1700 GMT winds then only four reports lie outside the zone. These four reports are:

(i) at 1000 GMT and 40,000 feet near Bristol,

(ii) at 1215 GMT and 28,000 feet over Yorkshire,

(iii) at 1014 GMT between 18,000 and 30,000 feet over the Midlands,

(iv) at 1525 GMT and 30,000 feet over Kent.

Of these:

Report (i) is in the vicinity of the tropopause,

Report (ii) is more than 100 nautical miles to the north of the section and the section is not really applicable to this report.

Report (iii) extends from 18,000 to 30,000 feet and from the original report it is doubtful whether turbulence covered the whole of this range; turbulence in the lower part of the range lies near the zone $R_i < 0{\cdot}5$ if suitable time adjustment is made. The upper part of this report is in a region of very strong horizontal anticyclonic shear; the cross-section suggests a shear in excess of the Coriolis parameter (about 0·4 knots per nautical mile). This excessive shear can be partly attributed to the breadth of the cross-section and may also be partly due to local wind fluctuations but it appears that the actual horizontal wind shear in the vicinity of the reported turbulence was at about the theoretical limit for dynamical stability.

Report (iv) lies in the zone of strong horizontal wind shear near the axis of the jet stream.

Conclusion.—The widespread turbulence of 13 November 1958 is seen to have been associated with an exceptionally strong wind shear both in the horizontal and the vertical. In accordance with previous findings (Bannon[1] and Jones[2]) the greatest number of the reports are on the low pressure side of a jet stream below the axis of the jet and there is considerable confirmation that low values of the Richardson number, probably R_i less than 0 .5, are associated with the turbulence, although not all the occurrences of turbulence can be explained in this way.

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OFFICIAL PUBLICATIONS

The following publications have recently been issued:

SCIENTIFIC PAPERS

No. 6—*Seasonal variation of the sea surface temperature in coastal waters of the British Isles.* By F. E. Lumb, M.Sc.

Charts of sea surface temperature for summer and winter in coastal waters of the British Isles are examined, and it is shown that basic summer and winter isotherm patterns exist which are very stable. A physical explanation of these isotherm patterns is outlined, and the importance of tidal currents in determining the summer patterns is stressed. Examples of isotherm charts for five-day periods in January, April, June, September and November 1958 are given and used to demonstrate that maps of the sea surface temperature distribution at any time of the year round the coasts of the British Isles can readily be drawn with the aid of a few sea temperature readings backed by a knowledge of the basic summer and winter isotherm patterns. The interpretation of sea temperature readings from light-vessels is discussed in relation to the basic isotherm patterns.

No. 7—Forecasting in the Falkland Islands and Dependencies, by S. D. Glassey.

This paper is a study of weather forecasting in the South Atlantic sector of Antarctica, mainly that governed by the Falkland Islands Dependencies Survey, together with details of particular weather sequences and local effects in the area. It is intended to serve as a guide to students of Antarctic meteorology. Fundamental surface features are discussed and a short summary of available upper air information is made.

No. 8—*Factors associated with the formation and persistence of anticyclones over Scandinavia in the winter half of the year.* By M. K. Miles, M.Sc.

All surface anticylones spending more than one day in the Scandinavian region during the twelve years 1946–57 (inclusive) have been studied synoptically. It was found that less than a fifth of the anticyclones appearing in the region persisted beyond three days. The rest usually moved east or south-east out of the region in this time. Nearly all of the strong anticyclones developed some 600 nautical miles to the east of a large-amplitude thermal ridge. Continued growth of this ridge for at least twenty-four hours after the anticyclone appeared in Scandinavia was usually required for persistence of the anticyclone. The persistent anticyclones were always accompanied by a fairly intense thermal trough in the west Atlantic, and the central pressure of any pre-existent warm anticyclone to the south or south-west of Scandinavia was usually less than 1030 millibars. The occurrence of east winds over Great Britain for a period of at least four days usually required a persistent anticyclone over Scandinavia, and this was especially so in January and February during the period studied.

No. 9—An experiment in the verification of forecast charts. By C. E. Wallington, M.Sc.

This experiment was carried out to build up experience of using various computed indices as indicators of the quality of forecast charts. It appears that the relatively simple root mean square errors are the most practical and useful of the indices considered. When discussing geostrophic wind errors it is important to specify the grid length over which the winds are computed; results of this experiment suggest that root mean square wind errors are approximately inversely proportional to the square root of the grid length.

No. 10—Incidence of, and some rules for forecasting, temperature inversions over the north-east Atlantic. By H. C. Shellard, B.Sc., and R. F. M. Hay, M.A.

Some statistical information is presented regarding the frequency, strength, height and persistence of temperature inversions and isothermal layers at the ocean weather stations I and J during one year. The relation between the occurrence of inversions, both frontal and non-frontal, and various synoptic features has been investigated and a number of significant relationships found. These are combined to give sets of rules which may be used for forecasting, from prognostic charts, the occurrence or absence of inversions over the ocean. Such forecasts are likely to be of interest mainly in relation to abnormal radio and radar propagation and, as this is most likely when a strong temperature inversion associated with a hydrolapse is present at low levels, special attention is paid to non-frontal inversions of 5°F or more with bases below the 750-millibar level. In this connexion it should be mentioned that the temperatures used were measured by radio-sonde and that the radio-sonde, due to its lag, tends to underestimate the strength of temperature inversions. Although the radio-sonde also measures humidity the humidity data have not been used in this paper because of their doubtful reliability.