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EFFECTS OF URBANIZATION ON LONG-TERM CHANGES OF WINTER TEMPERATURE IN THE LONDON REGION

By E. N. LAWRENCE

Summary. Changes of temperature in central London during the period 1920-68 are compared with changes at other stations in south-east England. Mean values of the daily minimum and maximum temperature, for the winter season (December, January and February), are examined. The most marked change, attributed to urban effects, is a *decrease* in the mean daily *minimum* temperature in central London, relative to surrounding stations, of approximately 1.5 to 2 degF (1 degC), and an *increase* of approximately 1 degF (0.5 degC) in the corresponding mean *maximum* temperature, between the 1930s and about 1950. These temperature changes are considered to be the result of urban improvements and of the difference between urban and rural areas in their response to natural climatic change.

Introduction. Differences in the temperature régime between London and the surrounding country are described by Chandler.¹ Changes of temperature with time at Manchester Airport relative to other stations in the area have been attributed² to the effects of urbanization. In central London, such meteorological changes with time include an increase of sunshine duration relative to the suburbs and surrounding country (see for example, Chandler,¹ Monteith³). Also, Monteith³ states that at Kingsway, in central London, the mean direct radiation (on a horizontal surface) per hour of sunshine increased from 21 mWh/cm² in 1957 to 27 mWh/cm² in 1963, consistent with the decrease in smoke in central London, following the Clean Air Act of 1956. The present note describes temporal changes in the difference between winter temperature in central London and that at surrounding rural stations during the period 1920-68. These changes can be attributed to changes in urbanization and to the difference between urban and rural areas in their response to natural climatic change. Urbanization is here defined to include all the artificial results of human habitation; winter is defined as December, January and February and is referred to by the year in which January occurs.

Data used. Monthly mean values of the daily maximum and minimum temperature were used for Kensington Palace (51° 30'N, 00° 10'W, 80 ft (24 m) above MSL: referred to as station K) in central London, and for the three relatively rural outlying stations of Porton, Wilts. (51° 07'N, 01° 42'W, 363 ft (111 m) above MSL: referred to as station P) approximately to the south-west of London, Woburn, Beds. (52° 01'N, 00° 35'W, 291 ft (89 m) above MSL: referred to as station W) approximately to the north-west of

London, and East Malling, Kent ($51^{\circ} 17' \text{N}$, $00^{\circ} 24' \text{E}$, 122 ft (37 m) above MSL: referred to as station E) approximately to the east of London (see Figure 1). The dates of the periods of the data are given in the results section.

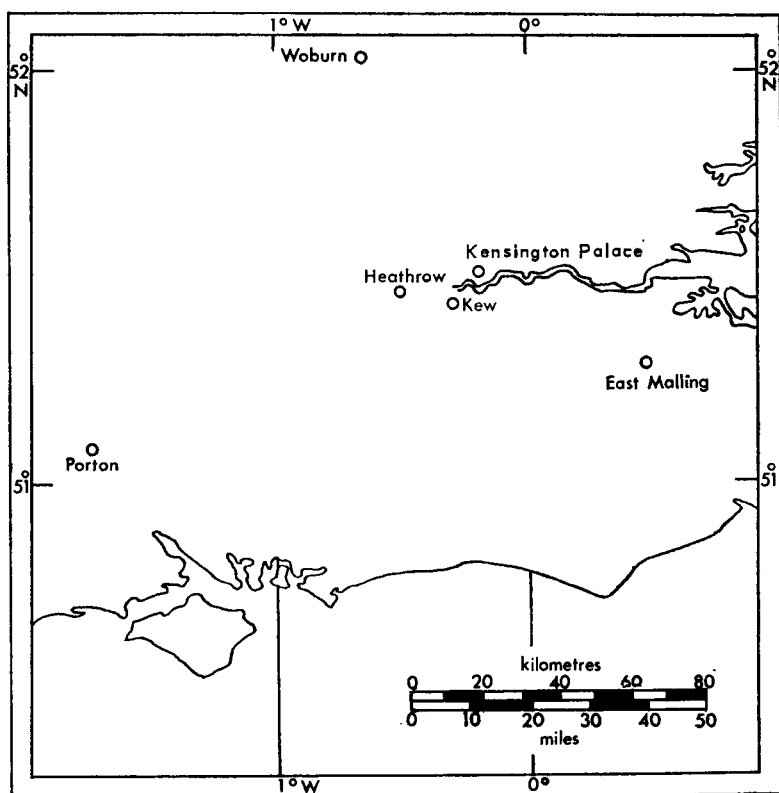


FIGURE 1—DIAGRAM SHOWING KENSINGTON PALACE (LONDON) IN RELATION TO SURROUNDING STATIONS

Winter mean values of sunshine duration and the run of wind refer to Kew Observatory ($51^{\circ} 28' \text{N}$, $00^{\circ} 19' \text{W}$, 18 ft (5 m) above MSL) where the anemometer is 75 ft (23 m) above the ground with an effective height of approximately 50 ft (15 m).

Winter data (1951–68) for illumination refer to Kew Observatory and to the London Weather Centre in central London (in Kingsway and later in High Holborn).

Minor changes in the sites, chiefly at Woburn, are neglected in the present investigation.

Results. Graphs are shown for the months of December, January and February combined, for the following elements :

- (i) Mean daily minimum temperature (Figures 2(a)–(d)), and mean daily maximum temperature (Figures 3(a)–(d)) for Kensington Palace (1921–68), Porton (1921–68), Woburn (1921–68) and East Malling (1926–68).

Smoothed curves of '10-year' running means are superimposed, plotted on the centre point of the period.

- (ii) Difference between mean minimum temperature at Kensington Palace and that at surrounding rural stations, together with the corresponding difference in mean maximum temperature (Figure 4).
Kensington Palace minus Porton (K - P: Figure 4(a)),
Kensington Palace minus Woburn (K - W: Figure 4(b)) and
Kensington Palace minus East Malling (K - E: Figure 4(c)).

Smoothed curves of '10-year' running means are superimposed.

- (iii) Mean values of the hourly run-of-wind (mean wind speed) (1921-68) for Kew Observatory with '10-year' running means (Figure 5).
- (iv) Mean daily duration of sunshine (1921-68) for Kew Observatory with '10-year' running means (Figure 6).

Discussion. Smoothed minimum-temperature curves (Figures 2(b), (c), and (d)) for Porton, Woburn and East Malling show little long-term change, but that for Kensington Palace (Figure 2(a)) shows a distinct downward trend of approximately 2 degF (1 degC) during the period of data shown.

Smoothed maximum-temperature curves (Figures 3(b) and (c)) for the longer-period stations of Porton and Woburn show a slight tendency to a downward trend, whereas Kensington Palace (Figure 3(a)) shows a downward trend from about 1925 to about 1942, and then a rise to a peak about 1952, followed by another downward trend. The corresponding curve for East Malling (Figure 3(d)) is similar to the corresponding parts of the curves for Porton and Woburn.

Smoothed minimum-temperature-difference curves (Figures 4(a), (b), and (c)) show a downward trend from about 1930 to about 1950 and then level out.

Smoothed maximum-temperature-difference curves (Figures 4(a), (b), and (c)) for K - P, K - W and K - E curves respectively show a steady rise up to about 1950 (preceded by a fairly constant value up to about 1935-40 in the K - P and K - E curves) and then the K - P and K - W curves level out while the K - E curve shows a downward trend.

The main feature of the three pairs of temperature-difference graphs (Figures 4(a), (b) and (c)) is their similarity, although the three stations are in different directions from London (see Figure 1). This result suggests that the trends shown are not due entirely to any changes from year to year in the natural distribution of wind directions.

There is another possible partly-natural cause of the trends in these temperature-difference graphs, namely, long-term trends in mean wind speed. For example, temperature differences could be increased as a result of lighter wind régimes, because light winds are often associated with maximum topographical effects on temperature. Thus, a steady decrease in mean wind speed could lead to a steady decrease in the dispersal of air pollution and so to increasing urban-rural differences in minimum temperature. However, it can be seen that the trend to *decreasing* minimum-temperature differences between about 1940 and 1950 is associated with a trend to decreasing mean

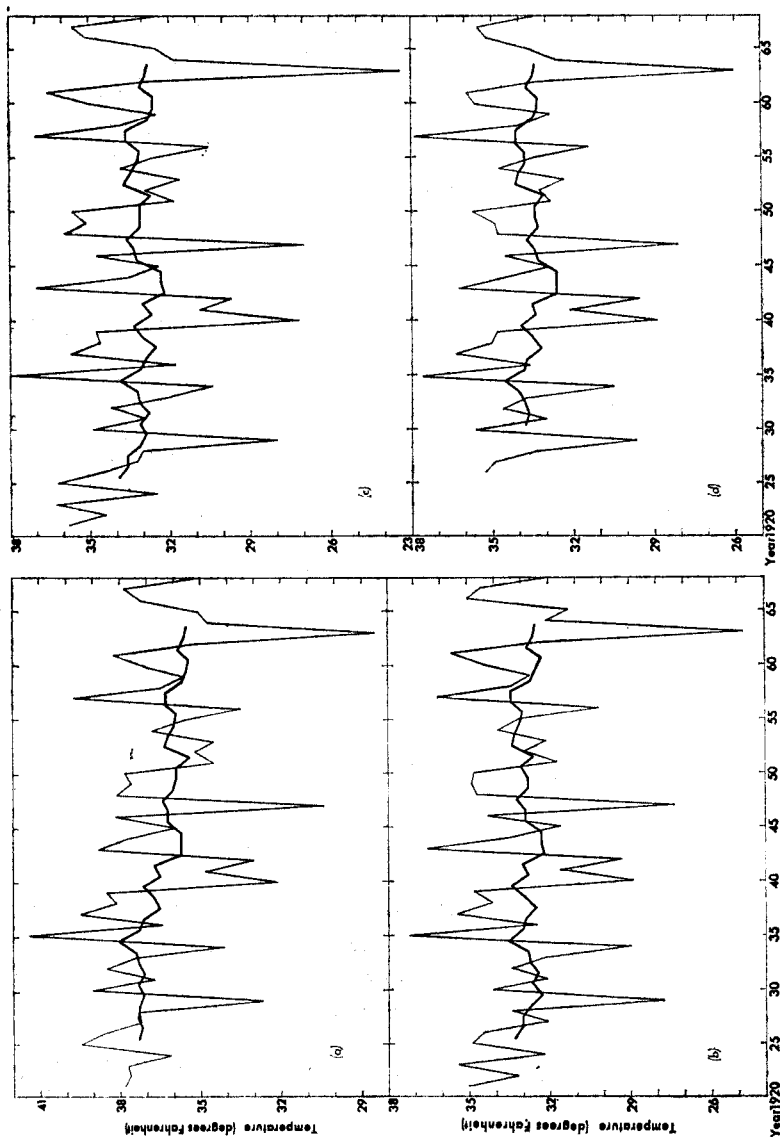


FIGURE 2—WINTER MEAN DAILY MINIMUM TEMPERATURE AND 10-YEAR RUNNING

MEANS

(a) Kensington Palace (London), (b) Porton, Wilts., (c) Woburn, Beds., and (d) East Malling, Kent.

— Mean daily minimum temperature

- - - 10-year running means

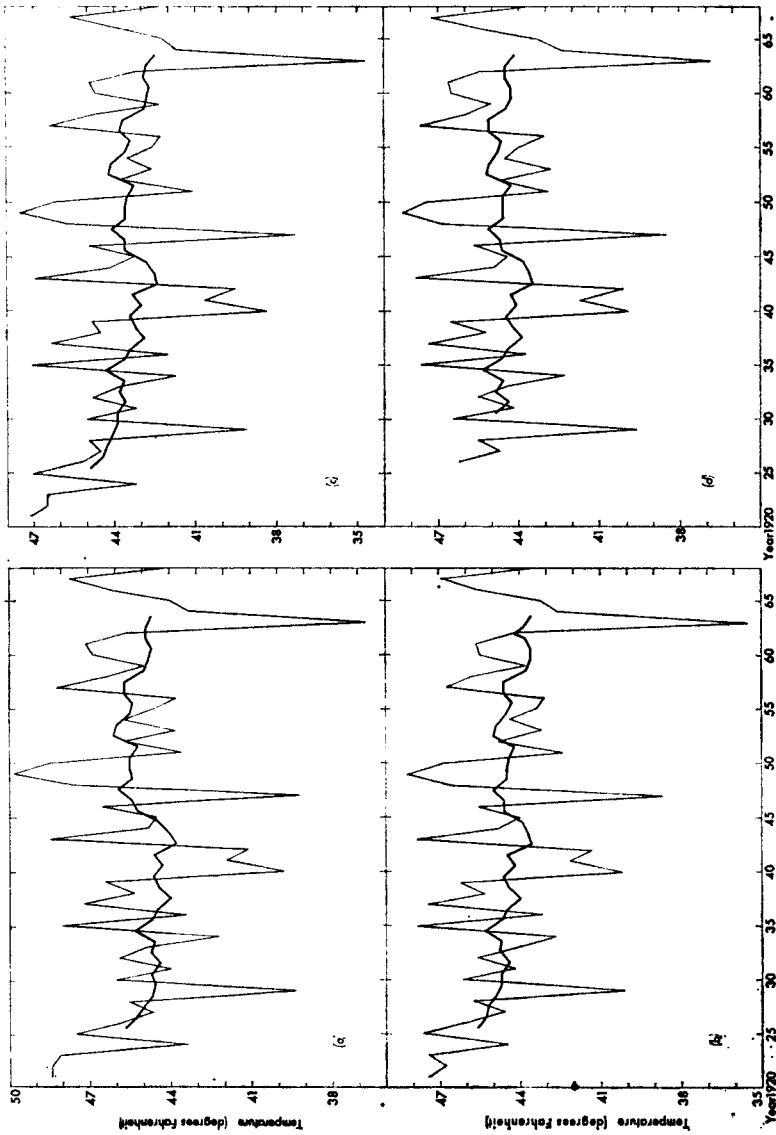


FIGURE 3—WINTER MEAN DAILY MAXIMUM TEMPERATURE AND 10-YEAR RUNNING MEANS

(a) Kensington Palace, (b) Porton, (c) Woburn and (d) East Malling.
—— Mean daily maximum temperature ——— 10-year running means

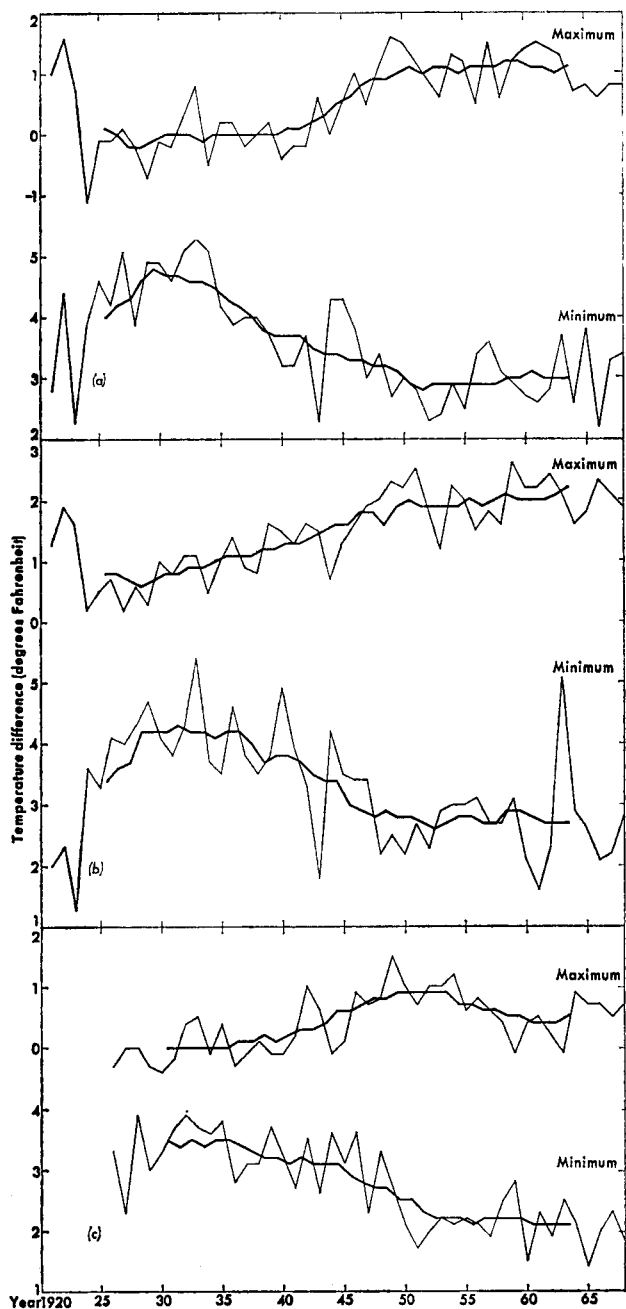


FIGURE 4—WINTER MEAN DAILY MINIMUM-TEMPERATURE DIFFERENCE AND MAXIMUM-TEMPERATURE DIFFERENCE BETWEEN KENSINGTON PALACE AND (a) PORTON, (b) WOBURN, AND (c) EAST MALLING, AND CORRESPONDING 10-YEAR RUNNING MEANS

- (a) Kensington Palace minus Porton (1921-68)
 (b) Kensington Palace minus Woburn (1921-68)
 (c) Kensington Palace minus East Malling (1926-68).

— Mean daily temperature difference

— 10-year running means

wind speed (at Kew; Figure 5); in general, trends in the temperature-difference curves cannot be explained as merely a result of trends in mean wind speed.

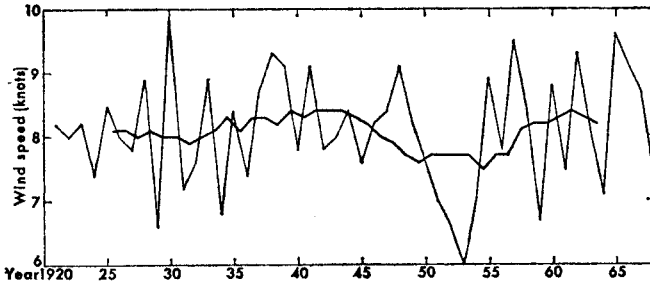


FIGURE 5—WINTER MEAN HOURLY WIND SPEED AT KEW OBSERVATORY AND 10-YEAR RUNNING MEANS
 ——— Mean hourly wind speed ——— 10-year running means

A further possible partly-natural cause of trends in temperature-difference curves is long-term trends in cloudiness. Like wind increases, an increase in cloudiness could reduce station differences and vice versa: for example, 'heat-islands' are less marked in strong winds and/or cloudy conditions. Conversely the relative increase, in Figures 4(a), (b) and (c), in London's maximum temperatures between 1935 and 1945 might be partly the result of a general (natural) decrease in cloudiness or increase in sunshine, but the trend in the duration of sunshine (Figure 6) does not support this explanation.

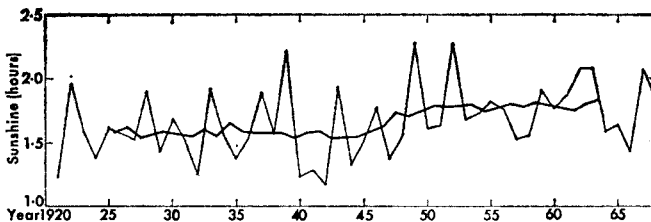


FIGURE 6—WINTER MEAN DAILY DURATION OF SUNSHINE AT KEW OBSERVATORY AND 10-YEAR RUNNING MEANS
 ——— Mean daily duration of sunshine ——— 10-year running means

However, there is an overall similarity between the sunshine trend (Figure 6) and the trends shown in the maximum-temperature-difference curves (Figures 4(a), (b) and (c)). The correlation coefficients between sunshine and maximum-temperature-differences, for 10-year running mean values, are + 0.92 (K - P), + 0.84 (K - W), and + 0.68 (K - E). These rather high correlations may result from the fact that retention of solar radiation in urban

areas, as compared with surrounding rural areas, is relatively greater when sunshine is greater.

The foregoing discussion shows that the main features of the temperature-difference graphs (Figures 4(a), (b) and (c)), namely the relative increase in mean maximum temperatures and the relative decrease in mean minimum temperatures between the 1930s and about 1950, cannot be explained entirely by changes in wind, cloud or radiation. It is suggested that the results reflect the increasing use of cleaner and more efficient heating methods. After about 1950, changes in temperature differences seem to be less marked, in spite of the Clean Air Act of 1956, and the fact that during recent years, there seems to have been in central London, (i) some increase relative to surrounding rural areas, in the duration of winter sunshine,^{1,3} (ii) an increase between 1957 and 1963 in the direct radiation per hour of sunshine,³ and (iii) a relative increase of winter illumination, as a proportion of that at Kew, from 0.8 in the early 1950s to generally 0.9 to 1.0 in the 1960s, and (iv) a decrease of fog both in central London⁴ between 1947 and 1962, and at London/Heathrow Airport⁵ between 1946 and 1963.

The levelling-out of temperature-difference trends after 1950* could result from a number of possible causes, for example, (i) decreasing minimum temperatures in central London could lead to greater fuel consumption and artificial atmospheric heating and so check the earlier decrease in minimum-temperature difference, (ii) the greater amounts of sunshine could cause greater heat-retention and so likewise inhibit the previous decrease in minimum-temperature difference and (iii) increasing mean wind speed after the early 1950s might well have masked any increase of maximum-temperature difference resulting from urban improvements.

Conclusions. Climatological data from 1920 for the London region suggest that the most marked changes in London's winter temperatures, relative to its surroundings, occurred between the 1930s and about 1950, when in central London, mean maximum temperatures increased by approximately 1 degF (0.5 degC) and mean minimum temperatures decreased by approximately 1.5 to 2 degF (1 degC), relative to surrounding areas. The data suggest that these changes are the result of (i) urban changes, as for example, the improvement in heating methods, and (ii) the difference in effects between London and surrounding areas caused by natural changes of climate, as for example, natural changes in sunshine.

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* During the middle 1940s the trend in the 10-year running means of the difference between minimum temperature at Manchester Airport in winter and that at neighbouring stations was similar to the trend at London. In the 1950s the trend at London levelled out, but the trend at Manchester Airport showed a marked increase of about 1 degF (0.5 degC), which probably reflects the results of the more extensive local urban development around Manchester Airport during this period.

CLEAR-AIR TURBULENCE OVER THE NORTH ATLANTIC; SOME NOTABLY TURBULENT PERIODS

By J. C. LENNIE

Summary. An examination was made of aircraft reports of clear-air turbulence. Notably turbulent periods occurred in two types of synoptic situations. In the first the turbulence was reported near a strong anticyclonically curved jet stream, and the association of this high-level feature with cyclonic deepening is shown in some cases. In the second situation the turbulence occurred in a large-amplitude ridge not far from the right exit of a jet stream. This high-level pattern belongs to a later stage of cyclonic development and is shown on most occasions to be associated with the point of occlusion.

Introduction. Although large numbers of aircraft cross the North Atlantic daily, there are seldom more than a few reports of turbulence. In 1967, for example, on more than 90 per cent of the 12-hour periods, 0000 to 1200 GMT and 1200 to 0000 GMT, not more than two turbulence reports per period were received at London/Heathrow Airport. A few periods, on the other hand, are notably turbulent. In 1967, on about 1 per cent of the 12-hour periods there were 10 or more reports of turbulence and it is these occasions, 9 in number, together with 2 equally turbulent occasions from early 1968 which are examined here. The numbers above refer to the area bounded by the latitudes 40°N and 60°N and the longitudes 10°W and 60°W, and to turbulence of intensity greater than light: the word turbulence is used in this sense throughout.

Frequent turbulence reports during a 12-hour period almost always indicate that the transatlantic aircraft have encountered, not widely scattered patches of turbulence, but one particularly turbulent area, the boundaries of which can be defined approximately from aircraft reports. This is so because the traffic pattern over the North Atlantic ensures that large numbers of east-bound aircraft are over the area concerned from 0000 to 0900 GMT daily, and large numbers of west-bound aircraft from 1200 to 2100 GMT daily. Present-day flight-planning procedures further ensure that in each instance most of the aircraft are concentrated on a few closely similar tracks. They almost all fly between 29 000 and 39 000 ft (9–12 km). The turbulence encountered at these flight levels is not necessarily associated with the zone of strong vertical wind shear under the jet stream in which clear-air turbulence is often found.

When the turbulence reports received during the notably turbulent periods were plotted on the most appropriate 300 mb chart (the 0000 GMT chart for east-bound aircraft, and the 1200 GMT chart for west-bound aircraft) the turbulent areas were found to be associated, broadly, with two types of contour patterns. These were (i) a broad, rather flat ridge with a strong contour gradient, and (ii) a jet stream orientated from between S and WSW debouching into a ridge of large amplitude and relatively light winds. The 300 mb chart, however, shows only the larger-scale features of the flow. The details of the wind field near the turbulent area can be shown more clearly by means of the winds reported by the aircraft. Since few of these are received simultaneously, it was necessary to illustrate the flow using winds measured at differing times. The period from which winds for this purpose were selected was made as short as possible consistent with adequate representation of the

wind field and usually proved to be about two hours. At least one such chart of winds with contemporary reports of turbulence was plotted for 10 of the 11 turbulent periods.

Five notably turbulent periods associated with strong winds in broad 300 mb ridges. Five periods were associated with the type of 300 mb pattern illustrated in Figure 1. Similar situations are shown in more detail in Figures 2, 3 and 4. The detailed charts show, for each of the four periods for which it was possible to prepare them from winds reported by aircraft, that the turbulence was near a very strong, anticyclonically curved jet stream, and that although some turbulence was clearly on the cold side of the jet stream and some on the warm side, the bulk of it was close to the core. There was also a marked concentration of turbulence near the axis of the ridge, almost half of the total of 94 reports, as Table I shows, being within 5 degrees of longitude upwind and 5 degrees downwind of the ridge axis. Since the wind reports are usually at intervals of 10 degrees of longitude there is, of course, some doubt about the precise position of the axis.

TABLE I—DISTRIBUTION OF TURBULENCE AROUND THE AXES OF THE FOUR BROAD STRONG 300 mb RIDGES

Date	Degrees of longitude upwind				Ridge axis	Degrees of longitude downwind			
	16-20	11-15	6-10	1-5		1-5	6-10	11-15	16-20
21 Jan. 1967	1		5	1	2	8			
2 Mar. 1967				5	1	2	6		1
8 July 1967			10	4	5	5	1		
2 Dec. 1967		1	1	7	1	2	14	6	5
Total	1	1	16	17	9	17	21	6	6

The turbulence on 2 December 1967 is something of an exception, for then it occurred not only around the axis of the ridge, but was experienced all the way from the downwind trough to the axis (Figure 4).

The vertical relationship of the turbulence to the height of the jet-stream core is shown in Table II. As the jet streams were all very strong the shear of wind between flight levels was marked, so that the accuracy of the heights assigned to the jet cores is probably better than average.

TABLE II—DISTRIBUTION OF TURBULENCE AROUND THE LEVEL OF THE JET CORE

Date	Jet height*	Flight level*					
		290	310	330	350	370	390
21 Jan. 1967	330	0	1	10	5	1	0
2 Mar. 1967	350	0	2	2	11	0	0
8 July 1967	320	0	0	14	11	0	0
2 Dec. 1967	300	0	1	8	12	11	5

* Heights expressed in hundreds of feet.

Number of turbulence reports below jet-stream level = 5.

Number of turbulence reports at and above jet-stream level = 89.

The preponderance of turbulence at and above the level of the jet stream may be real or only apparent, and due to the large numbers of aircraft flying at 33 000 and 35 000 ft. Correction for this imbalance in the numbers of reports from different flight levels has been made by expressing the number of turbulence reports at each flight level as a fraction of the total number of aircraft reports at that level in the turbulent area. Table III shows that of the aircraft reports at and above the jet, the proportion which indicate turbulence was four times the corresponding proportion below the jet.

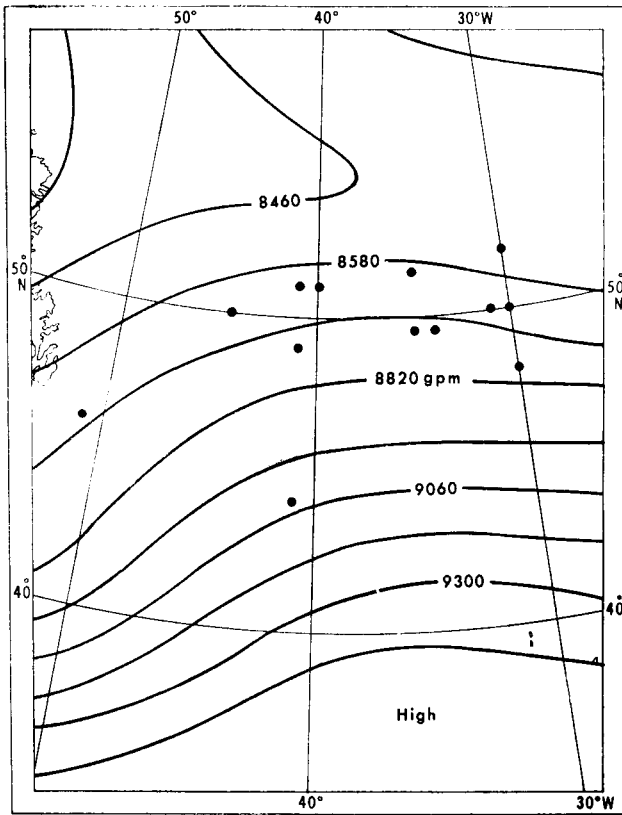


FIGURE 1—300 mb CHART, 0000 GMT, 21 JANUARY 1967
Dots show position of turbulence reported between 0100 and 0600 GMT.
Each dot may represent more than one report.

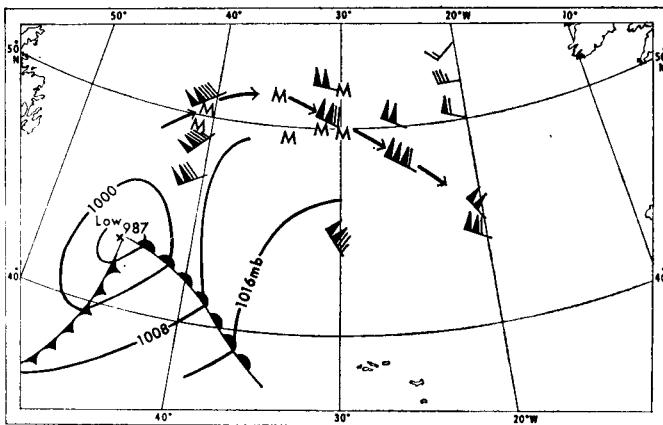


FIGURE 2—21 JANUARY 1967. AIRCRAFT-REPORTED WINDS AT ABOUT 33 000 ft
(10 000 m), 0405–0525 GMT, TURBULENCE 0435–0530 GMT
M = light to moderate, moderate and moderate to severe turbulence. Surface analysis 0600 GMT.
Arrows show approximate position of the jet stream.

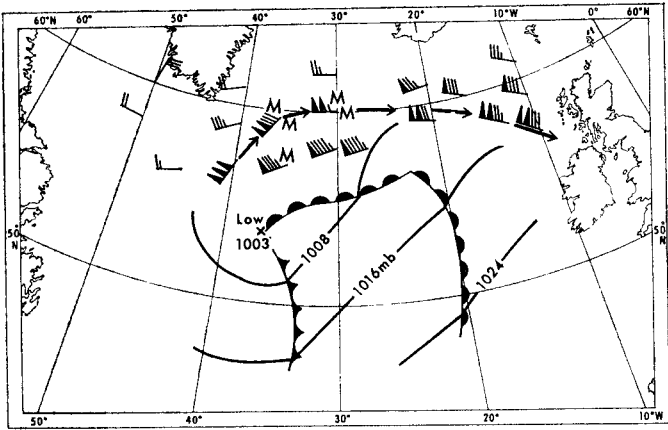


FIGURE 3—8 JULY 1967. AIRCRAFT-REPORTED WINDS AT ABOUT 35 000 ft (10 500 m), 1410 – 1535 GMT. TURBULENCE 1410 – 1540 GMT. M=light to moderate, moderate and moderate to severe turbulence. Surface analysis 1800 GMT. Arrows show approximate position of the jet stream.

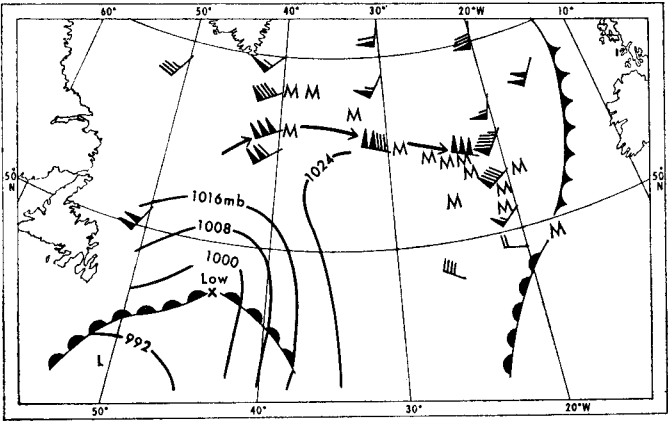


FIGURE 4—2 DECEMBER 1967. AIRCRAFT-REPORTED WINDS AT ABOUT 35 000 ft (10 500 m), 1335 – 1550 GMT. TURBULENCE 1405 – 1550 GMT. M=light to moderate, moderate and moderate to severe turbulence. Surface analysis 1800 GMT. Arrows show approximate position of the jet stream.

TABLE III—RATIOS OF TURBULENT TO TOTAL REPORTS IN RELATION TO THE LEVEL OF THE JET STREAM

Date	Below jet stream	At and above jet stream	Total
21 Jan. 1967	1/14	16/55	17/69
2 Mar. 1967	4/37	11/50	15/87
8 July 1967	0/12	25/61	25/73
2 Dec. 1967	0/7	37/134	37/141
Total	5/70	89/300	94/370
Per cent	7	30	—

So far it has been shown that on these four notably turbulent occasions the turbulence was near a very strong anticyclonically curved jet stream, that it tended to be concentrated round the axis of the ridge, and that much of it occurred at the level of the jet stream and above.

Binding,¹ when discussing turbulence in high-level ridges suggested that an increase in the speed or an increase in the anticyclonic curvature of the warm front jet stream, both of which may occur as a depression deepens, are factors tending towards an increase of turbulence. On the four occasions under discussion the jet streams were all of the warm front type, i.e. they were moving laterally towards colder air. So, in the light of Binding's suggestions, the surface features related to the jet streams were next examined. Table IV shows that on three of the four occasions the turbulent jet stream was associated with a deepening depression having a pronounced northward component of movement. On the fourth occasion the main feature was an old deep low with, on its eastern flank, a non-deepening secondary system moving rapidly NNE (Figure 4). In spite of the differences between the pressure pattern of the first three cases and that of the fourth, they have in common what appears to be an important factor, the capacity for driving warm air rapidly northwards.

TABLE IV—MAIN FEATURES OF THE SURFACE PRESSURE PATTERN ASSOCIATED WITH FOUR NOTABLY TURBULENT WARM FRONT JET STREAMS. *H* IS THE TIME OF THE SURFACE CHART NEAREST TO THE TURBULENCE

Date	Surface feature	Pressure at <i>H</i> -12	at <i>H</i>	12-hour pressure difference	Latitude at <i>H</i> -12	at <i>H</i>	12-hour movement north
		<i>millibars</i>			<i>degrees</i>		
21 Jan. 1967	Deepening warm sector low	1007	987	- 20	39	43	+ 4
2 Mar. 1967	Deepening warm sector low	1003	982	- 21	39	47½	+ 8½
8 July 1967	Deepening wave	1015	1003	- 12	45½	53½	+ 8
2 Dec. 1967	Deep occluding low	979	975	- 4	38½	39½	+ 1
	Secondary moving NNE*	998*	998	0*	44*	47½	+ 3½*

* Six-hour period only

Table IV provides support for the view that turbulence is particularly likely near the warm front jet stream during cyclogenesis, but in order to show the connection more clearly the situation leading up to the turbulent outbreak of 21 January 1967 has been examined in detail. Figure 5 shows schematically

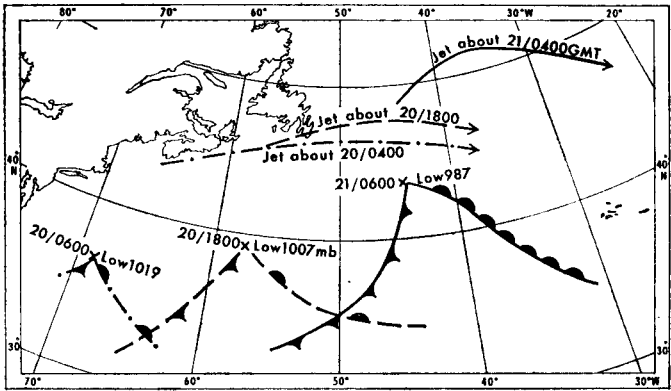


FIGURE 5—SITUATION LEADING UP TO THE TURBULENT OUTBREAK OF 21 JANUARY 1967

Positions of warm-sector depression at 12-hour intervals with the corresponding positions of the warm-front jet streams derived from aircraft reported winds.

the deepening depression with its frontal system at 12-hour intervals from 0600 GMT 20 January, and the positions of the warm front jet stream at about the same times obtained from aircraft reported winds. The details of the wind field in the vicinity of the jet stream about 0400 GMT on 20 January, when the depression was just beginning to deepen, are shown in Figure 6.

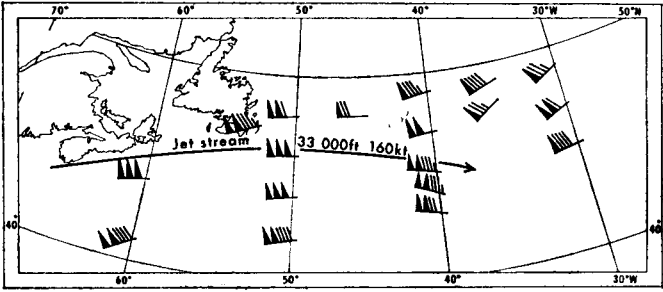


FIGURE 6—20 JANUARY 1967. AIRCRAFT-REPORTED WINDS AT ABOUT 33 000 ft (10 000 m) NEAR 0430 GMT WITH APPROXIMATE POSITION OF THE JET STREAM. The same jet stream about 24 hours later is shown in Figure 2.

About this time 60 reports were received from east-bound aircraft between 60°W and 40°W and within three degrees of latitude either side of the jet stream. No turbulence was reported. Twenty-four hours later, with the depression now deepened to 987 mb, the east-bound aircraft again encountered the jet stream. This time there were many reports of turbulence, mostly moderate, but occasionally severe. The changes which took place in the warm front jet stream during the 24 hours of cyclonic development can be seen by comparing Figure 2 with Figure 6. There is no apparent change in speed but there is a pronounced increase in the anticyclonic curvature of the jet stream.

Six notably turbulent periods associated with large-amplitude 300 mb ridges. The remaining six periods were associated with the type of 300 mb pattern illustrated in Figure 7. The relationship of the turbulent area to the wind field is shown in more detail for five of the six cases in Figures 8–12. The features of the wind field in the vicinity of the turbulent area which are common to all the illustrated examples are (i) the flow is anticyclonic and (ii) the wind speed decreases across the turbulent area in the direction of the flow.

Table V shows that more than half the turbulence occurred within five degrees of longitude upwind and five degrees downwind of the axis of the ridge and that there may be a tendency for more turbulence on the upwind than on the downwind side of the ridge.

TABLE V—DISTRIBUTION OF TURBULENCE AROUND THE AXES OF SIX LARGE-AMPLITUDE RIDGES

Date	Degrees of longitude upwind					Ridge axis	Degrees downwind	
	20	16–20	11–15	6–10	1–5		1–5	6–10
11 Apr. 1967				8	2	5	1	
8 Mar. 1967	1	5	1	3	3		1	
19 Dec. 1967	2	3	5	4	5		1	
23 Dec. 1967				1	11	4	5	11
8 Jan. 1968					2	4	8	5
27 Feb. 1968				6	24	9	3	
Total	3	8	6	22	47	22	19	16

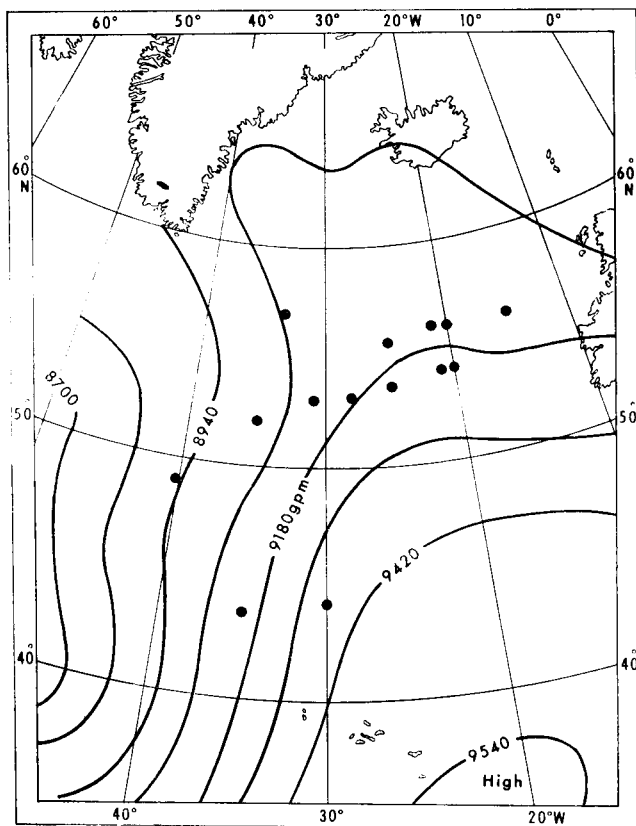


FIGURE 7—300 mb CHART, 0000 GMT, 19 DECEMBER 1967

Dots show position of turbulence reported between 0400 and 0800 GMT. A dot may indicate more than one report.

In this type of situation the winds in the turbulent area are too light for precise identification of the level of the jet-stream core, or the level of maximum wind in the ridge, but as far as can be judged, there was about the same proportion of turbulence reports below the jet-stream level as there was at and above it.

The 300 mb pattern common to all six periods is one often associated with a cold occlusion; and in five of the six cases the main feature of the synoptic situation was, in fact, a partially occluded low. Details are given in Table VI. In four cases (Figures 8, 9 and 10 illustrate three of them) the point of occlusion is either in or just upwind of the turbulent area. In the fifth case (Figure 11) the point of occlusion is some 300 nautical miles to the south of the turbulence, while in the sixth (Figure 12) the surface synoptic situation is quite different with the point of occlusion well to the north of the turbulence.

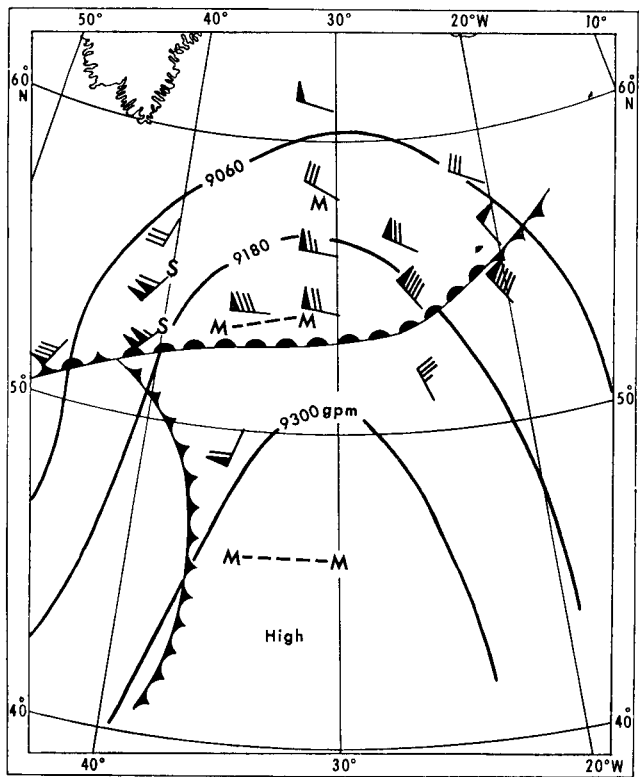


FIGURE 8—11 APRIL 1967. AIRCRAFT-REPORTED WINDS AT ABOUT 35 000 ft (10 500 m), 0505 – 0650 GMT. TURBULENCE 0515 – 0650 GMT
M = light to moderate and moderate, S = severe turbulence. - - - indicates continuous turbulence. Surface analysis and interpolated 300 mb contours for 0600 GMT.

TABLE VI—MAIN FEATURE OF THE SURFACE PRESSURE PATTERN DURING SIX NOTABLY TURBULENT PERIODS ASSOCIATED WITH LARGE-AMPLITUDE RIDGES.

H IS THE TIME OF THE SURFACE CHART NEAREST TO THE TURBULENCE

Date	Surface feature	Pressure		12-hour pressure difference	Latitude		12-hour movement north
		at <i>H</i> -12	at <i>H</i>		at <i>H</i> -12	at <i>H</i>	
		millibars			degrees		
11 Apr. 1967	Partially occluded low	987	983	- 4	42	48½	+ 6½
8 Nov. 1967	Partially occluded low	998	988	- 10	63½	66½	+ 3
19 Dec. 1967	Partially occluded low	991	993	+ 2	56½	57½	+ 1
23 Dec. 1967	Partially occluded low	967	959	- 8	58	63½	+ 5½
8 Jan. 1968	Partially occluded low	970	963	- 7	48	49½	+ 1½
27 Feb. 1968	Open warm sector low	976	980	+ 4	41	51½	+ 10½

Conclusions. During 11 of the most turbulent periods occurring over the North Atlantic in 1967 and early 1968 the turbulence, which was between



Photograph by courtesy of The British Petroleum Company Ltd

PLATE I—ICE ACCUMULATION ON OIL TANKER

January 1968 in the Baltic. With several inches of ice on her foredeck and upperworks, the 16 000 deadweight ton BP tanker *British Vigilance* arrives at the town of Gavle, Sweden, 120 miles north of Stockholm. An ice-breaker had to clear a path into the port for the tanker before she could unload her cargo of gas oil, in a temperature of minus 4°F (36° below freezing point). The weather in the Baltic was unusually bitter during the winter of 1967-68.

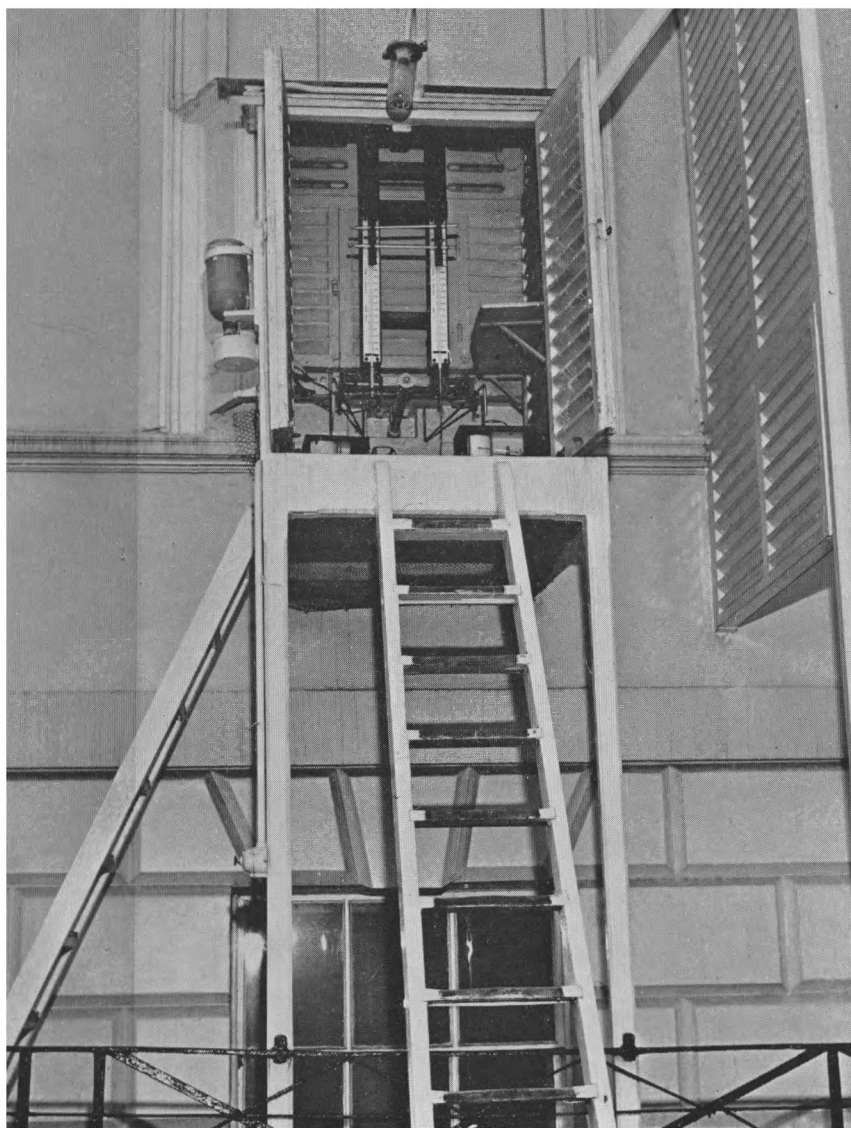


PLATE II—THE NORTH WALL SCREEN AT KEW OBSERVATORY (WITH THE DOORS OPEN)

The photothermograph thermometer bulbs can be seen in the lower left (the wet bulb) and the lower right; the stems of these thermometers are bent twice at right angles, the horizontal portions passing through the wall of the building so that photographic recording can take place inside. In the centre are two control thermometers, one dry bulb and one wet bulb. On the left, outside the screen, is a reservoir of distilled water feeding both the wet bulbs. On the right, outside the screen, is an additional louvered screen to cut off solar radiation from the setting sun in summer (the main entrance of the Observatory cuts off radiation at sunrise). (See page 30).

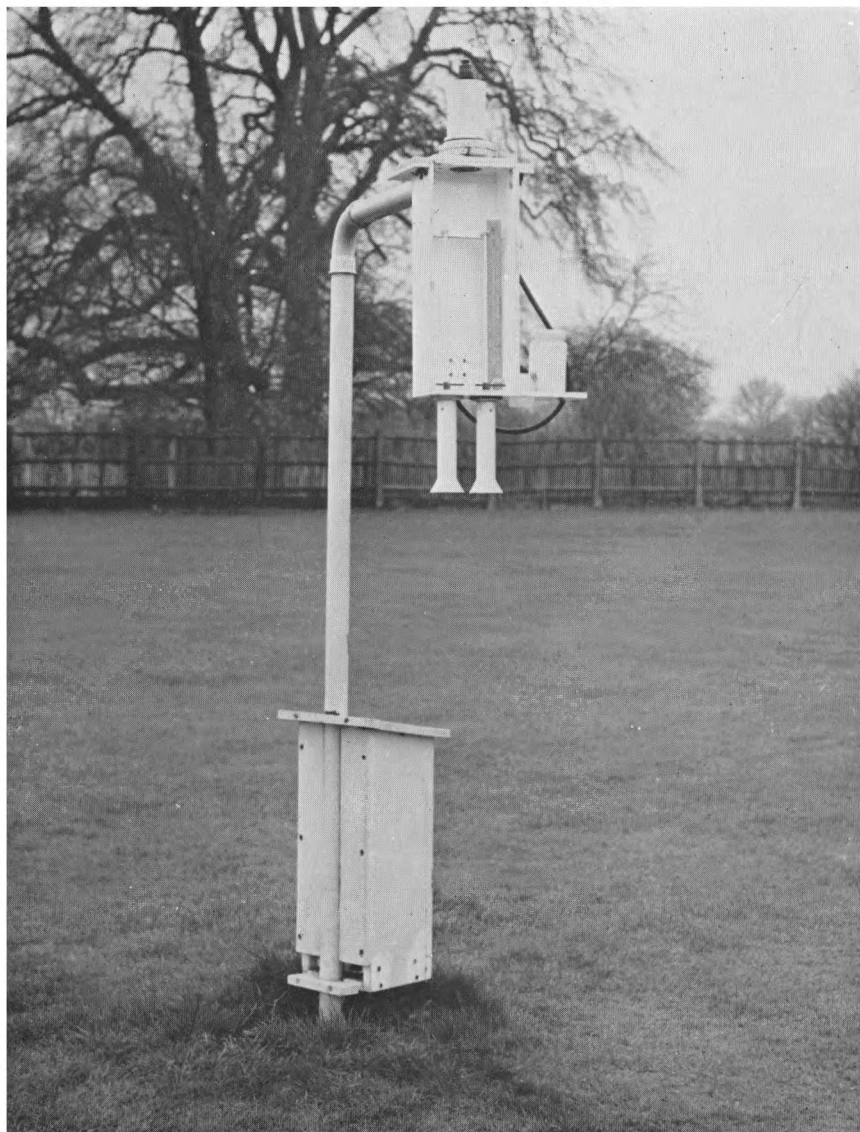


PLATE III—THE NEW ELECTRICAL RESISTANCE ASPIRATED PSYCHROMETER AT
KEW OBSERVATORY

Air is drawn up through the double-walled radiation shields at the base of the instrument, and over the resistance thermometer elements. Sensitive open-scale mercury-in-glass thermometers (which can be seen through the clear perspex front — together with a foot-rule) are permanently mounted with their bulbs in cylindrical cavities in the centre of the resistance element; these enable frequent checks to be carried out on the resistance record.

The resistance elements are 1.25 metres above the ground level and the psychrometer is situated near the centre of the large lawn. The trees in the background are about 80 feet (27 metres) high and are some 190 feet (63 metres) distant. (See page 30).

To face page 17

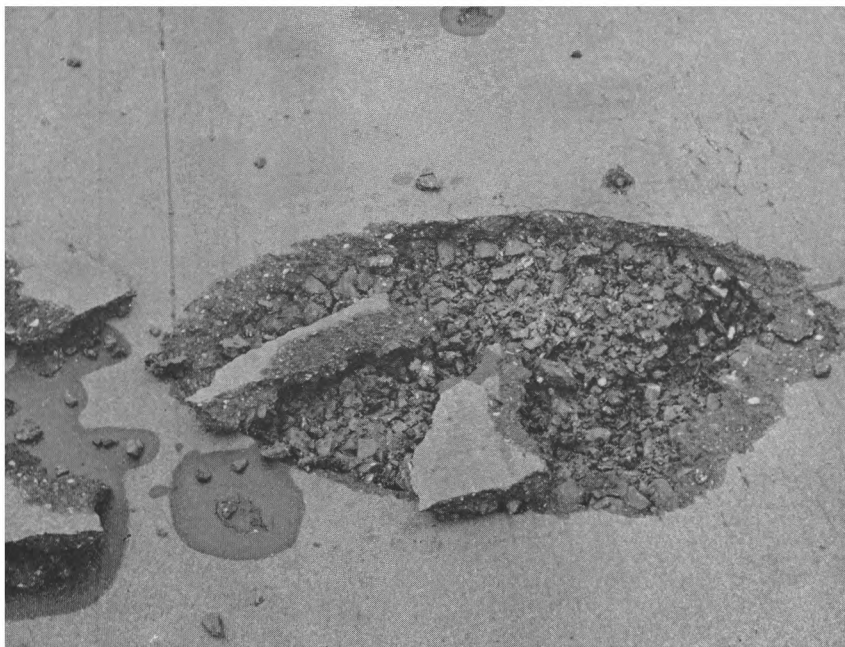


PLATE IV—LIGHTNING STRIKE AT RAF CHIVENOR, 2 JULY 1968 — A LARGE
CRATER TORN IN THE RUNWAY SURFACE



PLATE V—DEBRIS FANNING OUT FROM THE CRATER FORMED BY THE LIGHTNING
STRIKE AT CHIVENOR

See page 31.

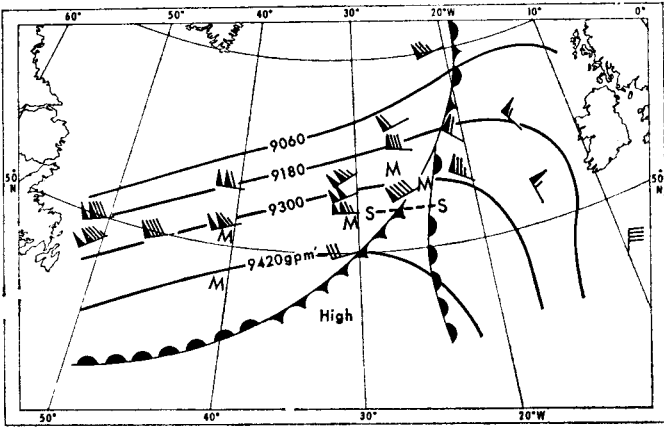


FIGURE 9—8 NOVEMBER 1967. AIRCRAFT-REPORTED WINDS AT ABOUT 35 000 ft (10 500 m), 0400–0555 GMT. TURBULENCE 0410–0550 GMT
M = light to moderate and moderate, S = severe turbulence. - - - indicates continuous turbulence. Surface analysis and interpolated 300 mb contours for 0600 GMT.

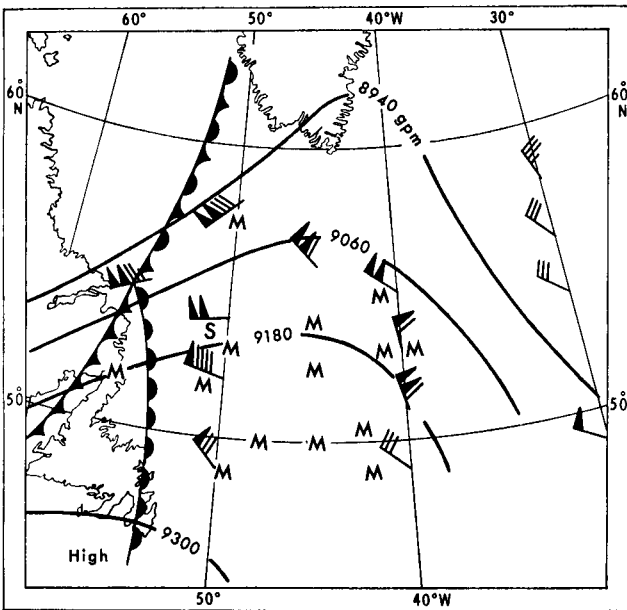


FIGURE 10—23 DECEMBER 1967. AIRCRAFT-REPORTED WINDS AT ABOUT 35 000 ft (10 500 m), 0400–0715 GMT. TURBULENCE 0405–0710 GMT
M = light to moderate and moderate, S = severe turbulence. Surface analysis and interpolated 300 mb contours for 0600 GMT.

29 000 and 39 000 ft, was all associated with anticyclonic curvature in the wind field. Two situations in which this type of high-level clear-air turbulence seems particularly likely can be recognized. The first is the broad ridge with strong winds which develops in the upper troposphere as a polar front depression deepens. Turbulence is then likely in the ridge near the warm front jet stream as it bends anticyclonically. The second situation arises as

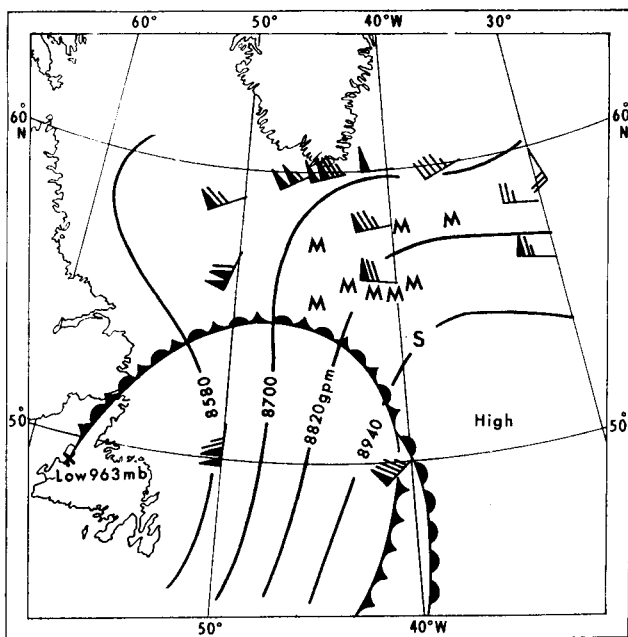


FIGURE 11—8 JANUARY 1968. AIRCRAFT-REPORTED WINDS AT ABOUT 35 000 ft (10 500 m), 1555–1755 GMT. TURBULENCE 1550–1745 GMT
M = moderate and moderate to severe, S = severe turbulence. Surface analysis and interpolated 300 mb contours for 1800 GMT.

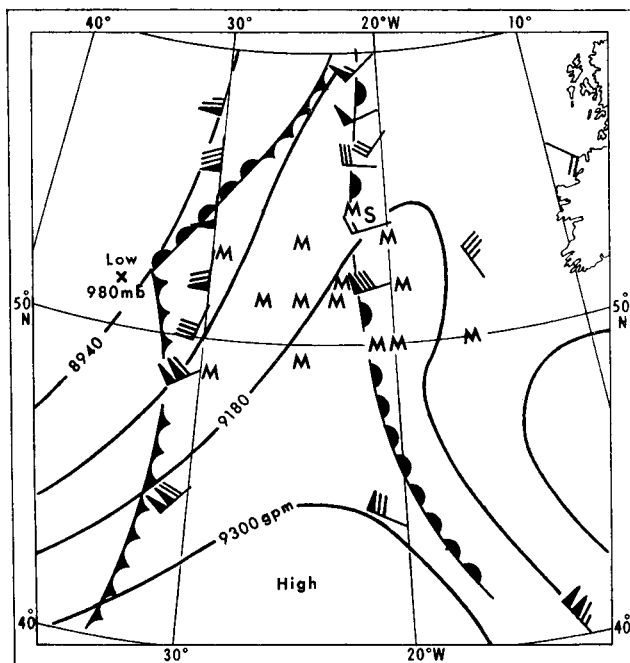


FIGURE 12—27 FEBRUARY 1968. AIRCRAFT-REPORTED WINDS AT ABOUT 35 000 ft (10 500 m), 0510–0800 GMT. TURBULENCE 0525–0755 GMT
M = light to moderate, moderate and moderate to severe, S = severe turbulence. Surface analysis and interpolated 300 mb contours for 0600 GMT.

the cyclonic development continues, and the amplitude of the upper ridge increases during occlusion. Turbulence may then occur in the ridge near the right exit of the cold front jet stream or, in terms of surface features, in the vicinity of the point of occlusion.

REFERENCE

1. BINDING, A. A.; Association of clear-air turbulence with 300 mb contour patterns. *Met. Mag.*, London, 94, 1965, p. 11.

551.509.322.7:311.214:629.13:681.3

THE COMPARISON OF SUBJECTIVE AND OBJECTIVE UPPER AIR FORECASTS FOR AVIATION (PART I)

By I. H. CHUTER, M.Sc.

Summary. Part I. Subjective forecasts of the 300 mb height field were compared with objective forecasts produced by means of a linear regression equation using the 1000, 500 and 200 mb forecast height fields. An objective method was used to compare the actual equivalent headwinds over a given route with those forecast. (Assessments were made on the 0000 GMT analyses charts and on the forecast charts valid for the same time — normally a 24-hour forecast.) The period covered was from August 1966–July 1967 giving about 360 forecasts, and these have been analysed in 3 sets of 120.

Headwinds were also converted into total flight times and assessments were made of timing errors in relation to the needs of airline operators. Root-mean-square errors in the objective forecasts of headwinds were lower than in subjective forecasts. An analysis of the total errors on each route showed that large errors were fewer in the objective forecasts than the subjective.

Part II of the paper will be published in the February issue and gives an analysis of errors in headwinds for individual 300 nautical mile zones on the air routes showing that the objective forecasting method was better than the subjective, and that forecast success does not depend on the geographical location of the zone. An analysis of the errors in estimated flight times shows that subjective methods increased the mean error.

Some of the possible sources of error in the data are discussed.

Introduction. Airline operators make extensive use of upper wind forecasts, especially over the North Atlantic where some choice of route is still possible.

The majority of Atlantic operations now take place between 30 000 and 40 000 ft (10 and 13 km), in the layer which frequently incorporates the jet stream, and the first purpose of flight planning is to select least-time tracks. Other factors such as clear-air turbulence and temperature are considered but for west-bound operations which are planned to avoid strong wind areas the emphasis is almost wholly on the forecast wind flow between 300 and 200 millibars.

Tests by Woodroffe¹ have shown that objective 300 mb forecasts by a regression technique were at least as reliable as subjective forecasts. Numerical forecasts for 300 mb have been produced, on the Meteorological Office COMET computer, by means of a linear regression equation using the 1000, 500 and 200 mb forecast height fields. Although results were available on an experimental basis in April 1966 they were not included in the routine output until September 1966.

Forecast verification. For the purpose of verifying the accuracy of forecasts it would seem to be most satisfactory to compare the actual time taken on a flight with the planned time derived from the forecast, but this was not attempted for several reasons. Firstly, the actual time may depend on non-meteorological factors, e.g. variations of flight level and route because of air traffic control instructions. Secondly, in the planning stage, allowance is made for initial climb and final descent and this requires some subjective interpolation. Also, the aircraft may experience temperatures that make it difficult or uneconomic to reach the planned flight level on certain stages of the route. Finally, forecasts are regarded as valid for departure over a period of six hours and no allowance is made for the flight durations.

An alternative and objective method was adopted based on the comparison of equivalent headwinds that an aircraft would experience on a specified route between London and New York at a constant level of 300 mb. Calculations were made for each of three routes, see Figure 1, known as the great circle, the polar curve and the rhumb line, which together cover a representative area of the North Atlantic.

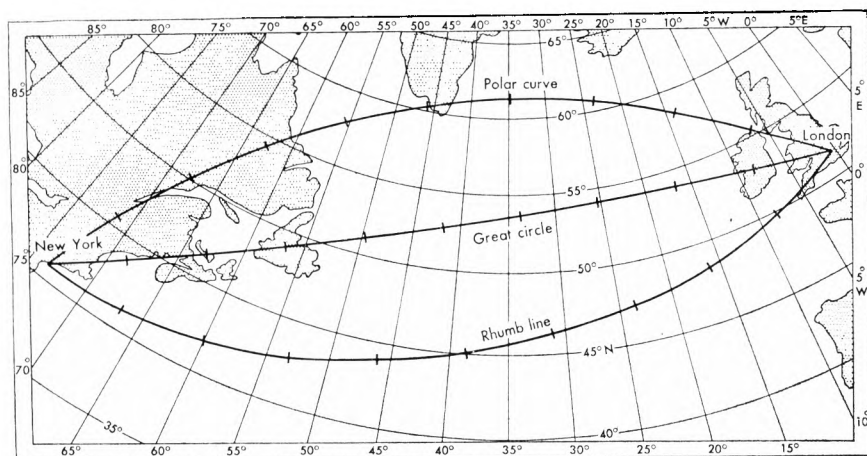


FIGURE 1—NORTH ATLANTIC AIRCRAFT ROUTES BETWEEN LONDON AND NEW YORK

Few actual flights are likely to follow any of these routes at precisely 300 mb (the average flight level for the majority of trans-atlantic jets being somewhat higher), and, strictly speaking, no fixed-time forecast is valid. Nevertheless the comparisons should indicate the relative accuracy of the forecast winds obtained by subjective and objective methods over an area which includes most of the London - New York flights.

Some characteristics of equivalent headwinds in relation to the vector properties of wind velocities, have been discussed earlier, by Howkins and Chuter.² The advantages in the use of headwinds include the property that they are scalar quantities, and the results bear a direct relationship to the principal object of the forecast, i.e. the accurate assessment of headwind for the calculation of pay-load and fuel requirements, and of flight time. The equivalent headwind E was obtained from the wind velocity using the relationship

$$E = V \cos \theta + \frac{V^2 \sin^2 \theta}{2 A}$$

where V is the wind speed

A is the aircraft speed

θ is the angle between the direction of the wind and that of the track.

The convention used resulted in a positive value for headwinds and a negative value for tailwinds. The flight time T is thus given by

$$T = L/(A - E) \quad \text{where } L \text{ is the track length.}$$

Extraction of the data. Two sets of data were used for the error assessments.

- (i) London/Heathrow Airport 300 mb analyses and forecasts.
- (ii) COMET 300 mb forecasts produced by a linear regression from the standard levels of 1000, 500 and 200 mb.

London/Heathrow Airport. On each of the routine analysis and forecast charts the three routes were drawn, each route being divided into 10 equal zones. The wind speed and direction were estimated for each zone and applied to a perspex scale, constructed for an aircraft speed of 400 kt, to calculate the equivalent headwind for that zone, the results being rounded to the nearest 5 kt. With the analysis charts, weight was given to the wind observations both from upper air stations and from aircraft reports. With the forecast charts, the presentation is in the form of contours and isotachs and interpolation of the isopleths is necessary to obtain the zone winds.

Assessments were made on the 0000 GMT analysis charts and on the forecast charts valid for the same time. The normal forecast period was 24 hours from the initial chart time though, in practice, later information, i.e. aircraft reports and 0600 GMT wind observations, could influence the forecast.

It should be noted that the total equivalent headwind for a route is often quoted as the arithmetic mean of the values for equal length zones. Strictly the total headwind should be derived from the mean of the time spent in each zone, i.e. the harmonic mean of zone speed. In practice the difference is only small but it does depend on the variability of the individual zone values. In one case when the headwinds in two zones of the same track were 170 kt and 20 kt, a spread of 150 kt, the two methods gave an overall route headwind difference of 8 kt.

All the Heathrow values were punched on paper tape for processing by the computer and since the calculations could be readily performed, all route headwinds quoted are the true mean values for the route (as far as division into a finite number of zones will allow).

COMET. Information is presented as values for a rectangular array of 47 by 41 points. When these points are plotted on a chart drawn to a polar stereographic projection (as currently in use for synoptic work in the Meteorological Office), they form an array of squares with origin at the North Pole and sides parallel to the longitudes of 35°W and 55°E.

Since the grid squares are of equal size the actual side length on the surface of the earth varies with latitude from about 180 nautical miles near the pole to about 120 nautical miles at 30°N. Over the area crossed by the routes the square side length is about 160 nautical miles.

The 1000, 500 and 200 mb forecasts valid 24 hours from 0000 GMT were used as the basis for the regression, though some 0600 GMT surface information is included to amend the 1000 and 500 mb level final forecasts from COMET.

The D -values, i.e. the difference between the contour height of a given pressure level and the height of that level in the standard International Civil Aviation Organization atmosphere, were connected by the regression relation

$$D_{300} = a + bD_{1000} + cD_{500} + dD_{200}$$

where a , b , c , and d are coefficients and the subscripts refer to the pressure level.

The values of these coefficients were mean yearly values and no seasonal or latitudinal variation was introduced.

The three London–New York tracks were drawn on a chart of 1:15 million scale having an overprint of the grid squares. Coefficients were determined for each square crossed by the tracks. These denoted the position of the square on the grid, the length of track in that square and the angle between the track and the square side.

The mean geostrophic winds for 300 mb were calculated using the heights at the corners of each square crossed, and these were applied to the track coefficients to determine the equivalent headwinds (aircraft speed 400 kt) for each of the 10 zones, and for the total routes.

Period covered by the data. In the four months August–November 1966 the Heathrow forecasts were made from charts produced subjectively, but from December 1966 to July 1967 they were based on COMET forecasts with some subjective adjustment to isotachs. The data have therefore been analysed in three four-monthly sections,

(1) August–November 1966, (2) December 1966–March 1967 and (3) April–July 1967.

In addition to the objective chart of forecast 300 mb contours received by facsimile at Heathrow there is a presentation of mean geostrophic winds for each grid point printed on the North Atlantic chart area. Isotachs can readily be constructed from these values, and by tracing these and the contour pattern, the usual contour-isotach documentation can be produced from the COMET forecast.

In order to retain some subjective control the forecaster can amend the isotachs as thought necessary, e.g. by making allowances for non-geostrophic flow or adding jet-stream core-speeds.

From the beginning of December the Heathrow forecast headwind assessments were made from charts produced in this way although in the first period the Heathrow forecasts were made from charts produced subjectively. The effect on the headwind comparisons should be that the errors in Heathrow and COMET forecasts become similar. Any differences would be due to the method of assessment, or the result of human amendment, or a combination of both.

Error assessments. For the assessment of forecast errors it was necessary to have actual values for verification. Since the COMET 300 mb analyses are also obtained by regressions, and do not directly use the 300 mb observations, the headwinds from the Heathrow charts were taken as the best estimate of the true values.

The 24-hour forecasts of both COMET and Heathrow for each route were compared with the corresponding Heathrow actuals, the errors being defined as forecast value minus actual value. As a reference, the errors were also computed for the 24-hour persistence of the Heathrow actual.

When considering the comparison of headwind errors over long routes it is possible that large errors on one part may be compensated by large errors of the opposite sign on another part. Although the flight times are unaffected it may be embarrassing for an aircraft to be blown considerably off course on one section of the route and then experience a similar effect in the opposite sense further along the route. Meteorologically the effect might result from a serious error in the placing of a trough, ridge or centre.

To give a guide to the extent of such an effect an analysis was made of the errors on individual zones of each track.

Additionally, an attempt was made to simulate the use of the information made by the operators in least-time track selection, by converting the headwinds into total flight times.

It was assumed that the three routes were the only ones available and a least-time track was selected using the forecast values. The corresponding actual values were then examined to see the timing error involved and if the correct track had been chosen. The aircraft speed was again taken as 400 kt.

Three timing errors were assessed :

- (i) The error on the chosen track — this indicates the difference between the flight time planned for the aircraft and the time actually taken.

This may be interpreted as the early or late arrival of the flight at its destination or may be related to the fuel to pay-load proportions.

- (ii) Time difference in the actual flight times between the chosen track and the least-time track. This will be zero if the correct track was selected.

This time may be interpreted as the difference between the flight time experienced by the aircraft and that available had the forecast been perfect.

- (iii) Time difference between the chosen track forecast, i.e. the planned flight time, and the least-time track actual. This will be equal to (i) if the correct track was chosen.

This value may be interpreted as the difference between the flight time planned for the aircraft and that available had the forecast been perfect. It can also be directly related to the economic loss resulting from errors in the forecast winds.

Results and discussion. *Headwind errors.* By definition a positive value indicates that the forecast headwinds are higher than the corresponding actuals. For west-bound flights this means that westerly winds were forecast as being too strong or easterly winds too light.

Root-mean-square errors. Figures 2(a) – (c) show the r.m.s. errors for the three routes for each month August 1966 – July 1967. For period (1), August – November, COMET values were consistently lower indicating the superiority over the purely subjective forecasts. The change of procedure coincided with the arrival of more unsettled winter conditions and the resultant rise in the

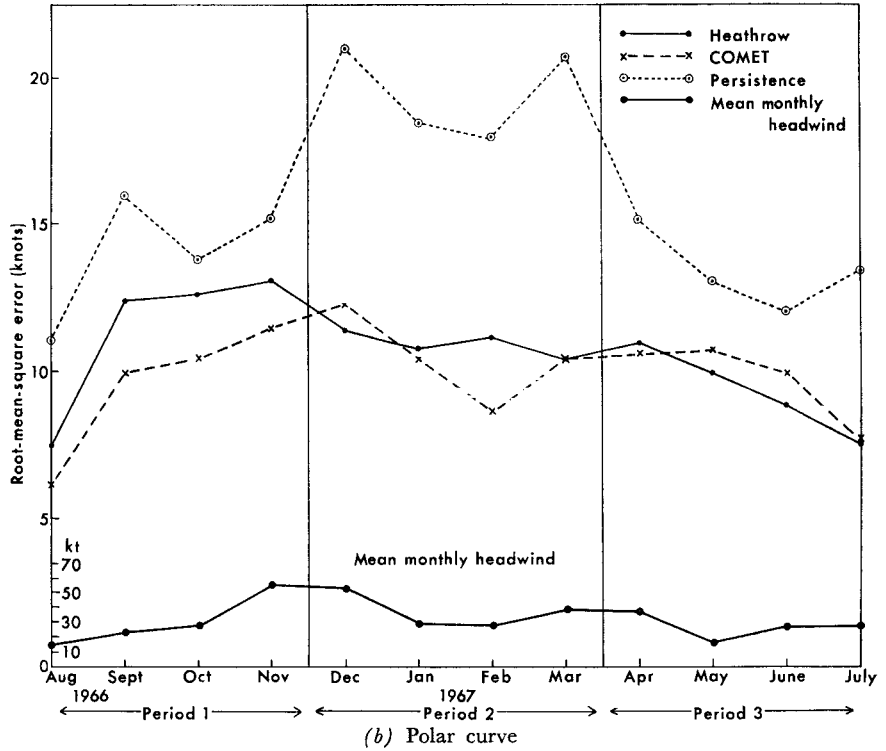
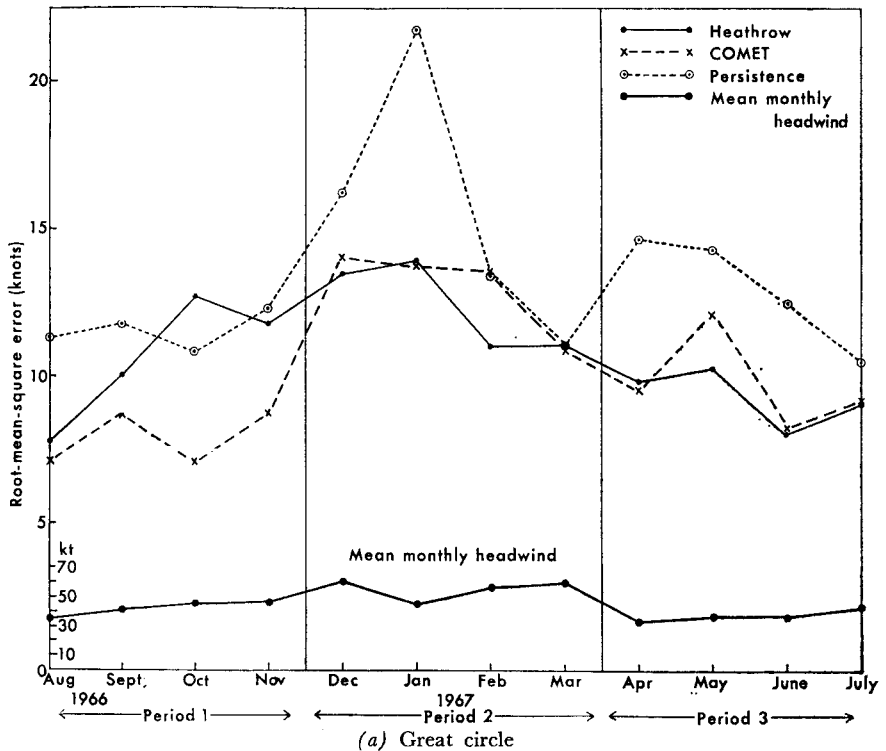
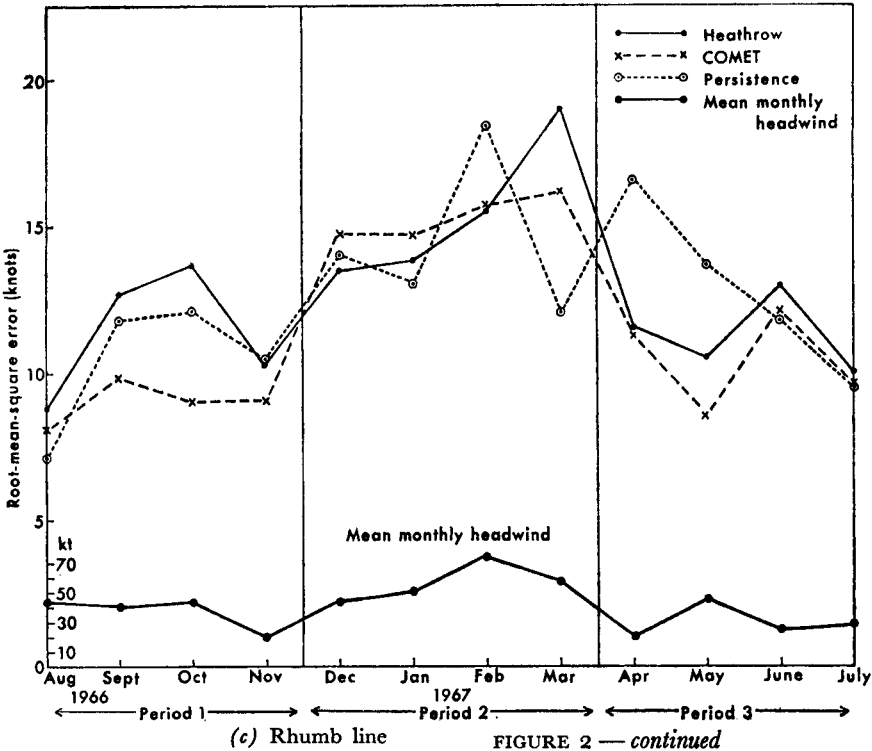


FIGURE 2—ROOT-MEAN-SQUARE ERRORS FOR EACH ROUTE AND PERIOD



persistence errors is reflected in the COMET values. The differences in period (2) indicate the extent to which subjective amendments to the forecasts affect the headwind errors. A marginal improvement for the February great circle track is accompanied by a similar worsening on the polar curve for the same month. In general the results for period (3), though smaller, follow a similar pattern and no significant improvement is introduced by subjective amendment.

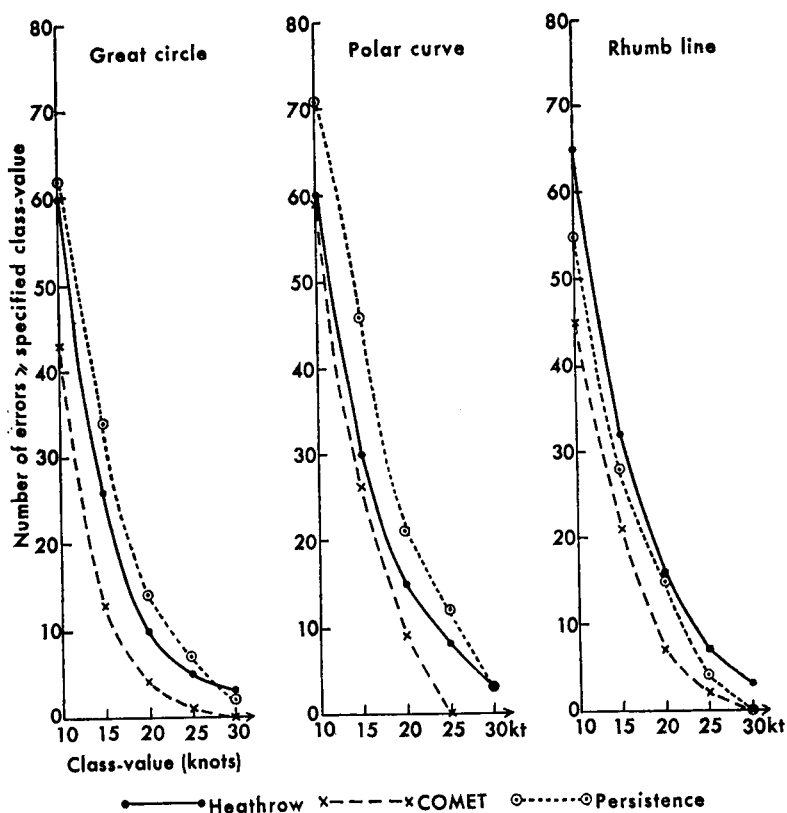
Whereas the errors for both forecasts for the great circle and polar curve generally improve on persistence this is not the case for the rhumb line. This is linked to the fact that the monthly mean error for the rhumb line forecasts, consistently has a positive value whilst that for persistence is, as expected, near zero, see Table I.

TABLE I—FOUR-MONTHLY HEADWIND MEAN ERRORS

	Period 1			Period 2			Period 3		
	Mean	S.D.	R.M.S.	Mean	S.D.	R.M.S.	Mean	S.D.	R.M.S.
Great circle									
Heathrow	+2.6	10.4	10.7	+2.3	12.3	12.5	+0.8	9.3	9.3
COMET	-0.2	8.0	8.0	-0.5	13.1	13.1	-2.7	9.7	10.1
Persistence	-0.2	11.5	11.5	+0.1	16.2	16.2	-0.4	13.1	13.1
Polar curve									
Heathrow	-1.6	11.5	11.6	-0.1	11.0	11.0	-1.2	9.4	9.5
COMET	-1.7	9.6	9.8	-2.7	10.2	10.6	-4.9	8.6	9.9
Persistence	-0.7	14.1	14.1	+0.1	19.6	19.6	+0.0	13.5	13.5
Rhumb line									
Heathrow	+4.3	10.7	11.5	+8.3	12.9	15.6	+5.3	10.0	11.3
COMET	+3.0	8.5	9.0	+9.5	12.1	15.4	+4.9	9.5	10.7
Persistence	+0.3	10.6	10.6	-0.0	14.5	14.5	-0.1	13.1	13.1

Period 1 August–November 1966, Period 2 December–March 1967, Period 3 April–July 1967. S.D. = standard deviation, R.M.S. = root mean square.

Total route errors. A frequency analysis of route errors was made by sorting into 5-kt classes for each route, forecast and period. The number of errors greater than or equal to a specified class value (no account being taken of sign) was assessed and the results are shown in Figures 3(a) - (c).

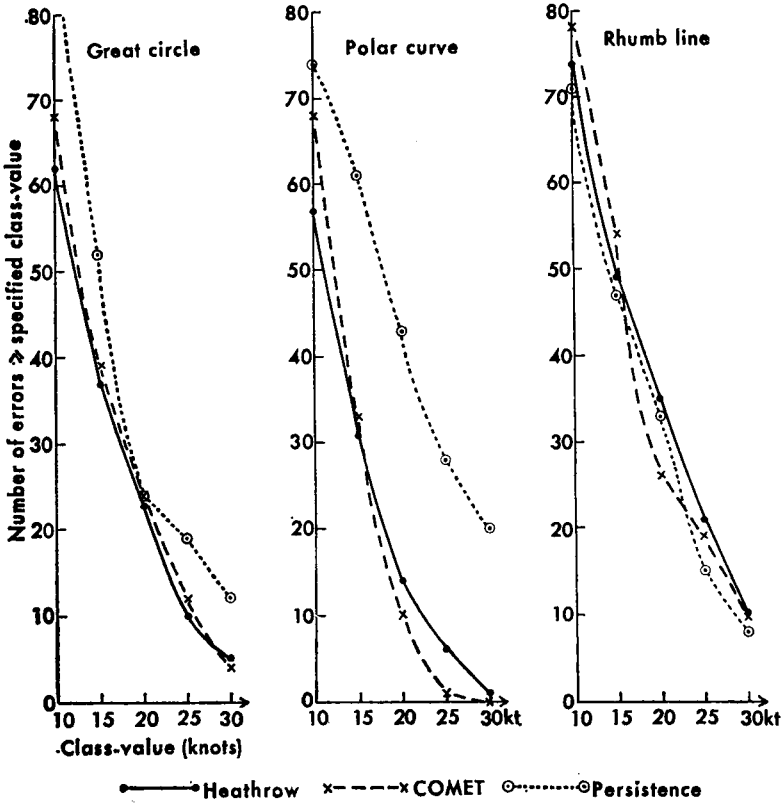


(a) August–November 1966

FIGURE 3—NUMBER OF ERRORS EQUAL TO OR GREATER THAN A SPECIFIED VALUE FOR THE WHOLE TRACK

For period (1) the superiority of COMET is again demonstrated by the fewer large errors. In periods (2) and (3) minor differences occur, but with about 120 cases considered in the construction of each line these cannot be regarded as significant. The anomaly for the rhumb line in producing little improvement over persistence is again apparent, especially in period (2).

One feature of the subjective amendment of the COMET forecasts is that 4-monthly mean errors, see Table I, for the great circle and polar curve are given a positive increment, whereas the already positive value for the rhumb line is scarcely affected. The reason for the positive increment is probably connected with the treatment of jet streams. These generally include a westerly component and so, when encountered, result in a positive headwind.



(b) December–March 1967

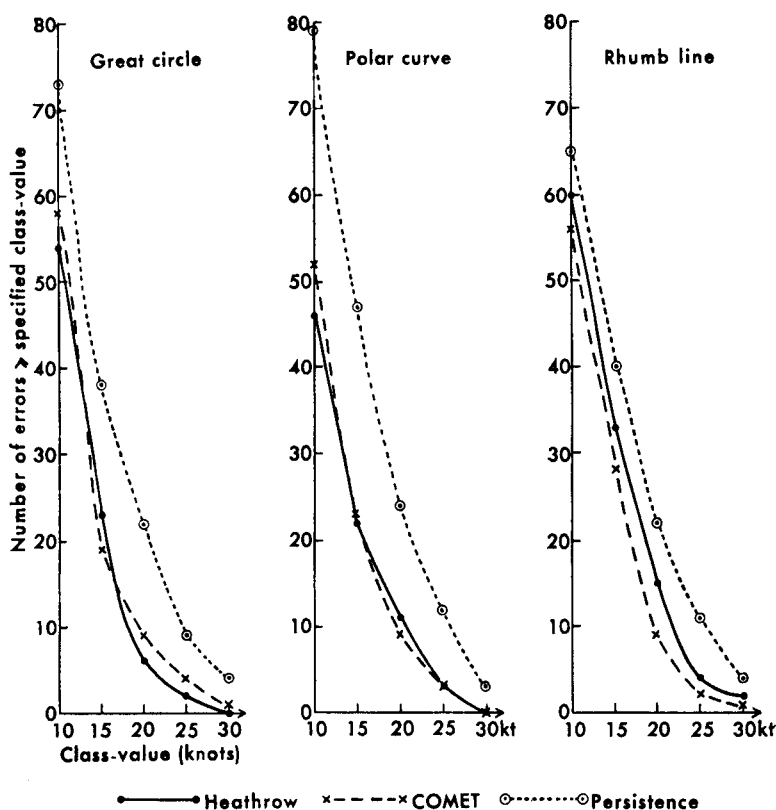
FIGURE 3 — continued

They are also regions of high horizontal wind shear. If the jet core-speed of a COMET forecast is subjectively increased, a higher horizontal shear is usually implied and a larger headwind error results from a given placing error.

It is difficult to put forward a reason for the consistent positive bias which will apply selectively to the rhumb line, but in the case of the COMET forecast it may be a failure of the model in the particular geographical area through which the route passes. Since the effect is greatest in winter it may involve the sea heating term. It can be seen from Table I that in winter the subjective amendment reduces the positive bias slightly. Even the August–November purely subjective forecast has a mean positive error and the reason for this remains obscure.

An alternative suggestion that the COMET winds are geostrophic and thus will seriously over-estimate the winds in the bottom of troughs is only valid if it can be substantiated that this feature applies selectively to the rhumb line and occurs sufficiently frequently over a considerable length of the route.

Part II of this paper will be published in February.



(c) April-July 1967 FIGURE 3—continued

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1. WOODROFFE, A.; A regression technique for objective forecasts at 300 millibars. *Met. Mag., London*, 95, 1966, p. 129.
2. HOWKINS, G. A. and CHUTER, I. H.; The effects on equivalent headwinds and flight times of errors in forecasting wind direction and wind speed. *Met. Mag., London*, 94, 1965, p. 341.

REVIEWS

Kinetics of phase transitions of water in the atmosphere, by L. G. Kachurin and V. G. Morachevskii. 250 mm × 180 mm, pp. iv + 124, *illus.* (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), Oldbourne Press, 1-5 Portpool Lane, London, E.C.1, 1967. Price: 56s.

I found this a rather disappointing book because although the authors promise to discuss a number of important topics, the treatment they actually give usually proves to be inadequate. One reason for this is that, as stated in the introduction, the book is based in its entirety on the authors' own results and therefore it inevitably presents a one-sided view of the subject.

The opening chapter discusses the basic physical principles of the kinetic theory of phase transitions, largely from a thermodynamic point of view. A number of fundamental equations are derived, but there is little attempt to evaluate the expressions to give the reader an accurate impression of the relative importance of the various terms under atmospheric conditions.

The second chapter is devoted to a discussion of the condensation of water vapour into the liquid phase. It is based on equations for the rate of growth of droplets in a supersaturated environment, but the authors explicitly state that they have neglected the effect of condensation on the temperature of growing droplets. It has been demonstrated repeatedly that this is by no means a negligible effect under atmospheric conditions, and therefore much of the discussion which follows must be suspect. The second half of this chapter is devoted to one of the authors' special interests, namely condensation 'torches' or 'plumes'.

The book continues with a discussion of the crystallization of supercooled water and concentrates on the rate of growth of the ice phase once it has been nucleated. I found the final section of this chapter which discusses electrical effects associated with freezing aerosols particularly disappointing. The authors have concentrated on the results of their own experiments and used them to make generalizations about electrification in real clouds, but they have given little attention to the extent to which their experimental conditions represent those in the atmosphere — a question which seems to me to be of crucial importance.

The closing chapter, which will probably be of greatest interest to Western cloud physicists, discusses the effect of introducing droplets containing surface active agents into homophase aerosols. The authors describe experiments which lead them to suggest that this may be an effective way of modifying the coalescence process in real clouds.

As is often the case with translations from Russian publications, the greatest value of this book to English language readers will no doubt be as an account of Russian work in this field and as a guide to the Russian literature.

J. T. BARTLETT

Measurement and estimation of evaporation and evapotranspiration, WMO Technical Note No. 83. 275 mm×215 mm, pp. xiii+121, Secretariat of the World Meteorological Organization, Geneva, 1967. Price: Sw. F. 15.

This Technical Note is the report of a working group, set up in 1962 by the WMO Commission for Instruments and Methods of Observation, to review current methods of measurement and estimation of evaporation, and to make recommendations on an interim international reference evaporimeter. The working group comprised V. A. Uryvaev (U.S.S.R.), M. H. Omar (U.A.R.), T. J. Nordensen (U.S.A.) and G. E. Harbeck (U.S.A.), with M. Gangopadhyaya (India) as Chairman.

The Note begins with a detailed description of instruments used for measuring evaporation, i.e. atmometers, evaporimeters and lysimeters, followed by a discussion of their merits and demerits, and of the results of evaporimeter comparisons. The general requirements for siting and laying out an evaporation station are also given. A review of the methods of estimating the evaporation from open water, soil and vegetation, are given in the second half of the Note. The water budget, energy budget, eddy correlation and aerodynamic methods and the combination equations of Penman, McIlroy and Tanner, are described in detail, with particular emphasis on the basic assumptions. Other more empirical methods are mentioned briefly.

This Note provides a concise review of the methods of measuring and estimating evaporation. It is much more useful for those beginning research in this field than for those wanting to make reliable routine measurements of evaporation. The unsatisfactory state of our knowledge is reflected by the conclusions of the working group, which was able to give only very general recommendations, and added a strong word of caution on the use of evaporimeter measurements to estimate evaporation from vegetation. There is a comprehensive bibliography containing about 200 references, though none later than 1964. As a result more doubt is cast on the validity of the assumptions used in the Bowen ratio than there might have been if the results published by Swinbank and Dyer in 1967^{1,2} had been available.

This WMO Technical Note, which gives a concise review of the methods available in 1964 for measuring and estimating evaporation, will be particularly useful for research workers entering this field.

J. B. STEWART

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NOTES AND NEWS

551.508.27

Kew Observatory

The historic north wall screen photothermograph at Kew Observatory (see Plate II), was devised and installed in 1866 by Balfour Stewart, the Superintendent, and Robert Beckley, the Observatory mechanic. Since October 1867 it has been the standard instrument at Kew for deriving air temperature and humidity. In this instrument, the temperature of two mercury-in-glass thermometers, one acting as a dry bulb and one as a wet bulb, are recorded by the photography of the movement of air bubbles in the mercury columns; the thermometer bulbs are housed in a louvered screen fixed on the north wall of the Observatory at a height of about 3 metres (10 feet) above the level of the artificial mound on which the Observatory is built, and about 5 metres above the general level of the Observatory lawns.

It has now been decided that the use of this non-standard exposure should cease. The measurements available from 1 January 1969 will be those made with an electrical resistance aspirated psychrometer (see Plate III) in an open position on the main lawn, the bulbs being at the standard height of 1.25 metres.

There has been an overlap period of two years between the two systems of measurements and the data from this period are being examined by the Climatological Branch.

Lightning strike at RAF Chivenor, Devon

A very heavy storm passed over Chivenor airfield between 0000 and 0100 GMT on 2 July 1968. Lightning struck the ground and quite a large crater was formed.

During the hour, heavy rain fell, extremely strong winds were experienced and a brilliant display of lightning was seen by the observer — the whole area being illuminated at times. Considerable damage was caused to buildings and property in the area, the power supply was disrupted, and lightning started a fire at a local factory and several premises experienced minor flooding.

Lightning struck the ground at the north-west corner of Chivenor airfield on the disused runway, which is constructed of asphalt. The lightning struck with such force that a large crater was torn in the runway surface (see Plate IV).

The crater formed was roughly elliptical in shape, being 2 feet in length and $1\frac{1}{2}$ feet wide. The depth of the crater at the centre was about 9 inches. Apart from one or two large chunks of asphalt lying in the crater it was a fairly clean-cut hole, with a few minor indentations in the runway surface surrounding the crater, see Plate V.

The crater was orientated almost north/south along its longest length and most of the considerable debris and rubble which was thrown up was deposited in a 20 degree arc fanning out from the crater, between 010 degrees and 030 degrees. Some of the debris was 50 yards from the crater.

M. H. LLOYD

Weather watch in the Arctic

The trawler *Orsino*, chartered by the Board of Trade, sailed to Icelandic waters at the end of November 1968; it will remain there until 30 April 1969. The ship carries an experienced meteorologist, Mr D. P. Smith, who is responsible for the provision to the British fishing fleet operating near Iceland of weather forecasts and warnings, especially those relating to the deposition of ice on ships (see Plate I). The meteorologist will work in close association with the Central Forecasting Office at Bracknell. Mr D. P. Smith served for three years on trawlers during the Second World War.

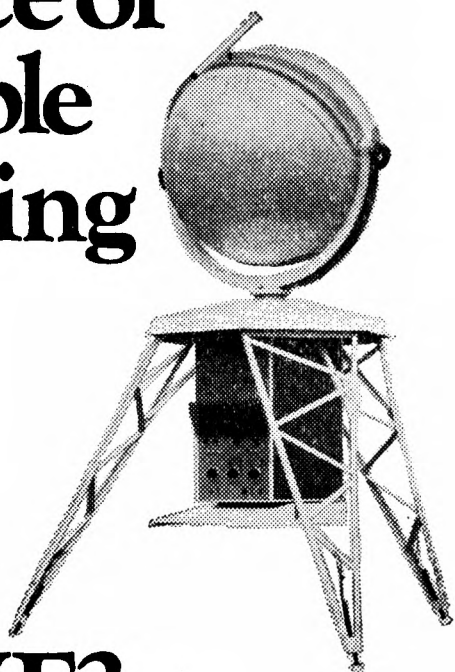
OBITUARY

It is with regret that we have to record the death of Mr D. A. C. Poynton (S.A.) on 9 October 1968.

CORRIGENDUM

Meteorological Magazine, December 1968, p. 374, Figure 2. Figure caption should read: FIGURE 2—SURFACE CHART 1800 GMT, 9 JULY 1968.

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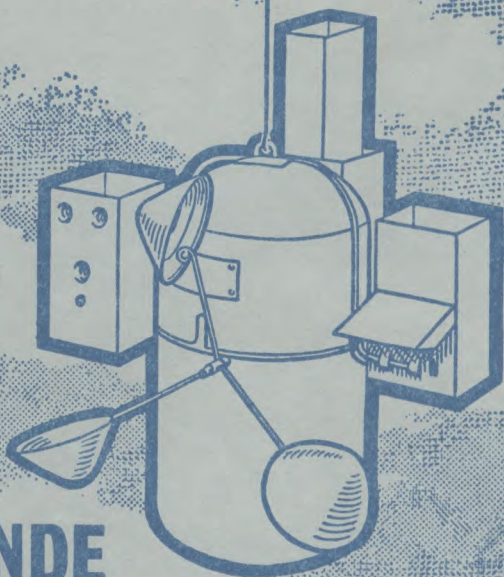
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NOTICES

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FORECASTING RAINFALL FOR THE SUMMER SEASON IN ENGLAND AND WALES

By R. A. S. RATCLIFFE and P. COLLISON

Summary. Changes in the average spacing, at 50°N, between the Canadian and European troughs on monthly mean 500-mb contour charts from April to summer are analysed. From this analysis some rules for forecasting the total amount of rainfall over England and Wales in summer are developed. The number of years (22) for which monthly mean 500-mb charts are available is not sufficient to give confidence in the stability of any rules developed solely from such a small sample; the 22 years have been supplemented therefore by 41 years (1899-1939) for which monthly mean 500-mb charts have recently been constructed using a statistical method developed in the Synoptic Climatology branch of the Meteorological Office. Generally the results show significant success as an aid in forecasting summer rainfall.

Introduction. Hay¹ has shown that monthly mean temperature anomalies over Europe and the North American continent in April have some value in the prediction of rainfall for the following summer (June, July and August) over England and Wales. Since monthly mean 500-mb contour charts take account of both mean surface pressure and mean 1000 to 500-mb thickness it was felt that such charts might be an even better guide to forecasting summer rainfall. Monthly mean 500-mb charts are available for the years 1946-67 inclusive. Daily values of surface pressure for grid points in the northern hemisphere for the period 1899-1939 have been obtained recently on magnetic tape from American sources. This data has enabled 'fictitious' monthly mean 500-mb charts to be constructed by computer for the 41 years covered by the data. It is not intended here to describe in detail the method of construction of these charts but the following brief account may be of interest.

Every monthly mean 500-mb chart can be constructed from two components, the normal 500-mb chart (in this case for 1951-66) and the 500-mb anomaly chart for the month in question. In our method the 500-mb anomaly was obtained for each grid point of each April chart by carrying out certain transformations on the April surface pressure anomaly for each year (again based on the 1951-66 normal). The transformations were selected to give the best possible approximation to the total 500-mb anomaly in the years 1951-66, for which actual charts are available for comparison, and then the method was applied to the earlier years for which surface pressure anomalies could be obtained but no 500-mb data existed. The transformations consisted of two parts :

- (i) Production of 1000-mb anomalies at each grid point, based on the surface pressure and temperature at the grid point.

- (ii) Production of an estimated 1000 to 500-mb thickness anomaly at each grid point, based on the surface pressure anomaly field in the vicinity of the grid point.

The two factors together comprised the best estimate of the 500-mb anomaly field for each April and they were added to the 500-mb normal at each grid point, by computer, to produce a best estimate of the 500-mb chart for April of each year. In the end the method adopted gave a standard deviation of rather over 30 metres for each grid point when real and fictitious charts were compared.

This paper presents the results obtained from a study of the 22 years of actual 500-mb data supplemented by the 41 years of 'fictitious' data. Results from the two sources are in good general agreement.

Mean 500-mb wavelengths. A study of the average spacing between the Canadian and European troughs on monthly mean 500-mb charts was made recently. How this spacing varies over the year was illustrated in the first Figure of a recent paper by Ratcliffe.² He showed that the average spacing between the troughs (measured at 50°N) changes from about 80 degrees of longitude in April to a mean of about 65 degrees of longitude for much of the summer (June, July and August).

In order to ascertain in more detail how this shortening of mean wavelength between April and summer comes about, it was decided to study the variability of the Canadian and European trough longitudes between April and the following summer. This was done by using computer-produced mean charts for each summer in the period 1949–67, the only years for which data were available in a suitable form, and comparing them with the 500-mb charts for April in the same years. The results obtained for the Canadian and European troughs are presented in Tables I and II respectively.

TABLE I—CHANGE IN LONGITUDE OF CANADIAN 500-MILLIBAR TROUGH AT 50°N BETWEEN APRIL AND SUMMER

Year	Longitude in April °W	Mean longitude in summer °W	*Change in longitude degrees
1949	65	50	+15
1950	75	75	0
1951	75 to 80	70 to 75	+5
1952	65	70	-5
1953	75	65	+10
1954	60	65	-5
1955	50	55	-5
1956	70 to 75	60 to 65	+10
1957	55	60	-5
1958	65	65	0
1959	75	55	+20
1960	55	65 to 70	-10 to -15
1961	50	65	-15
1962	60	65	-5
1963	55	60 to 65	-5 to -10
1964	60	65	-5
1965	60	70	-10
1966	40	65	-25
1967	60	75	-15
Approximate mean	62	65	-3

*Standard deviation approximately 10 degrees

TABLE II—CHANGE IN LONGITUDE OF THE EUROPEAN 500-MILLIBAR TROUGH AT 50°N BETWEEN APRIL AND SUMMER

Year	Longitude in April degrees	Mean longitude in summer degrees	*Change in longitude degrees
1949	40 to 45 E	20 to 25 E	-20
1950	5 E	20 W	-25
1951	5 to 10 E	10 to 15 W	-20
1952	45 E	Doubtful	
1953	5 W	0	+ 5
1954	30 E	0	-30
1955	25 E	30 E	+ 5
1956	15 E	0	-15
1957	15 to 20 E	0	-15
1958	15 E	10 W	-25
1959	10 W	Doubtful	
1960	20 E	10 W	-30
1961	40 to 45 E	20 E	-20 to -25
1962	10 E	0	-10
1963	30 E	5 W	-35
1964	5 W	5 W	+ 0
1965	20 to 25 E	0 to 5 W	-25
1966	20 E	0 to 5 W	-20 to -25
1967	10 E	10 W	-20
Approximate mean	18 E	0	-18

*Standard deviation approximately 11 degrees

Thus we see that on the average the shortening of mean wavelength takes place mainly through retrogression of the European trough from a mean April position of 18°E to a mean summer position near the Greenwich meridian. Nevertheless, individual years show considerable differences, as indicated in Tables I and II and extreme positions of the European trough in April vary through about 60 degrees of longitude from 15°W to about 45°E.

Development of forecasting rules. Figure 1, which shows the variation between the longitude of the European trough in April at 50°N and the rainfall over England and Wales for the following summer, was next plotted. The points on the figure are for all 63 years of the real and fictitious series except 1928 for which no European trough in April was detectable. The horizontal lines at 9.95 and 7.55 inches indicate the long period (90 year) tercile boundaries for England and Wales rainfall in summer.* Although there is a wide scatter of points on the graph a few facts can be deduced, of which the following seem important :

- (i) Of the 20 years with wet summers, 13 have their 500-mb European troughs in April in the longitude range $>10^{\circ}\text{E}$ to $<30^{\circ}\text{E}$. If the band is narrowed to include only the range $>10^{\circ}\text{E}$ to $<25^{\circ}\text{E}$ then 9 wet years are still included while the only dry year out of a total of 14 years is 1929. The figures for the real charts in this latter band are 5 wet years (out of a total of 8) and no dry years.

* Rainfall amounts in this paper have been quoted in inches as the data for England and Wales are available to the nearest 0.1 inch. The tercile boundaries are quoted to the nearest 0.05 inch (and the nearest millimetre) to achieve separation of the data groups. Figure 1 incorporates scales for inches and millimetres.

- (ii) In the two bands (a) westwards from 10°E and (b) eastwards from 30°E , out of a total of 43 years only 7 have wet summers and 3 of these (1909, 1910 and 1930) are only just in the wet tercile. For the real charts in these bands the figures are 2 wet summers in 14 years.

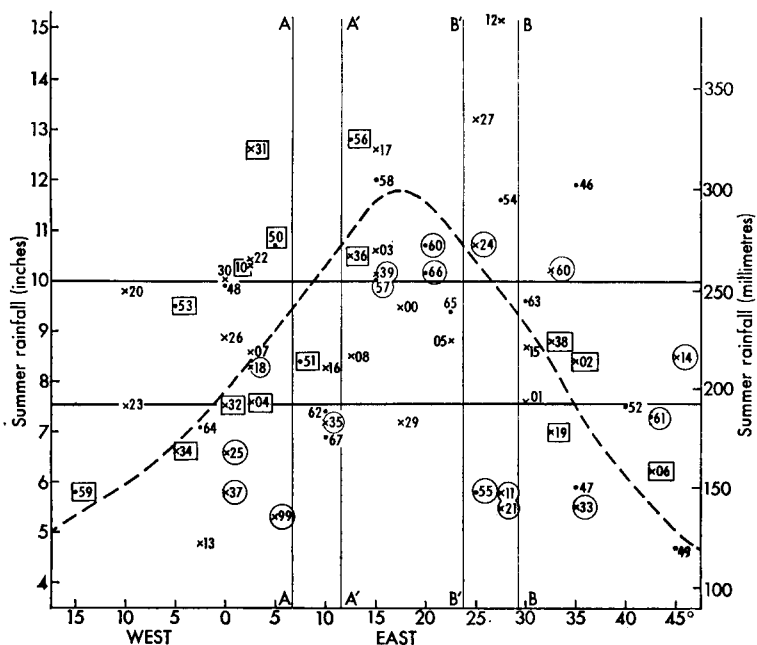


FIGURE 1—RELATIONSHIP BETWEEN SUMMER RAINFALL OVER ENGLAND AND WALES, AND LONGITUDE OF EUROPEAN TROUGH AT 50°N IN APRIL

Full lines are tercile boundaries of summer rainfall. AA' and BB' are areas of uncertainty. Figures represent the year, omitting the century. Dots for post-war data 1946-67 and crosses for fictitious constructed data 1899-1939. Figures are enclosed in circles when the Canadian trough was east of normal position, and enclosed in squares when the Canadian trough was west of normal position.

It has been shown by Lowndes³ that fine weather in summer in south-east England is usually associated with a 500-mb trough between 50°W and 60°W on a day-to-day basis. Ratcliffe² has also associated dry summer weather on a monthly time scale with 500-mb troughs east of the normal summer position (65°W) and wet summer weather with troughs west of 65°W . Thus it was considered possible that a Canadian trough in April east of its normal position might be associated with drier than normal summer weather to follow and if west of normal it might be associated with a wet summer.

A graph similar to Figure 1 was constructed, therefore, to show the relationship between the position of the Canadian trough in April and summer rainfall in England and Wales but this is not reproduced because the scatter is very large and no precise deductions can be made from it. Nevertheless, for all summers during which the Canadian trough was east of normal in April the average rainfall was 8.0 inches, while for all those with troughs west of normal the average rainfall was 9.0 inches. The real 500-mb data for the 22 post-war years shows the same trend (8.5 against



Photograph by W. H. Townsend

PLATE I—OROGRAPHIC CLOUD (MULTI-LAYERED WAVE CLOUDS) FORMED IN
AIRFLOW OVER MOUNTAINS OF GRAHAM LAND

The photograph was taken in September 1961 from Argentine Island (approx. 65°S and 65°W) with the camera looking NE. This picture won the first prize for Mr W. H. Townsend in the black and white section of the Meteorological Office Photographic Competition in 1967.



Photograph by D. McFarlane

PLATE 11—STRATOCUMULUS FROM ABOVE, SHOWING BILLOWS

The photograph was taken from 10 000 ft with camera looking east-north-east at 1505 GMT near Preston, Lancashire, 14 December 1967. The height of the cloud has been estimated as 3000 ft.

8.9 inches). Thus it is clear from Figure 1 that the position of the European trough in April is more important than that of the Canadian one from the point of view of wetness or dryness of the following summer. A curve of best fit was drawn through the points of Figure 1, leaving approximately the same number of points above and below the curve. It is seen that the rainfall curve shows a peak with European 500-mb troughs between 15 and 20°E in April. Bearing in mind that the average April to summer retrogression is nearly 20° of longitude (from Table II) it is easy to see that in such years the mean summer position of the 500-mb trough is likely to be near the Greenwich meridian—a position which is probably the optimum for copious summer rain. It is relevant to note that the points for most of the years in which the Canadian trough was east of 60°W (within circles in Figure 1) lie under the curve, i.e. summers drier than expected, while most of those in which the Canadian trough was west of 65°W (within squares in Figure 1) lie above the curve, i.e. summers wetter than expected.

Thus it appears that Figure 1 could be used as a forecasting tool for summer rainfall if a correction were applied for the position of the Canadian trough in April. The amount of correction applied is given in Table III.

TABLE III—CORRECTIONS TO SUMMER RAINFALL FORECASTS TO TAKE ACCOUNT OF LONGITUDE OF CANADIAN 500-MILLIBAR TROUGH AT 50°N IN APRIL

Longitude of trough (°W)	75	70	65	60	55	50
Correction to rainfall (inches)	+1	+½	0	0	-½	-1

This table was deduced from the following : (i) normal summer rainfall is about 8.8 in over England and Wales, (ii) the normal Canadian trough position in April is about 62°W; together with the previously noted fact that summers of years with Canadian troughs west of normal in April gave an average rainfall of 9.0 in, while those with troughs east of normal averaged 8.0 in.

The use of Figure 1 with corrections from Table III to obtain forecasts of summer rainfall in terms of terciles, gives the results shown in Table IV.

TABLE IV—RELATIONSHIP BETWEEN THE ACTUAL SUMMER RAINFALL IN ENGLAND AND WALES AND THE FORECAST RAINFALL

Actual summer rainfall	Forecast summer rainfall			Notes
		Wet	Normal	
	Wet	11(5)	8(2)	
	Normal	5(2)	8(1)	
	Dry	4(2)	6(1)	The figures in brackets are post-war real data. $\chi^2 = 16.6$ significant at the 0.5 per cent level.

It may be that an analysis such as Table IV attempts to deduce too much from the type of data available. It may be safer to consider Figure 1 as made up of three bands separated by areas of uncertainty AA' and BB'. If this is done the results in terms of terciles are as follows :

		Actual summer rainfall		
		Dry	Normal	Wet
(i)	Years west of AA	9(2)	8(2)	5(1)
(ii)	Years east of BB	7(4)	6(1)	2(1)
	Total of (i) and (ii)	16(6)	14(3)	7(2)
(iii)	Years between A'A' and B'B'	1(0)	4(1)	9(5)
		(Brackets enclose real data only)		

It is logical to consider AA' and BB' as areas of uncertainty when the rather large variability of the retrogression of the European 500-mb trough between April and summer is considered. For example although retrogression averages 18° of longitude (see Table II), in 1955 the trough progressed 5° while in 1954 the retrogression was 30° . Although no wet years actually occur in the longitude band between A and A' this is regarded as fortuitous as similar possibilities to those observed in the range B to B' could occur.

The safest statements based solely on the longitude of the European 500-mb trough at 50°N in April would be :

- (i) If the trough is at 30°E or further east *or* at 5°E or further west — forecast dry or normal. (Correct 30 times out of 37.)
- (ii) If the trough is east of 10°E and west of 25°E — forecast wet or normal. (Correct 13 times out of 14.)

Discussion. Results such as these lead one to question why the position of 500-mb troughs in April should apparently be so crucial for summer rainfall. The answer is probably very complex but it is believed to be connected with the nature of the underlying land surface. If snow cover in Canada near or west of Hudson's Bay is still deep in April this is likely to have some effect on the Canadian 500-mb trough, tending to hold it west of normal and hence tending to prolong the delay in seasonal warm-up of the land surface in that area. Similar considerations could apply in Europe ; if in April there is deep snow as far west as possible this may tend to hold the European 500-mb trough at about $10^\circ - 30^\circ\text{E}$ until the normal shortening of wavelength (mainly in May) takes place. On such occasions the European trough, undergoing the expected 20° of retrogression, will settle near the British Isles for the summer. Similar arguments could be applied in reverse ; the absence or reduction of snow cover in central Canada coupled with a snow-free Europe in April would allow the Canadian trough to occupy an eastern position and the European trough to recede into Russia thus enhancing the probability that the European trough would not retrogress as far as the British Isles in summer.

Conclusions. It is shown that the mean position of the European 500-mb trough at 50°N in April is almost 20°E and that the corresponding mean position averaged over the whole summer is close to the Greenwich meridian. In contrast the Canadian 500-mb trough retrogresses only about 3° during the same period.

A correlation between the position of the European 500-mb trough in April and summer rainfall in England and Wales is demonstrated; the wettest summers in general follow April 500-mb troughs between 10° and 30°E while most dry summers are preceded by April 500-mb troughs east of 30°E or west of 10°E .

When the Canadian 500-mb trough in April is displaced eastwards from its normal position near 62°W , the summers following are drier than usual while if the Canadian trough is displaced westwards (not beyond 75°W), the summers following are wetter than expected. These additional factors have been taken into account in deriving forecasting rules for summer rainfall in England and Wales.

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551.584.41(426)

STUDIES OF TEMPERATURE IN THE FOREST OF THETFORD CHASE — SPRING 1967

By G. W. HURST

Summary. Daily minimum temperature readings were taken at a number of places in the Harling area of Thetford Chase in spring and early summer 1967 at heights varying from 2 in to 72 in over different surfaces and under different conditions, and an analysis was made of the results. Run-of-wind readings were also made and analysed. Maximum and minimum bent-stem 4-in soil thermometers were in use from November 1966 to June 1967 and the observations obtained are discussed.

Introduction. In earlier articles Hurst^{1,2} described experiments with minimum thermometers exposed in different locations in Thetford Chase. This paper describes the final set of experiments, in 1967 on a much more restricted geographical scale, in the Harling neighbourhood. Instrumentation was much as before, but anemometers were installed at the different sites, and an interesting additional feature has been the introduction of maximum/minimum bent stem 4-in soil thermometers, with readings from November 1966 onwards.

Minimum air temperatures. Several of these sites were the same as in 1966, and for convenience the same numbers have been retained where possible for the various sites. Temperatures were read in degrees Fahrenheit as in previous years. Site 8, the open bare-soil site at Harling Nursery was again in use with both a shielded minimum thermometer at 4 ft and a mounted array of grass minimum thermometers from 2 in to 72 in. Site 10, the grassed site in the stagnant Harling compartment nearby was similarly instrumented, and so was a new under-cover site, taken as site 1; the percentage of overhead cover, assessed by a light-meter, was about 75 per cent. Site 9, the litter site near site 10, was equipped with 4-ft and 6-in thermometers (the latter without bulb shields) as was site 11, the small area of one square chain of bared soil in the grassed clearing (about 100 yd from site 10) and the nearby site 16 in Harling Ride, a long ride in a north/south direction and 90 ft broad, with trees 40 to 45 ft high on each side; there was a very slight down-slope of about one degree to the north. Run-of-wind anemometers were also installed at nearly all sites, and also for comparison at the completely open country at Kings.

Analysis. It is not proposed to go into the same detail of analysis as in the previous papers, but just to highlight the main results.

Readings at 4 ft. Table I shows the difference between temperatures (corrected for exposure) at the Harling sites and at Mildenhall from 1965 onwards.

TABLE I—DIFFERENCES OF AIR TEMPERATURES AT 4 FEET BETWEEN THE VARIOUS SITES AND MILDENHALL, 1965, 1966 AND 1967 (INCLUDING 1967 SITES ONLY)

Year	Temperature difference, site - Mildenhall for sites :					
	1	8	9	10	11	16
	<i>degrees Fahrenheit</i>					
1965		-1.3	-2.8	-3.0	-2.3	
1966		-1.8	-3.4	-3.4	-3.0	
1967	-1.0	-1.4	-3.4	-2.9	-3.0	-2.0
Sites :	1. Harling (under cover)	8. Harling Nursery	9. Harling (litter)	10. Harling (grass)	11. Harling (bare earth)	16. Harling Ride

Very little change is shown in Harling Nursery in three years and not much at the other Harling sites, but a curious feature is that for the first time, the temperature at 4 ft above bare soil at site 11 was not quite as warm as that over grass (site 10). The difference is very slight, and could well be due to the increased scrubby vegetation which has grown on the bare plot in the last two or three years. The variations between differences are however small enough to be almost within the limits of experimental error: for example, the 2.9 degF and 3.0 degF of 1967 for sites 10 and 11. The gain in freedom from frost within a ride (site 16) compared with open vegetated land is clear, and air at a height of 4 ft in the under-cover site 1 is distinctly warmer at night than over bare soil at Harling Nursery.

Frequency of years in 10 of frosts after certain dates. The risk of temperatures below 32°F and 28°F after a particular week was again assessed, exactly as before, and results were fairly similar. Table II summarizes the results, with the years 1965 and 1966 also taken into account for sites at which the information was available.

TABLE II—THE EXPECTATION OF AIR FROST AT 4 FEET, EXPRESSED AS THE NUMBER OF YEARS IN 10, AT THE VARIOUS SITES AFTER PARTICULAR DATES

No.	Week commencing	(a) Temperatures below 32°F					(b) Temperatures below 28°F				
		Site number					Site number				
		1	8	9	10	11	1	8	9	10	11
		<i>Number of years in 10</i>					<i>Number of years in 10</i>				
1	1 April	10	10	10	10	10	10	10	10	10	10
2	8 April	10	10	10	10	10	9	10	10	10	10
3	15 April	10	10	10	10	10	8	10	10	10	9
4	22 April	10	10	10	10	10	7	9	10	10	9
5	29 April	9	10	10	10	10	7	9	10	10	9
6	6 May	9	10	10	10	10	3	7	10	9	6
7	13 May	8	9	10	10	9	2	6	9	8	4
8	20 May	6	8	10	9	8	1	3	7	7	2
9	27 May	2	5	9	8	5	+	2	5	4	1
10	3 June	1	2	8	7	2	0	1	3	2	+
11	10 June	+	1	6	5	1	0	+	2	1	+
12	17 June	0	0	4	3	+	0	+	1	1	+
13	24 June	0	0	2	1	0	0	0	1	+	0

Sites as in Table I, + indicates 0.1 to 0.4

Thus in late May there is still about an even chance of a temperature as low as 28°F at Harling over litter, and much the same over grass, but the risk is considerably lower within a ride or over a large expanse of bare soil; the risk is very low indeed under a forest canopy. There is a slight improvement at Harling Nursery compared with the Harlings in 1967, mainly because of the slightly smaller difference in temperature between Mildenhall and Harling Nursery. Possibly the Nursery has been kept clearer in 1967. Harling Ride is slightly less favourable than the narrower Santon Ride of last year, but the Harling under-cover site is a little warmer than the somewhat less leafy High Lodge and Mundford sites of 1966.

Readings at 6 in. It is not proposed to say very much under this heading. A comparison with Kings as in previous years was not possible, because only weekly readings were being made at that station. Harling Nursery was therefore taken as the standard for 1967, and Table III shows the difference between the other sites and the Nursery for all the available years.

TABLE III—DIFFERENCES OF AIR TEMPERATURES (AVERAGE APRIL TO JUNE) AT 6 INCHES BETWEEN THE VARIOUS SITES AND HARLING NURSERY

Year	Temperature difference, site - Harling Nursery for sites :			
	1	9	10	11
			<i>degrees Fahrenheit</i>	
1965		- 4.0	- 4.4	- 2.1
1966		- 4.9	- 4.4	- 2.1
1967	- 0.4	- 5.3	- 4.7	- 1.8
		Sites as in Table I.		- 2.7

Interestingly, the grass (10) and the litter (9) sites at Harling are comparatively colder, if anything, and the small bare site less cold in 1967. Again, however, these differences are small and of doubtful significance.

Vertical array. Arrays exactly similar to those of 1966 were assembled. Three arrays instead of two were employed : Harling Nursery as before, Harling grass replacing Mundford as a grassed site in a clearing, and a third was installed at the Harling under-cover site. Figure 1 shows the weekly averages at the various heights for the three locations; the similarity between 1966 Mundford and Harling Nursery (Figure 1, Hurst²) and 1967 Harling grass and Harling Nursery is striking. In fact, the average temperature differences between 2 in and 72 in over the 13 weeks for Mundford in 1965 and 1966 and for Harling grass in 1967 were 3.9 degF, 4.5 degF and 4.6 degF; the means of the three coldest nights each week were 5.6 degF, 6.5 degF and 6.4 degF, and the largest inversions in the three seasons were 9.0 degF, 11.3 degF and 9.6 degF. The vertical structure over these rather enclosed grassed sites is thus very similar.

To make a comparison between 1966 and 1967 at Harling Nursery is not easy, as strong doubts exist about the accuracy of the 72-in thermometer in 1967. The instrument was checked on return to Bracknell and appeared in error by about 0.3 degF — just the difference between the average reading at 48 in and at 72 in. In 1966 the average minimum temperatures were virtually uniform from 12 in to 72 in, and apart from the 72 in reading of 40.3°F, the 1967 profile is also practically isothermal at 40.6°F. Because of this uncertainty, comparison of the 72 in and 2 in temperature differences between 1966 and 1967 cannot be made. The array mounted within the canopy brought out several interesting features. An average difference of 1.4 degF existed between 2 in and 72 in, and although the temperatures at 2 in and 6 in were below those above bare soil in the open, the temperature at 24 in (and from there upwards) was higher within the wood than over the open bare ground. The slope of the curve suggested a difference of about 1 degF from the 6-ft level probably to the forest canopy; immediately above this of course the temperature would be much lower, probably of the order of that near the vegetation-covered ground surrounding the wood. Temperature changes within the canopy will of course be far less than those outside, and day maximum temperatures particularly in sunny weather will be far lower than those out in the open.

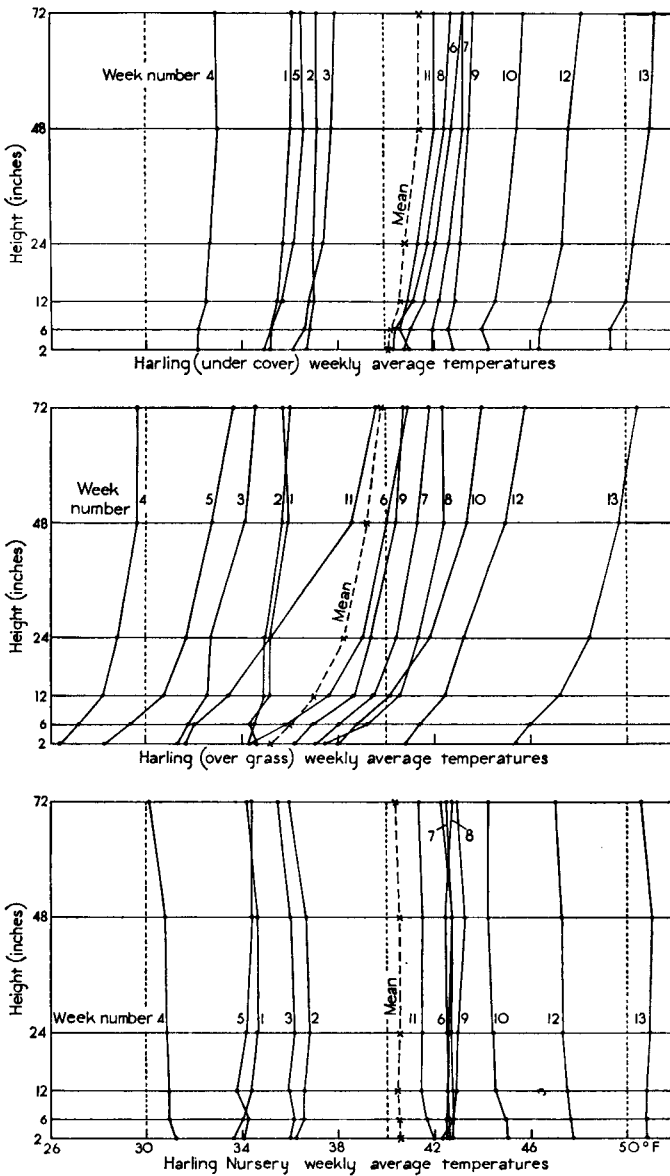


FIGURE 1—VERTICAL TEMPERATURE SOUNDINGS AT HARLING DURING APRIL-JUNE 1967

All three curves on Figure 1 show that week 4 (22-28 April) was outstandingly cold, but week 11 (10-16 June) was also comparatively very cold — and colder over grass than the 13-week mean. This naturally occurred during the period of cold northerly winds, and even near the south coast some overnight ground frost was reported on the mornings of 12 and 13 June. The coldest June night occurred at the end of week 10 on 9 June, with frosts at 4 ft at the other Harling sites, and near frost at Harling Nursery as well.

Cold nights were much more frequent in 1967 than in 1966 or 1965 and the Harling Nursery totals of nights with temperatures below 28°F varied from 5 at 2 in and 6 in to 7 at 12 in and above in 1967 compared with one at all heights in 1966. The total for the under-cover site in 1967 was 4 at 2 in, 2 at 72 in, and 3 at the intermediate heights. Temperatures below 32°F were recorded at all heights at Harling Nursery in the very cold spell in the first part of June, and in subsequent weeks too at the Harling grass site, but no temperatures below 32°F were recorded within the forest canopy after the first few days in May.

Airflow. For the first time in the experiments, run-of-wind anemometers were mounted, 11 in all. Four of these — at Kings, Harling Nursery, Harling litter and Harling grass — had standard agrometeorological (agromet.) exposures of about 6 ft above the ground and, for interest, comparison is made with the agromet. station of Santon Downham, 10 miles to the west-north-west. Five anemometers were exposed at 1 ft, a height more significant to young plants, at the same three sites at Harling and also at the Harling under-cover site and in the nearby ride. Additionally, two were placed at a height of 8 in at Kings, one in the open and the second in a furrow; the Kings anemometers were read weekly, but all the others were read daily at 0900 GMT.

As Figure 2 clearly shows, the windiest site at 6 ft was the open Kings, with a through flow of 14 761 miles during the 3 months; this corresponded to an overall average speed of 6.8 miles per hour, and the greatest weekly flow was 1643 miles from 20 to 26 May (9.8 miles per hour). Harling litter, a little surprisingly, was the second windiest site with a flow of air distinctly greater than that at Harling Nursery (12 134 miles compared with 11 005 miles). The Harling litter site is however rather more open than Harling grass, so the light airflow at the latter is quite acceptable; the total of 9850 miles is a partial estimate, because the anemometer was not exposed until 13 April. The enclosed nature of Santon Downham agromet. station is brought out by the very low value of the 13-week airflow (8950 miles).

Very interesting is the substantially greater air movement at 1 ft in Harling Nursery compared with the other sites. Airflow was about 50 per cent more than in the Harling compartment, where the air movement over the litter site was distinctly greater than over grass, as Figure 2(*b*) shows. Perhaps predictably, with its channelling of airflow (and therefore lessening of any cross-wind component) the wind in the ride was lighter, and very predictably the airflow within the forest (site 1) was much lower, amounting to only about 10 per cent of that at Harling Nursery. It is not intended to dwell on the Kings instruments, at a different height from the other anemometers, and read only weekly. The results have however been plotted on Figure 2(*b*) for comparison; this showed that the flow in the open at 8 in at Kings (4317 miles) is very similar to that over grass at Harling, especially in April and May. The 8-in anemometer in a furrow is obviously very protected, with a 13-week flow even less (704 miles) than the flow within the forest canopy at a height of 1 ft, where the total flow was 846 miles (a mean wind speed of 0.4 miles per hour).

In general, it can probably be concluded that over an open surface (exemplified by Harling Nursery) the wind at 1 ft is about two-thirds that at 6 ft, but that in a more stagnant terrain covered by grass or other low

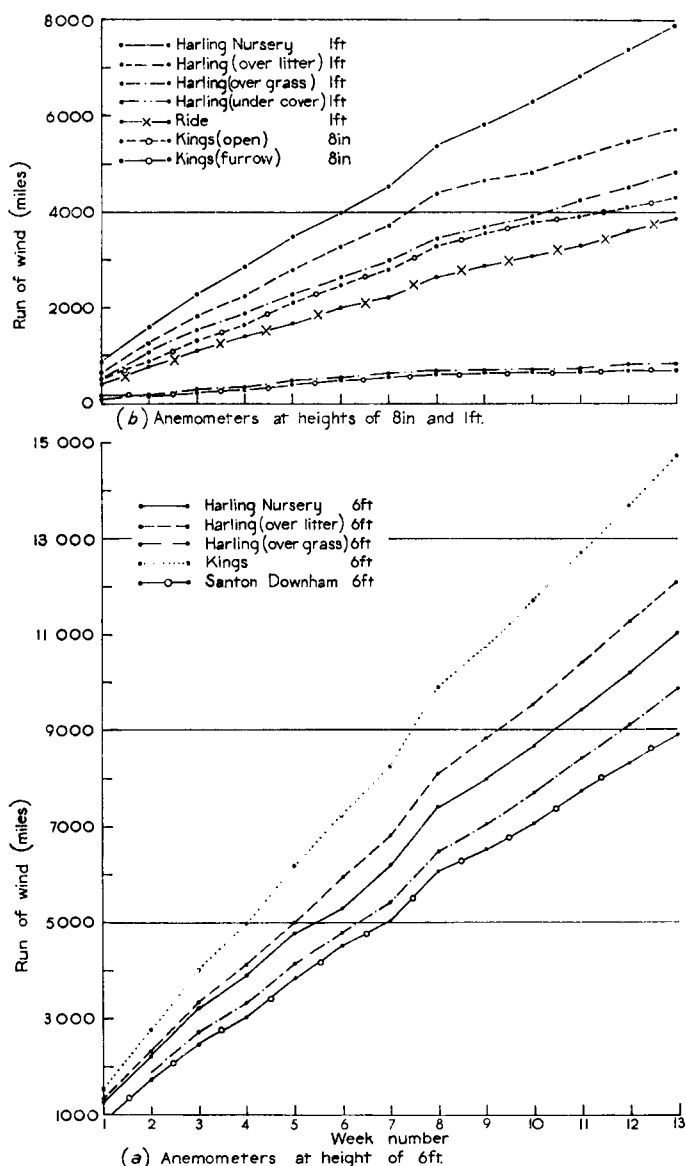


FIGURE 2—WEEKLY TOTALS OF RUN OF WIND AT VARIOUS SITES AT THETFORD
APRIL-JUNE 1967

vegetation, the factor is about half. Over similar vegetation at Kings, the airflow at 8 in was about one-third that at 6 ft, but airflow in furrows was relatively very light indeed. Finally, the records did not suggest any unserviceability of the anemometers, as the pattern of the divergence between the various sites was very similar from one week to the next.

Soil thermometers. Five maximum/minimum bent-stem 4-in soil thermometers were installed from November 1966 to June 1967 at the five

sites 1, 8, 9, 10 and 11. At sites 8 and 11 the instruments were put into the bare soil. At the other three sites (the litter site 9, the grass site 10 and the under-cover site 1) a tiny bare patch was cleared for the instrument. In January 1967, a sixth instrument was installed at the grassed site 10 with the absolute minimum of disturbance of the vegetation, and this is known as site 10a.

Well demonstrated in Table IV is the greater diurnal variation at Harling Nursery, and at the bare-soil site at Harling, sites 8 and 11, at all times of the year; only in cold January was there any other station within 1 degF of the diurnal variation of either of these two sites. Differences in pattern between the two bare-soil sites is slight, so the size of the bare-soil patch is not very significant in this respect, once a reasonable size has been attained. The diurnal variation is large in June, averaging about 15 degF (and a maximum of 25.8 degF). The litter site 9 with a small cleared square for the thermometer showed the next largest variation — a little more than site 10, but rather similar in most respects. This difference between sites 9 and 10 showed up consistently, with slightly higher maximum temperatures at site 9 throughout (averaging 1 degF difference a day), but the pattern of minima showed a change over the period, with site 10 less cold at night up to May.

The diurnal variation at the under-cover site 1 was the lowest of all the variations from sites with a continuous record throughout, being just about half that of sites 8 and 11; its mean daily maximum temperature in June was 10 degF below that at these sites. It gained over the other places in January, with an average night temperature over 37°F, 0.6 degF warmer than any other location; and indeed from November to March site 1 was the warmest site, with high minimum and not low maximum temperatures. By June it was easily the coldest, by day and by night. Finally, the fully grassed site 10a was in operation for only part of the time, but showed throughout its five months a considerably smaller daily range than site 11. The heat was very well retained at night, and only in June was the average night minimum at 4-in depth higher under the bare soil than under the grass carpet of site 11 — otherwise the grass cover provided the warmest soil. Day maxima of course were conspicuously low.

The data were also partly analysed for variability, standard deviations being calculated for the months of November, January (the month with the lowest diurnal variation) and June. In November, they ranged from 2.3 degF and 2.4 degF for sites 8 and 11 to 1.3 degF for sites 1 and 10; in January the variability is similar, but in June the standard deviation is as high as 5.1 degF at site 8, 4.7 degF at site 11 (and 4.5 degF at site 9), down to 1.8 degF at site 1 and 1.9 degF at site 10a. The winter figures were made slightly more difficult to analyse because a few of the figures were negative — a higher minimum value on one day than the maximum read the next ! The difficulties of reading such instruments in conditions of cold weather with snow or frost on the ground are fully recognized.

An indication of the range of diurnal variation is of interest. Greatest of course in June, highest values reached were 25.4 degF at site 8 on the 13th and 22.3 degF on site 11; lowest figures for these sites in this month were 5.3 degF and 4.7 degF respectively. These compared with the under-cover site 1 values of 9.9 degF and 3.2 degF, and the grass-covered sites values of 10.3 degF and 2.7 degF. In winter there were periods with frost (such as

4-13 January) when diurnal variation was virtually nil at sites 8 and 11 with temperatures just below freezing. The winter was so mild however that cold weather did not persist long enough for frost to penetrate to 4 in elsewhere.

Rather similar experiments were undertaken by Rider³ in 1954-55 with thermometers at various depths in the clay at Cambridge; records at 10 centimetres (4 in) showed much smaller values of diurnal change than experienced in the sandy soil of Thetford, but the ratio of diurnal variation under bare earth to that under a vegetated surface was of about the same order. It is also interesting to note that Johnson and Davies⁴ in experiments on Salisbury Plain with different types of soil, found, with sand, values for diurnal variation of temperature reasonably consistent with those found at Thetford.

Finally, it is of interest to examine average temperatures at a depth of 4 in at Thetford.

Figure 3 is a composite diagram showing (a) monthly data of average air temperatures and sunshine, and rainfall totals for Santon Downham, together with the average 4-in soil temperatures for site 8, and (b) average monthly values of the soil temperatures at the other sites minus site 8. This Harling Nursery site (8) was selected as the datum because it was representative of

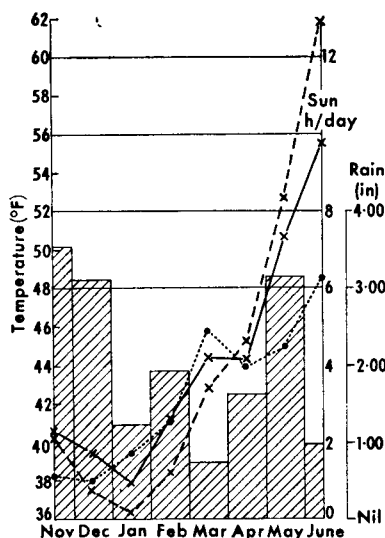


FIGURE 3 (a) — THETFORD AREA CLIMATOLOGICAL DATA AND SOIL TEMPERATURE MEANS FOR NOVEMBER 1966-JUNE 1967

x—x Mean air temp. Santon Downham
 •....• Mean sunshine Santon Downham
 x---x Soil temp. site 8 (Harling Nursery)
 Shaded area = total rainfall Santon Downham

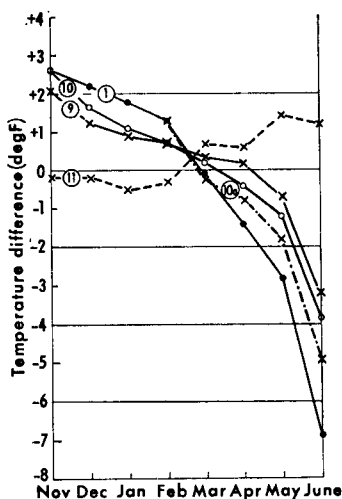


FIGURE 3 (b) — SOIL TEMPERATURES AT VARIOUS SITES MINUS SITE 8 (HARLING NURSERY)

•—• Site 1 minus site 8
 x—x Site 9 minus site 8
 o—o Site 10 minus site 8
 x---x Site 10a minus site 8
 x---x Site 11 minus site 8

a fairly exposed expanse of bare soil, and because it has frequently been used as a standard when comparing air temperatures in past experiments.

First considering the absolute readings, a mild winter was followed by an exceptionally mild and sunny early spring, a rather cold dull April, and frosts early in May. This is reflected by the average soil temperatures being rather lower than the air temperatures in winter, with a marked reversal for site 8 in early summer. Santon Downham is probably distinctly colder than Harling Nursery, so that the contrast at the former between soil and air temperatures will be greater in winter and less in summer.

Changes in the pattern of differences in soil temperatures between the various sites over the eight months are striking. Site 11, the moderate-sized bare-soil patch in Harling, changes little in relation to site 8, and broadly, temperatures in Harling Nursery are rather above those of the other Harling sites in winter, and rather below in spring and summer. This difference is seen in both day maximum and night minimum temperatures, and may reflect the greater stagnancy of air in Harling, with colder (air) temperatures in winter and greater warming in the summer.

The other four locations behave very similarly to each other — all several degrees warmer under a protective cover, be it grass, litter or forest canopy in winter, and very much colder in summer than under bare earth (e.g. site 8). The differences from November to March, in particular, are small, temperatures at sites 1, 9 and 10 and (from February) 10a lying within a one degree range. From April, differences become more pronounced, with an almost clear pattern in which site 1 is colder throughout, and site 9 warmer, with a difference between them of over 3 degF by June. The site with the coldest summer earth temperatures, very predictably, was that under a forest canopy site 1, and the next coldest was the completely grassed over site 10a. The other two sites are not very dissimilar (tiny bare patches), with the grass site slightly the colder.

Conclusions. The following conclusions are mostly based on the 1967 experiments, but for completeness some background mention is made of what was found in earlier work.

- (i) At a height of 4 ft, there was more freedom from frost within a forest canopy than outside (and appreciably more with denser canopy), but a narrow ride (less than say 20 yd wide) gives almost as much freedom from frost as 70 per cent canopy. Bare soil over an open surface affords better protection than a wide ride (say 30 yd or more across). Least favourable for freedom from frost are rather enclosed vegetation-covered sites.
- (ii) The findings above are reflected in years of freedom from frost. Thus at the start of June the risk of temperatures of below 28°F ranged from 5 years in 10 in places like Harling to 2 years in 10 at Harling Nursery or in a broad ride, and 1 year in 10 in a narrow ride or under light canopy. The risk is low under denser canopy.
- (iii) At a height of 6 in above the ground, differences in temperature in various exposures are considerably greater than at 4 ft. On the whole, a large expanse of bare soil affords maximum protection against cold temperatures, but dense canopy can give greater freedom

from low temperatures in a sudden short cold spell. Narrow rides are probably the next best frost preventer, followed in order by a small bare-earth area and a wide ride.

- (iv) The vertical arrays show that freedom from low temperatures was maintained at all heights between 2 in and 72 in over bare soil, with very big gains over natural vegetation, especially near the ground. The temperature in the lowest few inches under forest cover was lower than over bare soil, but above 2 ft the temperature within the canopy was higher.
- (v) Airflow at 6 ft is controlled mostly by the openness of the terrain, but at 1 ft or below the type of earth cover is important. Airflow near the ground was greatest over bare soil, and least within the canopy or near the level of a furrow top.
- (vi) Temperatures in late spring and early summer in sandy soil show a change of pattern. In early/mid spring, minimum temperatures are lower under bare soil than elsewhere, but in late spring and in early summer, night temperatures are less cold under bare soil than under vegetation or within a forest canopy. Average maximum day temperatures are always higher in spring and summer under bare soil than under some form of cover, and in June can average over 10 degF higher than soil temperatures under a forest canopy.
- (vii) Gradual changes in cover (such as more grass at Kings since 1965) bring about a changed frost risk above ground.

Acknowledgements. Again it is a pleasure to record indebtedness to the Forestry Commission for the advice and interest shown by Dr D. H. Phillips, and Messrs B. J. W. Greig and D. Burdekin of Alice Holt and to Mr F. Halls of West Harling, Thetford Chase, who made the observations to a very high standard of accuracy throughout.

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THE COMPARISON OF SUBJECTIVE AND OBJECTIVE UPPER AIR FORECASTS FOR AVIATION (PART II)

By I. H. CHUTER, M.Sc.

Summary. Part I of this paper (published in January) compared subjective forecasts of the 300 mb height field with objective forecasts produced by means of a linear regression equation using the 1000, 500 and 200 mb forecast height fields. An objective method was used to compare the actual equivalent headwinds over a given route with those forecast. (Assessments were made on the 0000 GMT analyses charts and on the forecast charts valid for the same time — normally a 24-hour forecast.) The period covered was from August 1966–July 1967 giving about 360 forecasts, and these have been analysed in 3 sets of 120.

Headwinds were also converted into total flight times and assessments were made of timing errors in relation to the needs of airline operators. Root-mean-square errors in the objective forecasts of headwinds were lower than in subjective forecasts. An analysis of the total errors on each route showed that large errors were fewer in the objective forecasts than in the subjective.

Part II gives an analysis of errors in headwinds for individual 300 nautical mile zones on the air routes showing that the objective forecasting method was better than the subjective, and that forecast success does not depend on the geographical location of the zone. An analysis of the errors in estimated flight times shows that subjective methods increased the mean error.

Some of the possible sources of error in the data are discussed.

Results and discussion. (Continued from Part I¹.)

Individual zone errors. The treatment of total route errors may be considered as a rather insensitive test and an analysis was made of individual zone errors, the zones being approximately 300 nautical miles in length.

The errors were sorted into 10-kt classes and, as before, the number of cases of errors greater than or equal to a specified value were assessed. The results for the three periods, forecasts and routes are shown in Figures 1 (a)–(c). Each curve is a portion of an assessment of about 1200 values. The tables

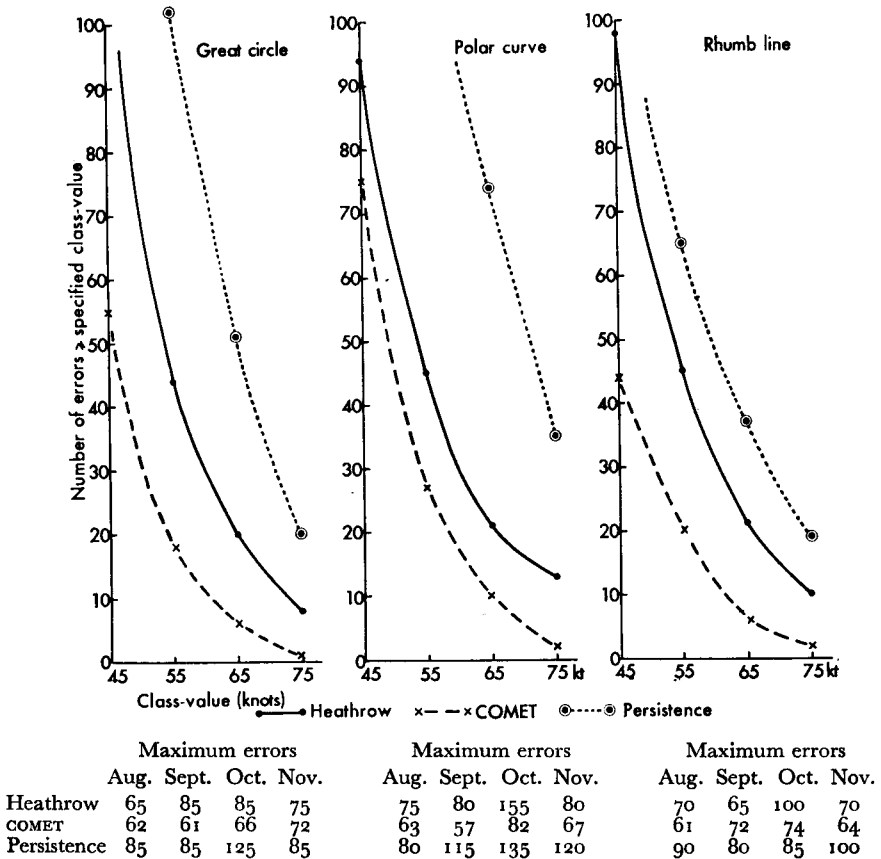


FIGURE 1 (a)—NUMBER OF ERRORS GREATER THAN OR EQUAL TO SPECIFIED VALUE FOR THE ZONE, AUGUST–NOVEMBER 1966

beneath each set of curves indicate the maximum zone errors for each forecast for each month and the highest value may be considered as the point where the curves intersect the class speed axis.

As before, during period (1) the COMET performance is better, but during period (2) subjective amendment has slightly reduced the number of higher errors on the great circle and rhumb line but not on the polar curve. The maximum zone error is however contained in the London/Heathrow forecast. For period (3) little difference has been made by amendment and for the rhumb line the change has been detrimental. The overall maximum zone errors are again in the Heathrow forecast.

An analysis was also made of the highest errors for each of the 10 zones of each track. This indicated that the geographical location of the zone did not have any significant effect on the forecast performance except with the western five zones of the rhumb line COMET forecast, which, in period (2), showed errors at the persistence level. This adds weight to the suggestion that a winter effect such as sea-heating may be failing in the COMET forecast model in this particular location.

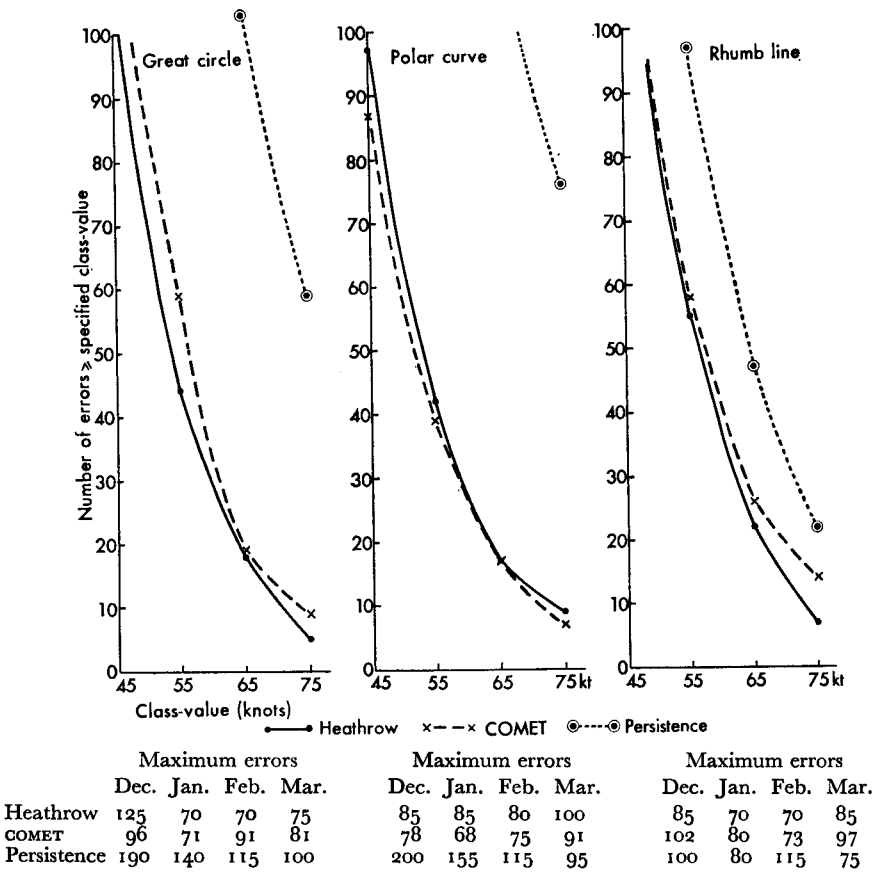


FIGURE 1 (b)—NUMBER OF ERRORS GREATER THAN OR EQUAL TO SPECIFIED VALUE FOR THE ZONE, DECEMBER 1966–MARCH 1967

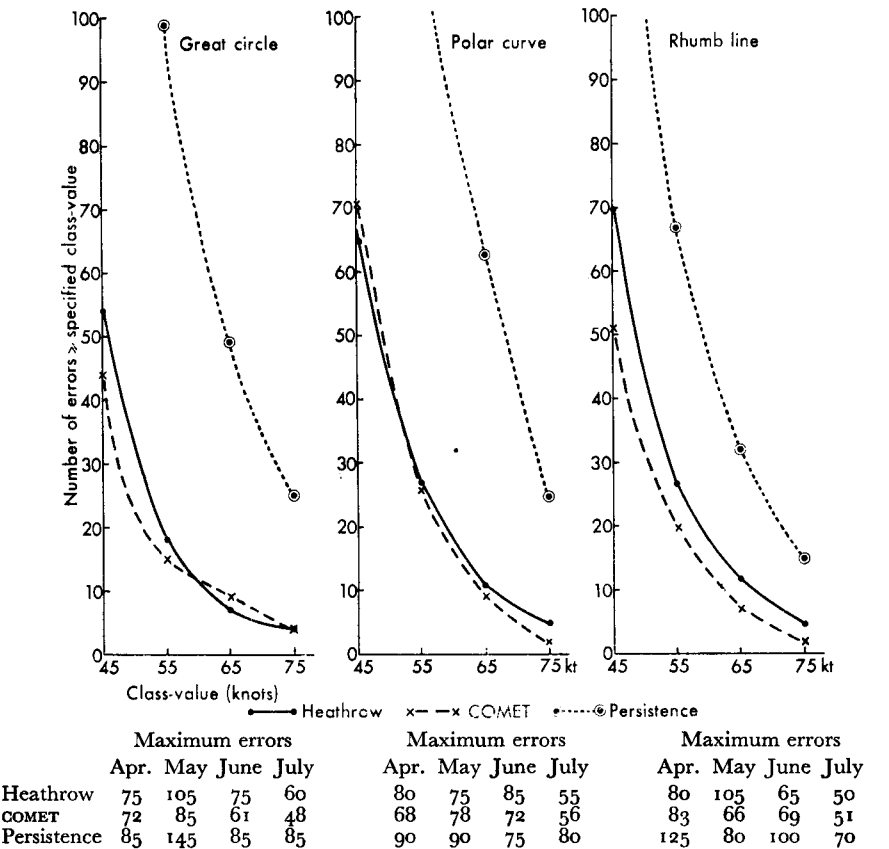


FIGURE 1 (c)—NUMBER OF ERRORS GREATER THAN OR EQUAL TO SPECIFIED VALUE FOR THE ZONE, APRIL-JULY 1967

It is perhaps surprising that there is no indication of any difference in performance over any particular section of the route, since it is often thought that developments in the eastern Atlantic are difficult to forecast because of the lack of observations to the west.

Timing errors. Table I shows a frequency analysis, in 5-minute classes of the time errors, representing the economic loss, between the planned least-time-route and the actual shortest route. The positive values arise when the forecast flight time was larger, i.e. the flight arrived early.

For period (1) it is quite apparent the Heathrow forecast has a far greater spread of errors than that of COMET, and this is reflected in the calculated standard deviation. For periods (2) and (3) the standard deviations are almost identical in the two methods but the mean error has been increased by between four and five minutes by subjective intervention. This suggests that when track selection is involved a 'safety factor' is incorporated by the human forecaster and this may be linked to the increasing of jet core-speeds mentioned earlier.

TABLE I—ANALYSIS OF ERRORS IN FOUR-MONTH PERIODS

Period 1 August–November 1966																								
Error range (minutes)																								
Negative values												Positive values												
55–51	50–46	45–41	40–36	35–31	30–26	25–21	20–16	15–11	10–6	5–1	0–4	5–9	10–14	15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	Mean	Standard deviation	
(a)			1	2	3	6	9	20	18	18	15	18	7	3	1	1						+0.1	12.0	
(b)					2	3	16	12	28	28	19	7	5									–1.1	8.7	
(c)	1	1	0	2	0	15	10	15	13	20	13	11	11	7	1	1						–0.3	13.8	
Period 2 December 1966–March 1967																								
Error range (minutes)																								
Negative values												Positive values												
55–51	50–46	45–41	40–36	35–31	30–26	25–21	20–16	15–11	10–6	5–1	0–4	5–9	10–14	15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	Mean	Standard deviation	
(a)			1	1	3	8	3	11	18	13	17	19	6	7	3	7	2	1	1			+5.0	15.0	
(b)			1	2	6	11	14	11	21	17	8	9	7	5	2	0	0	1				+1.0	14.9	
(c)	1	2	1	5	4	7	6	7	8	11	10	9	13	16	4	3	5	2	0	2	1	–0.1	21.8	
Period 3 April–July 1967																								
Error range (minutes)																								
Negative values												Positive values												
55–51	50–46	45–41	40–36	35–31	30–26	25–21	20–16	15–11	10–6	5–1	0–4	5–9	10–14	15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	Mean	Standard deviation	
(a)			1	4	9	14	21	30	13	17	8	3	1									+2.0	9.8	
(b)				4	9	16	17	22	20	19	10	3	1									–2.7	10.3	
(c)	1	1	2	5	9	13	14	22	12	10	12	8	5	5	2	0	1					–0.2	15.0	

(a) = Heathrow (b) = COMET and (c) = Persistence

(a) = Heathrow (b) = COMET and (c) = Persistence

The relative merits of early or late arrivals are open to discussion and may depend on the preferences of the operators. Punctuality could be ensured by varying speed and therefore fuel consumption in flight but in practice any gains from such manoeuvres are likely to be counteracted by air traffic control procedures.

Sources of possible errors. In many cases the forecast performance is judged on small differences in r.m.s. errors and it is of interest to estimate some of the errors involved in the measurements.

Assessment of true winds. The best assessment available of the true winds along a track at a given time is that from the Heathrow analysis charts. It should be noted here that although actual aircraft reports are of value, great care is required in their use. The reports are rarely at the precise height, time and position to be used on a particular part of the chart, and since they are spot winds they are subject to gustiness of varying periods. This latter effect may make them unrepresentative of the flow on the synoptic scale. In contrast, the wind measured by balloon and radar is the mean through a layer of a few thousand feet.

The assessment of a wind speed by eye from a chart is also subject to error, and it is well known that if several forecasters take measurements on the same chart different values may be obtained. A previous assessment² of this effect indicates that a standard deviation of about two knots may be involved for a route of 10 zones of 300 nautical miles.

It is necessary to measure the geostrophic wind over some distance which will depend, in the subjective case, on the lateral spacing of the contours and the angle made with the track. Distances probably lie on average between about 100 and 200 nautical miles. The wind is then applied to a nomogram to obtain the headwind, and directional errors can be introduced at this stage. The quoting of the result to the nearest 5 kt is probably sufficiently precise. Even if each zone of a track had 5-kt errors it is unlikely that they would all be in the same sense, so measurement errors for the total track will be considerably less than 5 kt.

COMET assesses the gradient through a grid square, about 160 nautical miles, and applies this wind to the length of track in that square. The calculation of headwind is then precise.

The forecast comparisons are, however, with respect to the standard analysis values, so even if these are in error the relative performance will be unaffected.

Effect of aircraft speed. The basis of all the calculations is an aircraft speed of 400 kt and thus relative performance is unaffected by changing this speed.

However, timing errors do depend on the aircraft speed, as does the absolute value of the headwind.

The contribution to total headwind of the beam component of wind velocity is given by $(V^2 \sin^2 \theta)/2A$ where V is the wind velocity, θ the angle to the track and A the aircraft speed. The maximum effect is then $V^2/2A$.

Considering an aircraft speed of say 500 kt the difference in beam component is

$$\frac{V^2}{2} \left(\frac{1}{400} - \frac{1}{500} \right) = \frac{V^2}{2} \frac{1}{2000} = \frac{V^2}{4000} \quad .$$

For a wind speed of 100 kt the difference would be about 2 kt. Since the track of the aircraft would be at right-angles to a jet stream to achieve this difference, it would soon pass across the belt of strong winds and the effect on the total route headwind would be small.

Thus changes of aircraft speed of this order can be neglected for headwind calculations.

The effect of aircraft speed on the time for a route of 3000 nautical miles is more complex but in near still-air conditions an error of 15 min at 400 kt is equivalent to about 10 min at 500 kt.

Conclusions and future developments. It is evident that the decision to introduce numerically produced forecasts for aviation purposes was well founded, because there is an improvement both in meteorological and economic terms. It is now possible for airline operators to produce flight plans by computer direct from forecast height fields.

The present method of producing the COMET 300 mb height field is extremely primitive and the scope for improvement is considerable.

The conclusion from the period December 1966 – March 1967 is that subjective intervention has resulted in no significant improvement to the COMET forecasts as determined by the equivalent headwinds over the whole routes. Consideration of individual zone errors indicates a marginal improvement in the number of large errors during the winter period on the great circle and rhumb line, but this trend is not continued in the subsequent period.

It is clear that the facility for human intervention has to be used with care to be justified.

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SOME OBSERVATIONS OF NIGHT MINIMUM ROAD TEMPERATURES

By J. S. HAY

Summary. Air and road surface temperatures were measured during two successive winters at each of two sites. Differences in the night-minimum values of these temperatures were generally small and no systematic variation with a number of meteorological and other parameters was evident. Two types of situation were recognizable however, in one of which the minimum air temperature was consistently higher than the minimum road temperature and in the other, consistently less, the difference being up to 3 degC or so at times.

When he is considering whether or not to issue a warning of icy roads for the ensuing night, a forecaster obviously must arrive at some estimate of the minimum temperature to be expected on roads in the forecast area.

Various techniques are available to him for forecasting minimum air temperature, but just how this is related to minimum road temperature is not at all clear as little relevant information appears to have been published. The relation between minimum air and grass temperatures on the other hand has been discussed in a number of papers, ^{1,2,3} but this cannot be assumed *a priori* applicable to roads in view of the very different natures, and presumably very different thermal properties, of grass and road surfaces.

This article is concerned with measurements of road and air temperatures which were made in the course of tests on ice-warning devices, on the carriageway of the M 1 motorway near Newport Pagnell during the winters of 1963/64 and 1964/65, and on a slip road off the M 4 motorway near Bray Wick during the succeeding two winters. The temperature sensors were thermocouples which were connected to a recording potentiometer containing an automatic reference junction. At both sites, one thermocouple junction and the first metre or so of the leads were embedded in the asphalt surface of the road so that the upper surface of the junction was exposed to the air. Another thermocouple was set up on the grass verge with its junction in a Stevenson screen at the standard height of 1.25 m. The resistance between metal plates embedded in the road surface was also recorded, thereby giving an indication of whether the surface was wet or dry. No other observations were made at Newport Pagnell but additional recorded measurements at Bray Wick included wind speed, net radiation and wet-bulb depression.

At the Newport Pagnell site, the carriageway of the M 1 runs in a south-east to north-west direction over level ground. The exposure of the Stevenson screen was poor to the south-west, with a solid fence nearby and some buildings beyond, but was otherwise satisfactory. At the time of the observations, the carriageway comprised a 10-cm rolled asphalt surface on a 35-cm lean-mix concrete base with a hoggin sub-base. At Bray Wick, the instruments were located at the start of a north-south section of the slip road, just after it curves sharply off the eastbound carriageway of the M 4. The adjoining ground to the east was level with the road surface but to the west, lay about 2 m below the road. The site was well exposed, the only obstructions being some buildings 30 m or so to the west. The road consisted of a 10-cm rolled asphalt surface and a 40-cm cement-stabilized base with a gravel sub-base.

For the purposes of the present analysis, minimum air (M_A) and minimum road (M_R) temperatures in degrees Celsius between the hours of 2100 and 0900 GMT next day were noted from the potentiometer charts, and the differences $D = M_A - M_R$ were determined. D was found to be substantially constant for much of the winter, as will be seen from Figure 1 where, for the sake of clarity, 10-day mean values are plotted. For the winter periods, the overall mean and extreme values of D were as follows :

Site Period	Newport Pagnell	Bray Wick
	Mid-November to end of January	Mid-November to end of February
No. of observations	121	171
Mean D degC	-0.1	+0.7
Max. D degC	+2.5	+3.2
Min. D degC	-6.2	-1.9

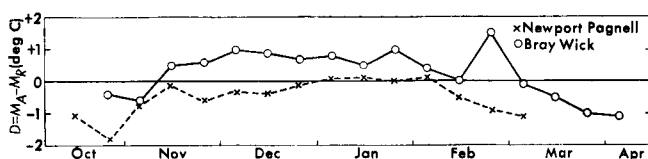


FIGURE 1—VARIATION OF 10-DAY MEAN VALUES OF D

However real the difference of 0.8 degC in these mean values of D may be, meteorologically it is probably of little consequence, being less than the usual error in forecast values of minimum air temperature. Combining the two sets of data then, the mean value of D may be taken as 0.3 degC or, rounding off to the nearest whole number, 0 degC.

Another feature to be noted from Figure 1 is that at both sites, before and after the winter periods used for determining the longer period means, D is essentially negative, i.e. minimum road temperature higher than minimum air temperature. This is no doubt due, in part at least, to the greater absorption of solar radiation by the asphalt road surface than by the adjoining grass surfaces. These remarks apply equally well of course to the winter months but, with lower solar elevations and shorter duration of daylight, the difference in absorption then will be less marked. Another factor possibly contributing to these negative values of D is the fact that the thermocouple measuring air temperature was above the grass verge. However, even if it was over the road surface, this is of such limited extent that, only in exceptional circumstances, would the screen temperature at 1.25 m be governed exclusively by heat transfer processes above the road.

On physical grounds, the value of D may be expected to be dependent, among other things, on wind speed and cloud cover prior to the attainment of minimum temperature, e.g. large positive values with clear skies and light winds. The data for Bray Wick were thus considered in greater detail as some supporting observations were available for this site. These did not actually include cloud cover but it seemed reasonable to assume net radiation to be inversely proportional to amount of cloud. Mean values of radiation and of wind speed were determined each night for the 3-hour period preceding the time of minimum temperature, or the earlier minimum when M_A and M_R were reached at different times. When the values of D were grouped according to wind speed and radiation, D was seen to be generally positive in sign for moderate and stronger winds, but otherwise did not vary systematically with these two variables. From further grouping or plotting of the data, there appeared also to be no dependence of D on :

- (i) the road surface being wet or dry,
- (ii) traffic density,
- (iii) the value of air or road minimum temperature,
- (iv) the times at which the minima occurred,
- (v) the time interval, sometimes several hours, between the two minima,
- (vi) wet-bulb depression.

Finding (ii) was based on the observations at Newport Pagnell, for which site hourly traffic counts were available.

The meteorological situations obtaining on occasions of extreme positive and negative values of D were next considered to see whether or not any

characteristic features were recognizable. Two facts to emerge were as follows :

- (i) If fog forms in the area, negative values of D of 3 degC or more may be obtained. This seems somewhat surprising since positive values of D might be expected in such conditions, at least before the fog formed. In some instances, the incidence of fog, judging by the high humidity and a sudden drop in outgoing radiation, was accompanied by a drop of a few degrees in air temperature whereas the road temperature remained more or less constant.
- (ii) If insolation, after a night of clear skies and light winds, is curtailed soon after sunrise by the spread of cloud ahead of a warm front, with the warm, cloudy air mass subsequently reaching the area, positive values of up to 3 degC for D will be obtained on the *following* night.

These two types of situation are illustrated in the temperature sequences shown in Figure 2. During the night of 28/29 December 1965, light winds and clear skies were fairly general over eastern England as a ridge moved from west to east across the British Isles. Some fog patches were reported from London/Heathrow Airport, about 20 km to the east of Bray Wick, and other places; the Bray Wick observations were consistent with the presence of fog. The value of D for the night was -1.5 degC. Around 0800 GMT on the 29th, cloud increased rapidly at Heathrow and, a few hours later, rain reached the area in advance of a warm front then moving into western districts of England. The warm front moved steadily eastwards to cross the area during the evening, being followed soon afterwards by the cold front. Thereafter the skies were largely clear for the remainder of the night though there were one or two light showers. The value of D for the night of 29/30 December was $+2.7$ degC. Apart from two brief spells around noon on 1 and 2 January 1966, the air temperature remained above the road surface temperature until the afternoon of the 3rd.

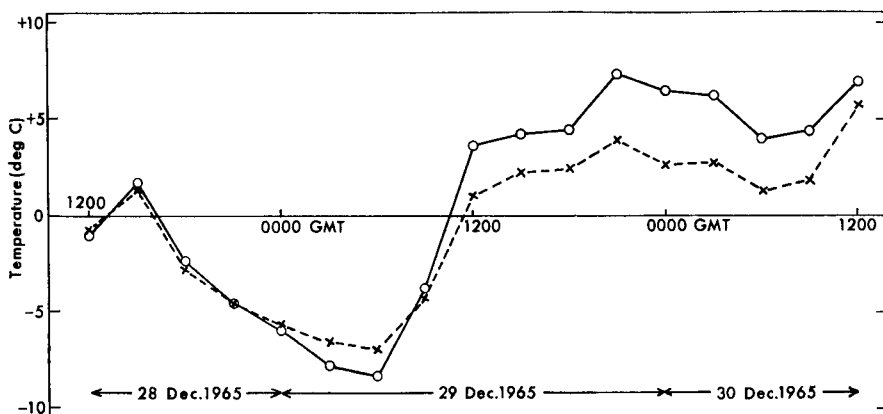


FIGURE 2—AIR AND ROAD SURFACE TEMPERATURES AT BRAY WICK FROM 1200 GMT ON 28 DECEMBER 1965 TO 1200 GMT ON 30 DECEMBER 1965
o = air temperature x = road temperature.

If the above findings are applied now to the problem of forecasting, it would appear that forecast values of M_R should be taken to be the same as forecast values of M_A for the period mid-November to mid-February. This however, should perhaps be regarded at the present stage as a guide rather than a rule in view of the limited amount of data, two incomplete winters at each site. It may be, too, that a different result would be obtained at another site with different topographical features and physical characteristics such as type of road construction, colour of surface, etc.

No mention has been made so far of the accuracy of the temperature measurements. There seems little reason to doubt the road surface temperatures as the thermocouple junction at each site was in good thermal contact with the road, and there could have been little or no thermal conduction along the leads to the junction. To check the air temperatures, the observed minima were compared with the minima measured at the nearest meteorological offices. In the case of Newport Pagnell, the mean difference from Cardington minima was -0.4 degC (96 per cent of the differences within 2 degC), while for Bray Wick the mean difference from London/Heathrow Airport minima was 0.2 degC (98 per cent of the differences within 2 degC). As the distances separating the sites under comparison were about 25 and 20 km respectively, the agreement is remarkably good. The temperature measurements used in the above analysis can thus be accepted with confidence.

The measurements were made in the course of work carried out by the Climate and Environment Section (Leader Mr L. H. Watkins) of the Ministry of Transport's Road Research Laboratory, and this article is contributed by permission of the Director of Road Research.

The assistance of Mr A. O. Grigg and Miss W. McHugh in extracting and analysing the data is gratefully acknowledged.

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AWARDS

L. G. Groves Memorial Prizes and Awards

In 1946 Major and Mrs Keith Groves instituted three annual prizes in memory of their son, Sergeant (Meteorological Air Observer) Louis Grimble Groves, RAFVR, No. 517 Squadron, Coastal Command, who lost his life while flying on a meteorological sortie on 10 September 1945. In addition a general purpose award, named the Second Memorial Award, was set up in 1960.

On 22 November 1968 the four awards for the year were presented at the Ministry of Defence, Whitehall, by Major K. J. Groves. The presentation was presided over by Air Marshal Sir Peter Wykeham.

The 1968 Aircraft Safety Prize was awarded to Flight Lieutenant J. F. Narramore, B.E.M., an Engineering Officer of Royal Air Force Lyneham, with the following citation :

'In recognition of his diligence, skill and impressive contribution to flight safety. Flight Lieutenant Narramore, an Engineering Officer, was responsible for the investigation of engineering defects involving the safety of Britannia aircraft, their successful diagnosis and comprehensive and effective follow-up action. These included the development of a Command modification to prevent the loss of life-raft panels, and another to modify the wheel-change jack which had been damaging the bogie beam on the undercarriage. He also carried out investigations into the source of contamination in booster-pump filters and corrected weaknesses in the lay-out of hydraulic pipelines which presented a serious fire risk and could have caused failures in the brake system. Although these investigations were only part of his normal task, he undertook them with meticulous thoroughness and determination.'

The 1968 Meteorology Prize was awarded to Mr A. H. Hooper, Senior Experimental Officer, Meteorological Office, with the following citation :

'In recognition of his work during the last four years on the development and trial of a new radiosonde system. The work demanded skills of a high order in the fields of electronic engineering, automatic data processing and upper air meteorology. Throughout the work Mr Hooper has shown tenacity and exceptional application in the face of many difficulties and setbacks, leading a small team very effectively by infecting them with his own enthusiasm. The result is that we now have a radiosonde which can be a world leader in performance. Its general adoption will lead to much better observations at much greater heights and enable the Meteorological Office to meet the demands of aviation for knowledge of conditions at such levels.'

The 1968 Meteorological Observers' Award was awarded to Mr W. J. Cox, Senior Scientific Assistant, Meteorological Office, with the following citation :

'In recognition of his pioneering work in the measurement of upper air temperatures and humidities from a merchant ship in the course of her normal voyages in the Atlantic and Indian Oceans. The leader of a team of two, Mr Cox demonstrated that it was possible to adhere to a scheduled routine in all weather experienced, which included gale force winds; the routine involved launching balloons and associated radiosonde equipment from an open deck, receiving data from the sonde and arranging for the timely despatch of the computed data to shore stations. His resourcefulness and infective enthusiasm has enabled the Meteorological Office to plan realistically to extend the operation to ten merchant ships in the coming four years as part of the United Kingdom contribution to the World Weather Watch under which aviation and other interests should benefit materially.'

The Second Memorial Award for 1968 was awarded to Dr J. D. Woods, Principal Research Fellow, Meteorological Office, with the following citation :

'During the past three summers Dr J. D. Woods has organized and led expeditions which have used skin-diving techniques to study directly the upper layers of the sea. Undertaking much of the underwater



PLATE III—AWARD WINNERS WITH MAJOR AND MRS K. J. GROVES AND AIR MARSHAL

SIR PETER WYKENHAM

Left to right : Dr J. D. Woods, Mr A. H. Hooper, Mrs W. J. Cox, Mr A. M. Dunning, Major K. J. Groves, Flight Lieutenant J. F. Narramore, Mrs K. J. Groves and Air Marshal Sir Peter Wykenham (see page 60).



**PLATE IV—MAJOR K. J. GROVES WITH MR A. H. HOOPER, WINNER OF THE MEMORIAL
PRIZE FOR METEOROLOGY**
(See page 60.)



**PLATE V—MAJOR K. J. GROVES WITH DR J. D. WOODS, WINNER OF THE SECOND
MEMORIAL AWARD**
(See page 60.)

observation himself, he has developed techniques for making the water movement visible by means of dye and designed new instrumentation for measuring temperature gradients.

His work has proved valuable not only for the new knowledge which has been acquired on the structure of the oceans and the transfer of heat between ocean and atmosphere, but as a stimulus to the theoretical understanding of stratified fluids in general and such related phenomena as clear air turbulence. Without Dr Woods' enterprise and initiative these underwater observations would not have been made.'

REVIEW

Formation of precipitation and modification of hail processes, by G. K. Sulakvelidze, N. Sh. Bibilashvili and V. F. Lapcheva. 250 mm × 180 mm, pp. v + 208, *illus.* (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), Oldbourne Press, 1-5 Portpool Lane, London, E.C.1, 1967. Price: 99s.

Scientists at the High-Mountain Geophysical Institute (VGI) in the Soviet Union have recently developed a seeding technique by which they claim they can virtually eliminate damaging hail from seeded hailstorms. The present book, written by the chief scientists involved in the VGI hail suppression programme, describes both the seeding technique and its scientific basis. Although designed for the specialist reader, this book is likely to be widely read since it offers the first convincing evidence of successful hailstorm modification. Despite the absence of statistical significance tests, the authors make a strong case for the success of their technique; to quote them, 'it is difficult to consider a fortunate accident the cessation of hail fall in 60 experiments directly after the introduction of the seeding reagent into the cloud and precisely in the place where it was introduced. It is also hardly possible to consider as accidental the fact that during three years of work in the most hail-prone regions of the Soviet Union (the northern Caucasus) not a single case of hail fall on the protected territory was observed'.

The first three chapters of the book are concerned with the vertical velocity structure of convective clouds and with the growth of the cloud droplets and hailstones. In addition to surveying some basic Russian and English language literature, the authors present some important observations and ideas of their own in order to establish the hail-growth model which serves as the basis for their hail suppression work. Particularly important are their measurements of vertical velocity profiles within convective clouds using no-lift, balloon-borne, corner-reflectors tracked by radar. They report that, although the updraught in developing clouds fluctuates strongly with height, the updraughts in mature clouds tend to resemble a relatively steady jet, with vertical velocities typically reaching 20 to 25 m/s in the middle or upper parts of the cloud. Stimulated by these observations and by their earlier direct measurements of liquid water contents of 20 to 30 g/m³ in mature convective clouds, the authors go on to suggest that the diminution in updraught velocity towards the top of convective clouds results in the gradual accumulation of high concentrations

of raindrops where the terminal fall-speed of the drops is comparable to the updraught velocity. They obtain an expression for the maximum attainable liquid water content in the so-called *accumulation zone* as a function of the vertical updraught profile, but their treatment is unrealistic in so far as it is one-dimensional and fails to take into account the decrease in the concentration of raindrops due to horizontal divergence above the updraught maximum. Nevertheless, as Professor K. Haman at the University of Warsaw has recently emphasized, it is still possible to account for the development of an accumulation zone in terms of the recycling of raindrops up and down around the level of maximum updraught velocity. In any case, regardless of how an accumulation zone is produced, the VGI scientists believe that such a zone should constitute a suitable environment for rapid hailstone growth provided that it is situated within the supercooled region. They propose a mechanism for hail production in which a few drops freeze spontaneously at the top of the accumulation zone (at a temperature between -15 and -22°C), and then grow very rapidly accreting supercooled drops as they fall down through the accumulation zone. Although heat budget considerations imply that hailstones grown in this manner will contain a high proportion of unfrozen water, the model does not explain how such hailstones are consolidated to enable them to survive melting during their final descent below the 0°C level. The probability of hail growth is assessed according to this model using thermodynamic 'slice' theory to predict the height and magnitude of the updraught maximum. If, for example, the updraught maximum is too low and the accumulation zone lies mainly below the 0°C level, then significant hail growth does not occur. The surprisingly good (90 per cent) accuracy of this method of hail forecasting in the northern Caucasus is given as evidence of the validity of the hail-growth model.

The fourth chapter discusses radar techniques used by the VGI workers for identifying hailstorms. Features such as the height of the echo top and the maximum radar reflectivity are used to determine whether or not hail is present within the cloud. The authors also suggest that it is possible to identify the accumulation zone as being associated with a reflectivity maximum aloft; however, they present no convincing evidence to support this claim. As far as the estimation of hail size within the cloud is concerned, the problem has always been that the back-scattering cross-section of hailstones whose diameter is comparable to the radar wavelength is a complex function of hail size, with stones of significantly different diameters sometimes displaying similar cross-sections. To circumvent this problem the VGI scientists use a two-wavelength radar approach in which they compare the reflectivities measured at 3- and 10-cm wavelength, assuming that the reflectivity is due to an exponential spectrum of hail sizes similar to that measured directly at the ground. Now this kind of approach was proposed in 1961 by Professors Atlas and Ludlam but it was not pursued in the West because its validity is not only influenced by changes in the shape of the hail size spectrum within the cloud, but is also influenced (i) by the dependence of the cross-section of hailstones upon their shape and liquid water content, and (ii) by the effect of the attenuation of radar energy at 3-cm wavelength by intervening precipitation. It is, therefore, interesting that this technique is apparently being applied with some success by the Soviet workers. They state, for example, that the mean error in the radar determination of hail size at the ground, allowing for melting below

the 0°C level, is as little as 35 per cent. By using a radar wavelength of 5 or 6 cm instead of the present heavily attenuated 3 cm, and by using in addition a third wavelength of about 20 cm, it should be possible to improve this accuracy significantly.

The fifth and final chapter in this book is devoted mainly to the VGI hail suppression technique itself. In essence this entails the dispersal of a seeding agent (PbI_2) into the accumulation zone at the -5°C level. The dispersal is carried out *directly into this zone* by means of artillery shells, since the authors believe that the seeding material becomes less effective as a nucleating agent if it first encounters water at temperatures above 0°C . The aim of the seeding is not to freeze all of the supercooled water in the accumulation zone but, rather, to increase the number of hail nuclei. The idea, as first proposed by Ludlam, is to increase the number of hail embryos competing for the available liquid water to the extent that none is able to grow large and most are able to melt completely before reaching the ground. Assuming a yield of 10^{14} nuclei per gramme of reagent and assuming that 1 in 10^4 of these produces a hail embryo, then about 10 g of reagent are required per 1 km^3 of air in order to promote sufficient competition to prevent the hailstone embryo from growing large. Such a dose needs to be repeated at intervals of 5 to 10 minutes so long as the hail cloud persists. The rate of propagation of the area of glaciation by seeding has been found to be as high as 10 to 20 m/s; possibly ice splinter multiplication processes are effective in accelerating the rate of glaciation. It is claimed that, not only does the hailfall at the surface cease soon after seeding, but also that the results of seeding can be observed by radar, for example, as a diminution of reflectivity in the seeded area. The range of a single anti-aircraft gun of the kind used to disperse the seeding agent is such as to permit an area of radius 10 km to be protected. The entire operation — consisting of the hail forecast using the 'slice' method, the identification of the hail-growth region by radars, the seeding by artillery shells, and finally the survey of the surface distribution of precipitation beneath the path of the seeded storm — is carried out like a well-planned military operation. One cannot fail, when reading this book, to be impressed by the all-round success claimed for all phases of the operation; however, this reviewer at least was worried by the feeling that things were sometimes almost, 'too good to be true'. Finally, although it seems reasonable to suppose that this study will serve as a blueprint for further hail suppression studies in other parts of the world, it is important to stress the need for more basic research into the structure of hailstorms, since it is by no means obvious that all hailstorms conform to the Rain-Storage Model proposed here.

This book is generally clearly written and well translated, although the reproduction of the photographs is poor and the mathematics in a few places is more detailed than need be. It is recommended reading for anyone with a specialist interest in precipitation physics or weather modification.

K. A. BROWNING

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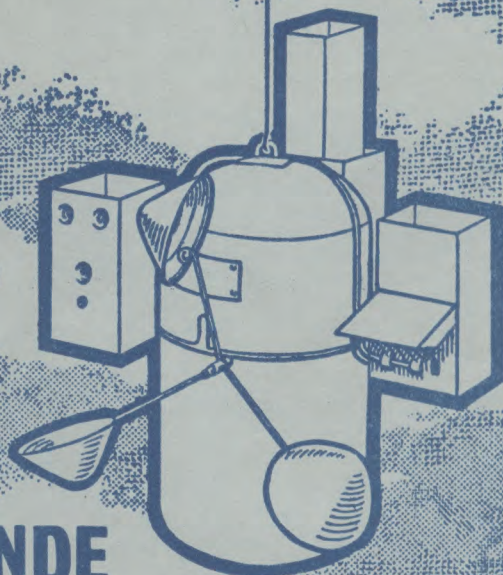
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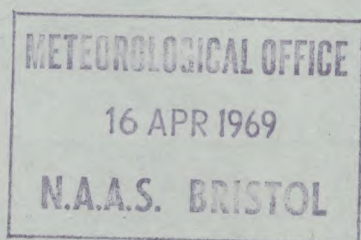
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SOME AIRCRAFT REPORTS OF HIGH-LEVEL TURBULENCE

By W. T. ROACH

In the past five years, the Meteorological Office has received about 300 reports of severe clear-air turbulence from U.K.-based civil and military aircraft flying mainly on European or Atlantic routes. A routine check is kept on the association of these reports with the relevant synoptic situations which, in most cases, are found to correspond to situations in which, from past experience, the occurrence of turbulence might be expected.

However, on some occasions the turbulence is particularly severe and widespread or possesses other features of sufficient interest to justify published comment. Previous cases have been described by Briggs^{1,2} and Lennie.³

One problem of considerable practical importance is, given a situation in which turbulence is likely, why should the turbulence encountered be severe on some occasions rather than light or moderate? One feature which appears to be emerging from a study of severe turbulence reports is that relatively rapid changes in the large-scale flow pattern are often occurring locally — e.g. in association with a developing depression — but so far, an adequate quantitative description of development relevant to the production of turbulence has not yet emerged.

In the five cases to be described here, significant development was present, but this is not the only interesting feature discussed. In three cases, it was possible to obtain copies of the original flight recording thus enabling a more objective assessment of the reports to be made.

Gravity waves in mid-Atlantic ? On two occasions in 1967 (24 January and 2 December) reports of prolonged turbulence encounters (about 1 hour) accompanied by quasi-periodic fluctuations in height and airspeed were reported by the pilots as 'standing waves', presumably by analogy with mountain waves, although in these cases the pilots would clearly not be able to infer anything about the phase velocities of the waves with respect to the ground.

(i) 24 January 1967

Extracts from the captain's report on flight BA 600/334 from Toronto to Prestwick as follows :

'Time approx. 0500 to 0600 GMT; position from 55°N 25°W to 55°N 12°W approx.; flight level 35 000 ft; Mach 0.8; ground speed 530 kt.

During cruise in clear air, there was a very rapid fall in temperature from about -63° to -72°C at about 0520 GMT followed by the onset of moderate turbulence with appreciable ASI (airspeed indicator) fluctuations. It rapidly became apparent that these were systematic and we were in standing-wave conditions... so I disengaged the height lock, advised ATC I was flying "attitude" and "rode with the wave"... This continued for about an hour with a short break of a few minutes around 13°W* when the OAT (outside air temperature) suddenly increased to -63°C . With the power set for Mach 0.8 level, the aircraft rose with the up-wave at up to 2000 ft/min with increasing speed to Mach 0.825 and (if not retrimmed or power readjusted) climbed 2000 ft before starting on the down-wave at up to 1500 ft/min descent with Mach No. falling to 0.78.... The complete cycle took $4\frac{1}{2}$ minutes giving a wavelength of about 40 miles and a peak-to-peak height variation of about 3500 ft.'

It seems very unlikely that this phenomenon could have been produced by aircraft behaviour alone. The aircraft recorder chart was later obtained and part of it is reproduced in Figure 1. The captain's report is largely borne out, but some extra features of interest are apparent.

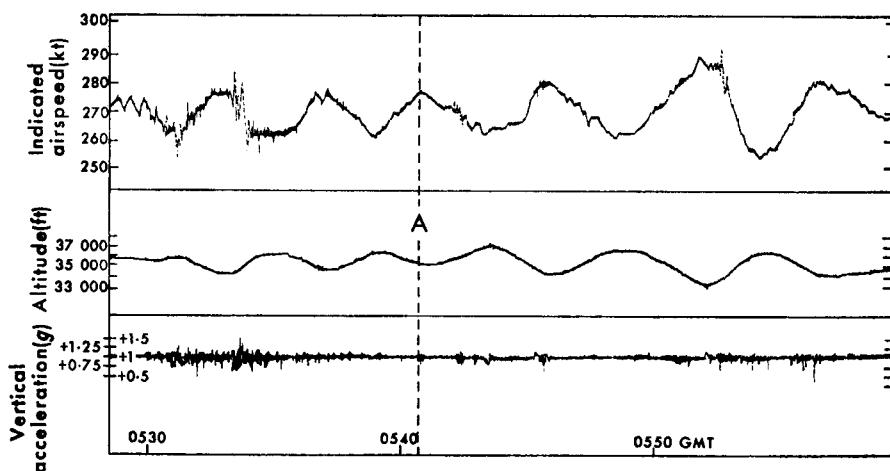


FIGURE 1—FLIGHT RECORD FROM THE RELEVANT PART OF FLIGHT BA 600/334,
24 JANUARY 1967

-- A -- Point at which heading of aircraft changed from 090° to 102°

(a) A change of aircraft heading of about 12° at 0540 GMT is accompanied by a distinct increase in wavelength.

(b) The oscillations in Mach number (Ma) reported by the pilot and the height oscillations in Figure 1 are in antiphase to the indicated airspeed (V_i) oscillations. This is consistent with a rough interchange between the kinetic and potential energies of the aircraft and also with the relation between V_i and Ma given by $V_i \propto Ma p^{\frac{1}{2}}$ where p is pressure.

* A break in the recorded oscillations appears near 0600 GMT.

According to the navigator's log the aircraft was at about $18\frac{1}{2}^{\circ}\text{W}$ at this time, not 13°W .

(c) The root-mean-square 'g' fluctuations (vertical-acceleration trace) are about $\pm 0.05 g$ most of the time, increasing in occasional bursts to 0.1–0.2 g. The 'g' trace has no obvious relationship to the long-period oscillations. The largest event appears to have been at about 0533 GMT when a drop of about 30 kt in V_i in 15 seconds was preceded by a 'g' spike of about $+0.5 g$ (1.5 g on the chart).

The change in heading can be used to infer some of the properties of the wave. If it is assumed that the aircraft is crossing a system of waves with straight parallel crests and troughs then

$$\lambda_a = \frac{U\lambda_t}{|U \cos \theta - u|}$$

where λ_a = apparent wavelength observed from the aircraft

λ_t = true wavelength

θ = angle of aircraft (air) track with direction of wave propagation

U = true airspeed of aircraft

u = phase velocity of wave with respect to the air.

This gives two equations for the two wavelengths $(\lambda_a)_1$ and $(\lambda_a)_2$ observed before and after the change in heading. The latter is known and gives a third equation $\theta_1 - \theta_2 = \Delta\theta$.

A fourth equation is obtained by making the not unreasonable assumption that the frequency of the wave is likely to be close to the Brunt-Väisälä frequency $N = [(g/\theta) (\partial\theta/\partial z)]^{\frac{1}{2}}$ and $N = 2\pi u/\lambda_t$ giving four equations which now enable us to solve for the four unknowns λ_t , u , θ_1 , θ_2 .

Meteorological information and measurements made on the recorder trace give

$$\begin{aligned} (\lambda_a)_1 &= 53 \text{ km} \\ (\lambda_a)_2 &= 75 \text{ km} \\ \theta_1 - \theta_2 &= 12^\circ \\ N &= 0.013 \text{ radians/s} \\ U &= 232 \text{ m/s} \end{aligned}$$

There are two solutions depending upon the sign of $U \cos \theta$:

λ_t	u	Direction of propagation
km	m/s	degrees
30	60	055
40	80	200

Unfortunately, a continuous record of the OAT was not available, otherwise an estimate of the wave amplitude could have been made. An estimate based on the assumption that the aircraft really 'rode the wave' and thus assumed the vertical velocity of air in the wave, gives an amplitude of about 600 m, but this is unreliable as changes of pitch will in general produce aircraft rates of climb or descent relative to the air.

Synoptic situation. The aircraft was crossing in a strong anticyclonic south-west flow at 250 mb (Figure 2) and at 0545 GMT was about 800 km north-north-east of the centre of a rapidly developing depression. The data in the area is too scanty to give more than a rough idea of the atmospheric structure in the proximity of the flight track. The tephigrams of ocean weather stations (OWS) 'I' and 'J' (Figure 3) suggest that the aircraft was flying in a layer of fairly stable air just beneath the tropopause near or just

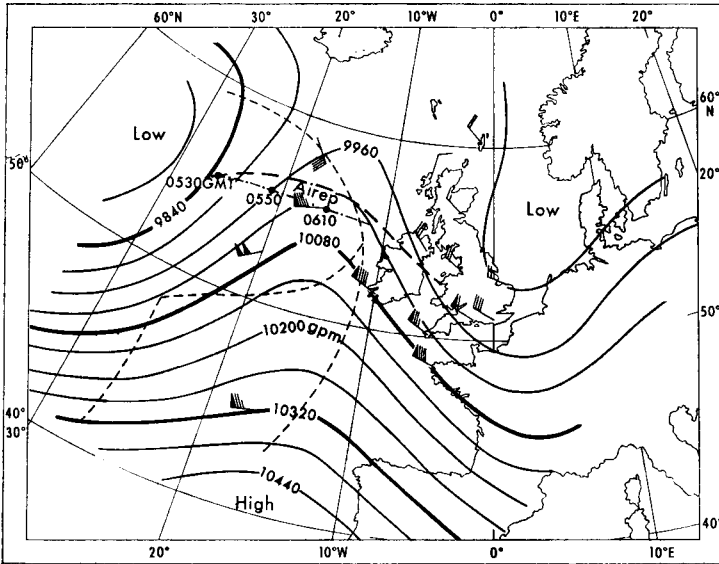


FIGURE 2—INTERPOLATED 250-mb CONTOURS FOR 0600 GMT, 24 JANUARY 1967

- Aircraft track during turbulent period
- Surface fronts at 0600 GMT
- Wind discontinuity suggested by pilot's report and radiosonde winds

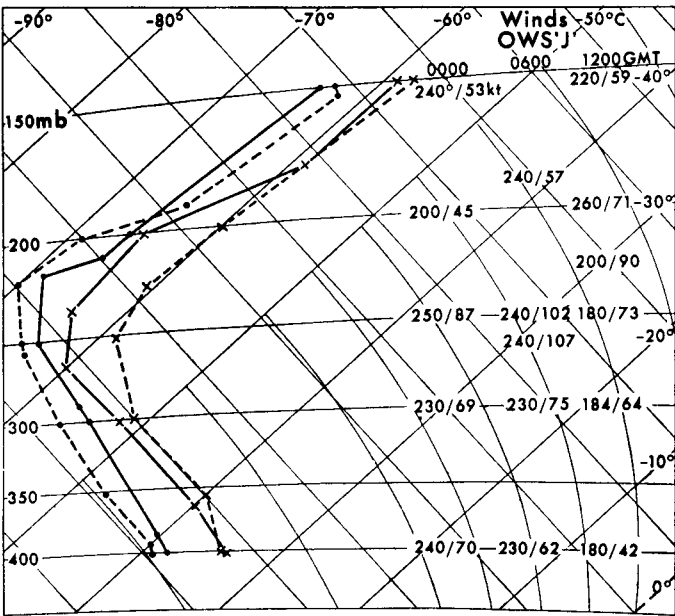


FIGURE 3—UPPER AIR TEMPERATURES FOR OWS 'I' AND 'J' AT 0000 AND 1200 GMT, 24 JANUARY 1967, AND WINDS FOR 'J' AT 0000, 0600 AND 1200 GMT

- OWS 'I' x—x OWS 'J' for 0000 GMT
- - - OWS 'I' x - - x OWS 'J' for 1200 GMT

above the level of maximum wind. The air immediately above the tropopause was extremely stable and contained a large negative wind shear. The sudden drop of 9 degC in the OAT at the beginning of the event strongly suggests that the aircraft entered a new air mass associated with development to the south.

Discussion. The suggestion that this disturbance was in some way triggered by the baroclinic instability developing to the south is plausible, although the mechanism of production is not known. The source of energy could lie in the moderate to severe turbulence created near the air-mass front encountered at the beginning of the event, in which case the wave would be propagated southwards, i.e. backwards into the northward advancing air mass of subtropical origin. Thus the second solution of our four equations is possibly the appropriate one.

There is a suggestion of a discontinuity in the wind field along a curve running east to west near 56–57°N and convex towards the north. It is conceivable that waves generated at this discontinuity and propagated southward would be focused to some extent by the curve. A curved wave-front would, of course, alter the solutions worked out for a straight wave-front, but, provided that the curvature is small, these should not be very different from the true values. Furthermore, there may be a preferred propagation of wave energy in a horizontal direction, a preference due possibly to some wave-guide effect produced by the vertical structure of the atmosphere. The fact that observations of marked wave effects of significant amplitude well away from mountains have been reported only rarely (e.g. Kuettner⁴) suggests that the right combination of conditions occurs only rarely.

(ii) 2 December 1967.

This event occurred during flight BA 561/032 from London/Heathrow Airport to Boston. No pilot report was available and most of the information was obtained from the flight record, part of which is shown in Figure 4. The aircraft entered a prolonged period of turbulence at about 1417 GMT (53°N 20°W) which continued until about 1525 (55°N 35°W). This period contained short patches of severe turbulence accompanied by marked fluctuations of height and airspeed during the periods 1443–1446, 1453–1458, and 1518–1521 (example shown in Figure 4). The amplitude of the V_i fluctuations approached the amplitude observed on 24 January, but the period was much shorter — about 25 s. Thus the possibility that this may have been some type of aerodynamic (phugoid?*) oscillation induced by the turbulence cannot be ruled out. Sympathetic oscillations can be seen in the height trace (amplitude about 45 m), and the 'g' trace (amplitude about 0.11 g). For approximately sinusoidal oscillations, the amplitude of the g-trace is about $4\pi^2 A/T^2$ where A is the amplitude of the height oscillation and T is the period. This gives $A \simeq 17\text{m}$ which is much less than that indicated by the altimeter trace. There is also no quantitative correspondence between height and airspeed changes, and the latter could have been due to an aerodynamic oscillation producing fluctuations in the airflow relative to the airframe which could affect the aircraft pitot-static system.

* Longitudinal periodic fluctuation in speed.

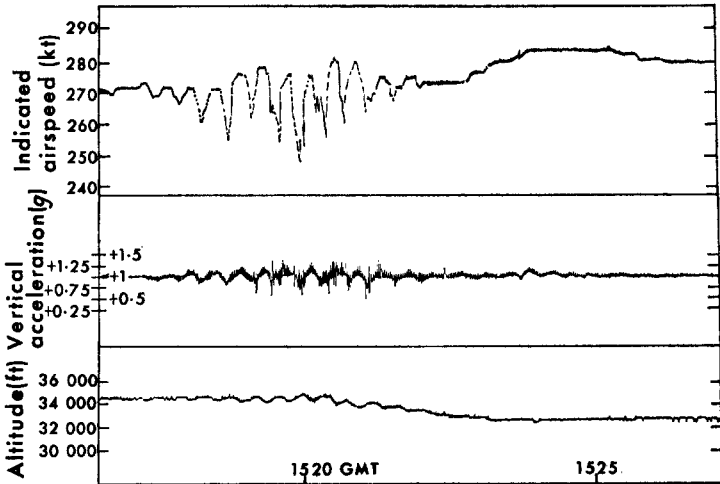


FIGURE 4—FLIGHT RECORD FROM THE RELEVANT PART OF FLIGHT BA 561/032, 2 DECEMBER 1967

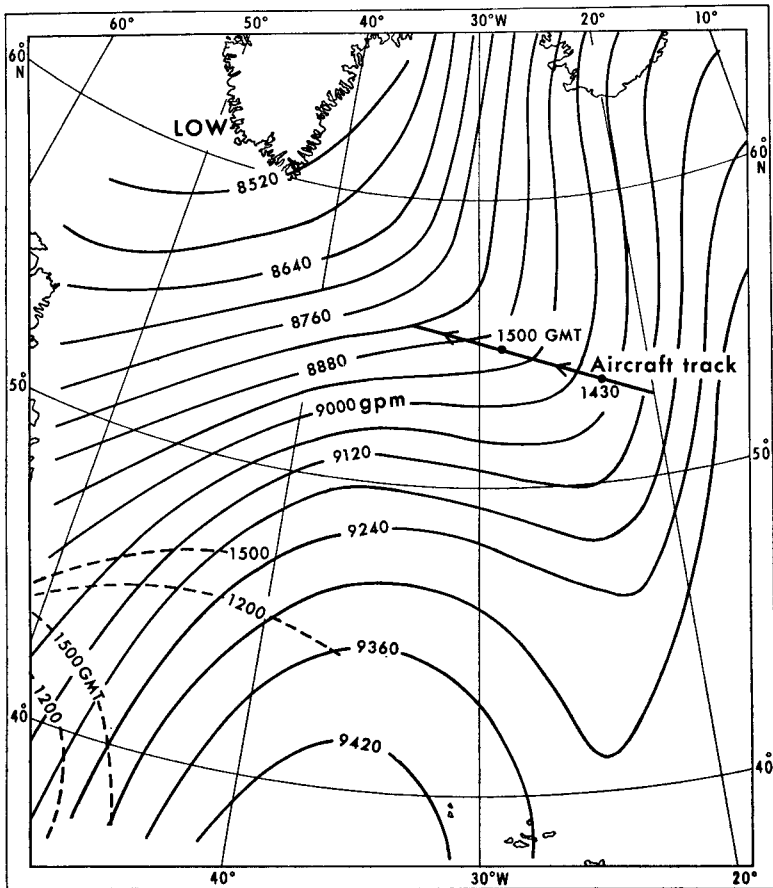


FIGURE 5—300-mb CONTOURS FOR 1200 GMT, 2 DECEMBER 1967
- - - - Surface fronts at 1200 and 1500 GMT

Synoptic situation. Figure 5 shows the 300-mb contours at 1200 GMT, about three hours before the event discussed. The aircraft track appears to run across the trough axis into the strong anticyclonic flow upwind of the trough. It would be natural to attribute the prolonged turbulence to the oblique traverse of the trough, but in fact the trough was moving north-east extremely rapidly and the aircraft winds (derived from ground track positions) indicate that the aircraft crossed the trough axis during the early part of the period of interest and was in the westerly (anticyclonic) flow after about 1440. OWS 'C' (Figure 6) reported a wind of 270° 155 kt (80 m/s) at 250 mb at 1200, and it is very likely that the aircraft was experiencing this headwind about three hours later.

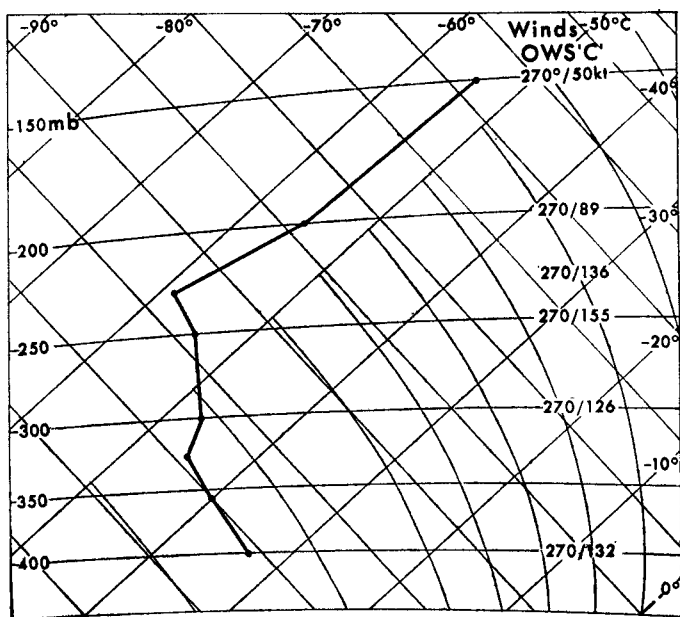


FIGURE 6—UPPER AIR TEMPERATURES AND WINDS FOR OWS 'C' AT 1200 GMT, 2 DECEMBER 1967

However, the point is not so much where the aircraft was in relation to the synoptic pattern, but that the whole area was one of very rapid change. There are, in fact, some features of this situation similar to those on 24 January, such as :

- (a) The flight was in a developing upper ridge situation ahead of a deepening depression to the south-west.
- (b) The aircraft was flying just beneath the tropopause.
- (c) There was a strong negative vertical wind shear above the jet core.

Why severe turbulence? Three examples are now described in which severe turbulence was encountered in 'conventional' situations—on the low-pressure side of jet cores—but the question arises as to why the turbulence was so violent in these particular cases.

(i) 5 October 1966.

The aircraft was flying at 32 000 ft (10 km) *en route* from New York to Heathrow when it encountered, with virtually no warning, a violent negative 'g' jolt of about -1 g followed by a short period of severe turbulence diminishing to moderate. This aircraft was one of the civil aircraft specially instrumented for the Civil Aviation Airworthiness Data Recording Programme (CAADRP) organized by the Air Registration Board (ARB) and the Royal Aircraft Establishment through BEA and BOAC. This turbulence encounter was picked out as a 'special event' and the ARB made available a copy of the flight record (Figure 7). This record is a good example of an occurrence of severe turbulence with only a few seconds warning, and makes a case for having seat belts at least loosely fastened during all flights.

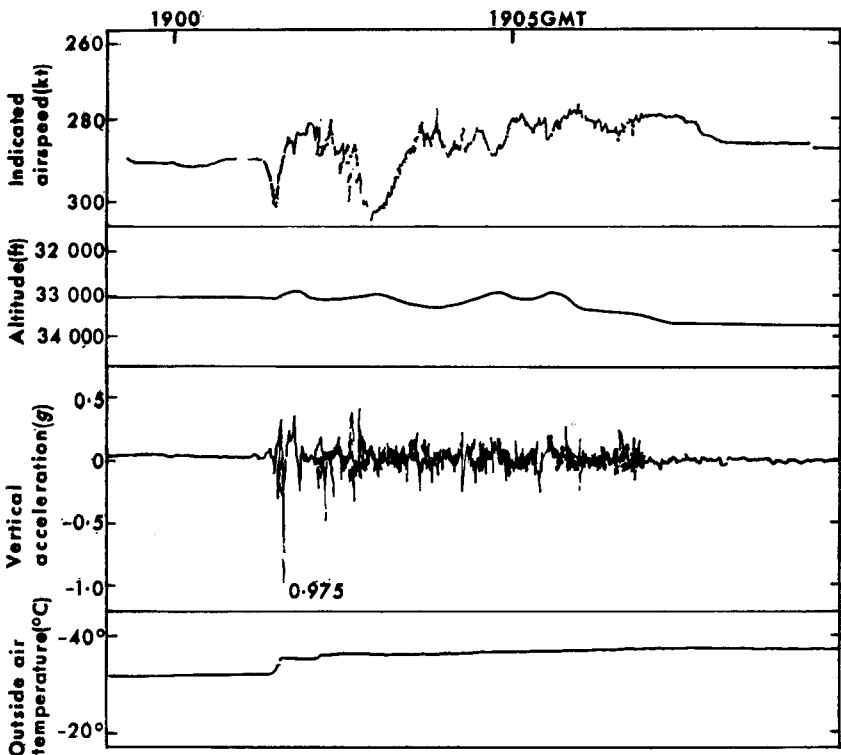


FIGURE 7—CAADRP 'SPECIAL EVENT' FLIGHT RECORD, 5 OCTOBER 1966

The turbulence was accompanied by large fluctuations in V_i (Figure 7). Of particular interest is the sudden decrease in the OAT of about 3 degC simultaneously with the initial large bump, followed by a further gradual fall

of about 2 degC over the next three minutes or so, after which the aircraft climbed to 34 000 ft (10.5 km) and left the turbulence.

Synoptic situation. The incident occurred at 1900 GMT about 100 km west of Shannon in a cyclonic south-west flow. Figures 8 (a) and (b) show the 300-mb flow seven hours before and five hours after the incident. Some development of a moderate nature occurred during this period. Warm frontogenesis occurred over western U.K. accompanied by a backing and tightening of the gradient at 300 mb ahead of the upper low. An attempt has also been made to draw tropopause contours, and these also changed during 12 hours in sympathy with warm advection over the U.K. and cold advection over the Western Approaches. The charts suggest that the tropopause was at 250 mb at the time and place of the event, i.e. only 500 m above the aircraft.

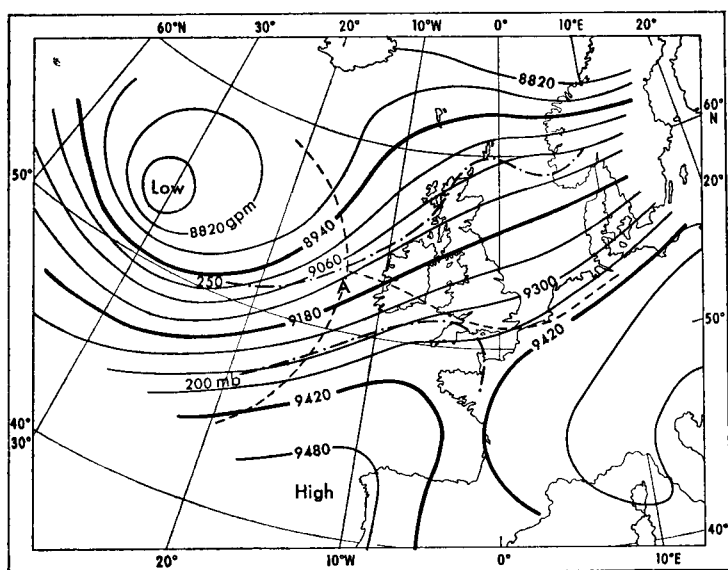


FIGURE 8 (a)—300-mb CONTOURS FOR 1200 GMT, 5 OCTOBER 1966

- Surface fronts at 1200 GMT
- Tropopause contours (50-mb intervals)
- A Position of -0.975-g spike in Figure 7

Discussion. It seems likely that the turbulence occurred as the aircraft crossed the tropopause. There must have been a thin, intense (thermally) stable layer immediately above the tropopause. This layer may have contained a large localized directional wind shear resulting from a south-west flow in the stratosphere riding up over a backed and backing flow in the upper troposphere. It is possible at that time and place that dynamical processes were producing rapid tightening of the vertical wind shear near the tropopause, resulting in locally severe turbulence acting to relieve the shear as it was being produced.

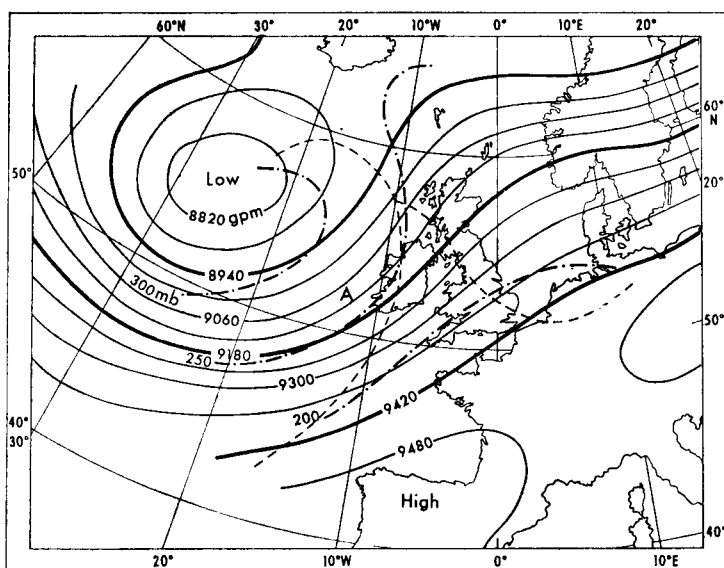


FIGURE 8 (b)—300-mb CONTOURS FOR 0000 GMT, 6 OCTOBER 1966

--- Surface fronts 0000 GMT

-.-.- Tropopause contours (50-mb intervals)

A Position of $-0.975\text{-}g$ spike in Figure 7

A change in true vertical velocity of about -15 m/s over a distance of less than 100 m would be required to produce a negative $1\text{-}g$ acceleration in a big jet clipper at 10 km altitude, and it seems likely that this can only have been produced by local breakdown of the shear layer as a whole; the aircraft may have entered the downward plunge of an internal 'wave breaker'. Also the small amplitude ' g ' oscillation of period about 10 s (i.e. about 2 km) just prior to the main event could be interpreted as a rapidly amplifying gravity wave just prior to breaking. This case was chosen as one in which study of the associated synoptic charts would not have led one to expect that turbulence would have been more than light or moderate, and conventional radiosonde data suggested that wind speeds and wind shears were nothing exceptional.

(ii) 10 February 1968.

On this day, two reports of severe or violent turbulence over the U.K. were received, and it is understood that there were several turbulence encounters on flight routes into Germany on that day, but no specific reports were received of the latter. Extracts from the U.K. reports follow.

(a) Lightning aircraft from Bristol Aeroplane Company, Warton.

'As Mach 1.3 was reached, Warton Approach passed a message from another Lightning that clear-air turbulence was encountered between $25\,000$ and $28\,000\text{ ft}$. This message was acknowledged, but flight remained smooth until reaching Mach 1.7 at $31\,000\text{ ft}$ about 30 miles (50 km) west of Warton about 1200 GMT . The entry into turbulence was very sudden, and for several seconds the pilot could do nothing but hang on to the stick and throttles. During this period it was impossible to control the aircraft which was bucking violently in every direction. The actual deviations

from the flight path were thought to be small, but the sharpness, random nature and high frequency of the bumps were disorientating. At this stage the pilot thought the aircraft might disintegrate. A determined effort was required to place the aircraft in a climb and to throttle the engine. The buffeting ceased on passing through 36 000 ft.

In approximately 1200 supersonic flights, the pilot has encountered CAT on many occasions, but the severity and extent has not caused undue concern until this particular incident.'

(b) Air Registration Board Trident aircraft flown from De Havilland, Hatfield.

'Severe turbulence was encountered at 21 500 ft over the Wash at 1140 GMT. The IAS was reduced from 330 to 270 kt and the aircraft climbed on a course of 070° magnetic, and left turbulence after about 5 minutes at 25 500 ft.'

Synoptic situation. A strongly anticyclonic westerly jet associated with a depression in the South-west Approaches was pushing slowly north against an old cold trough (Figure 9). Very large vertical and horizontal wind shears (of about 3×10^{-2} and 3×10^{-4} m/s per metre respectively) were reported on the northern boundary of the jet, and severe turbulence in these conditions is not surprising. A radiosonde cross-section (Figure 10) shows a well-marked frontal zone between the westerly jet and the relatively stagnant cold-pool air. Over Hemsby, this zone appeared to extend from 21 000 to 26 000 ft which agrees very well in time and place with the turbulent layers reported by the Trident aircraft.

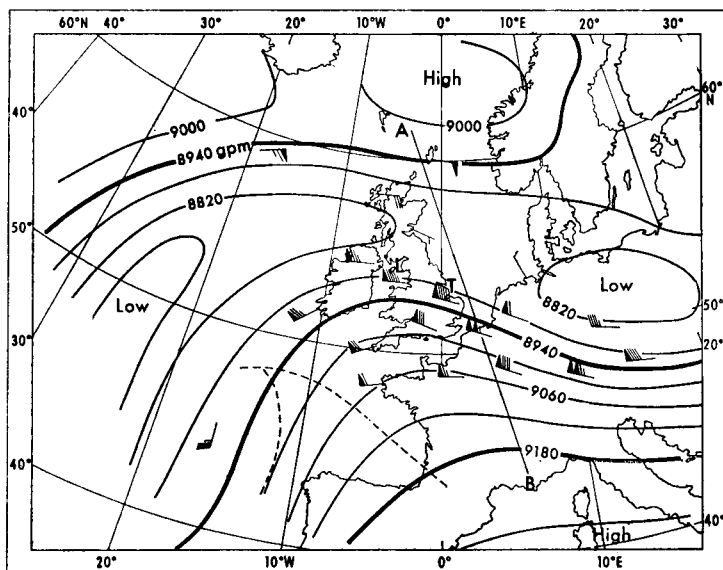


FIGURE 9—300-mb CONTOURS FOR 1200 GMT, 10 FEBRUARY 1968

- - - Surface fronts at 1200 GMT
- L and T Positions of the Lightning and Trident reports respectively
- A—B Approximate line of cross-section in Figure 10

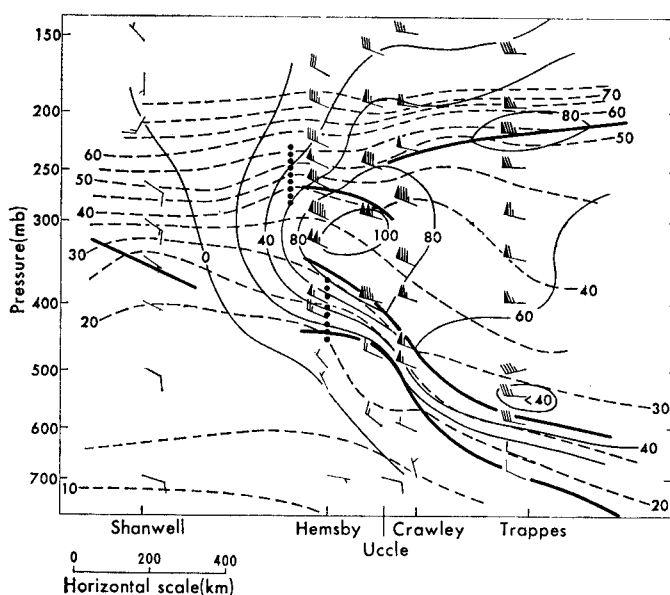


FIGURE 10—RADIOSONDE CROSS-SECTION ALONG AB IN FIGURE 9 FOR 1200 GMT, 10 FEBRUARY 1968

—— Isotachs (kt) - - - - Isentropes (°C)
 Turbulent layers reported by aircrew
 ——— Tropopause and frontal surfaces

(This is part of a cross-section drawn from $62\frac{1}{2}^{\circ}\text{N } 4^{\circ}\text{W}$ to $43^{\circ}\text{N } 5^{\circ}\text{E}$.)

Discussion. In contrast to the event on 5 October (*i*) on p. 72), the synoptic situation suggests that severe turbulence within the frontal zone would not be surprising, but the question still arises as to whether this could have been forecast. On this day, Preston issued at 0840 GMT a SIGMET of severe turbulence south of 54°N moving slowly north, but this was based on an earlier aircraft report.

We can usefully think of the frontal zone acting as a giant friction plate between the jet stream and the stagnant cold-pool air with the northward movement of the jet maintaining the pressure on the plate and therefore acting to maintain severe turbulence. Presumably decrease or cessation of this northward push would relax the pressure and decrease the turbulence.

(iii) 4 September 1967.

A Victor II aircraft of 100 Squadron, RAF, Wittering, piloted by F/Lt Bradley encountered turbulence at 1552 GMT at 40 000 ft over Liverpool. This was described as follows :

- (a) Moderate 0.5 g then one extreme spell of clear-air turbulence +4.3 g.
- (b) Climb to 44 000 ft, no clear-air turbulence At 1608 GMT, at 40 000 ft, violent airframe vibration.

Synoptic situation. A rapidly deepening depression was centred at about 54°N 16°W at the time of the incident and was moving east at about 30 kt.

Associated with this depression was a very mobile upper flow pattern with very large vertical wind shears above and below a jet core of winds about 130 kt at 230 mb. Particularly strong shears above the jet core were reported from Long Kesh, Aughton and Hemsby; at Aughton at 1800 GMT the 200–150-mb shear was 65 kt (see Figure 11). It is also of interest to note that the maximum wind over Aughton and Hemsby increased by 80–90 kt during the periods 0600–1200 and 1200–1800 respectively. A thin layer (5–15 mb thick) of extreme stability bounding the tropopause was evident on the Long Kesh and Aughton ascents at 1200 GMT and on the Hemsby ascent 12 hours later (Figure 12). This layer would be capable of supporting vertical wind shears of up to 5×10^{-2} m/s per metre before breaking up into turbulence, although localized intensification of shear could produce localized patches of very severe turbulence in the layers. It seems very likely that the aircraft encountered extreme turbulence within this layer.

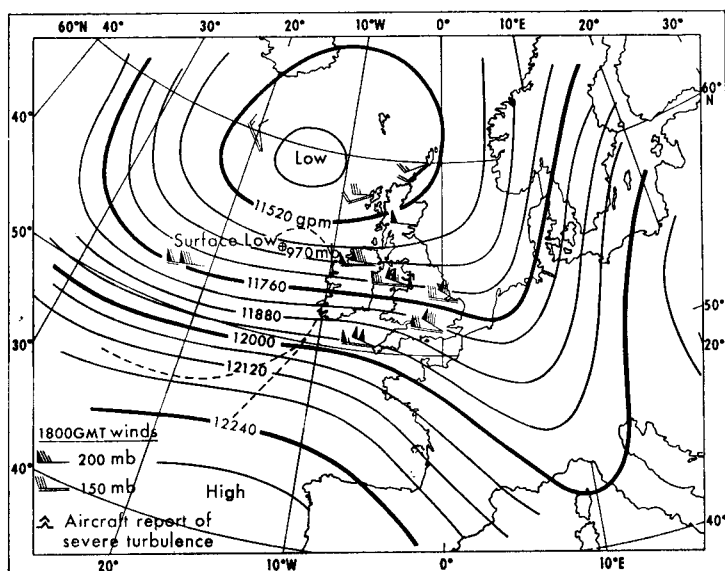


FIGURE 11—INTERPOLATED 200-mb CONTOURS FOR 1800 GMT, 4 SEPTEMBER 1967
 - - - - Surface fronts at 1800 GMT

Discussion. This is perhaps the most marked example of turbulence production in a developing situation. The intensity of development is unusual and rates of kinetic energy advection averaged over 6 hours of the order of 5×10^{-2} joules/kg per second imply values several times larger over shorter periods, which in turn imply the order of magnitude of energy available for turbulent dissipation.

From an aviation point of view, it suggests that of all development areas, the upper flow ahead of a rapidly developing depression is particularly to be avoided. In practice, this area will usually be in the north-east quadrant 400–800 km from the developing surface centre.

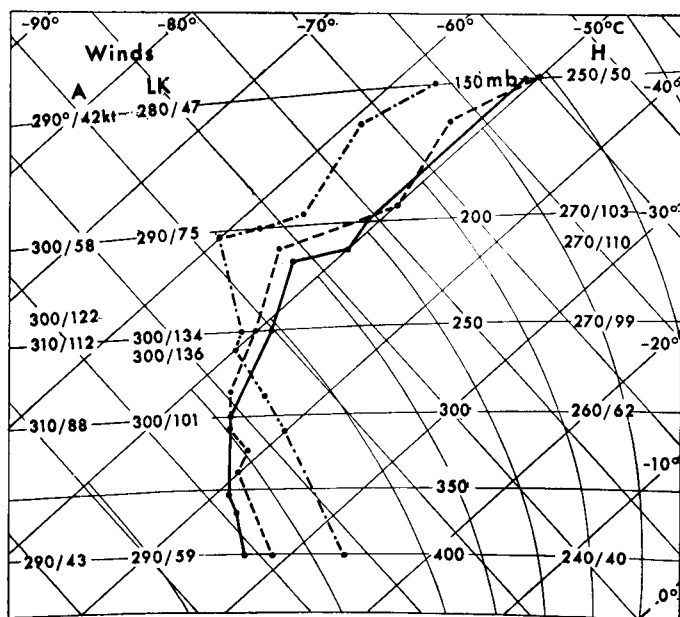


FIGURE 12—UPPER AIR TEMPERATURES AND WINDS FOR AUGHTON AND LONG KESH AT 1200 GMT, 4 SEPTEMBER 1968, AND HEMSBY AT 0000 GMT, 5 SEPTEMBER 1968

— Aughton (A) - - - - Long Kesh (LK) — Hemsby (H)

Acknowledgements. I am indebted to the Flight Data Acquisition Department of BOAC and to the Civil Aviation Airworthiness Data Recording Project for making relevant flight records available and for giving permission to publish copies of these, and to Mr B. A. Hall and Miss A. Peters of the Meteorological Office who assisted in working up the data.

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551.524.2(41-4):551.524.36

THE VARIABILITY, WITH TIME AND LOCATION, OF SPRING AND SUMMER TEMPERATURES IN THE UNITED KINGDOM

By G. W. HURST

Introduction. This survey attempts to put into perspective the present régime of temperatures over England, Wales and much of Scotland. Many aspects of agricultural and allied disciplines relate closely to spring and summer temperature levels, and a background is presented for an appraisal

of crops, or yields of honey, both geographically and over the last century or so. This follows up an earlier paper¹ on honey production and temperatures in July and August 1943–66. Throughout this paper the conventional definitions for seasons are used, with spring consisting of the months March, April and May, and summer of June, July and August, and for practical reasons temperatures are in Fahrenheit and heights in feet.

Methods of analysis. The survey has been prepared using four complementary methods of examination, with varying periods of availability of data.

- (i) Period 1841–1968.
Variability over time was assessed by examination of London temperatures² over the last century or so. Some justification is made for the application of these data to England and Wales as a whole.
- (ii) Period 1946–55.
The duration of time, in hours, with temperatures above certain levels was assessed for a number of specific localities in England, Wales, Scotland and Northern Ireland; arbitrary base temperature values of 50°F, 60°F and 70°F were chosen.
- (iii) Period 1931–60.
Using mean temperature data for various regions of Great Britain, average values of accumulated temperatures in spring and summer were obtained, and an indication was made of the effect of height change to such values. Standard temperature levels of 42°F, 50°F and 60°F were considered.
- (iv) Period 1931–48.
A short examination was made of the actual variability in seasonal accumulated temperatures over an 18-year period for two stations, one in south-west England and the other in the south-east Midlands.

Variability of spring and summer since 1841. In this analysis the Kew records from 1871 have been analysed with a (justified) extension to 1841 using Greenwich figures. The source of these data is *London weather*.³ That Kew temperatures could reasonably be taken as a basis for reflecting tendencies in the nineteenth century for England and Wales as a whole, was justified by a comparison of the two sets of data since 1900. It was preferable to use Kew figures rather than Manley's for central England³ because the Kew data had already been summarized in seasonal form.

Kew averages for both spring and summer for 1931–60 have been taken as standard (spring 49.0°F and summer 62.4°F), and for the purpose of this paper deviations from these figures of 1.0–1.9 degF have been regarded as warm or cold as the case may be, and of 2.0 degF or more as very warm or very cold. These values have been chosen arbitrarily, and have been designed to highlight extreme seasons; in the standard period 1931–60, extreme springs numbered 7 and extreme summers 6, out of the total of 30. Quintile boundaries as used by Murray,⁴ for example, were not adopted. Such boundaries vary each month and are by definition chosen to give as many occasions in each extreme as in any other quintile of temperature levels, i.e. in 30 years there would be 12 extreme summers.

Temperatures at both Greenwich and Kew were compared for 1871-80, a period for which both sets of data were published in *London weather*; this comparison showed the Greenwich average temperature higher by 0.4 degF and 0.9 degF in spring and summer respectively, with no change of pattern during the 10 years. Accordingly, to be comparable, Greenwich averages for 1841-70 have been taken as 49.4°F and 63.3°F — but it is emphasized that these were not the averages for Greenwich over that period.

Finally, deviations from the 1931-60 average temperatures (reduced to MSL) for spring (48.0°F) and summer (60.4°F) for England and Wales as a whole were categorized as very warm, warm, etc. in exactly the same way as for Kew. There did not appear to be any warming at Kew compared with the country as a whole since 1901 — if anything, there is a hint of the opposite. Table I shows the frequencies of springs and summers at different temperature levels for each decade from 1841 onwards.

TABLE I—DISTRIBUTION OF SEASONS IN EACH DECADE ACCORDING TO AVERAGE TEMPERATURE LEVEL. LONDON 1841-1968, ENGLAND AND WALES 1901-68

(a) Spring

Decade	London					England and Wales				
	VW	W	A	C	VC	VW	W	A	C	VC
1841-50	1	1	4	3	1					
51-60			3	1	6					
61-70		2	3	4	1					
71-80			5	2	3					
81-90			1	4	5					
91-00	1		4	1	4					
1901-10			4	6				6	4	
11-20		2	5	2	1		2	4	3	1
21-30		1	4	5			1	4	5	
31-40		1	7	1	1		3	5	1	1
41-50	2	1	6		1	3		6		1
51-60	2	2	3	2	1	2	2	3	2	1
61-68	1		5	1	1	1		6		1
Total 1901-68	5	7	34	17	5	6	8	34	15	5
1841-1900	2	3	20	15	20					

(b) Summer

Decade	London					England and Wales				
	VW	W	A	C	VC	VW	W	A	C	VC
1841-50	1		2	4	3					
51-60	2	1	2	2	3					
61-70	1		3	3	3					
71-80		1	5	3	1					
81-90			2	3	5					
91-00	1	1	4	1	3					
1901-10			4	2	4		1	4	1	4
11-20	1		2	3	4	1		3	4	2
21-30		1	6	1	2		1	3	4	2
31-40	1	2	5	2		1	2	6	1	
41-50	1	1	6	1	1	1	2	5	2	
51-60	1	1	3	3	2		2	6		2
61-68			5	2	1			5	1	2
Total 1901-68	4	5	31	14	14	3	8	32	13	12
1841-1900	5	3	18	16	18					

Note: VW Very warm } departure from average > 2.0 degF. W Warm } departure from average
VC Very cold } average 1.0 to 1.9 degF. C Cold }
A Average : departure from average 0 to \pm 0.9 degF.

Spring. Agreement between London, and England and Wales is fairly close, with England and Wales marginally the warmer. It is very interesting to note that there have been more very warm springs in London in the 28 years since 1940 than in the 100 years before; and, perhaps even more significant, the 28 years include 8 out of the total of 17 warm or very warm springs. Cold or very cold springs have numbered 2 a decade since 1930, whereas until 1900 over half the years were cold (by recent standards).

Runs of springs with similar characteristics were examined, and from 1841 to 1958 there were never two consecutive years with warm springs; 1959-61 however were all warm (1959 and 1961 very warm). Conversely, no runs of cold springs have occurred in the last 30 years. Earlier however there was a run of 4 years, 1929-32, and 1924 and 1925 were both cold; the period 1915-17 was cold, so were 1908-09 and 1899-1902. Springs from 1883-92 were continuously cold; 7 were very cold, including a run 1885-88. Earlier sequences consisted of 3 years in the 1870s, 2 years thrice in the 1860s, 2 years in the 1850s and 5 years running over the 1840s to 1850s.

Summer. London, and England and Wales figures are in close agreement, again with very slightly colder weather in London and little suggestion of any long-term change in the pattern between the two sets of data. Interestingly, the distribution of warm summers since 1841 does not vary much; indeed the only decade with two very warm summers was 1851-60. What is clear however, is the greater freedom from cold summers from the mid-1920s onwards, when cold summers averaged about 3 a decade (rather more than one of which was very cold), whereas before this, the decade average was almost 6, of which rather more than half were very cold.

The only runs of 2 or more warm summers in succession were in 1933-35 (1933 was very warm) and 1857-59 (1857 and 1859 were very warm — the latter year outstandingly so). Runs of cold summers were all too frequent in the past, but the only two since 1919 were 1962-63 and 1953-54; in the period from 1879-94 however, 13 of the 16 years were cold, and 9 very cold; 1890-92 were 3 very cold consecutive years.

Finally in this context, Table II shows the years in each decade in which both spring and summer followed a set pattern.

TABLE II—YEARS IN EACH DECADE IN WHICH THE TEMPERATURE RELATIONSHIP BETWEEN SPRING AND SUMMER FOLLOWED CERTAIN PATTERNS

Decade	Both warm	1 warm, other average	1 cold, other average year	Both cold
1841-50		46		45, 49, 50
51-60		57, 58	52, 54, 56	51, 53, 55, 60
61-70	68		61, 63, 64, 70	66, 67, 69
71-80			71, 73, 80	75, 79
81-90			82, 84, 87	81, 83, 85, 86, 88
				89, 90
91-00	93		94, 97, 98, 00	91, 92
1901-10			01, 03, 04, 07, 10	02, 08, 09
11-20		11	13, 17, 18, 19	15, 16
21-30	21		25, 27, 29, 30	22, 24
31-40	33	34, 35	32, 39	31
41-50		43, 45, 47, 49	41, 46	
51-60	59	52, 57	53, 54, 56, 58	51
61-68		61	63	62

Bold figures indicate that both seasons were very warm or very cold.

This table brings out clearly that the number of warm springs and summers (at least in relation to the 1931-60 averages) has never been high, and in 128 years, 1959 was the only really warm year. Warm, and what might be called fairly warm (i.e. one season warm, the other average), spring/summers were much more numerous between 1934 and 1957 than before or since.

It is the coldness of the years before 1931 which is striking. There have only been 3 cold spring/summers since 1925 (in 43 years) and there were 28 in the 85 years before; the 14-year period 1879-92 included 10 cold and 4 fairly cold occasions.

Duration of time with temperatures above certain levels. A number of arbitrary temperature levels were chosen, and the duration of time for which these levels were exceeded was assessed for a few widely spread localities. From information readily available in the Meteorological Office* Table III was constructed; this gives for various seasons the percentages of hours with temperatures above 50°F (i.e. 50.1°F or more), 60°F and 70°F for specified stations. In all cases the 10-year period 1946-55 was analysed.

The locations in Table III are (or were) nearly all at airfields making hourly temperature observations, so that, for example, the location of Elmdon (near Birmingham) is at least partially rural in character, and is probably tolerably representative of the central Midlands generally. Height differences between the stations are fairly considerable, and an attempt has been made to compensate for this in the yearly totals of percentages by applying the conventional compensation of +1 degF for each 300 feet of height above sea level.

In Table III (a), the 11 stations are in order of the actual percentage of hours in the year with temperatures above 50°F; the range is fairly wide, from just over 64 per cent to just under 40 per cent. Geographical control is reasonably marked with the percentages at the station in Ireland and at the two in east Scotland being distinctly lower than elsewhere; Renfrew in west Scotland is, however, above several stations in England; this is probably a combination of proximity to the west coast and a measure of urbanization. The lowest ranking English stations are both in the south, but compensation for height removes these anomalies and leaves Driffeld in the north and (surprisingly) Mildenhall in East Anglia as the two stations with the shortest time with temperature above 50°F in England. Variation of pattern in spring, summer and autumn is evident; in summer the change in percentage from one part of the country to another is not great, with high percentages everywhere. In autumn, however, the difference between southern England and northern Scotland, with the lower percentages, is much more manifest, and the geographical differences are still more noticeable in spring with variation from almost 60 per cent of the hours at Croydon to just over 25 per cent at Kinloss.

Contrasts are much greater in Table III (b), showing the percentage of hours with temperatures above 60°F, and geographical considerations are obviously more important. After height compensation has been made, percentages at all the Scottish and Northern Ireland localities are less than

* *Climatological Memoranda* Nos. 10-13, 16-20, 35 and 39.

TABLE III—PERCENTAGE OF HOURS WITH TEMPERATURE ABOVE 50°F, 60°F AND 70°F FOR VARIOUS STATIONS AND SEASONS

(a) Above 50°F

Station	Area	Height	Spring	Summer	Autumn	Year Actual	Year Compensated*
		<i>feet</i>				<i>percentage</i>	
Croydon	SE. England, inland	201	59.2	99.3	74.6	64.4	66.7
Elmdon	Central Midlands, inland	319	51.0	97.0	66.6	57.8	61.7
Pembroke Dock	SW. Wales, coastal	34	38.0	97.9	70.8	55.6	56.1
Renfrew	West Scotland, inland	26	39.0	95.1	57.8	50.7	51.1
Mildenhall	East Anglia, inland	15	38.7	93.1	54.3	48.7	48.9
Driffield	East Yorkshire, inland	69	35.4	92.1	55.7	48.2	49.0
Lympne	SE. England, coastal	341	33.1	94.3	57.4	47.2	51.2
Boscombe Down	South England, inland	414	35.1	91.5	51.2	46.1	51.3
Aldergrove	North Ireland, inland	217	28.3	89.0	47.9	41.8	44.8
Turnhouse	East Scotland, inland	114	28.3	86.7	45.8	41.5	43.4
Kinloss	NE. Scotland, coastal	15	25.5	85.4	43.4	39.8	40.0

(b) Above 60°F

Station	Spring	Summer	Autumn	Actual <i>percentage</i>	Year Compensated*	Order†
Croydon	9.4	54.6	15.6	19.9	21.7	1
Elmdon	5.0	39.2	9.6	13.1	15.9	6
Pembroke Dock	4.5	40.9	12.3	14.8	15.3	5
Renfrew	4.6	31.0	5.7	10.4	10.6	8
Mildenhall	9.5	51.2	16.0	19.3	19.4	2
Driffield	4.3	36.5	9.8	12.9	13.4	7
Lympne	6.1	47.2	14.2	16.8	19.8	3
Boscombe Down	6.8	43.8	11.2	15.5	19.2	4
Aldergrove	3.5	27.9	5.7	9.2	10.7	10
Turnhouse	3.2	27.4	6.7	9.3	10.2	9
Kinloss	2.7	22.7	6.7	8.1	8.2	11

(c) Above 70°F

Station	Spring	Summer	Autumn	Actual <i>percentage</i>	Year Compensated*	Order†
Croydon	1.5	13.0	1.5	4.0	4.6	2
Elmdon	0.4	6.9	0.7	2.0	2.5	5
Pembroke Dock	0.4	4.8	0.2	1.4	1.4	7
Renfrew	0.4	4.0	0.1	1.1	1.1	8
Mildenhall	1.5	12.9	1.9	4.1	4.1	1
Driffield	0.4	5.5	0.6	1.6	1.7	6
Lympne	0.6	7.5	0.9	2.3	3.2	4
Boscombe Down	0.9	10.1	0.8	3.0	3.8	3
Aldergrove	0.2	3.4	0.1	0.9	1.1	9
Turnhouse	0.1	2.0	0.3	0.6	0.7	11
Kinloss	0.1	2.1	0.4	0.7	0.7	10

* Compensated for height of station.

† Defined by actual percentage of year above temperature level.

Note : approximately 10 per cent = 220 hours/season
= 900 hours/year

half the Croydon value, and southern England is markedly warmer than the north. As with Table III (a), variation in percentages in spring is far greater than in summer, with autumn intermediate in this respect. Variability between seasons from place to place is interesting, with spring having only a slightly lower percentage of hours than autumn at Renfrew, but a far lower percentage at Pembroke Dock. Particularly interesting are the high percentages of hours at Mildenhall in East Anglia in this table, especially in spring and autumn.

Percentages of hours with temperatures above 70°F are, of course, far lower, and differences are much increased between inland areas in southern central and eastern England on the one hand and the coastal districts in the south-west and areas in the north on the other. Interestingly, Lymington continues warm, but although coastal, it is well above the sea (and probably not much affected by sea-breezes) and also not very distant from the continent so that the effects of warm south-easterly winds might be felt. The effect of the (now) cooling breezes from the sea over coastal south Wales can be seen at Pembroke Dock, and the place with the highest number of warm hours is East Anglia. The difference between Renfrew, for example, and Mildenhall, of about the same height above the sea, is illustrated by yearly totals of 100 hours and 370 hours respectively.

If the lower threshold for a particular agricultural activity (e.g. growth of an exotic plant, or the basic working temperature for a honey bee) is 50°F then Table III shows that differences in the overall percentages over the country are not very great, except perhaps in spring. A threshold of 60°F for the activity renders the effects of geographical control much more evident. The lowest totals are in the north and in both spring and autumn percentages are low in comparison with the more favoured southern areas. Districts near the south-west coast do not do as well with the 60°F threshold as with the 50°F level. It is probably not realistic to say much on the 70°F threshold, which heavily underlines geographical effects.

Geographical variability of accumulated temperatures. Regions defined by the *Monthly Weather Report* were taken for this analysis, and five areas were considered at first :

Region 4 The Midlands (from Yorkshire down to Oxfordshire).

Region 5 South-east England (Wiltshire/Hampshire and eastwards south of the Thames).

Region 8(a) South-west England and Wales (southern half of Wales, and Somerset/Dorset and counties to the south-west).

Region 2 North-east England (eastern counties from Lincolnshire northwards).

Region 1 Eastern Scotland (eastern half of Scotland south of Moray Firth).

Regional average temperatures for 1931-60 were taken as standard, and accumulated temperatures were calculated by Thom's method, using monthly average temperatures and their standard deviations (quoted by Shellard⁵). A reasonably accurate assessment of accumulated temperatures is gained, but not, of course, giving exactly the same figures as would consideration of maximum and minimum daily values.

Differences between the first three regions proved slight (the south-west containing a substantial inland area to set against coastal effects) and central and southern England and Wales were therefore considered as a whole, combining regions 4, 5 and 8(a). Accumulated temperatures above the conventional level of 42°F, and also above 50°F and 60°F were derived.

Height of ground was taken into account by allowing a 1 degF fall per 300 ft of height, and by computing values of accumulated temperatures for 600 ft and 1200 ft in each of the three areas. Table IV(a), (b) and (c) shows average accumulated temperatures for these three areas for sea level (any possible effect of sea-breezes, etc. being ignored), 600 ft and 1200 ft, with the three different temperature bases of 42°F, 50°F and 60°F. Accumulated temperatures are given in Fahrenheit degree days. If comparable Celsius temperatures had been used the values in the table should be multiplied by 5/9 to obtain Celsius degree days.

TABLE IV—AVERAGE VALUES OF ACCUMULATED TEMPERATURE ABOVE 42°F, 50°F AND 60°F FOR CENTRAL ENGLAND, NORTH-EAST ENGLAND AND EAST SCOTLAND AT SEA LEVEL, 600 ft AND 1200 ft

(a) Above 42°F									
Month/ season	Sea level			600 ft			1200 ft		
	C. Eng.	NE. Eng.	E. Scot.	C. Eng.	NE. Eng.	E. Scot.	C. Eng.	NE. Eng.	E. Scot.
<i>Fahrenheit degree days</i>									
March	100	95	95	65	65	65	40	40	40
April	195	155	115	145	115	85	105	80	55
May	345	280	235	285	220	175	220	160	125
Spring	640	530	445	495	400	325	365	280	220
June	495	440	385	435	380	325	375	320	280
July	605	570	500	545	510	440	480	445	380
August	605	550	480	545	490	420	480	430	375
Summer	1705	1560	1365	1525	1380	1185	1335	1195	1035
Spring and summer	2345	2090	1810	2020	1780	1510	1700	1475	1255
(b) Above 50°F									
March	10	15	15	0	0	0	0	0	0
April	45	35	15	10	15	0	0	0	0
May	120	85	45	80	55	20	50	30	5
Spring	175	135	75	90	70	20	50	30	5
June	260	210	155	205	160	115	150	105	75
July	355	320	250	295	260	190	240	205	140
August	355	305	225	295	245	165	240	195	115
Summer	970	835	630	795	665	470	630	505	330
Spring and summer	1145	970	705	885	735	490	680	535	335
(c) Above 60°F									
Spring	0	0	0	0	0	0	0	0	0
June	40	25	10	20	10	0	5	0	0
July	100	70	35	65	40	15	40	20	0
August	95	65	25	60	40	5	35	20	0
Spring and summer	235	160	70	145	90	20	80	40	0

Table IV(a) shows that approximately the same total temperature is accumulated above 42°F at sea level in spring and summer in Scotland as at 600 ft in north-east England and at 1200 ft in central England, but that in Scotland height effects are rather more important than geography. Roughly, the total spring and summer accumulation is 30 per cent more in central England than in Scotland (but in spring, accumulation is over 40 per cent).

Totals at sea level in central England for accumulation above 50°F are just about half those above 42°F but otherwise the fractions are less than half, and in Scotland at 1200 ft, for example, the accumulation of temperatures above 50°F is just about a quarter of that above 42°F. It is interesting to consider these figures in relation to the duration of temperatures above 50°F. The percentage time above 50°F (Table III (a)) did not vary nearly as widely as the accumulated temperature totals, but there were distinctly lower percentages in the east of Scotland, and also in north-east England.

An important point is that the Scottish curve of diurnal variation of temperature is distinctly flatter than the English, and as Table III (b) showed, the duration of temperatures above 60°F was much lower in east Scotland than in southern or central England, with northern England intermediate. This is brought out in the (probably unrealistic) accumulation of

temperatures above 60°F. The spring contribution is negligible, but in summer at sea level in central England the accumulation is 13 per cent of that above 42°F. Percentages are much lower elsewhere and at other heights — 4 per cent in eastern Scotland at the surface for example, and 7 per cent in north-east England at 600 ft. There is apparently practically no accumulation at all at 1200 ft in east Scotland.

In short, the quantity of heat (as rather inadequately reflected by heat sums) enjoyed in southern and central England is considerably higher than in northern England, and still more so than in eastern Scotland. This difference increases as the base temperature is increased, as higher ground is considered, and also, though less obviously, away from high summer; this effect is probably greater than it seems, as Thom's method tends to be less accurate with marginal figures.

Variability of accumulated temperatures from year to year. Seasonal totals of accumulated temperatures above 42°F have been established for two very contrasting localities: Gulval, Cornwall (50°N 5½°W, 50 ft), and Rothamsted, Herts. (52°N 1½°W, 420 ft). Table V shows their variability over 18 years (1931–48) for the various seasons (Smith⁶).

TABLE V—AVERAGE, MAXIMUM AND MINIMUM ACCUMULATED TEMPERATURES ABOVE 42°F FOR ROTHAMSTED AND GULVAL

Station	Characteristic	Spring	Summer <i>Fahrenheit degree days</i>	Autumn	Winter
Rothamsted	Average	594	1656	787	123
	Highest	814	1931	956	238
	Lowest	362	1452	647	44
	Range	452	479	309	194
	Range as per cent of mean	76.1	28.9	39.3	157.7
Gulval	Average	739	1676	1075	364
	Highest	890	1844	1289	454
	Lowest	548	1447	919	253
	Range	342	397	370	201
	Range as per cent of mean	46.3	23.7	34.4	55.2

The range as a percentage of the mean shows the greater variability inland at all seasons. In spring the frequency with which the highest Rothamsted reading exceeds the Gulval average is clearly not high, and in autumn the highest Rothamsted figure is not much greater than the Gulval lowest; in winter, the highest Rothamsted total recorded in the 18-year period is distinctly below the lowest Gulval figure. In summer, by contrast, differences are on the whole slight and, if fine and hot, Rothamsted figures can be considerably in excess of those at Gulval. Interestingly, highest values of accumulated temperature by no means always occur in the same years; in 1948 Rothamsted's highest spring value of 814 coincided with a not excessively high figure of 808 at Gulval.

In conclusion, it is emphasized that the period of analysis is relatively short, and lower totals for both Gulval and Rothamsted might be appropriate in spring and summer at least on many occasions a hundred or so years ago. If the base temperature had been taken as 50°F instead of 42°F, differences in spring, autumn and winter would have been greater, but the figures for summer would almost certainly have been reversed with higher accumulations in the Midlands than in the south-west.

Conclusions.

(i) A strong suggestion exists that in the south-east and probably also in most other parts of Great Britain, springs and summers used to be cooler many years ago, and that, in particular, warm summers were commoner in the 1930s and 1940s than before or since. Spring and summer temperatures have been far less cold since about 1930 than during the period 50 to 100 years earlier.

(ii) The percentage of hours with temperatures above 50°F varies over the United Kingdom, with distinctly smaller percentages in east Scotland and Northern Ireland than elsewhere, especially in spring. Factors like proximity to the sea and height are of considerable importance. A temperature base of 60°F greatly magnifies differences, inland southern districts being markedly warmer than other areas.

(iii) Heat accumulation above various temperature levels is considerably greater in central and southern England than in north-east England and in east Scotland, and differences are accentuated if higher ground is considered, and if the temperature base is lifted from 42°F to 50°F and especially to 60°F.

(iv) In summer, differences in accumulated temperatures above 42°F are slight between two very different places, Cornwall and the south-east Midlands, but over most of the year the south-west enjoys much higher totals of accumulated temperature. Variability is much greater away from the sea.

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A SHORT INVESTIGATION INTO THE RELATIONSHIP BETWEEN THE DURATION OF SUNSHINE AND TOTAL CLOUD AMOUNT

By F. B. WEBSTER

Introduction. If the percentage of sunshine expressed in terms of the possible duration and the mean cloudiness (as a percentage of complete cloud cover) over the same period are added together, the result is more than 100 per cent for most months of the year. Table I illustrates this for Valencia.¹

TABLE 1—SUNSHINE AND CLOUDINESS AT VALENTIA, 1881–1915

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
							<i>per cent</i>						
Sunshine	19	25	33	39	41	38	32	34	35	30	24	17	31
Cloudiness	77	76	72	68	68	71	77	73	70	72	74	78	73
Sunshine + cloudiness	96	101	105	107	109	109	109	107	105	102	98	95	104

The reason lies, in part, in the limitations of the Campbell-Stokes sunshine recorder which is not a perfect inverse recorder of cloud. Sometimes the cloud is too thin or the amount too small to prevent the sun from burning the card. During short alternating periods of sunshine and shade (such as occur when cumulus cloud is present) the burns on the recorder trace run together, giving an apparent increase in the sunshine. On the other hand, when the sun shines only through small breaks in the cloud and is mostly obscured, the observer may see relatively large areas of blue sky elsewhere and will report a mean cloudiness which is less than the mean cloudiness suggested by the sunshine recorder. In winter when the sun is low, it may fail to burn the card and, as the proportion of low sun to total daylight is greatest in these months, the discrepancy may be quite large. C. E. P. Brooks¹ made a study of the problem and produced a formula for estimating sunshine in those areas of the world where there were no sunshine recorders but where comprehensive observations of cloud were available.

The purpose of the investigation described in the present paper was to see what relationship could be established between the reported total cloud amount and type and the duration of sunshine, so as to help forecasters in describing the character of the day to the general public.

Cloud amount and sunshine. The data used were the observations from Mildenhall for the summer half of the years 1961 and 1966. The summer months were used because the public in general is more interested in them, and because of the difficulty in the winter months of the records being affected by a low sun failing to burn the card. The two years used were chosen completely at random and, apart from both having rather less sunny Aprils than usual, were unremarkable from the sunshine point of view.

The hours studied were those between which the public is likely to be most interested: 0900 and 1800 GMT. The hours were, however, curtailed in the earlier and later months, so that sunset was at least one and a half hours after the last observation used, and the complication of a low sun was avoided. The actual hours used were:

0900 to 1600 GMT	April and September
0900 to 1700 GMT	1–20 May, 21–31 August
0900 to 1800 GMT	All other occasions

This gave a total of 2992 observations.

The method used was to plot the hourly recorded sunshine against the mean cloudiness for that hour. The mean cloudiness for the hour 0900–1000 GMT was arbitrarily defined as the mean of the total cloud amount reported at the two observations at 0900 and 1000, and similarly for all other hours of the day. A trace and 7+ oktas were taken as one okta and 7 oktas respectively. A mean which included a half okta was thrown to the odd.

At first sight the method used for estimating the mean cloudiness of an hour is not particularly accurate; a number of situations can be envisaged when it

might be completely misleading. In practice, however, it seemed to work quite well and the scatter in the subsequent tables was less than might have been expected.

The fact that Mildenhall is an inland station in an almost featureless terrain means that complications which might occur in certain situations at coastal or mountain stations would not be present.

Table II shows the average sunshine in minutes recorded for the various values of mean hourly cloudiness. It would not be unreasonable to describe any hour in which the sun shone for 45 minutes or more as sunny. On this basis, Table II shows that hours having a mean cloudiness of up to $5/8$ would be regarded as sunny. It can also be seen that the major reduction in sunshine seems to lie between $6/8$ and $7/8$.

TABLE II—AVERAGE SUNSHINE ASSOCIATED WITH VARIOUS VALUES OF MEAN HOURLY CLOUDINESS, APRIL–SEPTEMBER IN 1961 AND 1966

Mean hourly cloudiness	0	$1/8$	$2/8$	$3/8$	$4/8$	$5/8$	$6/8$	$7/8$	$8/8$
Average sunshine (recorded in minutes)	60	59	59	57	54	49	40	19	1

Figure 1 shows the percentage occurrences of various periods of sunshine when cloud amounts were $0-2/8$ (Beaufort letter b), $3/8-5/8$ (Beaufort letter bc), $6/8-7/8$, and $8/8$. In the partly cloudy ranges ($3/8-5/8$) there was no sunshine on less than 1 per cent of occasions, and less than 0.4 of an hour was recorded on only 5 per cent of occasions. On the other hand, 0.8 h or more was recorded

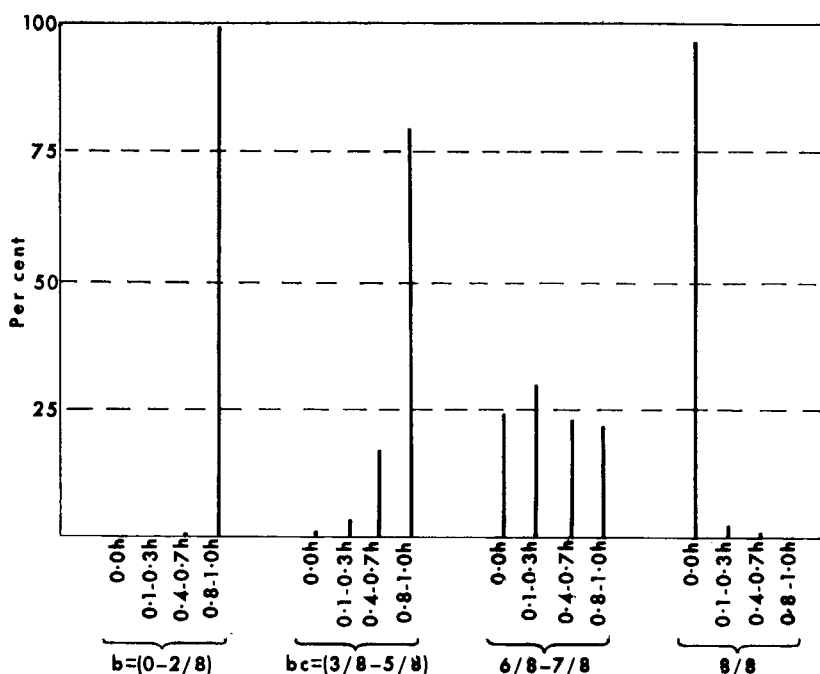


FIGURE 1—PERCENTAGE OCCURRENCE OF VARIOUS PERIODS OF SUNSHINE WHEN CLOUD AMOUNTS WERE $0-2/8$, $3/8-5/8$, $6/8-7/8$, AND $8/8$

on nearly 80 per cent of the occasions investigated. Hours with a mean cloudiness of $6/8$ to $7/8$ were more or less evenly divided. On 25 per cent of the occasions no sunshine was recorded; less than 0.4 h was recorded on 55 per cent of occasions, but 0.8 h or more was recorded 21 per cent of the time. It was thought that this wide variation in the sunshine recorded was probably due more to the type of cloud obscuring the sun than to any random variations in the cloud cover between two observations.

Cloud type and sunshine. In order to see what effect different types of cloud had on the sunshine recorded, the mean cloudiness calculated as above was ascribed arbitrarily to the predominating type of cloud. The following criteria were used to decide which of the various cloud types reported contributed most to the obscuration of the sun :

- (i) Only those cloud groups included in a synoptic observation and which would be plotted on a chart were used, i.e. clouds belonging to the types specified for the code groups² for low-level cloud (C_L), middle-level cloud (C_M) and high-level cloud (C_H) as described by the World Meteorological Organization (WMO).
- (ii) That type of cloud having the largest reported amount was judged to contribute most to the obscuration of the sun and was designated as the 'main' type. If the same type was reported at different levels, the individual amounts were added together to obtain the total amount for that type. It was accepted that on the few occasions when this method was used, the total amount for the type could be greater than that which actually occurred.
- (iii) If two different types had the same reported amount, the lower cloud was taken as the main type.
- (iv) If the main type changed from one observation to the next, the main type in the later observation was used, unless the cloud decreased to nil, when the last main type was used.

The clouds were classified into broad classes as follows :

<i>A</i> Convective low cloud	WMO types C_L 1, 2, 3 and 9
<i>B</i> Stratiform low cloud	WMO types C_L 4, 5, 6 and 7
<i>C</i> Middle-level cloud	All WMO types C_M
<i>D</i> High-level cloud	All WMO types C_H

WMO type C_L 8 was regarded as class *A* or *B* depending on whether the cumulus or stratocumulus predominated according to the criteria (i) to (iv) stated above. Fog was regarded as class *B* when it was thick enough to obscure the sky, but was disregarded otherwise. Sky obscured was counted as eight oktas in calculating the mean cloudiness.

For a mean cloudiness of up to $4/8$ there was little difference between the various classes, and the amounts of sunshine corresponded fairly closely to the values given in Table II. The few occasions of sunshine that occurred with a mean cloudiness of $8/8$ were equally distributed between all classes. The most, 0.6 h, was recorded when class *D* (cirriform cloud) predominated. Figure 2 shows the average sunshine recorded for the four classes with a mean hourly cloudiness of $5/8$, $6/8$, $7/8$. It is evident that, for the same mean cloudiness, more sunshine occurred with classes *A* and *D* than with classes *B* and *C*.

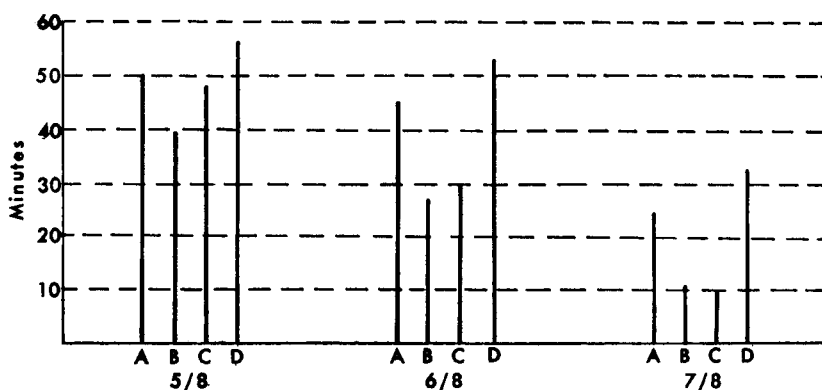


FIGURE 2—AVERAGE HOURLY DURATION OF SUNSHINE RECORDED FOR FOUR CLASSES OF CLOUD COVER WITH A MEAN HOURLY CLOUDINESS OF 5/8, 6/8 AND 7/8

Moreover, for classes *B* and *C* the sum of the percentage cloud amount and the percentage sunshine is rather nearer 100 per cent (only slightly over 100 per cent for a mean cloudiness of 7/8) than is the case for classes *A* and *D*.

There are a number of possible reasons for the greater amounts of sunshine with classes *A* and *D*, but the amount for class *D* (cirriform cloud) is perhaps not unexpected. This cloud is usually dense only in patches and it is normally only during the transition of cirrostratus into altostratus that it becomes thick enough to obscure the sun to any extent. The reason for the amount of sunshine for class *A* is not quite so clear. It is surprising to find that an almost total cover of basically cumuliform cloud gives, on average, such a significant amount of sunshine. Apart from the difficulties of measuring by the Campbell-Stokes recorder the short bursts of sunshine which are a feature of cumulus skies, the probable reason for the increase in sunshine recorded with this class of cloud is that the method of estimating total cloud cover allows the sides of cumulus clouds, especially those towards the horizon, to contribute as much or more to the final estimate than the actual base. It is, of course, the amount of cloud in the immediate direction of the sun which affects the sunshine received.

In view of the almost complete absence of sunshine when the mean cloudiness was 8/8 there was a suspicion, when compiling the results, that if 7+ oktas had been taken as 8/8, instead of as 7/8, the average sunshine for a mean cloudiness of 7/8 would have been even higher than it was. It seemed that with any significant breaks at all some sunshine was likely. It was noticed, too, on many occasions that whenever a large total cloud amount was made up of several small cloud masses at different levels there was usually a significant amount of sunshine recorded.

Discussion. This investigation treats only part of a large and complex problem. The total amount of cloud is not the only factor which decides the amount of sunshine received at any one place. There is no simple relationship between breaks in a cloud mass and the resultant sunshine. An important factor is the position of frequently occurring cloud formations in relation to the sun and the observing station, e.g. cloud formations confined to the land in the afternoon will not interfere with sunshine at a station on a south-facing

coastline, but will decrease the sunshine received on a north-facing coastline. High ground near a station may also affect the local relationship between cloud and sunshine. Nevertheless it is suggested that this investigation of the relationship between cloud and sunshine at Mildenhall may serve as a general guide for meteorologists forecasting for an inland area in flat surroundings.

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551.577.37(420)

A FURTHER NOTE ON THE HEAVY RAINFALL OF 10 JULY 1968

By P. R. S. SALTER

Introduction. In a previous article by Salter¹ on the rainfall of 10 July 1968 an approximate rainfall map was indicated in Figure 1. It should be pointed out that the isohyets in that diagram were drawn according to the observations available on a day-to-day basis from the relatively sparse network of synoptic stations. These were the only rainfall data available to the author at the time of writing the original article. A detailed rainfall map for the rainfall of the 24 hours ending 0900 GMT on 11 July 1968, based on the observations from the dense network of rainfall stations, is now submitted.

The rainfall. The accompanying diagram illustrates the total rainfall for the 24 hours ending 0900 GMT, 11 July 1968, for south-west and central England. Falls of 100 mm or more occurred in several areas of England and helped to create flood conditions from the rivers draining these particular areas.

The first region was an area high up in the Quantock Hills (Somerset) just east of Crowcombe which is itself over 400 ft above MSL. A second region was the small area between Stanton Harcourt (Oxford) and Cumnor (Berks.) on either side of the River Thames. Another part which received at least 100 mm was a narrow strip from Shipston-on-Stour (Warwick) to Dowdeswell (Gloucester) which is about 4 miles east of Cheltenham. This strip showed that there the heaviest rainfall occurred on the north-west side of the Cotswolds. Also receiving 100 mm was the area of Lincolnshire west of Alford enclosing South Thoresby and Old Bolingbroke.

Two further areas of high rainfall remained to be noted. In the Peterborough area 100 mm fell in a zone from near Raunds (Northants.) to just south of Fosdyke (Lincs.) and there was a very narrow strip which had over 125 mm between Fletton and Whittlesey extending for several miles to the north-east and to the south-west. Severe flooding occurred south of Peterborough in the Alconbury villages of Huntingdonshire.

The final area to be mentioned may be described as a 'super rainfall' area consisting of parts of Wiltshire, Gloucestershire, Somerset and Devonshire. There the 100-mm isohyet extended from Malmesbury (Wilts.) to Bristol and eastwards to include Bath and southwards to Upottery (Devon). Within this area the maximum rainfall was on the hill-sides of the Chew valley where a

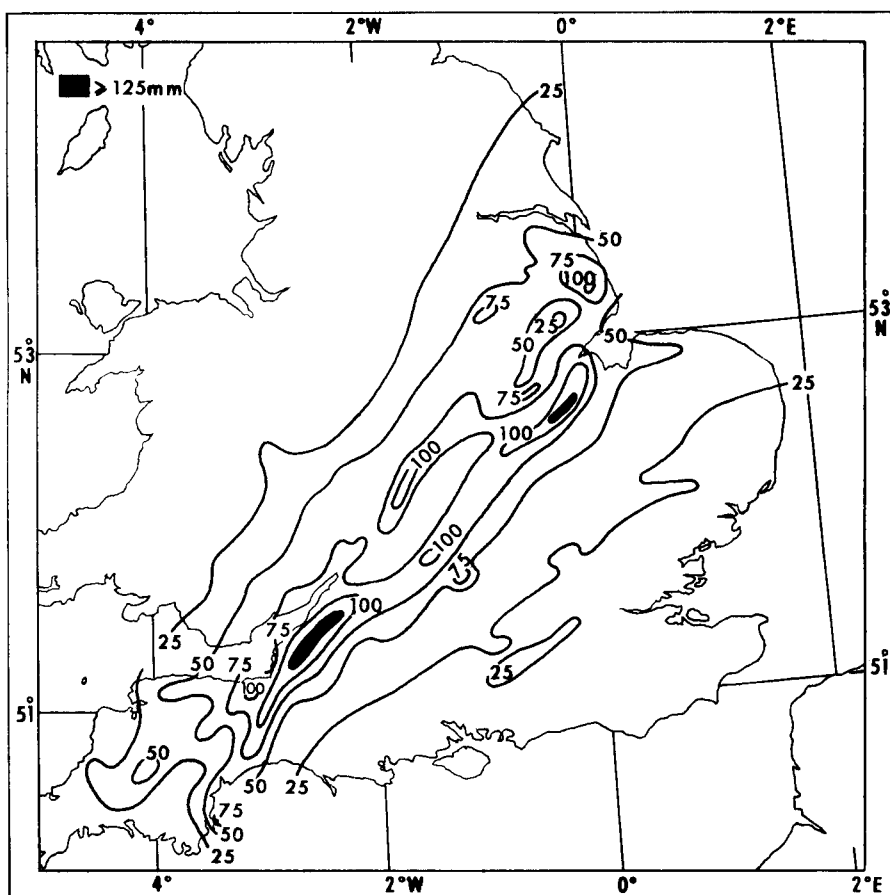


FIGURE 1—RAINFALL FOR 24 HOURS ENDING 0900 GMT, 11 JULY 1968
Isopleths at 25-mm intervals

total greater than 175 mm was recorded in 24 hours. The River Chew flows from the north-east side of the Mendip Hills and joins the Bristol Avon on the north-east side of Keynsham. The exceedingly heavy rainfall in the Chew valley led very quickly to flood conditions which caused material destruction and loss of life downstream. The torrent of the River Chew helped to swell the River Avon and to flood parts of Bristol which was itself receiving heavy rainfall.

It should not be forgotten that parts of some south coast towns were flooded by substantial rainfall accompanying thunderstorms which developed near the south coast during the early hours of 10 July. Inconvenient and damaging as this was to the population there, the rainfall received was of a smaller magnitude than that which occurred in the region of the Chew Valley. In addition to the affected parts of the south coast, flooding and flood damage occurred in many towns and villages which received a rainfall substantially less than 100 mm.

It should be pointed out that this description of the heavy rainfall is intended to be brief since the object of the original article was to survey the synoptic events which led to the rain. Again the reader is reminded that the original rainfall map¹ was an approximate distribution based on reports from synoptic stations. The difference in that map, and the map of the present article, shows very clearly how much vital information is supplied by the rain-gauge network in assessing reasonably accurate rainfall distributions.

A full account of this heavy rainfall is being prepared for *British Rainfall 1968* in a study by Miss Pauline Gray.

Acknowledgements. The author is grateful to the Hydrology Branch of the Meteorological Office for kindly supplying the detailed rainfall map.

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551.574.1:613.

INTERNATIONAL CONFERENCE ON CLOUD PHYSICS, TORONTO, AUGUST 1968

By J. C. DRAKE

Nearly 300 scientists attended the International Conference on Cloud Physics held at Toronto University in August. Tribute must be paid to Professor R. List, for the efficiency with which the arrangements for the conference were handled and for the organization of the social events which were thoroughly enjoyed by all. These included a reception given by the President of the University of Toronto, a banquet at Niagara Falls, sponsored by the Hydro-Electric Company of Ontario, and arrangements to attend rehearsals of the Canadian National Opera Company.

The business of the conference ranged from considering the importance of microscopic nuclei to the modification of weather on a continental scale. With such a broad field one might have expected a flood of new information and ideas, whereas in fact there were few papers that had not already appeared in the literature in one form or another. In all, about 150 contributions were submitted for the five working days, and in order to deal with this large volume of material an experimental format was introduced. The papers were divided into topics and each topic was introduced by a keynote paper that summarized present knowledge and development in the particular field. The individual papers were then surveyed by a series of lead speakers and followed by discussion from the conference floor.

This format led to severely cramped time schedules, leaving insufficient time for adequate discussion either in the body of the conference or in the 'corridors'. It is suggested that future conferences should select the material to be presented, even though this may mean breaking from the tradition that a published contribution is a ticket to attend.

Most notable among the presentations were the description of the University of California (Los Angeles) cloud tunnel with its high stability of flow that will enable investigations into water-drop problems without the use of mechanical supports, and the parametric method developed by E. K. Berry for the handling of cloud droplet growth problems. The Russian work on hail prevention was extremely impressive, but would have been even more convincing had they been less dogmatic in their statistics of success. The subject of electrification, one must conclude, is as confused as ever.

The overall impression generated by the conference is that the role of the one-man micro-physical experiment in the laboratory is rapidly diminishing, although often physically enlightening, and that much more rewarding advances in understanding weather will come through the effort now being put into the analysis of the real atmosphere.

OFFICIAL PUBLICATION

The following publication has recently been issued: *Averages of earth temperature at depths of 30 cm and 122 cm for the United Kingdom, 1931-60.*

The aim of this book is to provide earth temperature data for the use of workers in agriculture, horticulture, and the construction industries, and to aid research in climatology and other branches of geophysics. There are tables of averages and extremes of earth temperature at depths of 30 and 122 cm for many places in the United Kingdom. Monthly standard deviations and frequency tables of temperatures at a depth of 30 cm are also included for a number of places. Methods of measurement, site differences, diurnal and annual variation, variation with depth, snow and grass cover, notable winters and comparison with earlier averages are some of the subjects discussed and illustrated with diagrams. The tables are arranged in climatological districts to facilitate comparison but an alphabetical index and a map showing the position of places makes for ease of reference. Following modern practice, all figures quoted are in metric units but appropriate conversion tables are given in Appendices.

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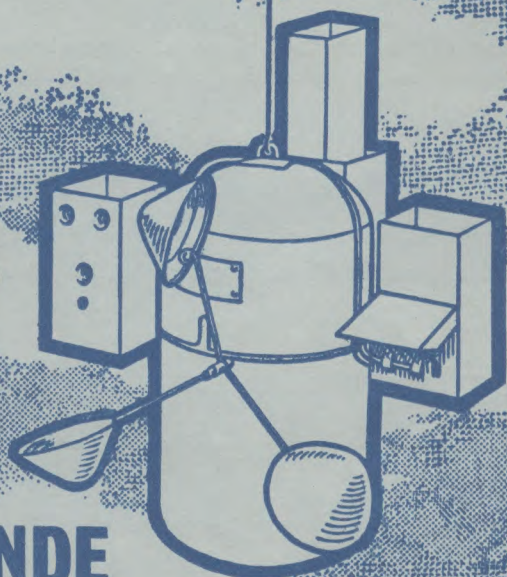
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DIURNAL VARIATION OF THE INCIDENCE OF MONSOON RAINFALL OVER THE SUDAN (PART I)

By D. E. PEDGLEY

Anti-Locust Research Centre, London

Summary. Using 15 years' data from 17 autographic rain-gauges in the Sudan, the diurnal variation of the incidence of monsoon rainfall has been tabulated by months. The considerable differences in space and time are systematic and reveal clearly defined patterns. These patterns are discussed in terms of the likely mechanisms for rainfall growth and suppression. Day-time convection, leading to a maximum incidence during the afternoon or early evening, is dominant only at places distant from the Ethiopian highlands. Elsewhere, rainfalls are more evenly distributed throughout the day, with weak maxima possible at any time, depending on location and month. However, an early morning maximum occurs widely. The Ethiopian highlands appear to influence the diurnal patterns in several ways and over distances of hundreds of kilometres.

Introduction. There is still a widely held opinion that tropical rains fall most frequently in the afternoon and evening, and that they are a result of the well-known diurnal cycle of convection. However, evidence is accumulating to show that the maximum incidence can occur at any time of day, and that the timing can vary considerably over short distances. As examples, reference may be made to descriptive studies from Africa^{1,2} and southern Asia. ³⁻⁵

In the Sudan, it has long been known⁶⁻⁸ that rain at Khartoum falls most frequently during the hours of darkness, particularly between sunset and midnight, and that this pattern changes little throughout the period of significant rainfall, May to October. Oliver⁹ states that around Khartoum most rain falls at night, whereas in the western Sudan there is a concentration between midday and sunset. Ireland¹⁰ gives the late afternoon or early evening as a general time of maximum rainfall frequency.

Over the Sudan, away from the Red Sea coast, rainfall is effectively confined to a definite season. In the extreme south of the country, for example at Juba (Figure 1), average monthly falls of 0.1 inch (2.5 mm) or more occur in every month of the year,¹¹ but further north at Malakal the rainy season lasts only from March to November. Further north still, the season becomes progressively shorter: at Khartoum it extends from May to October, at Atbara from July to September, whilst at Wadi Halfa the very scanty rains fall mostly in July and August. The length of the rainy season at a given

locality depends upon the duration there of the equatorial westerlies. These winds of the lower troposphere blow to the south of the intertropical convergence zone (ITCZ), whilst above about 2 km winds are easterly up to the tropopause. North of the ITCZ, the north-easterly trades blow at low levels. Only the westerlies contain moisture sufficient for the formation of rain clouds. The ITCZ undergoes a seasonal traverse of the Sudan: it moves northwards during the first half of the year to reach a maximum latitude on average between Atbara and Wadi Halfa during July and August, after which it retreats southwards, rather more quickly than it advanced, to reach the extreme south of the country in December and January. On only a few days each year is the ITCZ found to the north of Wadi Halfa.

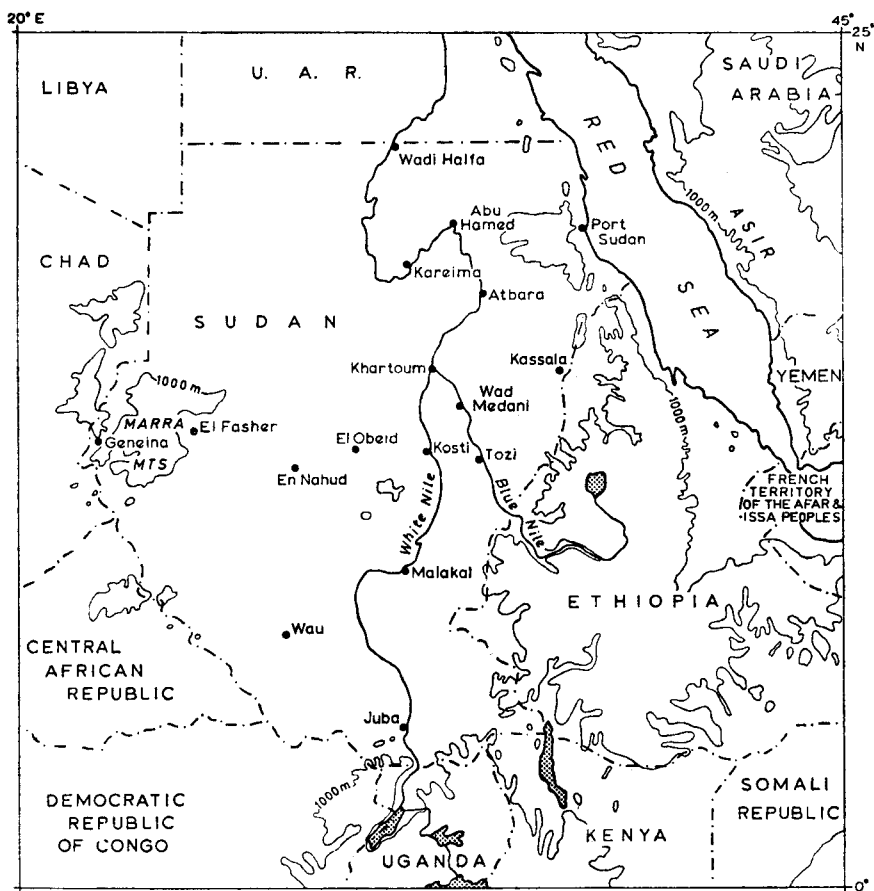


FIGURE 1—MAP OF THE SUDAN SHOWING PLACES MENTIONED IN THE TEXT

Data. As part of a larger study of the ITCZ over the Sudan, an analysis has been made of the diurnal incidence of rainfall at 17 synoptic reporting stations, based on autographic rain-gauge data tabulated by the Sudan Meteorological Service. These tabulations listed, for each hour of the day, the number of occurrences of rainfall in each month, over a period of 15 years

at most places. To reduce irregularities in the diurnal patterns resulting from the use of such a short period of observations, particularly for the northern stations with infrequent falls, the data were combined into three-hourly periods. Table I presents them in this form. These periods are referred to in the following discussion in general terms, and all times are local (GMT plus two hours) :

00-03 h = night	12-15 h = early afternoon
03-06 h = early hours	15-18 h = late afternoon
06-09 h = early morning	18-21 h = early evening
09-12 h = late morning	21-24 h = late evening

For each three-hourly period the combined number of hours with rain is made up from data for the three constituent one-hourly periods and expressed in Table I as a percentage of a total number of hours with rain in all 24 one-hour periods. For example, during July at Khartoum, of the 475 hourly periods with rain, 18 per cent were between 00 and 03 h. In this instance, there were 40 occasions for the period 00-01 h, 31 for 01-02 h, and 17 for 02-03 h. The total, 88, is 18.7 per cent of the 475 hourly periods. Expressing all eight entries to the nearest one per cent, smoothing reduces this to 18 per cent. Only months with rainfalls exceeding 0.1 inch (2.5 mm) have been tabulated, except for Wadi Halfa where, because falls are so small, July and August occurrences have been combined.

Analysis. It is convenient to consider first the diurnal incidence of rainfall during July, at the height of the monsoon; August shows closely similar features. Although the diurnal patterns vary with location (Figure 2), the stations may be grouped under four types with the following characteristics:

- (i) Well-defined maximum in the afternoon or early evening, and infrequent rains from late evening to dawn. There is often evidence for a feeble secondary maximum during the early morning. Wadi Halfa, Kareima, Abu Hamed, En Nahud, Wau and Port Sudan.
- (ii) Rainfall well distributed throughout the day. There is a maximum, usually weak, in the *afternoon* or *evening*, and there is often also a feeble secondary maximum during the early morning. Atbara, Kassala, El Obeid, Malakal, Juba, El Fasher and Geneina.
- (iii) Rainfall well distributed throughout the day. There is a maximum, usually weak, in the *morning*. Kosti and Tozi.
- (iv) Well-defined maximum between late evening and the early hours with infrequent rains during the middle of the day. Wad Medani and Khartoum.

From Figure 2 it can be seen that the distribution of these four types of stations forms a definite pattern over the Sudan. Type (i) is to be found in the middle of the country, between the extensive highland massif of Ethiopia and the smaller Marra Mountains. Except for El Fasher and Geneina, the remaining stations of types (ii) to (iv) lie within about 700 km of the Ethiopian highlands. There is a progression northwards from type (ii) to type (iv); Kassala is the only exception.

Concerning the changes in the diurnal patterns through the rainy season, the stations can be reclassified as follows, using the same headings but

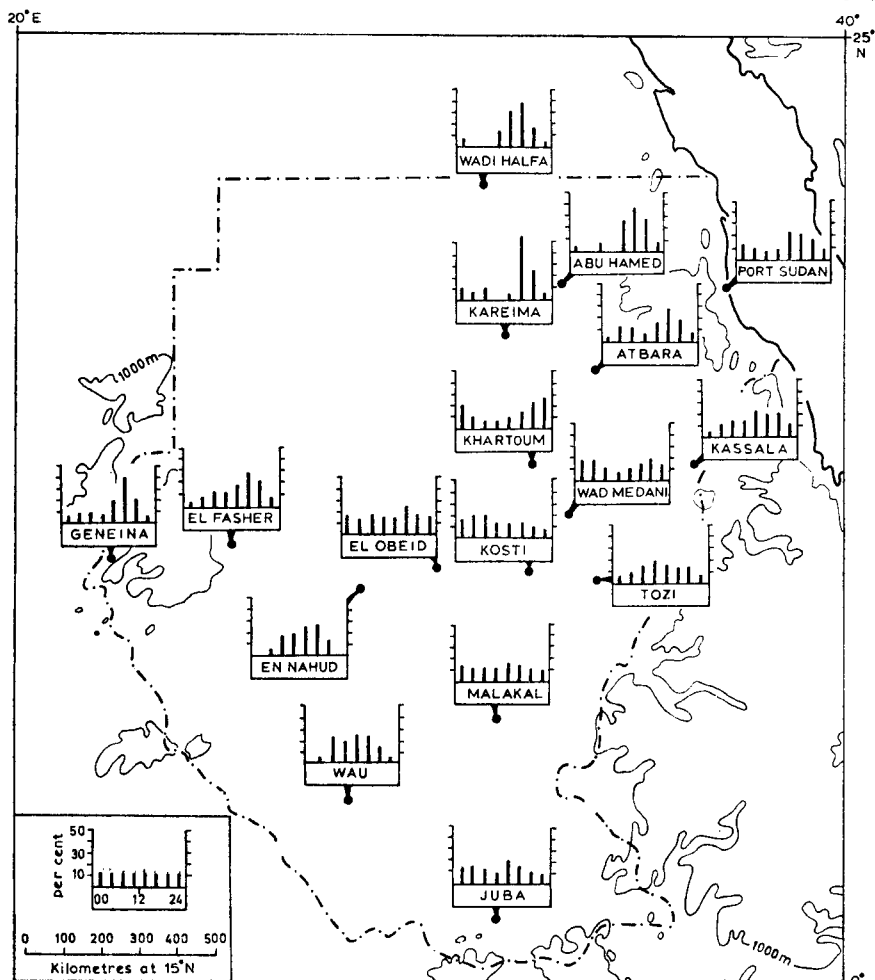


FIGURE 2—DIURNAL VARIATION OF RAINFALL INCIDENCE OVER THE SUDAN DURING JULY, BASED ON TABLE I. EACH HISTOGRAM SHOWS THE PERCENTAGE OF DAILY FALLS OCCURRING IN 3-HOURLY PERIODS.

referring to the *first* rainy month for each station as given in Table I (for example, June at Atbara, May at En Nahud):

- (i) Atbara, En Nahud, Wau, El Fasher and Geneina;
- (ii) Kassala, Wad Medani, El Obeid, Kosti, Tozi and Malakal;
- (iii) Juba;
- (iv) Khartoum.

Correspondingly, using the diurnal patterns during the *last* rainy month, the stations may be grouped:

- (i) Atbara, Tozi, En Nahud, Wau, El Fasher and Geneina;
- (ii) Kassala, Wad Medani, El Obeid, Kosti and Malakal;
- (iii) Juba;
- (iv) Khartoum.

The grouping is substantially the same at the two extremes of the rainy season.

From Table I, the following generalizations may be made. At distances greater than about 700 km from the Ethiopian highlands rain falls most frequently in the afternoon or early evening; at other times of the day it is unusual although there is a tendency towards a feeble secondary maximum in the early morning. This pattern applies throughout the rainy season. Nearer the Ethiopian highlands, falls of rain are more evenly distributed through the day although there is usually a weak maximum in the afternoon. At the height of the monsoon this maximum becomes progressively earlier in the day as Khartoum is approached from the south. Perhaps the most outstanding feature of these diurnal patterns is the persistence in all months of a maximum near or soon after midnight at Khartoum.

Discussion. Since rain clouds are formed by the ascent of moist air, it follows that the diurnal incidence of rainfall must be determined by the diurnal variations both of upcurrents and of moisture content. Some allowance must be made for the possibility of temporary storage, since clouds are observed to continue raining after the upcurrents have ceased.

Broadly speaking, upcurrents leading to rainfall may be divided into two types: those caused by mountains acting as a barrier to horizontally flowing airstreams, and those associated with low-level convergence of the wind field within disturbances particularly those developing in areas having horizontal temperature gradients. Over a flat country like the Sudan, barrier effects as a significant source of rainfall may be set aside. Disturbances, with low-level convergence, occur over a wide range of scales, but for convenience may be considered as either convection (small-scale, short-lived showers, or sometimes larger and longer-lived self-propagating convective storms) or synoptic-scale disturbances.

The moisture content of the air can be altered in three ways: by addition or subtraction of water vapour (evaporation or condensation), by mixing with different air (as a result of convection), and by replacement with different air (as a result of advection, both horizontal and vertical). Away from areas of falling rain, the only source of water vapour is the earth's surface. Over the Sudan, the swamps and cultivated areas along the Nile and its tributaries are local sources, together with the Red Sea, but it is likely that the majority of the vapour in the equatorial westerlies has been advected over long distances, especially from the South Atlantic Ocean. Water vapour is carried upwards both by convection and by mass-ascent within large disturbances. Horizontal advection may also be significant near the intertropical convergence zone (ITCZ), where moisture gradients are large. Thus, the moisture content is itself controlled by the windflow, including both convective and advective elements.

Synoptic disturbances. Before passing to a discussion of convection over the Sudan, it is convenient to consider first two mechanisms leading to mass-ascent, namely, travelling synoptic disturbances and the ITCZ. It is a fact that both the extent and the intensity of rainfall over the Sudan vary considerably from day to day, suggesting the existence of synoptic disturbances. Over eastern Africa, Johnson¹² has shown the existence of such disturbances but they were found not to be of the travelling type. Rain areas developed and decayed more or less *in situ*, not as a result of local instability but from

TABLE 1—PERCENTAGE DISTRIBUTION OF AVERAGE DAILY RAINFALL OCCURRENCES OVER 3-HOURLY PERIODS FOR EACH MONTH OF THE MONSOON SEASON AT 17 STATIONS IN THE SUDAN

		MONSOON SEASON AT 17 STATIONS IN THE SUDAN												Total to hourly obs.
		00 to 03	03 to 06	06 to 09	09 to 12	12 to 15	15 to 18	18 to 21	21 to 24	24 to 27	27 to 30	30 to 33	33 to 36	
TOZI 12°44'N 34°08'E	May	6	8	13	6	18	20	23	6	96				
	June	8	10	13	7	11	18	18	15	259				
	July	6	9	16	19	16	13	14	7	487				
	Aug.	3	7	18	14	15	16	16	11	427				
	Sept.	4	8	17	14	13	20	18	6	208				
	Oct.	0	1	5	13	31	33	11	6	127				
EL FASHER 13°37'N 25°20'E	June	4	14	9	8	9	26	24	6	135				
	July	2	9	11	11	17	27	20	3	397				
	Aug.	3	13	14	10	14	24	19	3	560				
	Sept.	5	13	14	6	20	22	19	1	161				
	Oct.	7	17	6	0	13	34	23	0	53				
MALAKAL 09°33'N 31°39'E	Mar.	6	16	18	15	17	17	10	1	96				
	Apr.	8	10	12	15	26	11	10	8	273				
	May	5	7	15	17	23	20	10	3	590				
	June	7	8	13	16	20	18	10	8	922				
	July	11	12	11	12	18	14	11	11	1330				
	Aug.	11	12	10	11	15	17	13	12	1386				
JUBA 04°52'N 31°36'E	Sept.	9	8	10	11	18	18	16	10	906				
	Oct.	7	7	7	9	21	21	17	11	558				
	Nov.	4	11	20	15	31	13	4	2	46				
	Jan.	5	3	28	12	14	11	14	13	64				
	Feb.	7	8	21	18	18	11	12	5	122				
	Mar.	6	11	21	17	12	10	13	10	402				
	Apr.	7	8	15	18	13	15	14	10	630				
	May	10	8	9	13	16	12	15	17	657				
	June	12	14	16	12	17	12	9	8	529				
	July	13	15	13	8	19	14	10	8	721				
	Aug.	10	17	17	12	15	14	9	6	729				
	Sept.	15	15	13	9	13	15	9	11	600				
	Oct.	15	17	14	10	12	10	10	12	658				
	Nov.	8	5	9	13	24	18	12	11	404				
	Dec.	12	9	19	9	16	13	11	11	121				

For most stations data refer to the 15-year period 1951 to 1965.
Exceptions are :

Wadi Halfa, 1951 to 1964 (14 years)
Khartoum, 1951 to 1966 (16 years)
Wad Medani, 1957 to 1966 (10 years)
Tozi, 1957 to 1965 (9 years)

dynamical causes, discussed by Johnson and Mörtz,¹³ and by Mörtz.¹⁴ There has not been a comparable study of such disturbances over the Sudan, but something of their nature can be deduced from the data of Table I. Thus, since travelling synoptic-scale disturbances are at most only modified by diurnal influences, their incidence over a particular place will not vary diurnally and rain associated with them should fall at all times of the day. However, because the presence of a disturbance influences the development of convection, the incidence of rainfall would probably not be exactly uniformly distributed throughout the day. A reasonably uniform distribution would suggest the presence, even dominance, of travelling disturbances; conversely, the absence of falls at a given place for some part of the day may be taken as indicative of the absence of these disturbances. As Figure 2 shows, it is the south-east of the Sudan that has the most even distribution of falls throughout the day, whereas both to the west and north of this area there are times when rainfall incidence falls to near zero. It is therefore reasonable to deduce that disturbances occur over the south-eastern Sudan, but they form and die *in situ*. Detection of these disturbances is difficult with the existing sparse network of stations observing upper winds. It may well be that they are of a meso-scale. In passing, it is interesting to note that there is increasing evidence¹⁵⁻¹⁷ for the existence of lower tropospheric cyclonic circulations moving westwards within the equatorial westerlies of West Africa. That the strongest disturbances are found in the west suggests an eastern origin but, from the evidence presented here, they do not seem to be related to those over the south-eastern Sudan.

The intertropical convergence zone. The ITCZ over the Sudan is associated on average¹⁸ with convergence in the low-level wind field, although this need not be true on any given occasion. This convergence will lead to some lifting but, because the atmosphere is only conditionally unstable, mass-ascent of unsaturated air will be small and the convergence is likely to be relieved by a few tall, narrow and intense upcurrents within cumulonimbus clouds — the 'hot towers' of Riehl and Malkus.¹⁹ Relative humidity is observed to be greatest around 500 mb so that any mass-ascent is likely to produce or thicken stratiform clouds near that level. Such clouds are frequently observed over the Sudan especially around dawn.

The observed hydrolapse and associated medium clouds, suggest subsidence above 500 mb. Now, the surface position of the ITCZ lies below the right exit of the core of the strong upper tropospheric winds known as the 'tropical easterly jet', a region where dynamically induced convergence and subsidence is to be expected and which has been invoked²⁰ as a cause of the extreme aridity of northern Africa in summer, contrasting strongly with similar latitudes over southern Asia. Tops of the stratiform medium clouds can be expected to lie, on average, near the base of the subsiding air, at a level also controlled by low-level convergence and ascent associated with the ITCZ. Thus, the altitude of the cloud tops should undergo changes accompanying diurnal variations of the low-level convergence. Now, both the westerlies and the trades over the Sudan show a diurnal variation of speed. Above the friction layer, they accelerate at night to reach a maximum around dawn at about 500 m above the ground; such maxima have been known for some time.²¹⁻²³ The resulting maximum convergence around dawn is

consistent both with an observed decrease in amounts of medium cloud during the morning, and the widely occurring tendency for rainfall incidence to increase in the early hours and early morning, sometimes leading to a weak secondary maximum (Figure 2). Synoptic reports around dawn show a predominance of light rainfall, sometimes continuous, in contrast to afternoon and evening showers and thunderstorms.

Concerning the origin of the night-time acceleration, studies in the U.S.A.²⁴⁻²⁸ have shown that, as a result of the rapid removal around dusk of drag associated with small-scale convective turbulence, winds at the top of the evening boundary layer accelerate from their previously sub-geostrophic speeds. Inertial oscillations can develop leading, on occasions, to considerably super-geostrophic speeds later in the night.²⁹⁻³¹ Such accelerations have been particularly noticeable^{32,33} with southerly streams possessing reversed shear, i.e. with warmest air to the left. Over the Sudan, the equatorial westerlies, deflected to south-westerlies by the Ethiopian highlands, have similar properties, with the axis of highest temperatures lying near the ITCZ, and a similar inertial oscillation is probably responsible, at least in part, for the observed diurnal changes of wind speed there in the lower troposphere.

Differential heating of the Nile plains and Ethiopian highlands. Bleeker and Andre³⁴ have suggested that broad-scale motions can be set up as a result of differential heating of air over a plain compared with the slopes of a neighbouring mountain mass. Over the central plains of the U.S.A. in summer, they found that diurnal variation in convergence of the wind fields in the lower and middle troposphere supported the suggestion. It is perhaps significant that the horizontal dimension of the circulation envisaged by Bleeker and Andre, between the Rockies and the central plains, is comparable to the distance between the Ethiopian plateau and the western part of the plains in the Nile basin. Suppression of afternoon cumulus development has certainly been observed elsewhere over low ground adjacent to mountains, although admittedly on a smaller scale than envisaged here. Thus, Malkus³⁵ described a 'subsidence ring' around the mountainous island of Puerto Rico, leading to a clear strip having a width comparable to the radius of the island. Concerning the Sudan, such a mechanism would enhance the development of convective storms over the Ethiopian highlands, and to a lesser extent the Marra Mountains, but inhibit their development over the plains, the effect decreasing with increasing distance from the mountains. Figure 2 shows that the normal, sharply defined late afternoon or early evening maximum associated with convection is present at places distant from the Ethiopian highlands, such as Wadi Halfa, Kareima and Abu Hamed, whereas at En Nahud and Wau the afternoon maxima are distinctly flat when one might expect a progressive increase in rainfall incidence from the time of onset to a maximum in the late afternoon or early evening. The flatness of the maximum could be attributed to a reduction of convective activity as a result of reduced insolation following the accumulation of persistent tops of cumulus clouds spreading in mid-troposphere. However, the coverage of medium-level clouds is observed to decrease from morning to afternoon. A likely cause of the flattening is a decrease in the lapse rate or, more especially, in the humidity of the environment during the afternoon as a result of weak subsidence.

Closer to the highlands, the influence on afternoon convection of subsidence, resulting from differential heating of mountains and plains, should be expected to increase. Type (ii) stations certainly show only weak afternoon maxima during the middle of the rainy season, and this subsidence hypothesis is supported by the tendency for these stations to show a type (i) diurnal pattern at the extremes of the season, when an afternoon or evening maximum becomes more pronounced. However, such a maximum could well be a result of a decrease in either effectiveness or incidence of disturbances able to yield rain at other times of the day, caused perhaps by the disturbances being nearer to the surface position of the ITCZ, where humidities are lower, on average, than further south.

Some of the type (ii) stations show a feeble secondary maximum in the early morning, but type (iii) stations have their greatest maxima in the mornings during the rainiest months. At Tozi this maximum is in the late morning; perhaps this is a result of extreme suppression of afternoon convection. However, at the limits of the rainy season, the late afternoon or early evening maximum returns strongly. If this reflects a weakening of the differential heating circulation in those extreme months, it is likely that latent heat, released within storms developing over the plateau during the height of the monsoon rains, adds to the energy of the circulation, since the direct daily heating of the plateau by insolation is not likely to vary significantly from May to October near 10° N as a result of either changes in elevation of the sun, or day-time cloud cover over the plateau. At Kosti, the maximum is displaced to the early morning. This may represent not only a strong suppression of afternoon convection but also an enhancement of rains around dawn, for reasons to be discussed.

Part II of this paper will be published in May.

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ACCURACY OF FORECASTING NIGHT MINIMUM AIR TEMPERATURES BY THE METHOD DUE TO SAUNDERS

By L. P. STEELE, P. A. J. STROUD and S. E. VIRGO, O.B.E.

Summary. This paper presents the results of a test of the method due to Saunders for forecasting night minimum temperatures at screen level. The test was made at 10 stations in eastern England for the period 1961-65 using the curves and corrections devised by Tinney and Menmuir.¹ The mean error of the whole set of forecasts was -0.3 degC with a standard deviation of 1.89 degC and the sample is of sufficient size to give a good indication of the order of accuracy which can be achieved by the method.

The percentage probabilities of air frost corresponding to certain forecast screen minimum temperatures are given in Table V and the relative contributions which the errors in the method and the errors in forecasting make to the total error are discussed and summarized in Tables VI, VII and VIII.

Tinney and Menmuir¹ have described how they constructed cooling curves for use with the method due to Saunders for forecasting night minimum air

temperatures for 13 stations in eastern England. The curves were based on about 14 000 observations made during the four years from October 1961 to September 1965 inclusive. For each station they devised two sets of curves: one for the summer from April to September, and the other for winter from October to March. The curves were worked out for clear nights and Tinney and Menmuir presented corrections to be made for other cloud amounts.

The present note reports the results of a test of accuracy based on independent data for the 12 months from April 1967 to March 1968 inclusive. For various reasons only 10 of the original 13 stations were able to participate in the test; their names are given in Tables I and II. The nomogram curves are constructed for clear nights and the corrections for various cloud amounts are linear, at least within the tolerances to which forecasters work. Thus for the purpose of the test it was sufficient that forecasts of night minimum temperatures (to the nearest 0.1 degC) were made for two classes of nights :

- (i) Clear nights — those when it was forecast that the average cloud cover would be 2/8 or less (excluding cirrus).
- (ii) Cloudy nights — those when it was forecast that the average cloud cover would be 6/8–8/8 (excluding cirrus).

TABLE I—SUMMARY OF RESULTS OF A TEST OF FORECASTING NIGHT MINIMUM TEMPERATURES BY THE METHOD DUE TO SAUNDERS, PERIOD APRIL – SEPTEMBER 1967

Station	Number of occasions	Clear nights			Number of occasions	Cloudy nights		
		Mean error*	Root-mean-square error degrees Celsius	σ		Mean error*	Root-mean-square error degrees Celsius	σ
Wyton	39	-0.30	1.78	1.75	58	-0.97	2.49	2.29
Waddington	21	-0.96	1.82	1.55	87	+0.31	1.99	1.73
Finningley	26	+0.55	1.82	1.73	39	-0.48	1.29	1.20
Marham	22	-1.93	2.48	1.56	37	-0.18	2.14	2.13
Mildenhall	61	-0.83	2.36	2.21	64	-0.17	2.13	2.12
Wittering	45	-0.77	2.44	2.31	20	+0.37	1.37	1.31
Cottesmore	9	+0.80	1.27	0.99	41	+0.22	1.63	1.61
Bassingbourn	27	-0.94	1.87	1.61	36	-0.77	1.92	1.76
Lindholme	27	-0.14	1.33	1.32	43	-0.75	1.80	1.63
Scampton	37	+0.76	1.49	1.24	46	-0.09	1.47	1.44
Totals and weighted means	314	-0.44		1.81	471	-0.23		1.81

Total number of occasions = 785. Mean value of σ for clear and cloudy nights = 1.81 degC.

*Error = forecast minimum temperature — actual minimum temperature.

TABLE II—SUMMARY OF RESULTS OF A TEST OF FORECASTING NIGHT MINIMUM TEMPERATURES BY THE METHOD DUE TO SAUNDERS, PERIOD OCTOBER 1967 – MARCH 1968

Station	Number of occasions	Clear nights			Number of occasions	Cloudy nights		
		Mean error*	Root-mean-square error degrees Celsius	σ		Mean error*	Root-mean-square error degrees Celsius	σ
Wyton	48	-2.00	3.37	2.71	51	-0.25	2.85	2.84
Waddington	36	-0.51	1.53	1.44	51	-0.04	1.92	1.92
Finningley	22	+0.15	1.17	1.16	34	-0.17	1.71	1.70
Marham	13	-0.08	3.32	3.32	28	+0.05	1.96	1.96
Mildenhall	42	-0.92	2.00	1.78	48	-0.76	2.25	2.12
Wittering	8	+0.77	1.74	1.56	35	+0.57	1.81	1.72
Cottesmore	12	-0.05	1.15	1.15	34	-0.13	1.13	1.23
Bassingbourn	16	-1.01	3.07	2.90	34	-0.08	1.75	1.75
Lindholme	17	-0.44	1.23	1.15	38	-0.10	1.48	1.48
Scampton	18	+0.42	2.03	1.99	57	+0.13	1.89	1.89
Totals and weighted means	232	-0.70		2.07	410	-0.10		1.95

Total number of occasions = 642. Mean value of σ for clear and cloudy nights = 1.99 degC.

*Error = forecast minimum temperature — actual minimum temperature.

Nights when precipitation was forecast were excluded and of course forecasts could be done only when forecasters were on duty.

Let B be the forecast minimum temperature, and A the observed minimum temperature, then the error $d = B - A$.

There is a preponderance of negative mean errors in both Tables I and II for both clear and cloudy nights, but this does not necessarily mean that the curves are biased. It may simply mean that a period of 12 months is hardly long enough to eliminate bias from the means; but the test was limited to 12 months for administrative and not for scientific reasons.

If n is the number of occasions in a sample, the root-mean-square error is given by

$$s = \sqrt{\frac{\sum (B - A)^2}{n}}.$$

Because the mean of the errors is not zero, s is not the same as the standard deviation σ in which the deviations are measured from the mean; but σ for the sample may be calculated from the formula

$$\sigma^2 = s^2 - d_m^2$$

where

$$d_m = (1/n) \sum (B - A).$$

The root-mean-square errors and standard deviations calculated in this way for individual stations for the summer six months and for the winter six months are shown in Tables I and II. While there are some fairly large differences in individual cases, these tables taken as a whole indicate that, on average, for all 10 stations over a whole year, the accuracy obtained in winter by means of the winter curves is of the same order as that obtained in summer with the summer curves; similarly the cloud correction used on cloudy nights produces results of the same order as those obtained on clear nights.

The errors in the forecasts consist of two parts: the errors due to the curves and the appropriate corrections and those due to forecasting wind, dew-point and cloud amount. The mean error due to the curves should be zero because of the way in which the curves were constructed — this will be examined more fully later. On the other hand, the mean forecasting error may or may not be zero. In fact the mean error of the sample is -0.3 degC; this is not large. Moreover, there is not much difference between the root-mean-square error and the standard deviation except in two or three instances. But as the mean of the sample is the best estimate of the mean of the population, it is appropriate to study the standard deviation σ rather than the root-mean-square error. Table III summarizes the values of the mean error and the standard deviation for all stations for the whole 12 months; σ works out as 1.89 degC.

TABLE III—SUMMARY OF FORECASTS FOR ALL STATIONS FOR THE WHOLE YEAR

	Number of forecasts	Mean error	σ
		<i>degrees Celsius</i>	
Clear nights	546	-0.55	1.93
Cloudy nights	881	-0.17	1.88
Clear and cloudy nights	1427	-0.31	1.89

Table IV shows the actual percentages of the forecasts which were within specified limits. For comparison it also shows corresponding percentages in a normal distribution with a standard deviation of 1.89 degC and a mean error of -0.3 degC. (The forecasts were actually made to a tenth of a degree, but Table IV has been compiled in half degrees to keep the table short.) The agreement between the two columns of figures is evidence that the distribution of errors in the forecasts approximates closely to a normal distribution.

TABLE IV—PERCENTAGE OF FORECASTS FALLING WITHIN SPECIFIED LIMITS

Limits (degC)	± 0.5	± 1.0	± 2.0	± 3.0	± 4.0
Actual percentage	26	42	71	89	95
Percentage for a normal distribution	21	40	70	88	96

Note: The figures on the line labelled 'Actual percentage' relate to the actual forecasts made during the period from April 1967 to March 1968. The figures on the last line are those which relate to a normal distribution with a mean of -0.3 degC and a standard deviation of 1.89 degC.

Probability of occurrence of an air frost. Because forecasts are often not wholly exact, it is possible for a frost to occur with a forecast above 0°C and it is also possible for no frost to occur with a forecast below 0°C. It would therefore be useful for forecasters to know the statistical probability of an air frost occurring with any particular forecast screen minimum temperature.

The distribution of forecast errors is illustrated in Figure 1, which represents a normal distribution of 1427 errors with mean -0.3 degC and standard deviation 1.89 degC as in the sample for 1967-68. Let the forecast night minimum temperature be +2°C. If this forecast is more than 2 degC too warm an air frost will occur. The probability of an air frost is therefore the same as the probability of an error more than 2 degC too warm. This

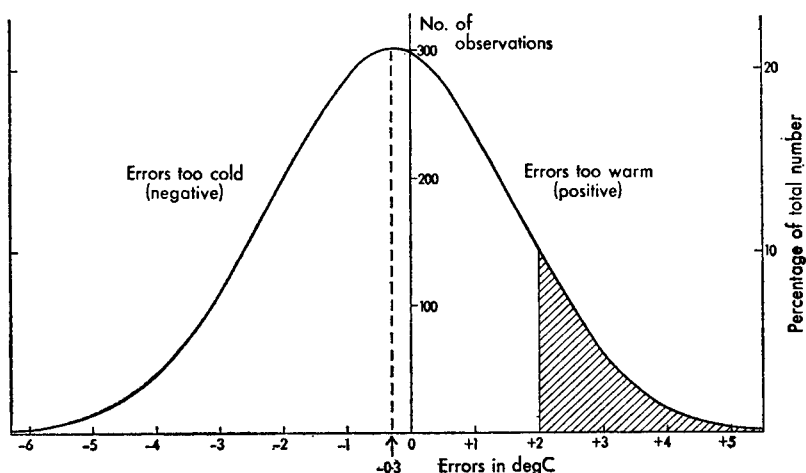


FIGURE 1—A NORMAL DISTRIBUTION CURVE OF FORECAST ERRORS

probability is the ratio of the shaded area in Figure 1 to the total area under the curve. To find the probability, a table of areas under the standardized normal curve² is used; under this curve the total area is unity, which corresponds to the maximum possible probability, and the mean is zero. Before the tables are used, the variable x must be standardized by subtracting the mean (-0.3 degC) and dividing by the standard deviation (1.89 degC), i.e. the mean of the distribution must be shifted to zero and deviations from it measured in terms of standard deviations; for example, if $x = +2$ degC, the mean $= -0.3$ degC and the standard deviation $\sigma = 1.89$ degC, then the standardized normal variable z is given by

$$z = \frac{+2 - (-0.3)}{1.89} \quad \sigma = 1.22\sigma.$$

From the tables the tail area to the right of $z = 1.22\sigma$ is 0.11 of the total area under the curve and this is the probability of an error more than 2 degC too warm. It is also the probability of an air frost when the forecast night minimum is $+2^\circ\text{C}$. Table V gives the percentage probabilities of an air frost for various forecast night minimum temperatures. Rounded off to some convenient percentage (say 10 per cent or 20 per cent) these figures based on the 1967-68 data provide forecasters with an indication of the frequency with which they may expect an air frost to occur with any particular forecast of screen minimum temperature.

TABLE V—PERCENTAGE PROBABILITY OF AN AIR FROST CORRESPONDING TO CERTAIN FORECAST SCREEN-MINIMUM TEMPERATURES

Forecast night minimum temperature($^\circ\text{C}$)	+4	+3	+2	+1	0	-1	-2	-3	-4	-5
Percentage probability of an air frost	1	4	11	25	49	64	82	92	97	99

Note: The probabilities are calculated for a normal distribution with a mean of -0.3 degC and a standard deviation of 1.89 degC, as found in the 1967-68 data analysed.

Sources of error. As stated before, the error in a forecast consists of two parts: the error due to the curves with the appropriate corrections, and the error due to forecasting mean wind speed, dew-point and cloud amount for the night. These two errors may be disentangled if the forecaster does his calculations again after the event using the actual conditions for the night as recorded in the *Daily Register*. Five stations did this and the results were called aftercasts.

Because of the instructions given to the forecasters at the beginning of the investigation, the aftercasts relate only to those nights when the cloud was forecast to be $0-2/8$ or $6/8-8/8$. If subsequent events showed that the actual mean cloud amount was in the range of $3/8-5/8$, the aftercast was made using the appropriate correction recommended by Tinney and Menmuir.¹

Let σ_n be the standard deviation of the errors inherent in the method, i.e. in the curves and the corrections

and σ_f the standard deviation of the errors made by the forecaster in forecasting conditions for the night.

These are related by the equation³

$$(\sigma_f)^2 = \sigma^2 - \sigma_n^2.$$

Values of each of these quantities are listed by season in Tables VI and VII and summarized in Table VIII.

TABLE VI—ANALYSIS OF SOURCES OF ERRORS: SUMMER 1967

Station	No. of occasions	Aftercast data using nights forecast as clear				No. of occasions	Aftercast data using nights forecast as cloudy			
		E_n	σ	σ_n	σ_f		E_n	σ	σ_n	σ_f
Finningley	31	+0.20	1.73	1.31	1.13	50	+0.27	1.20	0.83	0.87
Marham	21	-1.05	1.56	1.40	0.68	38	-0.83	2.13	1.62	1.39
Mildenhall	54	-0.55	2.21	1.34	1.76	62	-0.02	2.12	1.64	1.35
Wittering	24	+0.14	2.31	0.84	2.15	39	+0.34	1.31	1.11	0.69
Bassingbourn	21	-0.30	1.61	0.85	1.38	42	-0.50	1.76	1.09	1.29

TABLE VII—ANALYSIS OF SOURCES OF ERRORS: WINTER 1967-68

Station	No. of occasions	Aftercast data using nights forecast as clear				No. of occasions	Aftercast data using nights forecast as cloudy			
		E_n	σ	σ_n	σ_f		E_n	σ	σ_n	σ_f
Finningley	21	+0.50	1.16	0.88	0.76	34	+0.09	1.70	1.01	1.37
Marham	15	+0.97	3.32	1.69	2.86	26	-0.97	1.96	0.76	1.84
Mildenhall	35	-0.67	1.78	1.67	0.60	52	-0.07	2.12	1.83	1.02
Wittering	8	-0.47	1.56	1.47	0.53	35	+0.16	1.72	1.09	1.33
Bassingbourn	22	-0.17	2.90	1.26	2.61	28	-0.49	1.75	0.92	1.49

TABLE VIII—SUMMARY OF WEIGHTED MEANS FOR ALL FIVE STATIONS COLLECTIVELY

Period	Type of night	No. of occasions				
			E_n	σ	σ_n	σ_f
Summer 1967	Forecast as clear	151	-0.32	1.81	1.11	1.46
	Forecast as cloudy	231	-0.12	1.91	1.42	1.26
	All nights forecast	382	-0.20	1.87	1.29	1.36
Winter 1967-68	Forecast as clear	101	-0.06	2.13	1.74	1.56
	Forecast as cloudy	175	-0.19	1.87	1.25	1.40
	All nights forecast	276	-0.14	1.97	1.44	1.46
Whole year 1967-68	Forecast as clear	252	-0.22	1.93	1.37	1.49
	Forecast as cloudy	406	-0.15	1.89	1.34	1.33
	All nights forecast	668	-0.17	1.91	1.35	1.40
Winter 1963-64	All nights	350	0		1.56	

Notation for Tables VI, VII and VIII

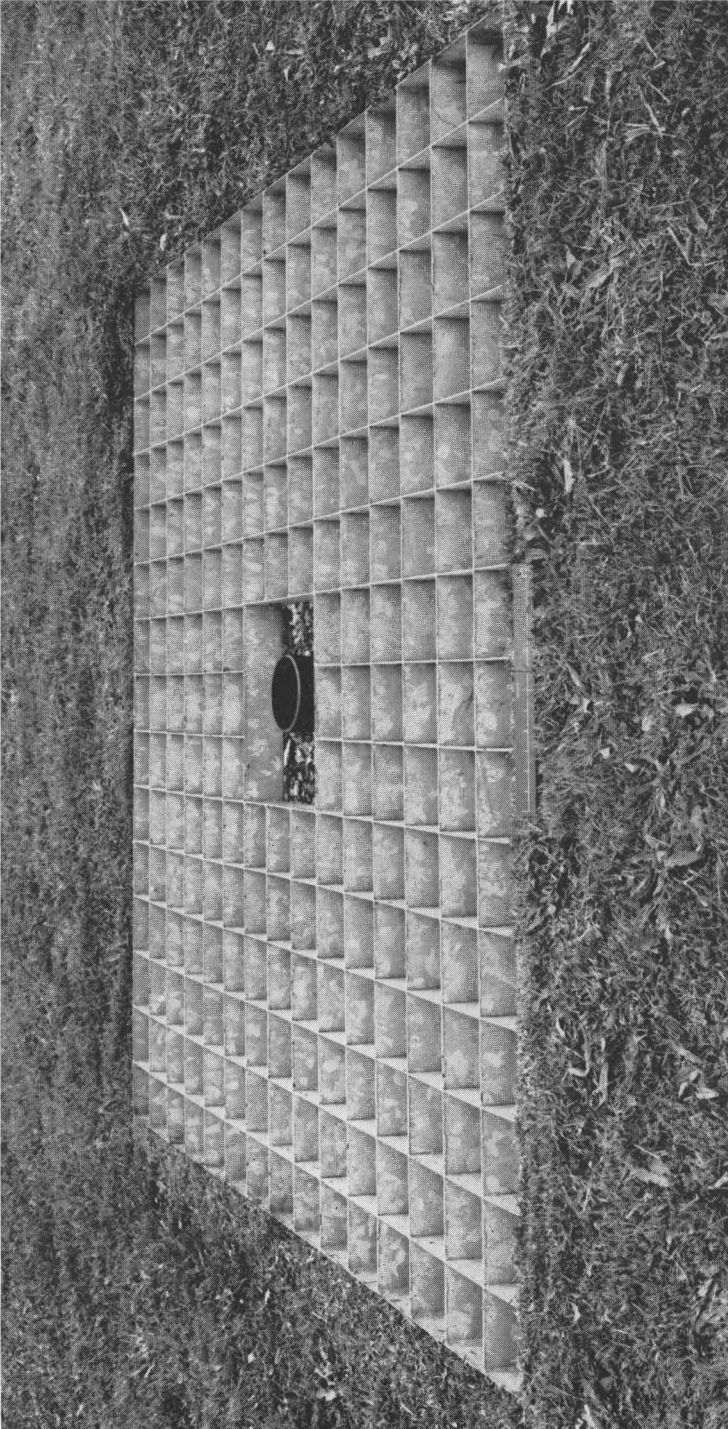
E_n is the mean error due to the curves and corrections.

σ is the total standard deviation of the sample.

σ_n is the standard deviation of the errors due to the curves and corrections.

σ_f is the standard deviation of the errors made by the forecaster in forecasting conditions for the night.

The investigation started with forecasts of clear and cloudy nights but, as stated above, some occasions of 3/8-5/8 cloud were included in the aftercasts, and it must be asked whether this invalidates the results. Gordon and Virgo⁴ reported a similar investigation for the winter of 1963-64 with no distinction between cloud amounts. Their results for the five stations concerned in the present investigation were compared by means of students' *t*-test with those in Table VII. As the difference was not significant at the 5 per cent level, the results in both investigations can be regarded as samples of the same population, and actual cloud amount therefore makes no significant difference to the minimum temperatures derived from the curves and corrections devised by Tinney and Menmuir.¹ Moreover, the *t*-test showed that the difference between the summer and winter figures in Tables VI and



Photograph by courtesy of the Institute of Hydrology

PLATE I—GROUND-LEVEL RAIN-GAUGE WITH GRID

See page 114



PLATE II—METEOROLOGICAL OFFICE
RAIN-GAUGE MK 2

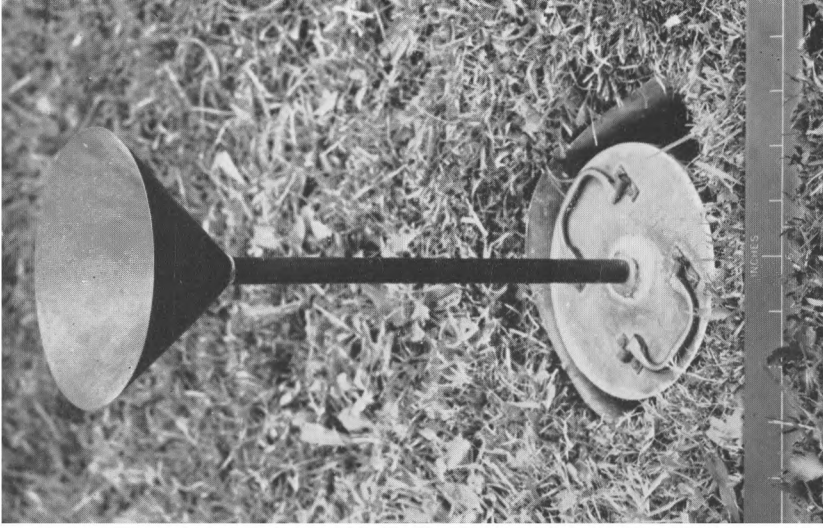


Photographs by courtesy of the Institute of Hydrology
PLATE III—METEOROLOGICAL OFFICE
RAIN-GAUGE MK 3

See page 115



PLATE IV—METEOROLOGICAL OFFICE
RAIN-GAUGE MK 4



Photographs by courtesy of the Institute of Hydrology
PLATE V—FUNNEL GAUGE

See page 115

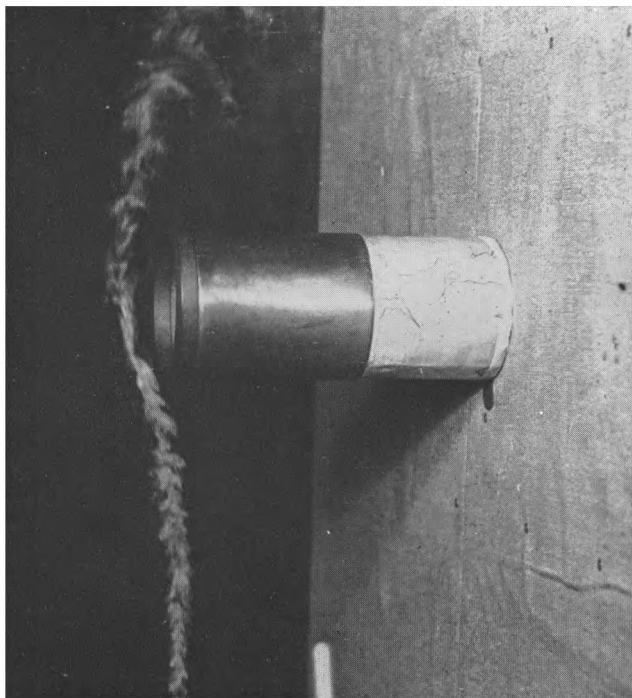


PLATE VI—SMOKE TRAJECTORY OVER MK 2 GAUGE
(Wind speed in tunnel 5.5 ft/s)

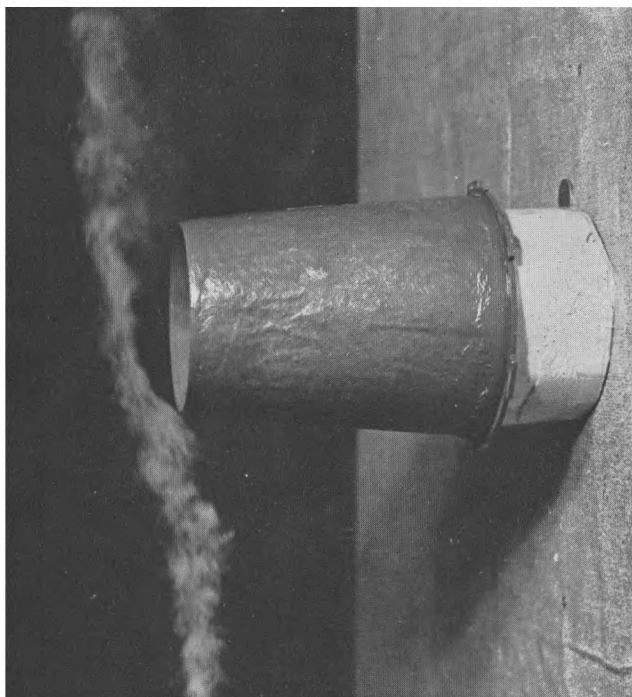


PLATE VII—SMOKE TRAJECTORY OVER MK 3 GAUGE
(Wind speed in tunnel 7.8 ft/s)

See page 115

Photographs by courtesy of the University of Southampton

VII was insignificant at the 5 per cent level and this justifies considering the year as a whole in Tables III and VIII.

The mean errors due to the curves should be zero because of the way in which they were constructed. These errors are shown as E_n for clear nights in Tables VI, VII and VIII, and the error for the winter of 1963-64, though based on all nights irrespective of cloud cover, has been included in Table VIII for comparison. This last error was exactly zero, but there was a slight negative bias in the summer of 1967 and in the winter of 1967-68.

Tables VI and VII show that there are wide variations in the ratio of σ_n to σ_f for individual stations; the ratios also vary from season to season. But when all clear and cloudy nights in the year as a whole are taken together, as Table VIII shows, the errors in the method and the errors made by the forecasters contribute roughly equal parts to the total.

Gordon and Virgo⁴ discussed the magnitude of errors in forecasts of night minimum temperatures by McKenzie's method arising as a result of forecasting wind, dew-point and cloud amount, and concluded that errors in forecasting low-cloud amount introduced the greatest errors into the forecasts of night minimum temperature. The present investigation into the accuracy of the method due to Saunders produced a similar result. Forecasters at four stations examined the synoptic situations on occasions when large errors occurred and found that the great majority could be attributed to errors in forecasting low-cloud amount; in particular the forecasters at Marham specified low cloud drifting in from the North Sea.

Acknowledgements. The writers acknowledge the co-operation of all who made the observations on which the curves and corrections are based and all the forecasters who participated in the test.

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RAIN, WIND AND THE AERODYNAMIC CHARACTERISTICS OF RAIN-GAUGES

By A. C. ROBINSON* and J. C. RODDA†

Summary. The airflow round four types of rain-gauge was studied in a series of wind-tunnel experiments using tuft indicators and also smoke trajectories. A transparent gauge was used in checking that there were no air currents within the gauge. Quantitative assessments of the wind fields over the gauges were obtained from measurements made by a hot-wire anemometer which could be moved in a vertical plane oriented along the direction of the wind.

After the wind-tunnel experiments the four gauges were installed beside other gauges and rainfall measurements made over a period of six months so that comparisons could be made. The largest catch was made with a ground-level gauge.

* Post-graduate student, Department of Civil Engineering, University of Southampton.

† Institute of Hydrology, Wallingford, Berks., and part-time Lecturer, Department of Civil Engineering, University of Southampton.

Introduction. Standardization of particular instruments and uniformity in the method of their installation and observation are given particular attention by the meteorologist. In the case of the measurement of rainfall, the dimensions of the rain-gauge that make up the non-recording network in Britain and its method of siting have become standardized over the past 100 years. Now there are few instruments in the United Kingdom that do not have the rim at a height of 1 foot and an orifice with a diameter of 5 inches — exceptions being the recently introduced Meteorological Office gauges¹ based on an orifice area of 150 square centimetres. A note on the units used appears at the end of this article. In other countries, different standards have been adopted for height and size of gauge and there is also a considerable variety of shape and observer practice, as well as different rules of siting. Because of these contrasts, it is not always a simple task to compare rainfall records from different parts of the world and to assist this, several comparisons of various national gauges have been made.² In addition, an interim reference precipitation-gauge has been adopted by the World Meteorological Organization and is being tested at a number of sites.³

However, it does not follow that because a particular type of gauge is employed as a standard throughout a national network, the performance of that gauge will necessarily be standard from site to site. This is due to a number of factors, the most important being wind, especially its effect on drops falling towards the gauge. Wind interacts with features of the gauge surroundings and particularly with the gauge itself, to produce eddies which divert some drops from the gauge funnel. Such effects can be extremely variable from site to site, in spite of the use of subjective rules for site selection. They cause the amount caught by the conventional elevated gauge to be less than the quantity of rain reaching the ground. This fact has been established in a number of experiments carried out in different parts of the world in which standard rain-gauges have been compared with weighing lysimeters,⁴ with accurate measurements of lake level,⁵ and with other rain-gauges installed with their rims flush with the ground surface and surrounded by a non-splash surface.^{6,7,8} Ground-level gauges (Plate I) are being employed at a number of sites in Britain and at one, a standard gauge has caught 6.6 per cent less rain over a period of five years than a ground-level gauge and considerably less during certain individual storms.⁹ These differences may not be important to the meteorologist, but in hydrology this systematic error¹⁰ in the measurement of rainfall can be highly significant. It is particularly serious where the complete water balance of a catchment is being studied, also in flood investigations and in the assessment of water resources. In this respect meteorologists and hydrologists differ in their needs for information about rainfall; where the former can be content with an index of rain, the aim of the latter should be to obtain measurements of a known accuracy. This is particularly difficult when there is no absolute standard for rainfall measurement and until such a standard becomes available, gauges that are not subject to the source of the most serious error, namely wind, must be considered to produce the most satisfactory results.

Aerodynamic studies. In view of the importance of wind in the measurement of rainfall, it is surprising that so few studies of the aerodynamic characteristics of rain-gauges have been carried out.^{11,12,13} Even fewer

attempts have been made to provide an objective method for classifying rain-gauge sites to replace the somewhat arbitrary procedures in use at present.

The first of these problems has been studied in a series of wind-tunnel experiments carried out at Southampton University.¹⁴ The gauges used were the top sections of the Meteorological Office Mk 2 gauge, the new type Meteorological Office gauges (Mk 3 and Mk 4) and a metal Funnel Gauge (Plates II-V). The Funnel Gauge consisted of the bare essentials of a gauge: a sheet-copper funnel, five inches in diameter, slant length three and a half inches feeding into a copper tube half an inch in diameter. The top sections of each of the other gauges were mounted on cylindrical sand-filled bases such that the rim of each gauge stood one foot above the false floor of the tunnel.

Preliminary experiments to examine the airflow around each gauge were conducted using indicator tufts stuck to the gauges. The results of these experiments showed that wind speeds initially between 2 and 22 ft/s in an empty wind tunnel changed when a rain-gauge was placed in the tunnel. The air speed increased as the air passed over the top of the gauge and turbulence occurred above each gauge.

Smoke was injected into the airstream and photographs were taken of the smoke trajectories over the different gauges for wind speeds between 1 and 17 ft/s at 2-ft/s intervals, some of these results being shown here (Plates VI-VII). The results of the smoke experiments showed that up to wind speeds of 5 ft/s a slight deflexion of the air occurred over the gauges and that this deflexion appeared almost the same for all gauges. At wind speeds above 5 ft/s the smoke was lifted clear of the tops of the gauges and at about 7 ft/s the trajectory flattened out and retained approximately the same lift over the gauges for wind speeds up to 17 ft/s. The results from the Funnel Gauge were an exception, as in this case complete lift occurred at a much higher wind speed (about 14 ft/s) while at the same wind speed the amount of lift appeared to be less than for the other gauges. Observation of the smoke showed that the speed of the air increased as it passed over the top of each gauge. The height of the lift of the smoke trajectory above the gauge appeared to increase with increasing diameter of gauge and with increasing sharpness of the leading edge of the gauge for equal wind speeds. The latter point was investigated by moulding plasticine into various shapes around the rims of the gauges, a smoother profile producing less lift.

A full-scale transparent model of the top of the Mk 2 gauge was made to study the effects of air movement inside the gauge. The height of the funnel within this gauge could be altered and tests were conducted with the funnel at various depths from the rim of the gauge, namely: 0 in, 1½ in, 3 in, and 4¾ in (the normal distance). The results of tuft and smoke experiments using this gauge showed that there was little movement of the air within the gauge and that no circulating currents were set up within it that could contribute to the lift.

In order to obtain a quantitative assessment of the wind fields over the gauges, use was made of a constant-resistance hot-wire anemometer^{15,16} that could be traversed in a vertical plane along the direction of the wind. The hot wire was calibrated for varying wind speeds using a pitot tube, calibrations being made at the beginning and end of each experiment because the

calibration curve changed with tunnel temperature. Hot-wire traverses were made over the centre of each gauge starting some four inches in front of the leading edge, finishing just beyond the rear of the gauge and extending six to seven inches above it.

The results of the hot-wire anemometer experiments showed that the gauges exhibited similar aerodynamic characteristics; in particular a surface of separation was set up by the leading edge of each gauge that curved backwards over it (Figure 1). Above this surface the wind speed reached a maximum while below it a turbulent zone was set up, in which the wind

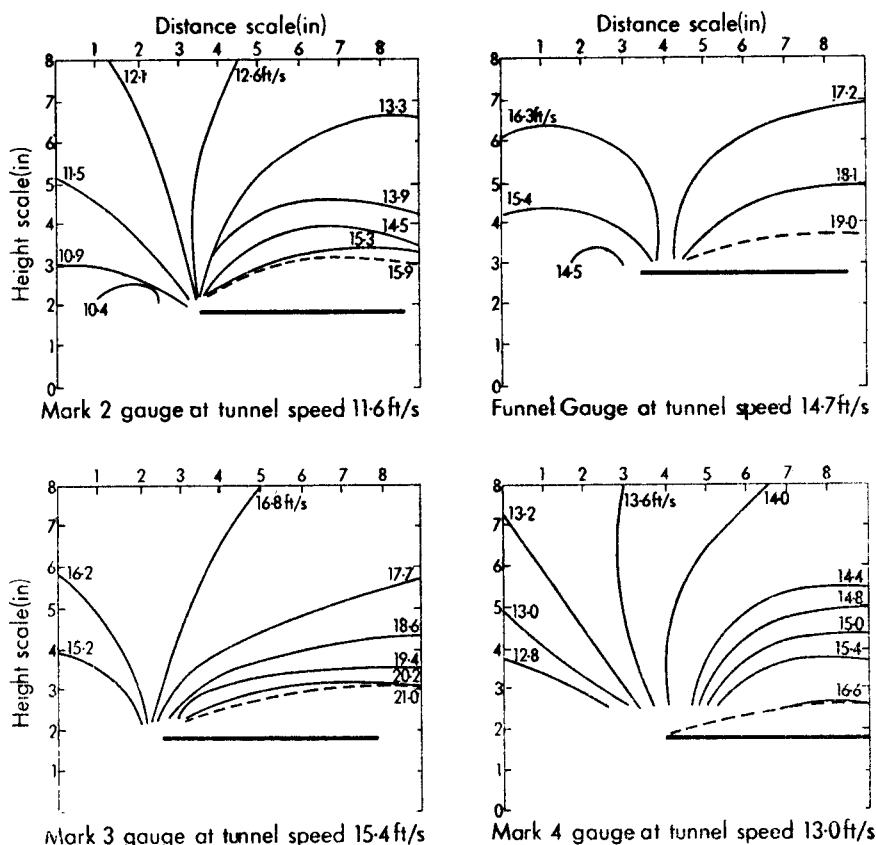


FIGURE 1—WIND-SPEED CONTOURS FOR TRAVERSES ACROSS RAIN-GAUGES

Note: The height and distance scales are referred to arbitrary zeros but the position of the gauge orifice is indicated by a thick black line on each diagram. The pecked line denotes the surface of separation. Wind speeds are indicated in ft/s and in each diagram the wind is blowing from left to right.

speed dropped considerably below the normal tunnel wind speed. The size of this zone increased with increasing wind speed, while the sharpness of the leading edge also affected its dimensions. Above the turbulent boundary, the air speed increased as it passed over the gauge, this speed depending upon the area that the gauge projected against the oncoming wind and the sharpness of the leading edge (Table I). Of the four gauges the simple cylindrical and near cylindrical shapes of the Mk 2 and Mk 3 gauges appeared to produce the least satisfactory patterns of airflow. On the other hand the more complex shapes of the Mk 4 gauge and the Funnel Gauge caused less distortion of the wind field.

TABLE I—DETAILS OF WIND-TUNNEL EXPERIMENTS

Gauge type	Speed in empty tunnel	Maximum speed above gauge	Speed increase	Max. height of turb. boundary above gauge
	<i>ft/s</i>	<i>ft/s</i>	<i>per cent</i>	<i>inches</i>
Mk 2	11.6	15.9	37	1.3
Mk 3	15.4	21.0	36	1.9
Mk 4	13.5	17.7	31	1.2
Funnel	14.7	19.0	29	1.2

Of course, under natural conditions, rain-gauges are subjected to a wind field which fluctuates in speed and direction and exhibits a marked profile. However, even the artificial wind-tunnel conditions must give some guide to the performance of a gauge in a real environment. In fact, when a Mk 2 gauge was placed on grass in the open and smoke was let out through the funnel, a turbulent boundary was seen and when smoke was discharged across the gauge, the flow pattern appeared similar to that existing in the tunnel.

Determination of the catch of different types of gauge. Determining the relationship between catch and the aerodynamic characteristics of a gauge is a more difficult problem than establishing the characteristics themselves. An examination of drop trajectories above the gauge by photography might provide the best solution, but there would be considerable difficulties in analysing the enormous amounts of data that would be produced. In addition, drop size would have to be measured continuously and this is not an easy task. Whether the study could be made in the open is another point that would require careful attention, because provision of the necessary facilities under cover would require an appreciable investment of capital.

An alternative, which is not entirely satisfactory, is to carry out comparative tests of the different gauges at one site. References to such comparisons abound in literature concerned with rain-gauges and usually the gauge that catches the most rain is considered the best, often without any sound reason. However, in this case, the results of the gauge comparison could be interpreted in the light of the wind-tunnel tests and from knowledge gained in previous field experiments. So following the work in the wind tunnel, the four gauges were installed alongside a number of other gauges in the site at Wallingford and compared over a period of six months. During the test it was found that the Funnel Gauge caught more rain than any other instrument except

the ground-level gauge (Table II). Of the conventional gauges, the Mk 3 caught the most and the Mk 4 the least — a somewhat surprising result in view of the slightly better performance of the latter gauge in the wind tunnel and its supposedly improved shape. Interchanging some of the gauges during the course of the experiment, confirmed that these differences in catch could not be ascribed to any consistent pattern in the distribution of rainfall across the site — a point that had been investigated in an earlier experiment. The Funnel Gauge seemed to operate best in light showers, but it caught less than the other gauges during prolonged or heavy rain, independent of wind speed. This suggests that splash-out was taking place when the surface of the funnel was wet and that under such conditions splash would be the chief source of error rather than wind. In fact, the Funnel Gauge appeared to cause a comparatively small disturbance in the wind field, so it is likely that the trajectories of drops falling over this gauge would not be greatly altered and under-registration of catch would be lessened.

TABLE II—SUMMARY OF RAIN-GAUGE RESULTS FOR WALLINGFORD

(a) Monthly table (period 16 Jan.—30 June 1968)

1968 Month	Mk 2	Ground- level gauge	Turf-wall gauge	Mk 3	Mk 4	Funnel Gauge
<i>inches</i>						
16-31 Jan.	0.24	0.27	0.26	0.23	0.21	0.27
Feb.	0.98	1.04	1.04	0.99	0.96	0.99
Mar.	0.76	0.87	0.83	0.77	0.72	0.87
Apr.	2.06	2.20	2.14	2.13	1.95	2.09
May	2.98	3.13	3.03	3.07	2.88	3.12
June	2.29	2.41	2.37	2.32	2.22	2.37
Total	9.31	9.92	9.67	9.51	8.94	9.71

(b) Daily table

1968 April	Mk 2	Ground- level gauge	Turf-wall gauge	Mk 3	Mk 4	Funnel Gauge	Wind*
<i>inches</i>							<i>mile/h</i>
1	0.009	0.014	0.015	0.001	—	0.004	5.5
2	0.093	0.140	0.142	0.100	0.099	0.107	3.5
3	0.009	0.011	0.011	0.009	0.008	0.011	4.0
15	0.078	0.083	0.082	0.083	0.074	0.083	3.7
16	0.249	0.274	0.258	0.257	0.227	0.238	5.1
17	0.293	0.303	0.302	0.308	0.290	0.292	2.0
18	0.269	0.273	0.265	0.265	0.242	0.257	3.4
19	0.020	0.018	0.021	0.023	0.017	0.024	1.5
21	0.003	0.007	0.004	0.003	0.001	0.007	0.5
22	0.005	0.007	0.006	0.007	0.007	0.006	0.8
23	0.071	0.074	0.072	0.075	0.066	0.078	3.3
27	0.243	0.256	0.251	0.253	0.239	0.250	3.2
28	0.229	0.240	0.235	0.244	0.218	0.232	3.3
29	0.178	0.188	0.180	0.184	0.161	0.185	2.0
30	0.313	0.311	0.299	0.316	0.305	0.313	2.0
Total	2.062	2.199	2.143	2.128	1.954	2.087	

* Average wind speed during rain.

Note: After rain the bottles containing the rain water are replaced by dry empty bottles and weight of rain is measured.

There are, of course, other ways of reducing the effect of wind such as by using a turf wall (Figure 2) or trying to eliminate it by employing a ground-level gauge. However, there may still be a slight amount of air movement

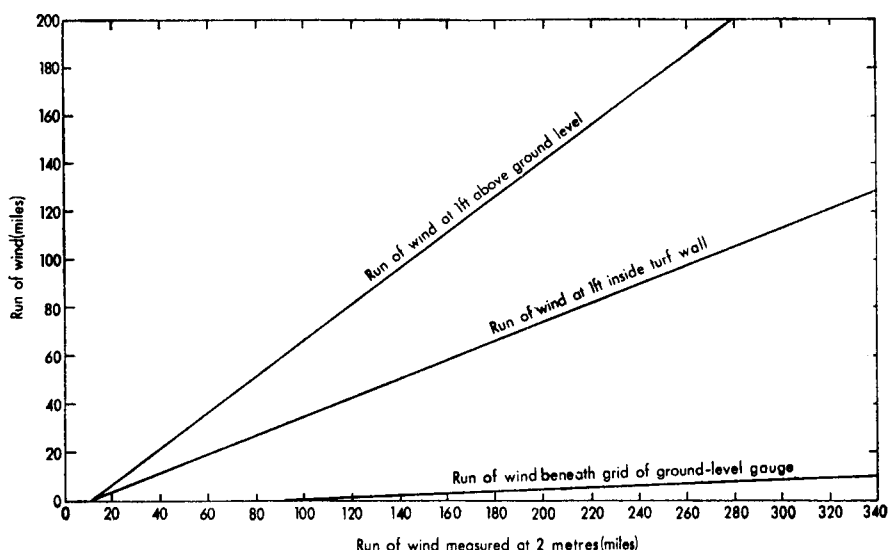


FIGURE 2—RELATIONSHIP BETWEEN RUN OF WIND AT A HEIGHT OF 2 METRES AND AT OTHER POSITIONS

about the ground-level gauge that might influence its performance. Nevertheless of the gauges tested, the ground-level gauge must be considered as producing results nearest to the true rainfall, whatever that might be for Wallingford. A system of ground-level gauges installed at representative sites throughout the country would provide a more realistic assessment of the amount and distribution of rainfall and might even allow adjustments to be made to past records.

Note on units used in this article. Measurements were made in feet per second, miles per hour, inches (rainfall and various dimensions), and miles (run of wind).

For comparison purposes the following conversion factors may be used:

$$\begin{array}{ll} 1 \text{ ft/s} &= 0.3048 \text{ m/s} & 1 \text{ inch} &= 25.4 \text{ mm} \\ 1 \text{ mile/h} &= 0.447 \text{ m/s} & 1 \text{ mile} &= 1.609 \text{ km.} \end{array}$$

(Ed. note: See letter to editor on page 126.)

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THIRTEENTH RADAR METEOROLOGY CONFERENCE

By K. A. BROWNING

The Thirteenth Radar Meteorology Conference was held on 20–23 August 1968 at McGill University, Montreal. The programme was divided into sessions on radar instrumentation, measurement techniques and signal interpretation, radar climatology, severe storms, precipitation physics, meso-scale analysis, clear-air echoes, precipitation measurement, wind measurement, operational applications, and scattering and absorption. Altogether 125 papers were accepted and these were published by the American Meteorological Society in Conference Proceedings which were distributed to participants well in advance of the conference. At the conference, each author, instead of presenting his own paper, participated in an open discussion initiated by brief critical comments and questions from the session chairman. The planning of the sessions was finalized during informal workshops held at the beginning of the conference.

A feature of this conference was the increased number of contributions involving Doppler radar. Altogether there were over 20 papers involving Doppler radar, half of them being technique-oriented and half phenomenon-oriented. Doppler radar was shown to be a versatile tool in turbulence studies and for making wind measurements on the mesoscale; however, limitations in the accuracy of measuring updraught velocities in intense convective storms were recognized.

Another notable feature was the increasing interest in the application of high-power radar systems to study the structure of the clear atmosphere using refractive-index inhomogeneities as tracers. Clear-air structures observed

by radar fall into two categories: (i) clear-air convection at low levels in which the radar detects turbulent humidity gradients at the edges of rising bubbles of air, and (ii) clear-air layers at middle and upper tropospheric levels in which the radar detects refractivity turbulence associated with temperature fluctuations within turbulent layers in regions of strong vertical wind shear.

Progress in operational applications of radar, on the other hand, has been disappointingly slow in recent years. Successful identification of hail, for example, still hangs in doubt, particularly using radars at 3-cm wavelength. However, it was again emphasized that, despite limitations in the accuracy of the measurement of rainfall intensity because of uncertainties in drop-size distributions etc., there were still many areas where radar could furnish vital information unobtainable by other means. Two interesting techniques were proposed to resolve the problem of the determination of drop sizes; one of these involved the measurement of the effect of raindrop vibrations and the other involved a bistatic* approach. Unfortunately, both approaches require an accuracy of measurement not attainable at present.

During the conference, special excursions were organized to visit a new high-resolution 10-cm radar which the McGill group has installed in the Montreal area. Another high-resolution radar, which the McGill group are using in Alberta, has already yielded remarkably detailed descriptions of three-dimensional precipitation patterns within hailstorms. When related to surface hail surveys, these can be expected to provide useful constraints on the mathematical models that are now being constructed to account for the precipitation distribution in terms of realistic airflow patterns. The Alberta radar was also specially designed for polarization studies. With radars such as this we can look forward to a renewal of studies of lightning and a search for new means of hail identification.

At the end of the conference a useful summary session was held in which the session chairmen attempted to focus the discussion on the conference highlights. Prof. Hosler, in discussion of the application of radar to mesoscale studies, made the point that the prediction or control of weather on the scale which affects most people depends upon thorough observation and comprehension of mesoscale circulations. He went on to say that while obvious progress was being made by using radar techniques to define mesosystems, progress would be greater if more of the observational systems were brought to bear upon the same cloud system in a co-ordinated way. It is with this in mind that the present writer hopes that integrated studies involving radar and other techniques will find their way into phenomenon-oriented conferences dealing with such topics as, for example, cloud physics.

* A bistatic radar is one in which the transmitting and receiving antennae are separated by a considerable distance.

REVIEWS

A note on climatological normals, WMO Technical Note No. 84. 275 mm × 215 mm, pp. x+19, Secretariat of the World Meteorological Organization, Geneva, 1967. Price: Sw. F. 4.

This note discusses the problem of fixing the optimum length of record for stable meteorological statistics and the means of overcoming difficulties arising from a dearth of records, the heterogeneity of the data, the variability of climatic elements and above all, the nature and extent of climatic fluctuations.

The main text is divided into 11 sections which vary in length from about half a page to two pages. These sections are as follows: (1) Introduction, (2) The presentation of climatological data, (3) The nature of climatological time series, (4) The stability of normals, (5) 'Standard length of record' and 'reference period', (6) The reference period *vis-a-vis* the purpose of normals, (7) The influence of climatic fluctuations on reference period, (8) Review of results (for temperature, atmospheric pressure, precipitation, humidity, wind and radiation), (9) Short-period averages and 'adjusted normals', (10) Statistical parameters to be mapped in climatic atlases (means, standard deviations, extremes and values for various probability levels of occurrence) and (11) Concluding remarks (which form a useful summary of the rules recommended for practice).

The main text is preceded by a brief summary, and section (8) of the text contains a small but useful table listing the approximate lengths of period (in years) needed to obtain stable frequency distributions for temperature, humidity, cloud, visibility and precipitation, for various topographical conditions (island, shore, plain, mountain) and for two broad latitudinal belts, namely extra-tropical and tropical. For many practical purposes however, longer periods may be desirable, for example, a five-year period for visibility in the London area would not be sufficient, in view of the recently recorded ten-year cycles of atmospheric pollution. Indeed, near a large (constant) urban source, the period necessary for visibility statistics can hardly be less than that for wind.

The presentation is not over-mathematical and the style is clear though considerably 'condensed'.

The note is especially valuable to meteorologists, particularly practising meteorologists, also to students and teachers of meteorology or geography from the senior-school stage upwards. For more advanced study, the list of over 30 references is far from comprehensive, omitting for example, a notable contribution¹ from a one-time member of the responsible working group of the WMO Commission for Climatology, in which the author concludes, that in view of the change in climate taking place over the greater part of the globe, a 30-year period is scientifically unjustified.

E. N. LAWRENCE

REFERENCE

1. RUBINSTEIN, E. S.; On the problem of the averaging period in climatology. *Trudy glav. geofiz. Obs. Leningrad*, Vyp. 181, 1965, p. 46.

The encyclopedia of atmospheric sciences and astrogeology, by Rhodes W. Fairbridge. 260 mm × 185 mm, pp. xv + 1200, illus., Reinhold Publishing Corporation, New York, 1968. Price: £16 6s. 6d.

This encyclopedia is one of Reinhold's *One-volume encyclopedias* and is in fact Vol. II of the *Encyclopedia of earth science series*, the first volume being devoted to oceanography. As the title indicates the text is concerned both with the atmospheric sciences, mainly meteorology, and with astrogeology, a term which has not yet reached the dictionaries and is meant to include those parts of knowledge which are in the borderland of astronomy and geology, such as the properties of the earth, its near neighbours and other celestial bodies. A precise definition is given under the corresponding entry in the encyclopedia itself.

We examine an encyclopedia such as this in a different way from that in which we examine a text which has a unity of purpose, thought and writing; such unity cannot be easily attained in a large number of articles which are written by many different people and are juxtaposed by an arbitrary alphabetic convention. Perhaps above all we prize in such a book authority, vigour, clarity and uniformity, and many of the foibles which pass unnoticed or uncommented on in a text by a single author become painfully apparent in an encyclopedia in which adjacent articles are necessarily of different style and standard. It is clearly impractical to read the whole text or even all of the articles on meteorology, and one must therefore base a judgement of the whole on a selection, a procedure in criticism which must infuriate those whose articles are not read but who must yet share any general shafts of disapprobation.

There are about 300 entries in the text, ranging from comparatively short items of about 100 words to substantial essays of thousands of words, and liberal illustrations and tables are found throughout. There is a lot of good, sound meteorology to be found in these articles; the list of contributors ensures this and indeed bad meteorology could scarcely escape the eyes of critics so vigilant as Professor Fairbridge and his editorial team. On the whole the choice of material has been well conceived; if dynamical meteorologists think that there is a weighting towards static meteorology, i.e. climatology, maps of mean conditions, statistics, etc., they will reflect that this is inevitable in an encyclopedia if not in a textbook because the former must contain a lot of factual knowledge. About 4000 entries are listed in the index; presumably about half are meteorological so that clearly anyone in search of information is likely to find what he wants or a reference which will help him to find it elsewhere. No one could be seriously misled by anything that I have read.

There are, unfortunately, signs of hasty writing and a lack of editorial uniformity which occasionally blur the authority, vigour and clarity that we expect. The preface states that every article has been read by a competent critic, but we all use slipshod expressions in our speech which we do not use in writing, and too many of these loose expressions have escaped the critic's net. For example, what are we to understand on p. 136 from the following, 'In earth science it is usual to employ rectangular co-ordinates x , y , z with x as the east-west direction y north-south' This is the complete

antithesis of the usual meteorological co-ordinate system and does not appear to be used elsewhere in the book. Does the following from p. 1147 make sense? 'The geostrophic wind may be considered the top (non-frictional) level of the Ekman spiral.' Again, is it true as stated on p. 1107 that 'modern numerical weather prediction is largely based on conservation of absolute vorticity, referred to the absolute (non-rotating) frame'?

The symbolism is not always uniform throughout the volume; for example the Greek 'nu' and two types of 'vee' are used for the velocity in the y -direction, and μ , m , M are used in the equation of state (under Equation of State, Lapse Rate and Density). The tables are usually well set out but one or two appear without any mention in the text, and occasionally the reader is left to guess at the units; on p. 446 one supposes that vapour pressure means saturated vapour pressure, that it is given in inches of mercury and that at 30°F, 25°F, etc. it is referred to ice. These particular tables do not agree with the *Smithsonian Tables* and their original source is not given. The units used throughout the book have not been standardized and perhaps it is a little surprising to find absolute humidity in grains per cubic foot.

It is a matter of opinion as to whether it is wise to include in one volume entries for subjects which appear to be quite disparate. One could argue a good case for an encyclopedia devoted to oceanography and meteorology, as illustrated here by the frequent reference to Vol. I. There do not seem to be many common problems of the atmospheric sciences and astrogeology, perhaps not surprising when astrogeology is itself a borderland of two disciplines, so that there appears to be two separate books interleaved by the accidents of the alphabetic entries. No doubt uniformity of size of the volumes played some part in the decision to produce this particular volume, and it would be unwise to comment until the series is completed. In any case the meteorologist will be glad of the glimpses that are afforded him by the non-meteorological text of a wide-ranging field of knowledge of planets, cosmology, relativity theory and so on. There are very substantial and readable essays on such subjects as the moon, the solar system and space science. Do these articles seem better written because one is far less familiar with their content?

There is no doubt that this volume will deservedly find its way on to every library shelf where meteorology is well represented, for despite my criticisms it is fundamentally a sound reference book.

E. KNIGHTING

Meteorology and atomic energy 1968, edited by David H. Slade. 200 mm × 260 mm pp. x+445, illus., available as TID-24190 from Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U.S. Department of Commerce, Springfield, Virginia 22151, 1968. Price: \$3.00.

It has been said* in reference to the peaceful application of nuclear energy: 'In history no technical conquest has ever been carried to a higher degree of safety and no other industry has caused so little damage to life and health.'

* Dr E. J. Henningsen, Deputy Director-General, Danish National Health Service, W.H.O. seminar 1965: 'Protection of the public in the event of radiation accidents.'

Considering the predominantly injurious biological effects of radiation and the risk of severe accidents, it is surprising how safely radiation has been controlled and applied within different spheres of community life.'

There are very many aspects to this safety problem, and some of these involve meteorology. Meteorology enters first of all in the choice of site of a nuclear energy facility and its design and future operating character. Then in rather more exceptional cases it may be applied in day to day operations, especially at test sites, where routine releases may be large enough that certain meteorological conditions may seriously reduce the normally excellent dispersive character of the atmosphere. Concentrations then would involve risk if control were not applied. Finally, meteorology is inevitably involved in the unlikely event of an accident, so that human communities may be protected and areas of contaminated agricultural foodstuffs assessed.

This commendable book *Meteorology and atomic energy 1968* covers the whole problem, starting with a brief history of the atomic energy industry in the U.S.A., the development of safety measures and the meteorological theory on which these measures have been based. Although the eight chapters have been written by different authors, the whole work constitutes a very coherent and authoritative story which is clearly told, very readable and generously illustrated throughout. The first edition was written only 13 years ago in 1955 but in common with much of science, the advance within the subject has been so great that this second edition necessitated a complete rewrite. It thus brings together experimental data and theory that is up-to-date and can be found nowhere else in this form.

It is interesting for readers of the *Meteorological Magazine* to discover how very widely a practical technique for estimating diffusion of passive material from a continuous point-source in terms of broad stability conditions is now used. This was a method developed by Pasquill in 1958 in response to a request from the Atomic Energy Commission in Britain and it later appeared in these pages in 1961 when it was realized that a wider audience wished to use it. Its general success is now leading others to modify it for use in such specialized cases as, for example, dispersion over a city.

One of the most heartening advances described in this book is the emergence, after so many years of comparative confusion, of a really satisfactory description of the rise of buoyant plumes. Over twenty formulae for calculating plume rise have been published since 1950 and none of these have been universally accepted. Now Briggs has carried out a very thorough examination of most of the available data and with the help of dimensional analysis has begun to introduce order for the very first time. The account of this comparatively recent work is given in Chapter 5.

All in all, *Meteorology and atomic energy 1968* may be highly recommended to both seasoned scientists in this field and the new 'entrant' who requires a clear and comprehensive account. The price is very reasonable at \$3.00 and my only regret is that, in this otherwise excellent production, the soft cover will surely not out last the continuous handling the book is destined to receive.

LETTERS TO THE EDITOR

Rain, wind and the aerodynamic characteristics of rain-gauges

We have read this paper¹ with interest and from our own recent field experiments would not disagree with the general conclusions to be drawn from Table II(b), namely that a ground-level gauge catches some 5 per cent more rain than the 5-in Mk 2 copper gauge; that the Mk 3 gauge catches about 3 per cent more than the Mk 2 gauge; that the Mk 4 gauge catches 5 per cent less than the Mk 2 gauge. (All gauges, except the ground-level gauge, have the standard exposure with rim at 1 ft (30 cm.). However, the paper raises more problems than it solves in so far as the reported wind-tunnel tests indicate that, of the Mk 2, Mk 3 and Mk 4 gauges, the latter presented the 'best' profile in so far as it caused the least disturbance to the wind field. As the authors suggest, the field result is therefore inconsistent with the wind-tunnel observations, implying that the latter are of doubtful value, certainly without additional refinement. More seriously, they lead to conclusions which field experience does not support. The Mk 4 gauge was adopted in preference to the Mk 3 gauge because the latter during field trials showed a significantly higher catch than the Mk 2 and the better profile of the Mk 4 was therefore logically expected to lead to an even higher catch, perhaps approaching that of a ground-level gauge. Further, the Mk 4 costs less to produce than the Mk 3. Needless to say, field experience has been disappointing, particularly as earlier tests of eliminated gauges similar in profile to the Mk 2 and Mk 4 showed a marked trend in favour of the latter.

The only way in which the field trials with the Mk 4 gauge could be made consistent with the wind-tunnel experiments reported here, would be to assume that the Mk 4 gauge is subject to out-splashing losses not compensated by any in-splashing. No evidence has been found that this in fact occurs and it is contrary to the expectation that the internal shape, approximating to that of a wine-glass or tulip, should be the best shape to avoid such losses.

In their second paragraph the authors state that certain differences (between gauges) may not be important to the meteorologist but are very significant to the hydrologist. This is so only in that the meteorologist (and presumably the hydrologist) is firstly concerned with consistency throughout a network as a first step towards accurate measurement. In considering the many measurements which enter into a quantitative water balance in an average catchment, it is as well to bear in mind that the rainfall determination, poor though it may be, is likely to be one of the most (if not the most) reliable observation.

Meteorological Office, Bracknell

A. BLEASDALE N. E. RIDER

REFERENCE

1. ROBINSON, A. C. and RODDA, J. C.; Rain, wind and the aerodynamic characteristics of rain-gauges. *Met. Mag., London*, 98, 1969, p. 113.

551.509.322.7:311.214:629.13:681.3

The comparison of subjective and objective upper air forecasts for aviation (Part I).

Some queries have been made about the term 'polar curve' used in my article on 'Comparison of subjective and objective upper air forecasts for aviation' (*Met. Mag.*, 98, 1969, p. 19). The route represented by 'polar curve' (e.g. Figure 1) is an arbitrary route decided upon in consultation with London/Heathrow Airport, and can be described roughly as a reflection of the rhumb line in the great circle or a route which lies approximately as far north of the great circle as the rhumb line is south of the great circle.

I. H. CHUTER

OFFICIAL PUBLICATION

The following publication has recently been issued: *Tables of surface wind speed and direction over the United Kingdom.*

The 12 tables in this publication have been made possible because the number of stations for which analyses are available has increased. Table I presents average frequencies of wind speeds and of wind directions at 21 selected stations for the period 1950 to 1959. Table II contains means and maxima of the highest hourly wind speeds at 73 stations and Table III presents the means and maxima of the highest monthly gusts. Tables IV to IX give, for 43 anemograph stations, the average number of days in each month and the year on which gust speeds exceeded 33, 40, 50 and 60 knots and the average number of hours in each month and the year with gusts exceeding 33 and 47 knots. Table X consists of monthly and annual average percentage frequencies of hourly mean wind speeds and directions combined. Tables XI and XII give, for hourly mean speeds and gust speeds, maximum values likely to be exceeded only once in 10, 20, 50 and 100 years at 66 anemograph stations. These last two tables are obtained using the Gumbel theory of extreme values and as such present predictions of the extreme values and not, as in the preceding tables analyses of observations.

HONOURS

The following awards to members of the Meteorological Office were announced in the New Year's Honours List, 1969:

O.B.E.

A. J. Willis, Chief Experimental Officer, Training Command, RAF.

M.B.E.

D. F. MacGregor, Shore Engineer, Ocean Weather Ships.

OBITUARY

It is with regret that we have to announce the death of Mr F. F. Harrington (X.O.) on 1 December 1968.

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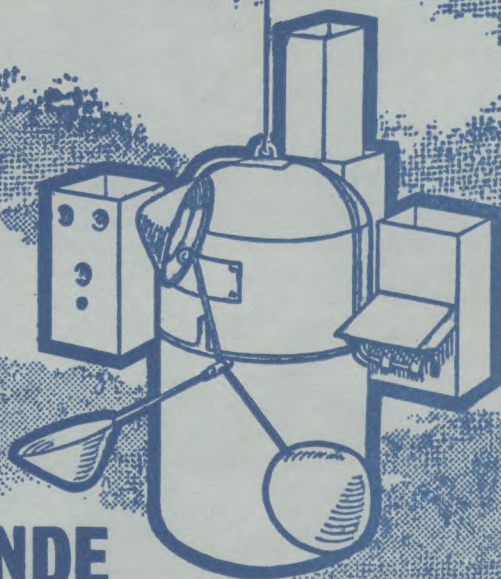
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NOTICES

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Upper air observations at the Seychelles, 1963–64

By P. B. WRIGHT, B.Sc. and R. A. EBDON

This memoir presents the upper air observations made in the Seychelles during the International Indian Ocean Expedition in 1963–64 at a radiosonde station which was set up and operated by the Meteorological Office.

The observations are discussed, and a comparison is made with similar observations from Gan.

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THE METEOROLOGICAL MAGAZINE

Vol. 98, No. 1162, May 1969

551.577.31(624)

DIURNAL VARIATION OF THE INCIDENCE OF MONSOON RAINFALL OVER THE SUDAN (PART II)

By D. E. PEDGLEY

Anti-Locust Research Centre, London

Summary. Using 15 years' data from 17 autographic rain-gauges in the Sudan, the diurnal variation of the incidence of monsoon rainfall has been tabulated by months. The considerable differences in space and time are systematic and reveal clearly defined patterns. These patterns are discussed in terms of the likely mechanisms for rainfall growth and suppression. Day-time convection, leading to a maximum incidence during the afternoon or early evening, is dominant only at places distant from the Ethiopian highlands. Elsewhere, rainfalls are more evenly distributed throughout the day, with weak maxima possible at any time, depending on location and month. However, an early morning maximum occurs widely. The Ethiopian highlands appear to influence the diurnal patterns in several ways and over distances of hundreds of kilometres.

Discussion. (Continued from Part I.¹)

Day-time convection. Growth of convective clouds is favoured not only by instability but also by a moist environment, because mixing of the cloud with a dry environment results in evaporational cooling that reduces the buoyancy. Over the Sudan, the troposphere south of the intertropical convergence zone (ITCZ) is conditionally unstable to great heights, exceeding 200 mb in the south, and it is also potentially unstable to about 500 mb above which level the lapse rate is slightly less than the saturated adiabatic value. Insolation almost always produces some convective clouds, commencing during the morning. Near the ITCZ, the higher temperatures and lower dew-points of the surface air are associated with cloud bases that are higher than those observed at places more than, say, 500 km south of the ITCZ (typically, 3 km above the ground compared with 1 km). Mixing of these clouds with their environment should result in the tops of the great majority not exceeding the break in lapse rate near 500 mb (about 5 km above the ground). Now, calculations² suggest that continental cumulus clouds only 2 km deep are unlikely to give any significant rainfall, and this conclusion

has been substantially confirmed by observation.^{3 4} By contrast, clouds 4 km deep, and with base temperatures about 20°C, must be expected to give light or moderate showers. Moreover, these shower clouds should develop progressively earlier in the day further south from the ITCZ, at least within the first 500 km. For type (i)¹ stations during July, the sharp maxima in late afternoon or early evening at Wadi Halfa, Kareima and Abu Hamed, contrasting with the broad, flat maxima at En Nahud and Wau, probably reflect this difference in timing of onset of daytime showers. This inference is supported by the progressive change in diurnal pattern at En Nahud and Wau during the rainy season, for it is observed that at the extremes of the season, when the ITCZ lies near each station, the maxima become sharper and they shift to late afternoon or early evening. However, the heaviest rains will fall from tall convective clouds penetrating into the upper troposphere, tops then being above, say, 200 mb. Such clouds are more likely both later in the daily heating cycle and further from the surface position of the ITCZ, i.e. where environment humidities throughout the troposphere are sufficiently high to allow the development of clouds whose cores rise almost undiluted by mixing,⁵ and whose core temperatures follow a lapse rate that is almost adiabatic. Near the ITCZ, showers can be expected to fall from only the relatively few clouds whose tops penetrate above 500 mb.

Diurnal variations of both instability and hydrolapse will influence the diurnal distribution of convective rainfall. However, in the absence of direct observations, it is possible only to consider some mechanisms which could lead to diurnal variations of instability and hydrolapse, and then to seek in Table I for evidence supporting the existence of such mechanisms.

The effect on convection of increased afternoon divergence accompanying differential heating of the Nile plains and the Ethiopian highlands has already been discussed. Increased night-time convergence of low-level winds near the ITCZ, although probably contributing to the secondary maximum of rains from stratiform medium clouds around dawn, is unlikely to result in convective storms in the absence of insolation.

Self-propagating storms. Differential horizontal advection should result in an increase of potential instability during the night, when high values of wet-bulb potential temperature are advected from the south in the lower troposphere. Such instability, and the presence of considerable vertical wind-shear, is favourable to the persistence of self-propagating storms on a meso-scale.^{6,7} There is some indication that such storms occur over the Sudan. Thus, during the rainiest months, both Wad Medani and Khartoum have maxima near midnight and minima near midday. At Khartoum this pattern persists throughout the rainy season, whereas at Wad Medani it reverts to a type (ii) pattern at the extremes of the season, with a maximum in the early evening. The infrequency of rainfalls during the middle of the day at both stations suggests both the suppression of afternoon convection and the rarity or ineffectiveness of disturbances. However, there is no doubt that convection is an important source of the late afternoon and evening rains because thunder at Khartoum is particularly frequent at that time of day.^{8 9,10} A lower, but almost constant, incidence of thunder persists until about dawn, suggesting the presence of self-propagating storms, although the higher incidence of rainfall during the night and early hours compared with the evening indicates

that these storms are likely, in general, to be decaying before they reach Khartoum. The diurnal distribution of squalls there is similar to that of thunder,¹⁰ although Freeman¹¹ states that fully developed squall-lines are rare at Khartoum.

It has been observed¹² over western Africa that 'tornadoes', showing many of the properties of self-propagating storms, develop preferentially over high ground. The Ethiopian highlands have been suggested¹³ as the source of widespread thunderstorms affecting the Sudan, and in particular the western slopes are considered^{10,11,14} as being the origin of 'disturbance lines' crossing Khartoum, and observed there by radar. At Kassala, near the potential source region for such storms, Table I shows there is a maximum in rainfall incidence during early evening in most months of the monsoon, weakest in the middle. This is consistent with the occurrence of self-propagating storms. Also, since the distance between Kassala and Khartoum is about 400 km, and since typical storm speeds have been measured¹⁰ by radar at 50–60 km/h from the east, the maximum rainfall incidence at Kassala during the early evening would be consistent with the observed maximum at Khartoum during the night or early hours. Thus, the fragmentary data available suggest that self-propagating storms occur at Khartoum, even though many have probably started to decay, when they would be represented mostly by longer periods of light rain from massive anvil debris moving with the upper easterlies.

At Wad Medani, the diurnal pattern suggests a slightly earlier arrival time than at Khartoum; this is consistent with the former being closer to the Ethiopian highlands. Perhaps the early morning maximum at Kosti is augmented by some of these storms. However, their frequency may well decrease southwards from the ITCZ since Tozi shows a very minor secondary maximum in the early evening. Bhalotra¹⁵ gives the zone 150 to 400 miles south of the ITCZ as being that most frequented by these storms. At El Obeid, the evidence for self-propagating storms is slender. Thus, the diurnal incidence of thunder^{8 10} shows a strong maximum in the late afternoon with a feeble secondary maximum in the early morning. However, the strongest squalls, stated to be associated with westward moving squall-lines, are observed to commence near mid-morning, and this is consistent with observed storm speeds and the distance of El Obeid from the highlands. El Obeid is therefore likely to be near the limit of propagation. This agrees with the findings of an unpublished inquiry by Sissons (quoted by Bhalotra¹⁰) which did not support the idea that squall-lines from Ethiopia could propagate as far as western Africa.

Mid-tropospheric plume from the Ethiopian highlands. The Ethiopian highlands act as a high-level heat source. Warm air, resulting from both insolation and, particularly during the rainiest months, release of latent heat, must therefore be expected to stream downwind as a plume in mid-troposphere. The northern edge of this plume would lie near 15°N, the approximate latitude of the northern tip of the Ethiopian plateau. Below this plume, the low-level south-westerlies would be potentially cooler but beneath its northern edge the temperature differences would decrease or disappear, and the resulting increase in lapse rate would enhance the development of convective clouds. Such a mechanism for the localization of deep convection has been demonstrated by Carlson and Ludlam⁷ for plumes originating over the high

plateaux of Spain and Mexico. It is suggested here that a similar plume exists over the eastern Sudan; its presence would not only explain the peculiar persistence throughout the monsoon of night-time rains at Khartoum (dependent on the topographically determined northern edge of the plume), but also contribute to the suppression of afternoon convection over the Nile plains beneath the plume, by decreasing instability during the afternoon and evening. With easterly components of about 20 km/h in mid-troposphere, the plume's influence can be expected to extend several hundred kilometres across the plains.

Radiational cooling of cloud tops. At the height of the monsoon rains, an Ethiopian plume, topped at perhaps 500 mb, is likely to contain much medium cloud. These clouds could contribute to the night-time falls of light rain over the nearby plains, but their frequency should decrease westwards. They would be affected by the night-time increase of convergence near the ITCZ, and perhaps also by night-time cooling of their tops by loss of radiation. An increase of lapse rate within the cloud would then develop, thereby tending to make it denser, particularly by inducing cellular overturning. Coalescence would probably then be accelerated within localized regions of increased liquid water content. After dawn, direct absorption of insolation would warm and disperse or thin the cloud. In this context, it is interesting to note that Fritz and MacDonald¹⁶ have measured, from an aircraft over the U.S.A., a 20 per cent absorption of insolation by extensive layer clouds with tops near 500 to 400 mb. This effect would also lead to an early morning maximum incidence of rain from medium cloud. Both Kraus¹⁷ and Lavoie¹⁸ argue that this mechanism plays an important role over the open ocean in producing a maximum in the early hours, the former for temperate-latitude oceans and the latter for showers from trade cumulus over the low-latitude Pacific Ocean. In both instances, however, the other diurnal mechanisms discussed here are unlikely to be of significance.

Lavoie, in discussing a number of mechanisms for the diurnal variation of rainfall from tropical oceanic cumulus, concluded that the most important factors were the associated variations in depth and stability of the convective layer. Both of these would be modified by low-level convergence, and there is increasing evidence¹⁹ to show that, at least for the tropical Pacific, convergence associated with the atmospheric thermal tides is able to influence significantly the diurnal rainfall pattern, leading to maxima around sunrise and sunset. The first maximum has been observed at some Pacific islands, and it is tempting to consider the dawn rains of the Sudan as being attributable, at least in part, to a tidal effect extending to medium levels. Certainly the widespread occurrence of dawn rains over northern Africa south of the ITCZ, and elsewhere, suggests the presence of a global-scale mechanism related to the daily solar cycle.

Sea-breeze. At Port Sudan, monsoon rainfall is slight, but there is a pronounced afternoon maximum, flat in July, although with a more definite early afternoon peak in August. Both effects suggest the suppression of convection, although at Port Sudan this is more likely to be a result of low-level advection of cool air by the sea-breeze rather than of subsidence associated with heating of the Ethiopian highlands. Whereas both thunderstorm and squall incidence have maxima during the late afternoon,²⁰ confirming that

the rains at that time are essentially convective in origin, the secondary maximum near midnight is not associated with thunder. These night-time rains probably fall from medium clouds which, however, are much less common around dawn than at, say, Wau or En Nahud. They may well originate as storms that developed earlier over the Asir plateau of Saudi Arabia, the upper parts having drifted in the easterly winds aloft.

Conclusions. The main point of this study has been to present an analysis of the diurnal incidence of monsoon rainfall over the Sudan, and to show that the variations in this incidence from place to place follow a clearly defined pattern. A number of mechanisms have been suggested to account for the variations in diurnal incidence, most of which have already been discussed for other regions. Although, in the absence of direct observations, it is not possible to prove the existence of these mechanisms over the Sudan, evidence has been presented which suggests that a number of them do in fact exist there. In many of them the Ethiopian highlands play a significant role.

Perhaps the main conclusion is a confirmation that the diurnal incidence of tropical rainfall can vary widely, even over an area that is topographically rather uniform. In addition, the following generalizations can be made concerning rainfall over the Sudan.

- (i) Day-time convection is the dominant control on rain formation only at places distant from the Ethiopian highlands by about 700 km or more. A maximum incidence is then found in the late afternoon or early evening; it is broader (implying earlier onset) further south from the surface position of the ITCZ.
- (ii) Nearer the mountains, the diurnal distribution becomes more even throughout the day, probably a result of the presence of weak disturbances. However, a weak maximum ascribable to day-time convection can still be detected at most places. The weakness of this maximum is probably a result, at least in part, of suppression of convection over the plains caused by afternoon subsidence accompanying the development of a diurnal, large-scale, plains-mountains wind system due to differential heating. Weak suppression also seems to be present at places more distant than 700 km.
- (iii) A weak secondary maximum in the early morning is widespread. Its origin is doubtful but may be complex, involving increases during the night of both potential instability and low-level convergence resulting, respectively, from increased differential advection and from an inertial oscillation of the low-level wind field following the rapid release at dusk of drag caused by day-time small-scale convective turbulence. Medium-level clouds appear to account for most of these early morning falls; these clouds may be cooled and thickened as a result of night-time loss of radiation from their tops. The thermal-tide could also contribute to rains around dawn.
- (iv) An extensive plume of warm air probably develops daily in mid-troposphere over the Ethiopian highlands, streaming downwind across the Nile plains. Such a plume would not only add to the suppression of day-time convection over the nearby plains, but also

enhance the localization of deep convection to beyond its northern edge. This, together with the increased differential advection accompanying the inertial acceleration of the low-level winds after dusk, probably accounts for the notable evening maximum of convective storms in the Khartoum area. The timing of this maximum remains essentially unchanged throughout the rainy season.

- (v) Self-propagating convective storms probably develop over the eastern plains, but more particularly over the western slopes of the Ethiopian highlands, subsequently travelling westwards. Most of these storms seem to decay into periods of lighter rain before reaching the Nile. A few similar rains may also cross the Red Sea from the Asir plateau, to affect the coast of the Sudan around midnight.

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551.591.36(421)

VISIBILITY VARIATIONS AT LONDON/HEATHROW AIRPORT

By J. BRIGGS

Summary. A table is presented for the frequencies of visibility changes in fog at London/Heathrow Airport in periods between four minutes and one hour. The analysis is based on transmissometer records on occasions when visibility was in the range 100–1300 m for periods of three hours or more during June 1965–September 1966.

Best and Fielder¹ used transmissometer records selected from six days in 1956 to study short-period variations of visibility at London/Heathrow Airport. Recently, occasion has arisen to summarize occurrences of visibility below certain limits at Heathrow, and for this project it was necessary to examine some three years of the transmissometer data. Since the data were basically similar to those used by Best and Fielder it seemed worth while to take the opportunity to repeat their analysis for a much larger sample.

For the project which initiated this work, the transmissometer records for the period June 1965 to May 1968 were examined and a note was made of each individual observation—observations being made at four-minute intervals—for which the indicated visibility was 1300 m or less. In view of the amount of material available it was decided to restrict the extension of Best and Fielder's analysis to those occasions between June 1965 and September 1966 when the indicated visibility was below 1300 m for at least three hours. The base-line of the transmissometer during the period concerned was about 200 m (actually 200 yd) so that estimates of visibility below 100 m could not be made with reasonable accuracy, and the selection of fogs studied was therefore further restricted to exclude periods in which the indicated visibility was below 100 m. The final analysis included some 22 periods of fog, totalling over 145 hours of record.

The percentage changes from the initial visibility were tabulated for time intervals of 4, 8, 12 . . . 56, 60 minutes. When all visibilities initially in the range 200–999 m were considered together, the results did not reveal appreciable differences between the occurrences of positive and negative changes, but when the range of initial visibility was subdivided some differences were shown. The lowest sub-range, 200–399 m, had more positive than negative changes whereas the highest sub-ranges, 600–999 m, had broadly similar frequencies of positive and negative values for the smaller percentage changes but fewer large positive than large negative changes. It is apparent that these differences were largely imposed by the analysis conditions—clearly the limit of 1300 m means that a visibility initially at 800 m cannot change upwards by more than 62.5 per cent or an initial 1000 m by more than 30 per cent, whilst the lower limit of 100 m imposes a limit to negative changes of 50 per cent for an initial visibility of 200 m and of 75 per cent for an initial visibility of 400 m. Since the middle range, 400–599 m, was fairly free from the effects of the artificial limits imposed by the analysis, and since this range had about even occurrences of positive and negative changes, it appeared reasonable that actual occurrences of positive and negative changes of visibility are about even throughout the whole range of initial visibility although the occurrences may be recorded unevenly. Accordingly separate analyses of positive and negative changes were abandoned, and Table I was prepared showing percentage changes (increases or decreases) in various visibility ranges and for a selection of time intervals.

TABLE I—PERCENTAGE OF VISIBILITY CHANGES EXCEEDING SPECIFIED PERCENTAGES OF THE INITIAL VISIBILITY

Time interval minutes	Initial visibility range metres	Number of occasions*	Specified percentage of initial visibility									
			10	20	30	40	50	60	70	80	90	100
					<i>per cent</i>							
4	200-399	248	40.3	24.2	16.1	8.9	7.3	5.6	4.0	3.2	2.8	2.8
	400-599	406	23.4	13.1	7.9	6.0	3.9	2.2	2.2	1.0	0.5	0.2
	600-799	318	30.5	10.7	5.7	2.5	1.6	0.0	0.0	0.0	0.0	0.0
	800-999	365	26.8	9.6	5.5	3.0	1.9	1.1	0.3	0.0	0.0	0.0
8	200-399	245	49.4	33.5	20.4	13.5	11.8	9.0	7.8	6.5	4.9	4.9
	400-599	403	30.5	17.1	11.2	7.4	6.2	5.5	2.2	1.5	1.5	1.0
	600-799	318	39.0	21.4	13.5	6.3	5.4	3.1	0.6	0.0	0.0	0.0
	800-999	363	42.1	16.8	7.4	5.0	2.8	1.9	1.1	0.5	0.0	0.0
12	200-399	247	57.9	40.5	26.3	19.4	15.4	13.7	12.5	11.3	10.5	8.9
	400-599	399	35.5	20.3	14.3	10.5	8.0	6.5	5.0	3.0	2.8	2.3
	600-799	315	50.2	23.5	14.0	9.2	6.0	3.2	1.9	1.6	0.3	0.0
	800-999	356	45.5	19.7	9.3	5.6	2.5	1.4	1.1	0.0	0.0	0.0
20	200-399	244	68.8	48.4	38.9	29.5	25.4	22.5	19.7	18.0	17.2	16.4
	400-599	391	46.0	25.8	16.1	12.8	10.0	7.9	5.4	3.6	3.1	2.0
	600-799	308	58.8	30.5	18.5	13.3	7.5	4.5	2.6	0.7	0.3	0.3
	800-999	347	53.3	28.5	14.7	7.8	4.6	2.3	1.4	0.9	0.0	0.0
28	200-399	238	76.5	54.2	43.7	34.5	29.0	25.6	24.0	22.7	19.7	18.9
	400-599	384	51.3	27.6	21.4	16.1	12.5	9.4	7.6	6.0	5.2	4.2
	600-799	298	65.4	37.2	20.8	14.8	9.7	5.7	3.3	0.3	0.0	0.0
	800-999	336	56.3	32.4	20.2	9.8	6.5	3.0	1.8	0.9	0.0	0.0
36	200-399	233	76.8	54.1	43.8	37.3	30.9	28.3	27.0	24.9	21.5	20.6
	400-599	374	56.4	33.4	23.8	18.2	12.6	10.4	9.4	8.0	6.1	3.7
	600-799	291	71.8	39.2	24.4	16.5	11.3	7.6	3.4	1.4	0.7	0.3
	800-999	326	63.8	33.7	19.3	9.5	5.8	4.0	2.1	0.0	0.0	0.0
44	200-399	226	77.0	58.4	47.5	38.5	31.9	29.6	27.0	25.7	23.0	22.1
	400-599	363	58.9	33.3	24.2	18.7	13.5	9.9	8.5	6.9	5.2	4.4
	600-799	284	75.3	43.3	27.5	17.3	10.9	6.3	2.1	1.4	0.0	0.0
	800-999	318	67.6	37.7	24.5	11.3	4.4	1.1	0.4	0.1	0.0	0.0
60	200-399	209	79.4	65.6	51.7	42.1	35.9	32.1	32.1	28.2	26.3	25.1
	400-599	339	64.0	38.6	24.5	19.8	15.6	12.4	9.4	8.3	5.6	4.4
	600-799	267	78.3	49.4	34.5	23.6	12.0	6.7	3.4	1.9	0.7	0.4
	800-999	304	73.0	45.7	29.9	14.5	6.9	3.6	2.6	0.3	0.0	0.0

* From the period June 1965 to September 1966 occasions were selected when visibility was ≤ 1300 m for 3 hours or more and when visibility did not fall below 100 m. Percentage changes were based on initial visibility between 200 and 999 m and changes to below 100 m and above 1300 m were excluded.

The table reflects the effects already discussed and, making allowance for these effects, it seems that there is little real difference between the three highest ranges of visibility, and it is considered reasonable to use the figures for the 400-599 m range as being typical of the whole range from 400-999 m. However, the difference between the 200-399 m and the 400-599 m range is more substantial. This difference can be partly attributed to the increased relative importance at the lower range of factors which are reasonably constant through the two ranges—for example these ranges are near the optimum range for accuracy using the given base-line length and so observational errors should change little through the range 200-599 m. However, it seems likely that the difference between the two lowest ranges may be partly due to more basic physical factors. For visibilities in the region of 200 m most fogs are water-droplet fogs, whereas in the region of 599 m the effects of solid particles are still relatively important. So the increased variability as visibility falls toward 200 m may be due to droplet growth becoming effective on increasing numbers of particles.

The mean changes for time intervals from four minutes up to one hour are indicated in Figures 1 and 2 for the initial visibility ranges of 200–399 m and 400–599 m respectively. The figures show the expected increase in occurrences of larger changes as the time interval increases. Figure 3 is a plot of the 50 per cent probability value against time for the two ranges. Extrapolation back to zero time of the two curves indicates that the probable error of the observations was about 2 per cent of the actual visibility. Moreover, it seems that the probable change in one minute in visibility is about 2.5 per cent of the initial value when this is in the range 400–599 m but is up to 3 per cent of the initial value when this is as low as 200–399 m.

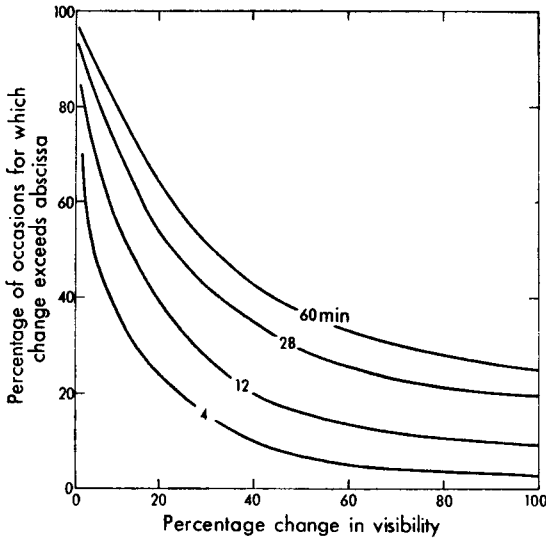


FIGURE 1—CHANGES IN VISIBILITY IN SPECIFIED TIME INTERVALS, INITIAL VISIBILITY 200–399 METRES

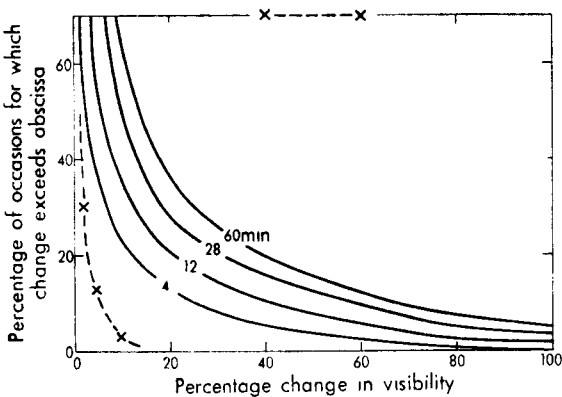


FIGURE 2—CHANGES IN VISIBILITY IN SPECIFIED TIME INTERVALS, INITIAL VISIBILITY 400–599 METRES
x --- x 50-second values (Johannessen²)

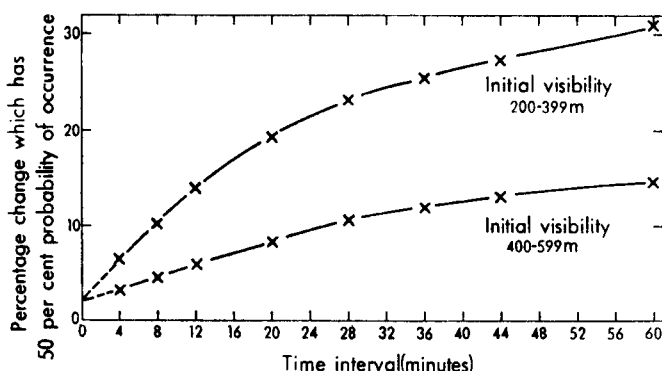


FIGURE 3—CHANGE IN VISIBILITY WHICH HAS 50 PER CENT PROBABILITY OF OCCURRENCE IN A SPECIFIED TIME INTERVAL

As must be expected the results are in good agreement with those of Best and Fielder. It would be of interest to check the general applicability of the figures by comparing the results with similar data for other places but such data are hard to come by. Johannessen² has quoted variabilities of transmissivity over time periods of less than one minute for a transmissometer network at Washington. His values for a time interval of 50 seconds and initial visibility below 1 mile are shown in Figure 2. Ito³ has studied the variability of runway visual range (RVR) at Tokyo Airport and finds that the range of variation in 10 minutes amounts to one-fifth to a half of the runway visual range itself in low RVR conditions. These results are in reasonable agreement with the results presented here, for Figure 1 indicates that 50 per cent of the changes of visibility in 10 minutes are in the range 10 to 50 m when the initial visibility is 200 m, but some 15 per cent of the 10-minute changes exceed 100 m.

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A RELATIONSHIP BETWEEN MINIMUM AIR TEMPERATURES AND DURATION OF FROST IN LATE SPRING

By J. COCHRANE

During April and May most frosts are not accompanied by winds exceeding five knots, and are associated with a diurnal temperature curve of an approximately sinusoidal form.

It would be reasonable to expect that the period of time with temperature below 32°F would increase as minimum temperature decreased, so an attempt has been made to establish a relationship between these factors by examining hourly temperature data for the months of April and May from 1958 to 1967 for three stations — Mildenhall, Gatwick and Pershore.

Most of the original data were in degrees Fahrenheit and this scale has been used in the analysis. Approximate Celsius equivalents are given in parenthesis, where appropriate, but tests and standard errors apply only to the results quoted in Fahrenheit.

All nights with freezing temperatures were considered, irrespective of cloud cover variations. In this article the duration of frost (in hours) was taken as the number of hourly observations with a temperature of 32°F (0°C) or below. As many of the original data were expressed in whole degrees, a few occasions where temperatures were as high as 32.4°F (0.2°C) have been included in the analysis. Occasions when the minimum temperature qualified, but no single observation was as low as 32°F — i.e. when the temperature fell to freezing-point between two observations — were given a nominal duration of one hour.

The relationship between minimum temperature and duration of frost on 95 nights with freezing temperatures is shown in Table I.

TABLE I—MEAN DURATION OF FROST ASSOCIATED WITH DEGREES OF FROST IN APRIL AND MAY

Degrees of frost		Mean duration of frost hours	Number of occasions*
<i>Fahrenheit</i>	<i>Celsius</i>		
0	0	1.0	10
1	0.5	1.8	21
2	1.1	3.6	13
3	1.7	3.9	17
4	2.2	6.0	11
5	2.8	6.4	8
6	3.3	8.0	7
7	3.9	8.7	4
8	4.4	11.0	1
9	5.0	8.3	3

* Number of nights with freezing temperatures at Mildenhall, Gatwick and Pershore during 1958-67.

The correlation coefficient between degrees of frost and duration is 0.98 and regression analysis gives (see Figure 1) :

$$D = 1.06 (32 - T_{\min}) + 1.06$$

$$[D = 1.90 (0 - T_{\min}) + 1.06 \text{ for temperatures in } ^\circ\text{C}]$$

where D = duration in hours and T_{\min} = night minimum temperature.

The regression is significant at the 0.001 per cent level with standard errors of regression coefficient of 0.03 and of the estimate D , of 0.50.

For practical purposes the relationship may be conveniently reduced to

$$D = 1 \text{ hour per degF of frost} + 1 \text{ hour.}$$

$$[D = 2 \text{ hours per degC of frost} + 1 \text{ hour.}]$$

This predictor was tested by calculating the expected duration of frost in April and May for individual nights at Boscombe Down, Waddington and Elmdon and comparing this with the actual duration (as defined above). The distribution of errors (predicted - actual) is given in Table II.

TABLE II—FREQUENCY OF ERRORS IN PREDICTED DURATION OF FROST IN APRIL AND MAY AT SELECTED STATIONS
Difference (predicted - actual) in hours

	-5	-4	-3	-2	-1	0	1	2	3
	number of occasions								
Boscombe Down (1957-67)	1	3		8	5	3	2		
Waddington (1949-67)	1	1	3	1	6	9	8		1
Elmdon (1950-67)		1	3	7	11	28	24	10	2
All stations	2	5	6	8	25	42	35	12	3

The mean (observed) duration of frost is 4 hours, the average error, irrespective of sign, is approximately $1\frac{1}{2}$ hours and almost 75 per cent of the errors lie within the range ± 1 hour.

The method cannot give good results for frosts accompanied by wind (relatively infrequent in April and almost unknown in the British Isles in May) and a few occasions where a sinusoidal temperature curve obviously did not exist have been ignored in this check. However, several occasions where the observations indicated a rather flattened curve were included and it is likely that restricting the check to purely radiation nights would give an even closer agreement.

Nevertheless, the size of error involved is sufficiently small for the method to give results which could be useful in planning for frost protection in late spring, but caution should be exercised in applying the results to areas of particularly sandy or very moist soils.

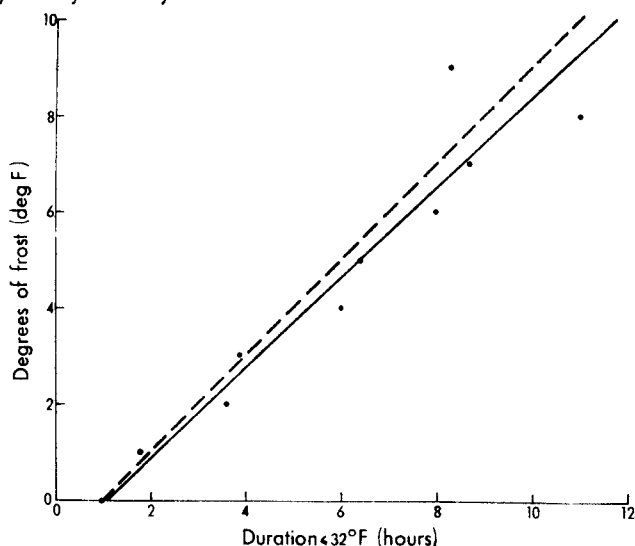


FIGURE 1—REGRESSION OF DURATION ON DEGREES OF FROST

— — — — — $D = 1 \text{ hour per deg F of frost} + 1 \text{ hour}$
 ————— $D = 1.06 (32 - T_{\min}) + 1.06 \text{ hours}$

It is theoretically probable — and in fact Figure 1 hints — that the relationship does not remain linear for minimum temperatures below about 25°F (-4°C), and extrapolation for temperatures outside the range of this analysis would not be justified unless a much larger margin of error could be accepted.

Acknowledgement. I am indebted to Messrs A. J. Heasman and R. P. Rumney for work on the extraction of basic data.

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PREDICTION OF MONTHLY RAINFALL OVER ENGLAND AND WALES FROM 15-DAY AND MONTHLY MEAN TROUGHS AT 500 mb

By R. MURRAY

Summary. An examination is made of the positions of mean troughs at 500 mb on the 15-day time-scale from America to Europe in connection with predicting monthly rainfall over England and Wales. Although the 15-day means are not as helpful as the 30-day mean troughs in monthly rainfall prediction, consideration of mean troughs on both time-scales appears to improve the monthly rainfall forecasts.

Introduction. In a recent paper Ratcliffe¹ developed simple synoptic criteria relating the positions of the American and European 500-mb monthly mean troughs at 50°N to monthly rainfall over England and Wales in the following month. It was thought desirable to investigate whether the prediction of monthly rainfall would be improved further by taking account of 15-day mean troughs at 50°N as well as the monthly mean trough positions. For convenience in computation the mean data were for three pentads from 1 January to 13 August and from 3 September to 31 December, but for four pentads from 14 August to 2 September.

Empirically derived criteria concerning the longitudes of the mean troughs were used by Ratcliffe¹ for predicting rainfall one month ahead during the April–August period (prediction for months May–September); slightly different criteria were used for the September–November period (prediction for months October–December), and for the December–March period (prediction for months January–April). In this note these criteria were applied to the 15-day mean trough positions for the period 1949–66.

Here F_1 , F_2 and F_m have the following meanings :

- F_1 = prediction based on the positions of the 15-day mean troughs at 500 mb in the first half of month,
- F_2 = prediction based on the positions of the 15-day mean troughs at 500 mb in the second half of month,
- F_m = prediction based on the positions of the monthly mean troughs at 500 mb.

Period April–August. There were only 12 occasions when F_1 , F_2 and F_m all suggested the same prediction. It might be thought that the accuracy of such predictions would be high. In fact the mean score for these 12 cases is 1.8 compared with 1.7 for the 77 cases given in Ratcliffe's Table I. The scoring system used here is the one employed in the Synoptic Climatology Branch of the Meteorological Office (see Freeman²). In this system a correct forecast is allocated 4 points. An incorrect forecast of average rainfall is given – 2 points. A forecast of below (or above) average rainfall is given 0 or – 4 points if it is one or two terciles in error respectively. Over a long period forecasts no better than chance would give a zero score. Forecasts with mean scores greater than about 1 are generally satisfactory and those with mean scores greater than 2 are usually considered to be very good.

It is of interest that on occasions when F_m could not be made there were no occasions when F_1 and F_2 were in agreement. However, on six occasions F_m was made, yet neither F_1 nor F_2 could be made since the half-monthly

troughs were not located in the proper longitude zone near the British Isles (five of these forecasts were correct). There were several other possible combinations of F_m , F_1 and F_2 (e.g. no F_m , F_1 and F_2 different), but in general these separate classes involved quite small numbers. Nevertheless it was reasonable to combine some categories, with the results as indicated in Table I.

TABLE I—MEAN SCORES ACHIEVED WITH SPECIFIED PREDICTIVE CONDITIONS IN 1949-66 DURING THE PERIODS (a) APRIL-AUGUST, (b) SEPTEMBER-NOVEMBER AND (c) DECEMBER-MARCH; IN EACH PERIOD FORECASTS ARE FOR THE FOLLOWING CALENDAR MONTH

Type	Period (a)		Period (b)		Period (c)	
	Number of forecasts	Mean score	Number of forecasts	Mean score	Number of forecasts	Mean score
1. F_m and F_1 agree, no F_2 or it disagrees	16	2.2	14	1.5	6	1.3
2. F_m and F_2 agree, no F_1 or it disagrees	15	1.1	5	4.0	7	4.0
3. F_m and F_1 or F_2 or both agree	43	1.7	23	1.8	23	2.2
4. F_1 only	63	0.9	30	0.1	35	1.0
5. F_2 only	53	0.5	32	0.4	27	0.6
6. F_m only (i.e. Ratcliffe's procedure)	77	1.7	43	1.5	49	1.0

From Table I (column (a)) it is seen that forecasts on the basis of F_1 only (type 4) or F_2 only (type 5) are generally inferior to F_m . There is a suggestion that the trough positions in the first half of the month are at least as important as trough positions in the second half of the month (compare types 1 and 4 with 2 and 5).

Examination of the contingency tables from which the mean scores of section (a) of Table I were obtained shows quite clearly that the main success comes from the prediction of the wet tercile R_3 (R_3 = wet, R_2 = average, R_1 = dry). For example, in type 1 the 8 forecasts of R_3 were all correct; in type 2 the 6 forecasts of R_3 resulted in 5 R_3 and 1 R_2 months; in type 3 the 20 forecasts of R_3 were followed by 15 R_3 and 5 R_2 months. In none of these three types were the R_2 or R_1 forecasts particularly successful. The detailed data used in type 3 are shown in Table II. The chi-square value is about 15 which implies significance at the 0.5 per cent level.

TABLE II—RELATION BETWEEN THE POSITIONS OF MEAN TROUGHS AT 500 mb IN A MONTH DURING PERIOD APRIL-AUGUST AND THE RAINFALL OVER ENGLAND AND WALES IN THE FOLLOWING CALENDAR MONTH. PREDICTIONS WERE MADE WHEN THE MONTHLY MEAN TROUGH POSITION AGREES WITH EITHER OR BOTH 15-DAY MEAN TROUGH POSITIONS, AND TROUGHS EXIST BETWEEN 20°W AND 25°E

Actual England and Wales rainfall in following months (terciles)	A	Trough exists between 20°W and 25°E but neither A nor B satisfied.		B
	Troughs at or west of 65°W* and between 20°W and 5°E*.			Troughs 45°-65°W* and 5°E*-25°E.
	Forecast R_3 (wet)	Forecast R_2 (average)		Forecast R_1 (dry)
Actual R_3	15	1		4
Actual R_2	5	4		4
Actual R_1	0	4		6

* Following Ratcliffe,¹ if trough is exactly on one of these longitudes, consider only the other trough. If both troughs are marginal, forecast normal.

Period September–November. There were no cases where both F_1 and F_2 agreed whilst F_m was different or not applicable. Nor were there any cases with F_1 , F_2 and F_m all different. However, on six occasions F_1 , F_2 and F_m were all in agreement but surprisingly only one forecast was fully correct. An interesting case arose in which there was no F_m (i.e. the monthly mean trough was not in a suitable position) but F_1 and F_2 differed (i.e. the 15-day European troughs existed). In 14 examples of this type results were quite useless; indeed much better forecasts would have been made by forecasting the opposite rainfall classes when R_3 and R_1 were indicated by F_1 or F_2 .

The mean scores which applied to specified forecasts categories are given in Table I. It is clear that forecasting monthly rainfall on the basis of the mean trough positions in either the first half- or the second half-month is not helpful (see types 4 and 5). The types 2 and 3 suggest that rather better forecasts were made when some account was taken of the 15-day mean trough positions as well as of monthly trough positions. However, type 2 consisted of only four cases and the mean score must therefore be regarded as fortuitous. Even type 3 consisted of rather few cases.

Period December–March. On two occasions F_1 and F_2 were in agreement but no F_m applied; no forecast was correct. There were no occasions when F_1 and F_2 agreed and each differed from F_m . On five occasions the only possible prediction on the basis of trough positions was on the first half-month data; the forecasts were all correct. On the other hand, each of the three predictions made on the basis of the second half-month trough positions (i.e. F_2 but no F_1 , F_m) was in error by one tercile. The categories referred to in the preceding two sections under (a) and (b) in Table I are given under (c) in the same table.

Predictions made on the basis of mean trough positions in the first half of the month (i.e. type 4 which takes no account of the whole month or the second half-month positions) were about as accurate as forecasts on the basis of the whole months trough positions (i.e. type 6). However, type 5 predictions were marginally inferior to both types 4 and 6. Types 2 and 3 predictions gave the best results, although the exceptional results under type 2 cannot be regarded as typical in view of the smallness of the sample. The occasions which made up the type 3 cases are given in Table III. The data are insufficient for statistical testing, but it is of interest that the chi-square value is about 16 which suggests that the results are significant at the 0.5 per cent level.

Conclusions. Applying Ratcliffe's criteria for monthly mean 500-mb positions at 50°N to 15-day mean trough positions, does not in general result in materially better forecasts of monthly rainfall for England and Wales than are given by considerations of monthly mean trough positions alone. This result is perhaps not surprising in view of the fact that the Ratcliffe method was developed on monthly means. A similar method developed on 15-day means with the specific objective of predicting monthly mean rainfall would no doubt be based on rather different trough boundaries in the different seasons, and it might be expected to apply with more success than the procedure used here. Furthermore, there is the possibility of the existence of fluctuations in atmospheric circulation with periods around a

TABLE III—RELATION BETWEEN THE POSITIONS OF MEAN TROUGHS AT 500 mb IN A MONTH DURING PERIOD DECEMBER–MARCH AND THE RAINFALL OVER ENGLAND AND WALES IN THE FOLLOWING CALENDAR MONTH. PREDICTIONS MADE WHEN THE MONTHLY MEAN TROUGH POSITION AGREES WITH EITHER OR BOTH 15-DAY MEAN TROUGH POSITIONS, AND MEAN TROUGHS EXIST BETWEEN

Actual England and Wales rainfall in following months (terciles)	20°W AND 25°E		
	A Troughs at or west of 75°W* and between 20°W and 5°E*. Forecast R_3 (wet)	Trough exists between 20°W and 25°E but neither A nor B satisfied. Forecast R_2 (average)	B Troughs 50°–75°W* and 5°E*–25°E. Forecast R_1 (dry)
Actual R_3	3	2	1
Actual R_2	1	5	0
Actual R_1	0	3	8

* Following Ratcliffe,¹ if trough is exactly on one of these longitudes consider only the other trough. If both troughs are exactly marginal, forecast normal.

month, as suggested, for example, by a table of synoptic 'singularities' presented by Lamb,³ in which the dates of several singularities tend to be separated by intervals of roughly a month. If such 30-day fluctuations occurred at all widely in atmospheric processes then clearly 15-day means could be seriously affected by them; some features on the 15-day time-scale might not persist owing to domination by the 30-day wave. However, there is no conclusive evidence in this study that the smaller success achieved in using 15-day rather than 30-day means for predicting rainfall on the monthly time-scale can really be attributed to the existence of atmospheric oscillations with periods about 30 days.

There are, nevertheless, some combinations of 15-day and monthly mean trough positions which tend to improve the rainfall predictions. For the April–August period, predictions of wet months are very successful when the monthly and at least one half-monthly trough indicator are in agreement. For the September–November period there are apparently marginally better predictions when the monthly and at least one half-monthly trough indicator agree, especially when the second half-monthly and monthly predictions are in agreement. However, the sample is too small for firm conclusions on this point. Finally, for the December–March period, there is a definite indication that the forecasts are more accurate when at least one of the half-monthly predictions, especially when this refers to the second half of the month, agrees with the prediction made from the monthly mean trough positions.

It is likely that 15-day mean trough positions at 500 mb will prove useful in predicting rainfall over 15-day periods. However, progress in the examination of rainfall prediction on this time-scale awaits the completion of the data processing of daily rainfall from stations selected to represent rainfall over England and Wales.

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THE ONSET OF THE INDIAN SOUTH-WEST MONSOON AND EXTRATROPICAL 500-mb TROUGH AND RIDGE PATTERNS OVER EUROPE AND ASIA

By P. D. de la MOTHE and P. B. WRIGHT

Summary. The 500-mb trough and ridge patterns over Europe and Asia are examined in order to seek a relationship with the onset of the Indian south-west monsoon. In particular the behaviour of the Asian ridge and the wavelength variations across it are studied. It is demonstrated that these variations in association with a mean trough at 500 mb near longitude 75°E in middle latitudes are closely linked with the reversal of wind at 200 mb over northern India and the onset of the south-west monsoon.

Introduction. The onset of the Indian south-west monsoon in late May/early June has been extensively studied from many points of view, particularly since the beginning of what might be termed the aerological era, roughly 1945, and it has long been recognized that the onset and withdrawal of the monsoon are part of general circulation changes occurring in the tropical and subtropical zones. This has been amply demonstrated by many authors, notably Sutcliffe and Bannon,¹ Yeh, Dao and Li,² Lockwood³ and Wright.⁴

However, in spite of availability of substantial middle- and upper-tropospheric data, not much attention has been paid to relationships which are known to exist between the onset of the monsoon and changes in the circumpolar westerlies of middle and high latitudes. Furthermore, the studies made so far have not generally covered a long sample of years. In some cases, data for only one or two years have been examined.

One of the earliest investigations was that of Yin.⁵ This was a comprehensive study of the monsoon in 1946 with particular reference to the 500 mb flow and associated jet fluctuations in northern latitudes. Yin first demonstrated that the onset of the monsoon was related to the northward shift of a low-latitude westerly jet. The northward movement of this jet, from the south to the north of the Himalayas, is linked with a shift of a mean trough from about 90°E to near 80°E. He also showed that the movement of the jet was correlated in time with a general rearrangement of the long-wave pattern in the northern hemisphere.

Sutcliffe and Bannon¹ suggested that conditions in middle latitudes may be relevant to the monsoon process, since they 'are known to show very large variations from year to year over Europe between extremes of persistent blocking and progressive westerlies.'

Flohn⁶ considered that a factor of importance to the onset of the monsoon was the formation of a mean trough near 68°E correlated with a west-north-westerly flow over central and eastern Europe.

Ramaswamy⁷ published 15-day mean 500-mb charts associated with an abnormally early and late onset of the monsoon, but the major part of his work^{8,9} showed that monsoon 'breaks' were related to 500-mb middle-latitude patterns over Eurasia.

In the present work it was decided to look for a relationship between the onset of the monsoon and the pentad(5-day period)-mean trough and ridge positions at 500 mb over the eastern hemisphere between latitudes 40° and 70°N during April, May and June of the years 1949-66.

First, a study was made of the 16-year (1949–64) average positions, and then individual years were considered.

Seasonal variations in 16-year average positions of troughs and ridges. The 16-year average of the positions of the 500-mb pentad-mean troughs and ridges at 50°N shows several marked changes occurring in the Eurasian sector during the first six months of the year (Figure 1, reproduced from de la Mothe¹⁰).

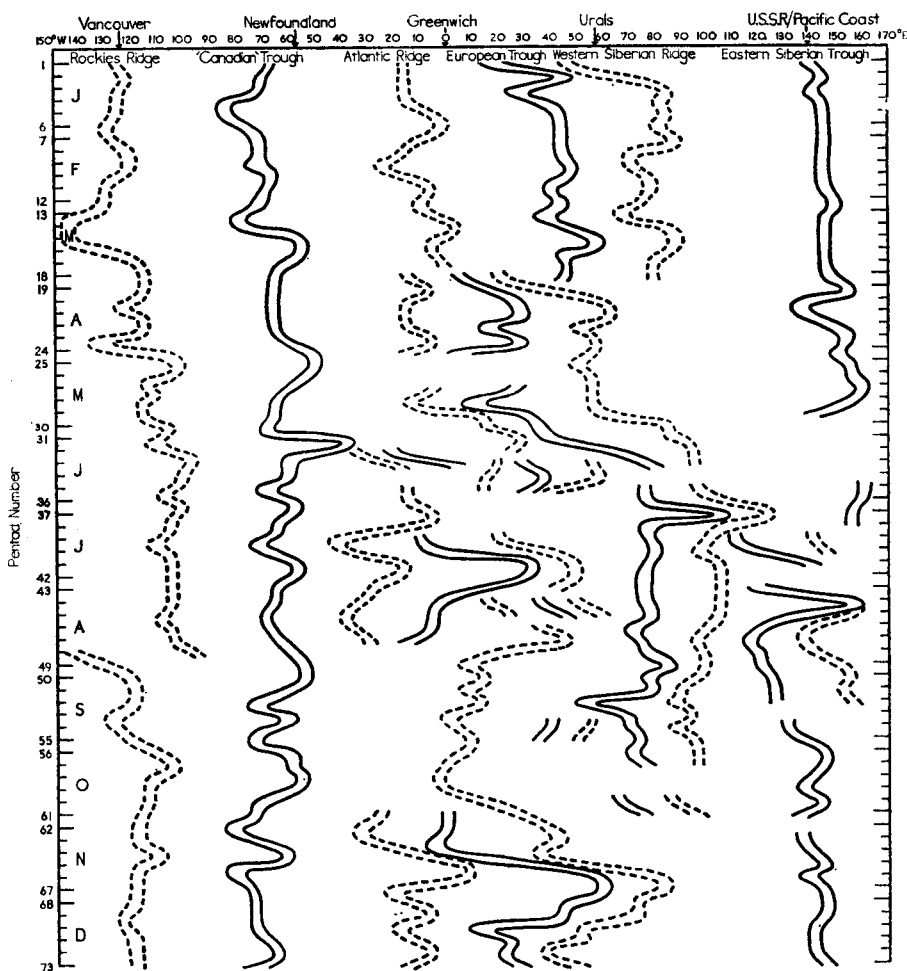


FIGURE 1—AVERAGE POSITIONS OF PENTAD-MEAN TROUGHS AND RIDGES AT 500 mb AROUND 50°N. PERIOD 1949–64

During January to March the Asian (western Siberian) ridge lies in the sector 70°–90°E; there is a deep trough at 140°–150°E, and a shallower trough (the European trough) between 30° and 50°E. In pentad 1–5 April a change occurs, and by 6–10 April a new régime has become established; the Asian ridge is now at 50°–60°E, and the European trough is shallow and

fluctuating between 10° and 30°E . The deep trough over eastern Asia, however, has moved slightly eastwards to between 150° and 160°E . This régime persists until 21–25 May.

In pentad 26–30 May another marked change occurs. The deep trough over eastern Asia, after filling gradually during the spring, moves eastwards into the Pacific. The Asian ridge moves east to about 90°E , and the trough over Europe progresses eastwards reaching longitude 70°E in pentad 5–9 June.

Thus there are two major changes. The first is in early April, the second in late May, and both changes occur at about the same time as those taking place in the tropical flow patterns described by Wright.⁴ The first change in April corresponds to the decrease in the 200-mb zonal component at Bombay, while the second relates to the seasonal rearrangement of tropical patterns which is associated with the onset of the monsoon.

The mean trough which becomes established near 70° – 75°E in pentad 5–9 June remains near these longitudes throughout the monsoon period, thus replacing a mean ridge which was noticeable in the winter up to the end of March.

This particular change is associated with a general decrease in wavelength, since one or more new subsidiary mean troughs and ridges are apparent at this time and remain a feature of the summer season around the hemisphere.

It is worth noting that the date of the establishment of the mean trough near 70° – 75°E , i.e. pentad 5–9 June, is coincident with the average date of the onset of the monsoon over the west coast of India, as derived by Ramdas¹¹ *et alii*.

Seasonal variations of the 16-year average wavelength. In a previous note by de la Mothe,¹⁰ it was suggested that the wavelength variations of the mean flow at 500 mb in middle latitudes could be related to seasonal circulation changes in adjacent sectors of the hemisphere. The graph showing wavelength variations across the Asian ridge is reproduced in Figure 2. There are once again two clear and well-marked changes, one in the first half of April, the other in late May/early June. Between these two distinct periods of change there is an intermediate period when the wavelength across the Asian ridge, instead of decreasing, shows an average increase from 81° of longitude in pentad 16–20 April to 97° in pentad 16–20 May. Subsequently, there is a dramatic shortening of mean wavelength to 65° in pentad 31 May–4 June. Thus, between the winter régime of January, February and March and the summer régime of June, July and August, there are clearly two profound changes of the long-wave pattern in the Eurasian sector of the hemisphere.

It is worth noting that as far as May and June are concerned the wavelength variations agree with and confirm, over a longer period, those shown in the work of Yin⁵ and also Yeh, Dao and Li.² These authors reproduced trough–ridge diagrams, for 1946 and 1956 respectively, showing variations of pentad-mean 500-mb contour heights between latitudes 40° and 70°N as functions of longitude and time. The diagrams clearly show the maintenance, or slight increase, of wavelength across the Asian ridge during May prior to the breakdown of the pattern at the end of May, so that by early June a new régime of shorter wavelengths prevails.

The foregoing suggests that a study of individual years would be justified.

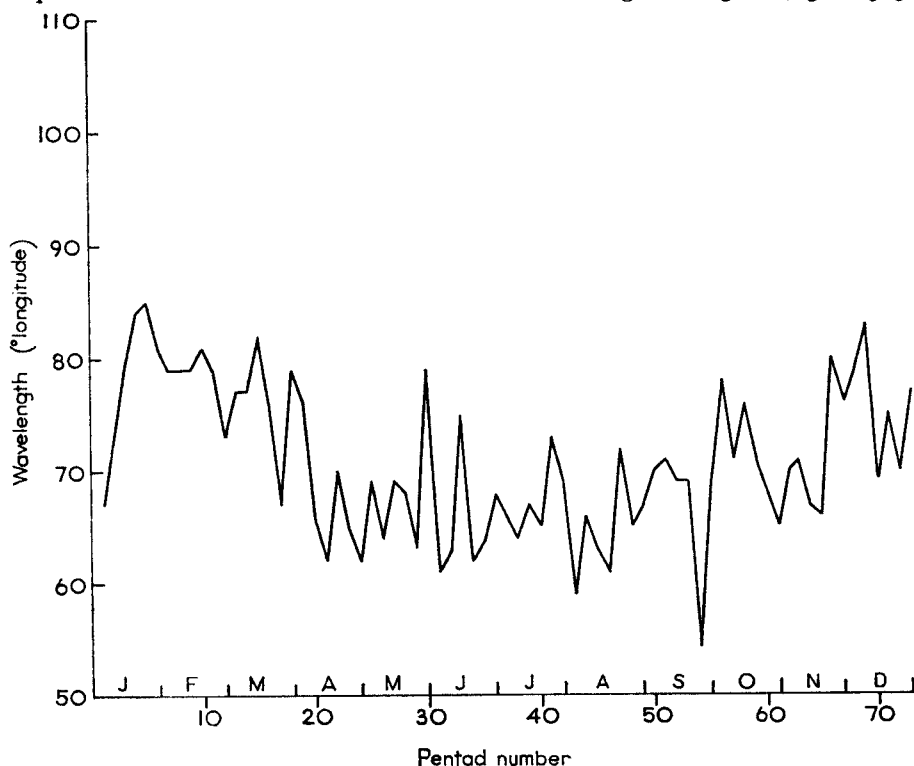


FIGURE 2—AVERAGE WAVELENGTH ACROSS ASIAN RIDGE (500 mb) AT 50°N.
PERIOD 1949-64

Seasonal variations in positions of troughs and ridges during individual years. To study each year separately a preliminary examination was made of the trough-ridge positions around latitude 50°N. However, it soon became apparent that the use of a single latitude alone was unsatisfactory, mainly because the eastward flow of troughs and ridges from pentad to pentad trended to obliterate longer-term changes.

Therefore, to extend the investigation to all latitudes, circumpolar 500-mb contour charts were produced for the northern hemisphere to latitude 35°-40°N, covering May and June of each year, 1949-66. As Yin⁵ and others have stressed the importance of the Himalayan/Tibetan plateau in connection with circulation changes occurring at the time of the onset of the monsoon, the high ground of the plateau above 10 000 ft (3 km) was marked on each of the 500-mb pentad charts. Next, the advance of the monsoon boundary at the surface (northern limit of monsoon or NLM) was plotted as a daily position. The data for this were taken from the *Indian Daily Weather Report*^{1,2} which since 1956 has published daily 1.5-km flow charts showing the NLM. For the period 1949-55 it was necessary to examine the 1.5-km flow charts, from which, with the aid of the synoptic review and relevant rainfall data, a reasonably accurate position of the NLM was derived.

From consideration of the wavelength changes peculiar to May and June, and bearing in mind some of the factors deemed important by previous authors, it was decided that the following features should be considered when examining the 500-mb pentad-mean contour charts for each individual year :

- (i) The maintenance or slight increase of mean wavelength across the Asian ridge during late April and May leading to a sudden and dramatic increase in wavelength about the end of May.
- (ii) The decrease of wavelength likely to be associated with the formation of a trough fluctuating between 70° and 80°E, on average near 75°E (i.e. just west of the Himalayas), and possibly extending northwards to the polar vortex, or at any rate to high latitudes.
- (iii) An assessment of the general character of the flow over Europe and western Asia between the time of occurrence of (i) and (ii) and the onset of the monsoon, i.e. whether zonal or meridional flow prevails, obtained subjectively by an examination of the sector from 40°–70°N between Greenwich and 90°E. This assessment is given in Table I.

TABLE I—SUBJECTIVE ASSESSMENT OF 500-mb FLOW OVER EUROPE AND WESTERN ASIA PRIOR TO AND AT TIME OF MONSOON ONSET

Year	Assessment	Year	Assessment
1949	Meridional	1958	Meridional
1950	Zonal	1959	Zonal, becoming meridional
1951	Meridional in west, zonal in east	1960	Meridional
1952	Meridional	1961	Zonal
1953	Meridional	1962	Zonal, becoming meridional
1954	Meridional	1963	Meridional in west, zonal in east
1955	Meridional	1964	Meridional, becoming zonal in high latitudes
1956	Weakly zonal, becoming meridional	1965	Zonal, becoming meridional in high latitudes
1957	Zonal	1966	Meridional

The procedure adopted in practice was to measure the wavelengths between the relevant troughs and ridges in the Eurasian sector on each chart using a transparent overlay. Since the latitude zone under consideration was 40°–70°N, it was decided to take measurements along latitude 55°N. As a further aid, trough–ridge diagrams were available for each year at latitude 50°N. In this way, a close study was made of the flow pattern and wavelength changes in latitudes 50°–55°N, which were considered to be reasonably representative of the circumpolar westerlies between 40° and 70°N, at least as far as wavelength measurements were concerned. It must be pointed out here that, for a given pentad of the year, mean wavelengths observed on individual pentad charts are often appreciably different from wavelengths measured on a long-period mean chart for the same pentad. This is a natural result of the fact that in the longer-term averaging process, many of the minor oscillations are smoothed out or removed.

The dates of the various changes were found and Figure 3 shows diagrammatically the results of this examination. The diagram presents also the dates of a further event, namely, the collapse of the 200-mb westerlies at Bombay. As previously mentioned, it has been well established by several authors that the disintegration of the 200-mb low-latitude westerlies is closely related to the onset of the monsoon. Therefore it seems logical to link this event with what may be happening at about the same time at 500 mb in middle and high latitudes.

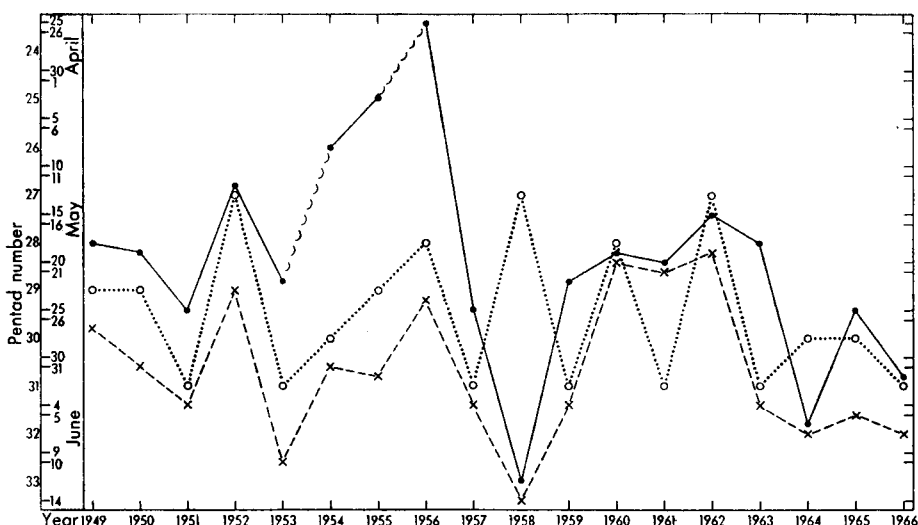


FIGURE 3—DIAGRAMMATIC REPRESENTATIONS OF YEAR-TO-YEAR VARIATIONS

- 1949-53 Date of first easterlies at 200 mb at Aden (Sutcliffe and Bannon¹).
- - - x - - - 1954-55 Middle day of last pentad with a mean westerly component at 200 mb at Aden (Lockwood³).
- o o 1956-66 Date when 200-mb westerly component at Bombay fell below 5 kt (Wright⁴).
- x - - - x Date of major wavelength changes across Asian ridge in middle latitudes.
- x - - - x Date when northern limit of monsoon (NLM) reached 13°N on west coast of India.

For the years 1956-66, the dates shown are those derived by Wright⁴ from running pentad-means of the 200-mb zonal wind component at Bombay. For the period 1949-55, the dates shown are those derived by Sutcliffe and Bannon¹ and by Lockwood.³ These dates, however, refer to chagnes of the 200-mb zonal wind component at Aden. The use of Bombay and Aden 200-mb data on Figure 3 was considered justified because both stations are fairly close in latitude and both are reflecting essentially the same circulation change in their high-level wind data although at slightly different times. A comparison of the overlapping period of the two sets of data shows that both events are clearly part of the same process of change, although the Aden change is generally about a pentad earlier than that at Bombay.

Figure 3 also includes the date of the onset of the monsoon, defined in this instance as the date when the NLM reaches 13°N on the west coast of India.

Discussion. It is clear from Figure 3 that there is a close relationship between the various events. However, certain years require comment.

In 1954 and 1955 the 200-mb changes shown in Figure 3 appear to have occurred much earlier, relative to the other changes, than in the remaining years. This may be the result of the criterion used for these two years in Figure 3; the ten-day mean charts of the 200-mb wind field for 1954-60 published by Lockwood³ suggest that the decrease of Bombay zonal component below 5 kt normally occurs after the last pentad-mean westerly component is observed at Aden.

As regards 1956, the position is not clear. Although the *Indian Daily Weather Report* gives the date of onset of the monsoon as 24 May, as shown in Figure 3, many indications suggest (see p. 311, Wright⁴) that a surge of the monsoon occurred at the beginning of May. Upper tropospheric changes in the tropics support this. However, there was no sign of the formation of a 500-mb trough at 75°E until pentad 16–20 May, and then only rather weakly. It was not until pentad 26–30 May that the wavelengths decreased over a wide sector with the advent of a deeper trough near 75°E. Yeh *et alii*,⁵ who studied 1956 in some detail, confirm this on their trough–ridge diagrams of pentad-mean 500-mb contour heights between 50° and 70°N.

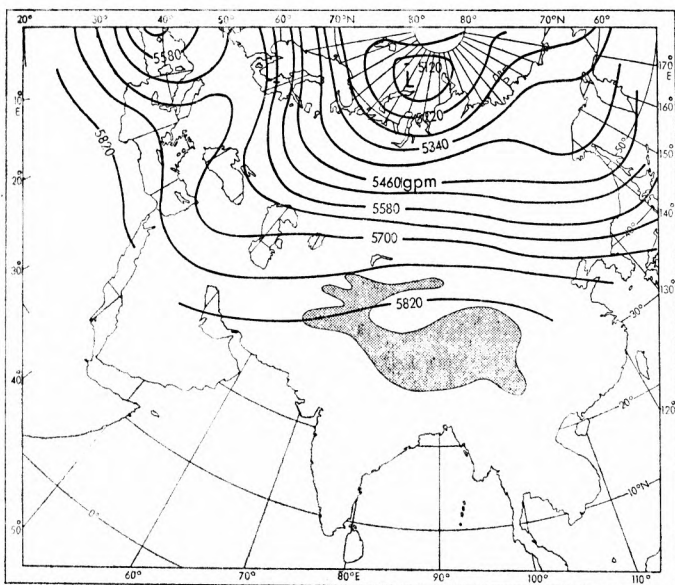
The year 1961 is also puzzling; the temperate-latitude changes appear to have played little part in the monsoon onset.

In 1958, and to a lesser extent 1964, both the onset of the monsoon and the decrease in the Bombay wind component occurred later than the changes at 500 mb. It is notable that 'Relationship III' of Wright,⁴ which related the onset of the monsoon to the change in wind field which occurs during April, also broke down in those years. The present results confirm the suggestion that in those two years there was some other factor which delayed the establishment of the monsoon flow patterns after the middle-latitude 500-mb flow had become favourable for the change.

To sum up, it seems that in 1958 and 1961, and perhaps in 1956 and 1964, the behaviour of the middle-latitude 500-mb flow played little obvious part in the mechanism of the onset of the monsoon. For the majority of years, however, the sequence of events seems to be as follows :

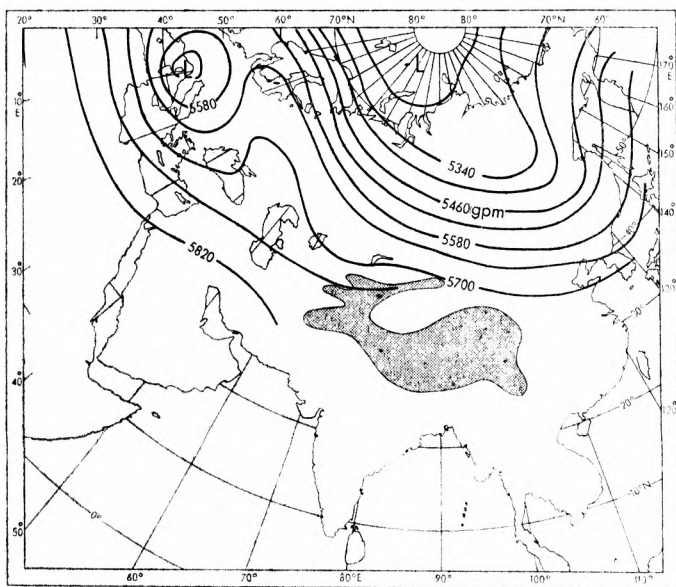
- (i) The 200-mb subtropical westerly jet over northern India collapses and another jet forms just north of the Himalayas.
- (ii) Similarly the 500-mb westerly flow is induced to flow north rather than south of the Himalayas.
- (iii) A mean 500-mb trough becomes established near 75°E, partly orographically imposed, and partly as a result of the seasonal decrease of wavelengths occurring about this time in the circumpolar westerlies.
- (iv) The establishment of this 500-mb mean trough near 75°E, with short wavelengths up- and down-stream, and on average, meridional flow (see Table I), results in a marked southerly component over the Indian subcontinent.
- (v) The advance of the monsoon follows immediately after these events, although in a minority of years it is evident that the 500-mb circumpolar patterns play little part and the underlying mechanism must be some other factor the influence of which is perhaps confined to tropical latitudes, and which also influences the rapid decrease of wind speed at Bombay.

Figures 4–9 show the sequence of events at 500 mb in 1949 which was typical in most respects. Middle-latitude wavelengths which had been long (Figures 4 and 5) decreased considerably in pentad 21–25 May (Figure 6), the 200-mb change having already occurred on 18 May (see Figure 3). The trough is well established and extends northwards to the polar vortex in



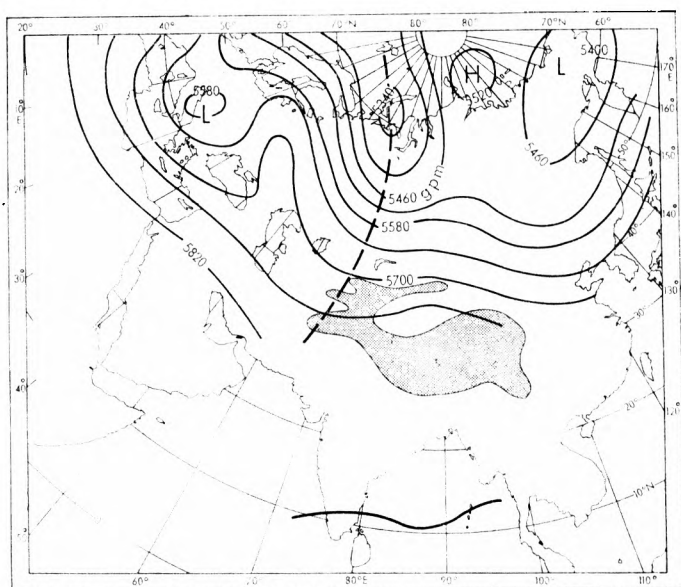
**FIGURE 4—500-mb CONTOUR CHART, PENTAD-MEAN VALUES FOR PENTAD 1-5
MAY 1949**

Stippled area is ground over 10 000 ft in the Himalayas



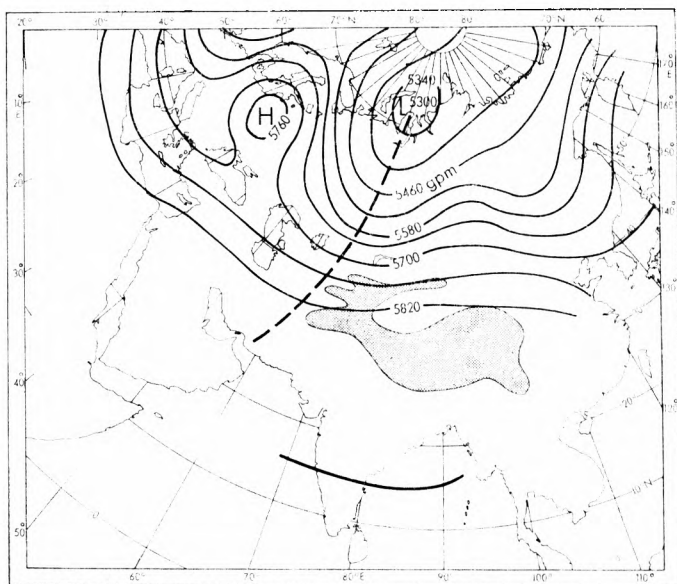
**FIGURE 5—500-mb CONTOUR CHART, PENTAD-MEAN VALUES FOR PENTAD 11-15
MAY 1949**

Stippled area is ground over 10 000 ft in the Himalayas



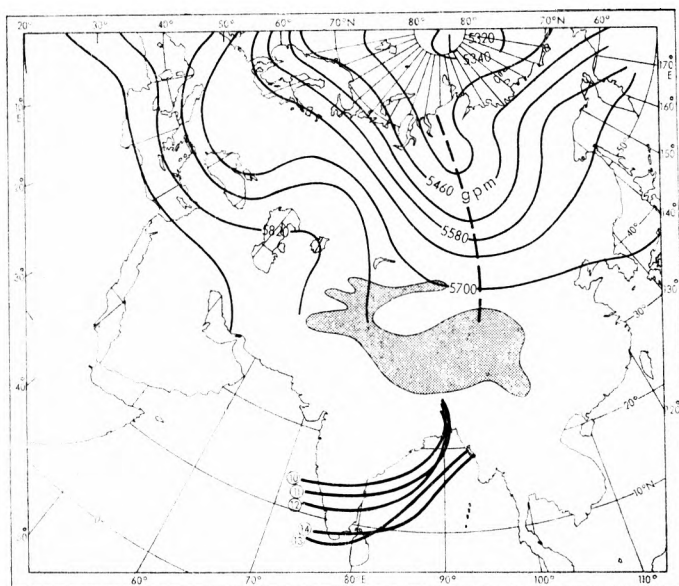
**FIGURE 6—500-mb CONTOUR CHART, PENTAD-MEAN VALUES FOR PENTAD 21-25
MAY 1949**

Stippled area is ground over 10 000 ft in the Himalayas
 ——— NLM boundary on middle day of pentad
 - - - Trough lines



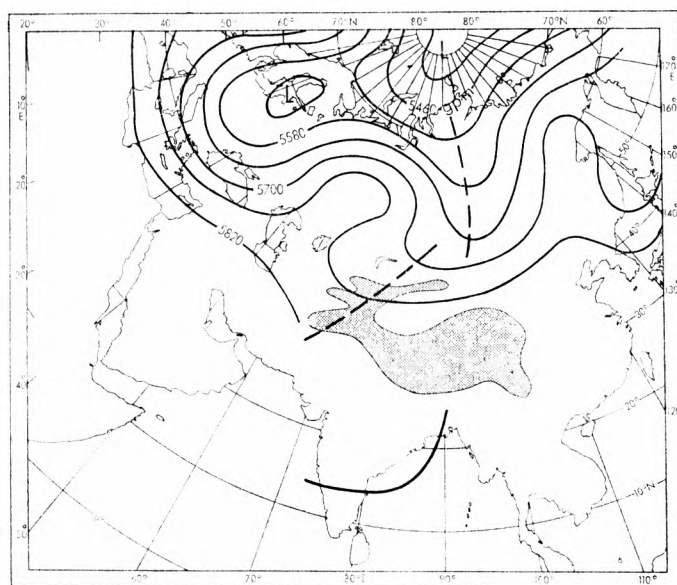
**FIGURE 7—500-mb CONTOUR CHART, PENTAD-MEAN VALUES FOR PENTAD 31
MAY - 4 JUNE 1949**

Stippled area is ground over 10 000 ft in the Himalayas
 ——— NLM boundary on middle day of pentad
 - - - Trough lines



**FIGURE 8—500-mb CONTOUR CHART, PENTAD-MEAN VALUES FOR PENTAD 10-14
JUNE 1949**

Stippled area is ground over 10 000 ft in the Himalayas
 ——— NLM boundary on each day of pentad
 - - - Trough lines



**FIGURE 9—500-mb CONTOUR CHART, PENTAD-MEAN VALUES FOR PENTAD 20-24
JUNE 1949**

Stippled area is ground over 10 000 in the Himalayas
 ——— NLM boundary on middle day of pentad
 - - - Trough lines

pentad 31 May–4 June (Figure 7) and the NLM has reached 15°N , having already passed 13°N on 27 May. It is interesting to note that in pentad 10–14 June (Figure 8) there is a temporary weakening and recession of the monsoon as the trough briefly moves to the eastern side of the Himalayan/Tibetan plateau. However, by pentad 20–24 June (Figure 9) a trough is forming west of the Himalayas again, although slanting rather steeply northwards to the polar vortex, and the NLM re-advances across the Indian peninsula. Note also the meridionality of the flow right across the Europe/Asia sector at this stage.

The dates of the 500-mb changes indicated in Figure 3 (excluding 1949, 1955 and 1965) show clear evidence of a two-year periodicity. This periodicity appears to influence the date of onset of the summer 500-mb régime in middle latitudes more than it affects the date of onset of the monsoon. Thus, by taking two-year averages, the correlation between the two curves would be increased.

Conclusion. The 500-mb flow in the circumpolar westerlies over Eurasia plays a significant role in the mechanism of the onset of the Indian south-west monsoon and close attention should be paid to the Asian ridge and changes of wavelength across it at this time. It is conceivable that, after due allowance has been made for the effect of any two-year oscillation, a useful forecasting aid could be evolved by careful evaluation of the behaviour of the mean wavelength across the Asian ridge during April and May, which has been shown to be closely correlated with other events already known to precede the onset of the monsoon.

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REVIEWS

The Antarctic atmosphere: Climatology of the troposphere and lower stratosphere, Folio 4, and Climatology of the surface environment, Folio 8, by W. S. Weyant (text). Antarctic map folio series, edited by Vivian C. Bushnell. 430 mm × 280 mm, pp. 4 with 8 plates, and pp. 4 with 13 plates. American Geographical Society, Broadway at 156th Street, New York, 1966 and 1967. Price: \$29.50 per set of 8 folios.

These two well-printed folios compiled by the National Weather Records Center with texts by W. S. Weyant provide a useful, if limited, English-language guide to the main climatological features of the Antarctic and the southern oceans. Because of the paucity of data over the oceans some of the plates should be treated with caution and not be taken to be as definite as some of the solid lines would indicate, especially where the heights and temperatures of the isobaric surfaces above the Pacific Ocean are concerned when there are no upper air stations within a 100° sector of longitude.

There is much to commend in the layout and presentation which uses graded colouring as well as isopleths. The period of data used for the upper air (1957–64) has smoothed out many of the eccentricities revealed in the earlier investigation by Alt, Astopenko and others, and demonstrates the regular nature of the Antarctic atmosphere compared with that of the Arctic. One striking feature is the crescent of warm air at 100 mb in the Indian and Pacific Ocean sectors between 40°S and 50°S (Plates 2 and 3 Folio 4). North of this belt the mean tropopause heights and temperatures (Plates 5 and 6) are six months out of phase compared with the continental values. As rightly pointed out in the text, caution should be exercised in taking for granted the relative humidities at 700 mb and 500 mb. Though not stated it would appear that the relative humidities are relative to water. At the ambient temperatures experienced, 60–84 per cent is often saturation relative to ice.

The folio of surface features — Folio 8 — is more of a mixed bag, covering surface temperature (Plate 1), ranges of air temperature (Plates 2 and 3), wind roses (Plates 4–7), air temperature and wind direction (Plates 8 and 9) cyclone tracks (Plate 10), number of days with blowing snow (Plate 11) and total and mean cloud amounts (Plates 12 and 13). As in the case of the upper air data there is a lack of observations over the oceans which limits the success of Plates 2 and 3, and although the surface circulation can be inferred from the wind roses, the omission of a mean sea-level pressure map is to be regretted.

Reduction of surface temperature to potential temperature shows that east Antarctica is much colder than west Antarctica so that the cold centre is about 85°S 70°E. The cyclonic tracks across west Antarctica are partly responsible for the difference, but the implication in the text that the occasional cyclone track between the Ross and Weddell Seas is in one direction only, is open to question. It is rather irritating to find Plates 2 and 3 in degrees Fahrenheit while all other plates are in degrees Celsius.

The influence of katabatic winds is seen in both wind roses and variations of temperature with wind direction, and there is remarkably little change in pattern from one season to the next. The persistence of the westerlies in mid-latitudes is well defined. One consequence of the wind is the number of days with blowing snow, shown in histogram form in Plate 11. Unfortunately

there appears to be something wrong with the data used, and it is significant that the U.S.A. maintained stations have a much higher frequency than stations operated by other nations. From personal knowledge and experience the Halley Bay figures are an underestimate and should be of the same order of magnitude as those at McMurdo. In mitigation it must be admitted that it is difficult to obtain accurate drift-snow data from published meteorological data because significant facts can be obscured in synoptic messages.

Cloud amounts are not in histogram form but are represented by cumulative percentages of cloud less than a given amount. The curves so produced are characteristic of the station and can also be used to deduce mean cloud amounts or to form a histogram. Continental and oceanic stations prove to be very different.

Throughout both these folios the compilers have used March, June, September and December as reasonably representative, which probably accounts for the statement in the text that the continental stations could be considered to have a two-season climate. However, the normal climatological procedure using April, July, October and January would probably have been more appropriate and, as far as temperature is concerned, typifies the seasons at Halley Bay.

The brief texts of both folios are useful but would not have suffered from expansion, and I would have liked to have seen details of the nature of the data used and a bibliography of the more important literature. The only comparable atlas is the Russian *Atlas of the Antarctic* (1966) which does contain surface pressure maps and uses the usual climatological months, but does not go into the same detail of the temperature régime. Comparing the two, the Russian upper air maps appear to be less smoothed and are probably to be preferred. But taken as a whole the new folios are complementary to the Russian work, and bearing in mind the limitations and excluding Plate 11 (Folio 8) these two folios are a welcome addition to Antarctic meteorological literature and cartography.

D. W. S. LIMBERT

Air pollution, by R. S. Scorer. 130 mm × 195 mm, pp. xiii + 151, illus., Pergamon Press Ltd, Headington Hill Hall, Oxford, 1968. Price: 45s. or flexi-cover 30s.

Professor Scorer is well known for his forthright views on air pollution and for his enthusiastic use of photography, and this little volume is a lively and entertaining reminder of both qualities. There are roughly 100 plates, many of them coloured, which form the basis for expounding fundamental principles and driving home practical lessons.

The general properties of airflow affecting travel of pollutants over flat country are dealt with first, and this is followed by a discussion of the rise and spread of plumes and of the way knowledge of these features can be used to estimate the dilution of a pollutant. In the next two chapters there is a discussion of the important effects of inversions, both in a high-level form and at the surface over sloping ground. Then follows a chapter on the appearance of plumes as determined by the physical nature and optical

effects of the plume constituents. Aerodynamic effects around buildings and chimneys are described in the sixth chapter. The seventh chapter discusses the various offensive aspects of air pollution and the book concludes with a chapter entitled 'Repercussions'. This underlines and reiterates the main lessons to be applied in living with air-pollution problems. In the domestic context of garden bonfires these include a recommended code of practice which no doubt many housewives will wish to have drawn to the attention of their neighbours.

As the author emphasizes, the processes of dispersion in the atmosphere are very complex. One of the features discussed at some length (in Chapter 2) is the effect of sampling time on the observed distribution of concentration downwind of a continuous source, and of the role in this connection of the wide range of eddy 'sizes'. At long distance from a source, when the plume has become wide, the bodily movement of a section of the plume is dependent on large eddies (slow variations in the wind). From this the author argues that a repeatable measurement of concentration requires a longer sampling time the longer the distance from the source. But these slow variations also affect the bodily movement of the plume at short distance and need to be included in the sampling if a reproducible value is to be obtained. Also important is the fact that as distance is increased there is a decrease in the proportion of the long-term average spread associated with crosswind bodily displacements of the plume. Consequently a short sample provides a more representative indication of average concentration at long range than it does at short range !

For meteorologists who are called upon to advise on air pollution the applicability and accuracy of diffusion formulae are vital matters. In this connection the author condemns the fallacy that pollution distribution may be calculated from some presumed universal formula, though he admits in his preface that he may seem to be overstating his case. It is undoubtedly important to deter the uncritical and uninformed use of diffusion formulae, but the useful quantitative advice which may be provided from a critical choice and use of formulae should not be forgotten or underrated.

F. PASQUILL

Environmental study, by J. B. Rigg. 220 mm×145 mm, pp. xi+298, *illus.*, Constable and Co. Ltd, 10 Orange St., London, W.C.2, 1968. Price 45s.

After reading this book, few people will disagree with the author's belief in the value of environmental study in the education of our young people. The book ranges over a wide field, covering the principal aspects of our physical environment, including the sun, the atmosphere, land and sea, rocks and soils, rivers and ground water, natural vegetation, and also deals with land utilization and the urban environment.

The author maintains that environmental study is an observational science, and throughout the book there is a great emphasis on practical work. The value of class discussions is also greatly stressed, and some controversial theories are deliberately introduced in order to stimulate the exchange of ideas.

Meteorology and climatology are dealt with in some detail, with separate chapters devoted to clouds, pressure systems and air masses, meteorological instruments and records, atmospheric pollution, and the weather and the individual. There are many practical activities in this section, for example calculating the amount of water vapour in a room and the heights of clouds, the interpretation of weather maps, making a rain-gauge, drawing a field-sketch of the sky to show the weather conditions, and the collection and analysis of solid particles from the atmosphere.

It is unfortunate that there are a number of misprints in the calculations and formulae. Another criticism, especially in view of the fact that the book comes within the high price-range, is that the publishers did not employ a studio for the drawing of the diagrams, many of which have a somewhat rough appearance.

However it should be a valuable reference book for teachers and intending teachers. As far as its use in schools is concerned, it is unlikely that a course in environmental study will be adopted for the more academically-minded pupils, who are closely involved with the G.C.E. examinations and whose curriculum is already overcrowded. The book might be used to suggest projects to A-level science students, and it could provide geographers with a series of basic experiments. In the less academic streams there should be more scope for this course, where a simpler approach could be worked out by the teacher, using the book as a guide.

F. R. DOBSON

OBITUARIES

It is with regret that we have to record the death of Mr D. K. E. Crome (X.O.) on 11 January 1969, and also that of Mr H. F. Hollands (X.O.) on 27 February 1969.

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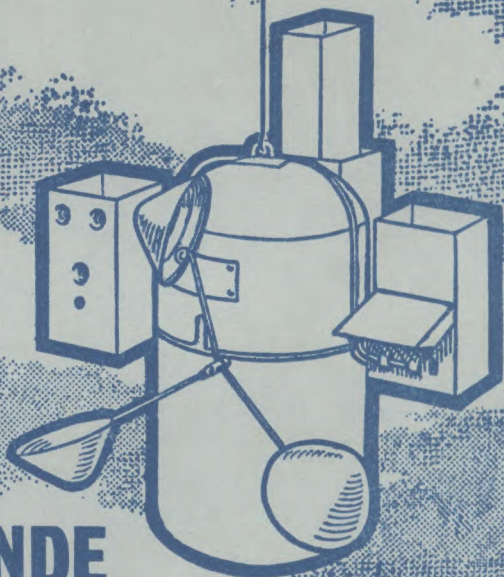
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NOTICES

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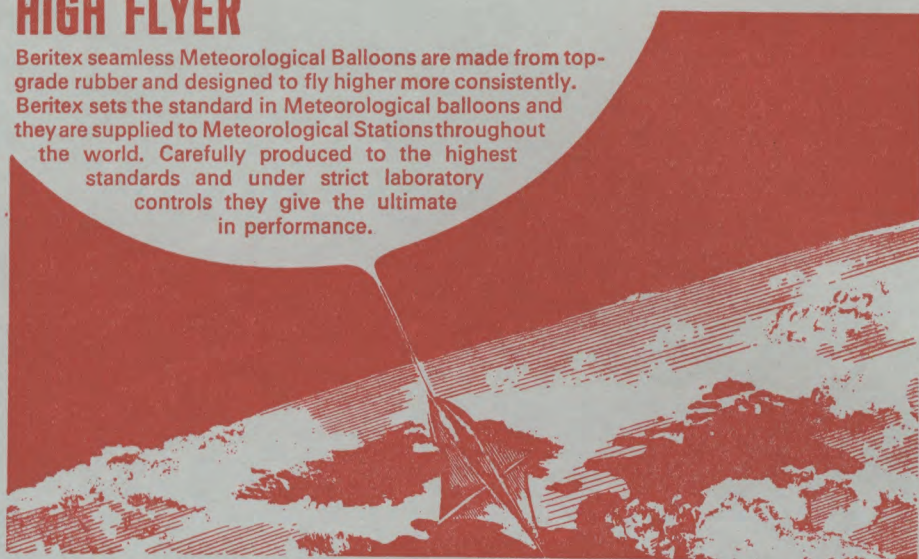
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THE METEOROLOGICAL MAGAZINE

KEW OBSERVATORY BICENTENARY 1769-1969

Vol. 98, No. 1163, June 1969

FOREWORD

By

THE DIRECTOR-GENERAL OF THE METEOROLOGICAL OFFICE

The story of a scientific institution with two hundred years of achievement behind it is almost bound to be worth the telling. This is especially true of Kew Observatory which will have a lasting place in the history of our subject. Built as an astronomical observatory for King George III, and managed in turn by the British Association, the Royal Society, the National Physical Laboratory and the Meteorological Office, it has provided a quiet, peaceful but stimulating atmosphere in which many famous physicists and meteorologists have done their best work.

Under the leadership of such outstanding men as Welsh, Balfour Stewart, Chree, Whipple (father and son), many of the greatest innovations in meteorology were born or developed there. The Kew-pattern barometer, the meteorograph, radiosonde, alti-electrograph and the early stages of our current rocket and satellite programme, to mention only some of the more important contributions, were landmarks in the development of our science.

Although it continues to be an active centre of investigation, the encroachment of suburbia and the demands of modern research make it unlikely that Kew's future will match its splendid past. It is therefore all the more important that its achievements should be set down for us to read and recognize the foundations on which we build. In paying this modest tribute to the work of our predecessors, we can only marvel at what they achieved with such slender resources, and be grateful for their enthusiasm, ingenuity, and, above all, their patient and dedicated scholarship.

I am most grateful to all those who have contributed to the preparation of this account, and especially to Mr L. Jacobs who conceived the idea and pursued it to a successful conclusion.

THE 200-YEARS' STORY OF KEW OBSERVATORY

By L. JACOBS

Kew Observatory was built as a Royal Observatory for George III in 1768–69, Sir William Chambers being the architect; it was originally, and rightly, called the King's Observatory at Richmond — the misnomer of 'Kew' came later (sometime between 1812 and 1841) and persists. There is no doubt that Dr Demainbray,¹ a most learned and capable man, who had been tutor to the Royal Family since 1754, had aroused the interest of the King in the forthcoming transit of Venus, due on 3 June 1769. The Observatory was finished in time and George III with the assistance of Dr Demainbray, observed the transit which began soon after 1900 hours. Fortunately the sky cleared soon after 1600 hours at the end of a rainy day with a veer of wind from southerly to westerly, no doubt behind a cold front. It must have been a trying time for the King (Plate I) and his party (Plate II) at Kew and for others awaiting this transit, including the Astronomer Royal, N. Maskelyne, and his six other observers at the Royal Greenwich Observatory. The significance of this transit is discussed in a section on astronomy on p. 163. References are made in the text to the Plates in this issue — Plates I to V illustrate the earlier days of the Observatory, including some of the personalities; Plates VI to IX give illustrations of more recent times.

Dr Demainbray was succeeded, on his death in 1782, by his son the Reverend Demainbray who continued as King's Observer (and for long also acted as royal tutor) until he was retired on pension in 1841 on the closure of the Royal Observatory. S. Rigaud, Dr Demainbray's son-in-law, is recorded as being assistant observer from 1769 until his death in 1814; then his son, S. P. Rigaud, F.R.S. (Savilian Professor at Oxford, first of Geometry and later of Astronomy), took over at the Observatory during the long vacations at Oxford so that the Reverend Demainbray could visit his parish in Wiltshire. This convenient arrangement continued until Rigaud died in 1839.

After this 1841 closure the astronomical and other equipment, including King George's collection of instruments and Queen Charlotte's natural-history collection were dispersed; the 1951 catalogue² of the Science Museum gives a good summary of the present whereabouts of most of the material.

Many scientists including E. (later General Sir Edward) Sabine³ (then General Secretary of the British Association (BA) for the Advancement of Science and later, from 1861 to 1871, President of the Royal Society) were anxious that the Observatory should be taken over for experimental work in physics by the Royal Society. At first the Royal Society agreed but soon afterwards refused. However, it was not long before Sabine and others renewed their application, this time to the BA which formally took over the building as a physical and meteorological observatory in May 1842.

It is not clear how F. (later Sir Francis) Ronalds came to take over the position as Honorary Superintendent which he did later in 1842, but he had been well known for many years for his work in atmospheric electricity.⁴ A list giving the dates of appointment of King's Observers and Superintendents

up to 1939 accompanies the Plate VI showing the more recent Superintendents. In the present Superintendent's room at Kew there is a memorial tablet⁵ giving the names up to 1939, accompanied by the available photographs⁶ and a silhouette (Plate IV) of the first King's Observer, Dr Stephen Charles Triboudet Demainbray, which was presented by his great-grandson in 1882. No representation is known to survive of the second Demainbray who died in 1854 at the age of 95.

Initially the management of Kew Observatory came directly under the Council of the BA, but from 1849 a special Kew Committee was appointed. From the beginning this Committee was a very active one, its members not only paying frequent visits to Kew but also providing special equipment and undertaking experiments themselves. Those notably engaged in this work were E. Sabine, J. P. Gassiot (see Plate V) and Warren de la Rue. Both the latter were businessmen (Gassiot was a wine merchant and de la Rue was a member of the family connected with the well-known paper manufacturing business) and were keenly interested in science (both were Fellows of the Royal Society) and published many scientific papers. When, in 1871, the BA was increasingly finding difficulty in financially supporting the Observatory, Gassiot came to the rescue with a donation of £10 000 on condition that the Royal Society took over the management. This was readily agreed and with the interest on this endowment, the increasing revenue from the verification work (see Dr Barrell's article) and a grant from the Meteorological Committee for Kew acting as the Central Observatory (see p. 167) the establishment was put on its feet. (The Royal Society still has a Gassiot Committee which looks after the Gassiot Fund and receives a brief annual report on the work at Kew.)

As discussed in Dr Barrell's article the National Physical Laboratory took over Kew in 1900. Finally the Meteorological Office assumed control from 1 July 1910.

The work at Kew has been very varied over the long years; the following summarized account is divided amongst the subjects of astronomy, general meteorology, upper air work, and geomagnetism, and is followed by a general section. Special topics are discussed in separate articles in this issue and in the July 1969 issue of the *Meteorological Magazine* (reference 34) and also in an issue of *Weather* (reference 18). The article by Dr Scrase is followed by a note by Jacobs to bring up to date the references to instruments, seismology and air pollution.

Astronomy. Transits of Venus across the sun are rare events occurring twice in about a century, the two events being separated by eight years. The first transit of Venus observed in this country was in 1639 and then by only two observers who made no measurements. Astronomers decided that observations of these transits of Venus represented a good opportunity, if sufficient widely spaced measurements were made over the earth, to calculate first the distance of the earth from the sun, later known as the astronomical unit, and then, from this, the general dimensions of the universe. Enthusiasm grew as the 1761 transit time approached and many countries organized expeditions to far parts of the world. The results were disappointing largely because the timing of the transit could not be made exactly owing

to what was known as the 'black drop' causing the spherical shape of Venus to be drawn out in a lingering neck as it passed across the edge of the sun, no doubt due to some atmospheric effect on Venus.

However, a greater effort was made for the 1769 transit and it was hoped that improved telescopes and methods of observations would yield definite results. Again, however, the 'black drop' interfered and this was reported by Demainbray (with little emphasis) in his account of the observations at Kew, and by Maskelyne (with great emphasis) in his account for Greenwich. Demainbray assures us in his manuscript notebook that the observers behind the seven telescopes manned at Kew, other than that looked through by George III, agreed with the royal timing to within one second; however, the timings of the seven observers at Greenwich differed by up to $60\frac{1}{2}$ seconds, for an event which was expected to be timable to within one second, and this kind of range was typical for observations elsewhere.⁷ Demainbray received a copy of the Greenwich observations, on 6 June, in a letter from the Astronomer Royal and these observations are recorded in the notebook. However, it is clear that while the Greenwich observations were published,⁸ and were used in the subsequent world-wide calculations,⁷ the Kew Observatory observations were not published (in fact they never appeared in print until 1926⁹); we may surmise that this is perhaps because Demainbray was puzzled as to the large range of timing in the observations at Greenwich, and merely reassured himself that the Kew Observatory observation (of both external and internal contact) was within this range. The effort of 1769 was notable for the fact that Captain Cook was sent out on his first voyage to the South Seas specifically to observe this transit of Venus and the observations of himself and those sent with him were included in the subsequent calculations.⁷ All in all, however, the results of the 1769 world-wide series of measurements were again disappointing although a mean value of the astronomical unit was, of course, obtained. In spite of these disappointments in 1761 and 1769 even greater expeditions set out in 1874 and 1882; the hope was that with improved telescopes the contact observations could be made with much greater precision and, in particular, the use of photography, for the first time, might resolve the difficulties with the 'black drop'; but the results obtained were no better than the older ones. To complete the story of the astronomical unit, later calculations were made from the study of the motion of the near asteroid, Eros.¹⁰ However, in recent years there has been an apparent discrepancy between the Eros results and those derived from measurements by radio astronomers. This discrepancy has now been resolved and an accurate and consistent value has been obtained for the astronomical unit.¹¹

On 4 June 1769, the day after the observation of the transit of Venus, an eclipse of the sun was observed at Kew but information is scanty regarding the astronomical work that went on at Kew during the remainder of the Royal period which ended in 1841. Dr Demainbray's grandson recorded in 1881¹ 'His Majesty [George III] frequently attended at the Observatory and procured the best clocks and watches that could be made and placed them in the Observatory under the Doctor's care, so that by daily observations of the sun when passing the meridian, the time was regulated to a second; and for many years the accurate time was taken from the King's Observatory at Kew, for the regulation of the clocks in both Houses of Parliament, at the

House Guards, St. James', and elsewhere, before the accommodation was so well and publicly afforded, as it is in the present day, from the Observatory at Greenwich'. It was clearly through this interest in clocks that John Harrison¹² was able successfully to appeal to George III in 1772 for the conclusion to his long tussle with the Board of Longitude regarding the £20 000 prize for determining longitude; George III personally with Dr Demainbray, supervised the testing of John Harrison's watch at Kew in that year. The original Demainbray manuscript book recording the excellent performance of the watch survives in the collection at King's College Library, London. (The book was mislaid from 1841 to 1960 and thus does not appear in the Science Museum Catalogue.³)

The next period of astronomical work started at Kew in the 1850s when Sir John Herschel, the astronomer, suggested the importance of a daily photographic register of the spots on the sun's disc in order to extend the series of visual observations by Hofrath Schwabe of Dessau who, in 1844, had announced the 11-year sunspot cycle (the discovery was not widely known until Humboldt drew attention to it in 1851). The Kew Committee agreed with the recommendation and a photoheliograph was constructed in 1856. It came into routine use from March 1858 (with various interruptions up to May 1863) under the personal supervision of Warren de la Rue, the chief observer being B. Loewy (who also made pendulum observations—see reference 9 in Dr Barrell's article). In 1860 an expedition headed by Warren de la Rue went to Spain not only with the photoheliograph but also with a portable observatory to photograph the solar eclipse of 18 July 1860. The mission was most successful and it was an important astronomical event in that, for the first time, it was made clear that the flame-like prominences belonged to the sun and were not produced by the deflexion of the sun's light through the valleys of the moon. The actual de la Rue photoheliograph was transferred to Greenwich in 1873 for an experimental period (to 1876). Several new photoheliographs on the Kew pattern were constructed in time for the expeditions in 1874 to observe the transit of Venus. One of these instruments was reserved for Greenwich and the series of solar photographs which began there in 1874 still continues at the Royal Greenwich Observatory, Herstmonceux, Sussex. The original de la Rue photoheliograph is now in the Science Museum. (In 1865 Schwabe presented his original notebooks with drawings of sunspots, from 1825, to Kew for study; this material is now with the Royal Astronomical Society, London, which had presented Schwabe, in 1857, a gold medal for his sunspot periodicity discovery.)

General meteorology. Meteorological observations were made one or more times daily covering the period 1773–1840; these observations are in manuscript books held in King's College Library, London, and have recently been placed on microfilm preparatory to detailed study by the Synoptic Climatology Branch of the Meteorological Office. (Whipple in 1937¹³ refers to the observations 'as so unsystematic that they are useless for statistical purposes'; however, this appears to be due to the fact that one book covering the period May 1783 to December 1803 had been mislaid; it was not found until reorganization of the library in 1960. Drummond also commented on this point¹⁴ and did not include consideration of these

older Kew observations in his account of cold winters in 1783–1942.¹⁵) The thermometers then were placed, as was the custom in the late 18th century, in a window having a northern aspect — the window here was in the north-east corner of the astronomical quadrant room (see Plate VIII). As, at this initial stage, the Observatory had no ground available on which to place instruments the rain-gauge was placed on a pole on the roof — it is clearly visible in the original of the 1792 print reproduced in Plate III, and Ronalds confirms the position in a later report.

When the British Association took over the Royal Observatory, meteorological observations were resumed from November 1842 and with some breaks (mainly in the period 1848–53) have been continuous to this day. The thermometers were removed from the window position and placed in a Glaisher-type screen (similar to that in use at Greenwich) from October 1849; this screen, placed on a pole fixed to the balustrade on top of the steps leading to the entrance (see Plate VIII), had to be turned by hand so that the thermometers were not exposed to the sun. From 1 January 1854 a large screen with double louvers, devised by Welsh (it was the forerunner of the Stevenson screen), was placed just in front of, and readable from, the balustrade, the thermometers being at the same height above the grass (11 feet) as for the Glaisher screen. The Welsh screen continued in use until the north-wall screen with its photothermograph, was adopted in 1867. From 1 January 1969¹⁶ this, in turn, gave way to an aspirated psychrometer at 1.25 metres above the lawn.

The famous Lt Maury wrote in August 1853 (via Sabine), asking for Kew to devise a marine barometer, for general use. Welsh satisfactorily made such a barometer (see Dr Barrell's article) and personally tested it at sea. There was also association with the Meteorological Office from its foundation in 1855, and Admiral FitzRoy wrote to Kew regarding the provision of standard instruments for the newly formed Office.

Much work has been done over the years at Kew on the development of various meteorological instruments and aids to computation. Ronalds's reports from the beginning deal with the photorecording of meteorological (and magnetic) elements (see p. 168). There was further development by Balfour Stewart and the mechanic, Beckley, so that the photobarograph (still in operation) and photothermograph were put into routine use from 1862 and 1867 respectively. (Indeed so much use was made of photographic recording, with a resultant delay in seeing the actual records, that the Meteorological Committee for the year ending 31 March 1914 reports that a considerable number of pen-recording instruments, already available elsewhere, were added to aid the work at Kew.) Welsh, then assistant to Ronalds and later Superintendent himself, invented a slide-rule for humidity (and one for geomagnetic elements) in 1851 and it was a later Superintendent, F. J. W. Whipple, who described the pilot-balloon slide-rule.¹⁷ There is no space here for further remarks on this meteorological work — the general references listed at the end should be consulted. The articles here by Robinson and by Scrase (and by Daws and Lacy¹⁸) give examples of types of meteorological research and Collingbourne's article (reference 34) describes the radiation investigations. The general layout of the Observatory and its grounds today can be seen from Plate VII.

Kew became the Central Observatory of the Meteorological Office in 1867 and soon after this six other United Kingdom observatories, Falmouth and Stonyhurst in England, Armagh and Valentia in Ireland, and Glasgow and Aberdeen in Scotland, were provided with recording equipment identical to that in use at Kew. Kew was responsible for the general organization of the scheme (Beckley made and installed all the instruments) and the results, including reproduction of the autographic records, were published in the *Quarterly Weather Report*; they still repay study. The Kew meteorological records over the last hundred years or so have been used in many publications, for example by Drummond^{15,19} and by Brazell,²⁰ and are quoted whenever current London weather records are being considered. The Old Deer Park (part of which later became a golf course) continues to surround the Observatory, and the nearest built-up area is some half a mile away. In spite of this there has been in recent years a slow rise of temperature both because of the increase of density of building outside the Park and the increase of heating in such buildings (Craddock²¹). Whereas in 1878 the differences, Kew (north-wall) – Rothamsted (Stevenson screen at an unchanged rural site 20 miles north of Kew), in monthly mean temperature were about 1.2 degF, a value corresponding to the difference in altitude between the stations, they had increased by 1963 to values of between 2.1 and 3.5 degF depending on the month. (Craddock²¹ also reviews the differences between north-wall and Stevenson-screen temperatures at Kew in 1879–81, 1923–26 and 1958–60 and concludes there is no significant change over the years. On balance, the daily mean temperature as estimated in each of these periods tends to be about 0.5 degF higher in the north-wall screen).

Upper air. In August 1847 Ronalds and his assistant Birt showed how a stable upper air platform could be obtained by holding a kite with three strings.²² It was suggested that a pulley on the kite would enable instruments to be raised and lowered readily, but there is no record that any actual measurements were carried out.

Welsh made four personal ascents in a balloon in 1852 (from the well-known Vauxhall Gardens, London) and discussed the results in detail.²³ There is evidence that W. Thomson (later Lord Kelvin) used the data in a paper which gave the first formulation of the dry adiabatic lapse rate and of the saturated adiabatic lapse rate.²⁴ Much later Sir Napier Shaw reviewed the results.²⁵ Ten years after Welsh, Glaisher commenced a new series of manned balloon ascents, also under the auspices of the British Association.^{26,27}

In the early 1900s W. H. Dines designed and operated cheap light-weight meteorographs which were sent up on unmanned balloons — those that eventually landed safely by parachute being returned to him for analysis of the record. This work was done first at Pyrton Hill from 1907, then at Benson from 1914 and finally was transferred to Kew in 1923. The results were published in the *Observatories' Year Books* up to the cessation of this work in 1939; thereafter radiosondes came into use as is described by Harrison in this issue, thus fulfilling the original 1842 plan by the BA to develop an 'apparatus for telegraphing the indications of meteorological instruments carried up in balloons or by kite, to an observer at the earth's surface'.

Geomagnetism. Sabine,³ mentioned above in connection with the 1842 BA takeover of Kew, had, as a young army officer in the period 1818–21, been responsible for physical (including geomagnetical and meteorological) and biological observations on two expeditions sent in search of the North-west Passage. Later in the 1820s he went on a further series of journeys and expeditions in which he made similar scientific observations, particularly in relation to geomagnetism and gravity. From 1827 onwards for the rest of his long life (he died in 1883 aged nearly 95) he was almost wholly engaged in scientific investigations. When the Royal Society agreed to the request by Humboldt, in 1836, to set up geomagnetic observatories in different parts of the British Empire, to join in simultaneous observations at set periods at stations already established elsewhere, Sabine was largely responsible for the general arrangements. The observatories at Toronto, St Helena, Cape of Good Hope and Hobarton, Tasmania, began their observations in 1840 (when similar observations also began at the Royal Greenwich Observatory), and it was Sabine who undertook the enormous task of publishing and analysing the results; he went on to collate all the available magnetic data for the world in a series of 'Contributions' to the *Philosophical Transactions of the Royal Society*. Besides his maps of world distribution, the most notable result of Sabine's work was his discovery that the daily range of magnetic declination increases with an increase in the number of sunspots. (This was also pointed out at about the same time by Lamont and Wolf.)

Thus when Ronalds came to Kew Observatory in 1842, Sabine was at hand to encourage him, particularly in the geomagnetic work. So far there was no recording of geomagnetic (or meteorological) elements. The mirror and scale method of increasing deflexions was due to Poggendorff in 1826, and this together with photography, invented in 1839, soon provided the answer to the problem. It seems clear that Ronalds was just ahead of Brooke, who prepared recording equipment for Greenwich in 1847, but Brooke received the Admiralty prize of £500 in 1848 and Ronalds, on protesting, was given a supplementary Government award of £250 the next year (as is recorded in the BA annual report).

The Ronalds photorecording magnetographs, for declination, horizontal and vertical components, were improved over the years by Ronalds and Welsh, and even by Faraday during a visit to the Observatory on 15 November 1850, and came into routine use at Kew from 1857. Sabine analysed the early results. Once these Kew magnetographs had assumed their final form there was a great demand from all parts of the world not only for the supply of such instruments, but also for the training of observers at Kew. The Kew Committee annual reports (see general references) up to about the end of the century give many details of this international co-operation. In November 1869 the Kew Committee reported that Kew had provided magnetographs and in most cases instruction at Kew, for the observatories at 'Java, Coimbra, Lisbon, United States, St. Petersburg, Florence, Stonyhurst, Melbourne, Bombay and Mauritius', and there were others later. There was in this period hardly a scientific expedition organized at home or overseas that did not refer to Kew for advice, training and supply of instruments (and this refers also to instruments other than magnetographs) and for discussion of the results; for example, Livingstone's expeditions to Africa from about 1858,

the Polar Year Fort Rae Expedition of 1882–83 and the Antarctic expeditions from 1899 to 1914.

Scott's history of Kew²⁸ gives an account of the geomagnetic (and other) work up to 1884; it has a particularly useful bibliography of papers relating to Kew, including those of Sabine. Chree²⁹ gives a later account,³⁰ and his 1912 book³¹ describes his researches in geomagnetism up to that time. In the early days of magnetic recording funds were not available for a complete reduction of the magnetic traces and analysis was confined to five quiet days per month (selected by the Astronomer Royal up to 1912 and thereafter by the International Centre at de Bilt, Holland). One result of Chree's analyses was to show that these days were atypical particularly in considering secular variations. He extended this work in a special full analysis of all traces in the period 1890–1900 — the results were published in the *Philosophical Transactions of the Royal Society* in 1908, 1910 and 1916. Later work, particularly in the study of the 27-day recurrence tendency of magnetic disturbance, and the survey of Kew data from the start of the recording, is described in a number of *Geophysical Memoirs* of the Meteorological Office by Chree (numbers 17, 22, 30 and 43, 1921–28) and Stagg³² (numbers 29, 32, 36, 40 and 42, 1926–28) and in a final joint paper.³³ Full publication of the geomagnetic data started from 1911 in the *British Meteorological and Magnetic Year Book* and this was followed, from 1922, by the *Observatories' Year Book*. The records at Kew were disturbed by electric trams and trains from about 1900 to the end of the recording in 1925 but it is worth mentioning that the geomagnetic recording carries on at Eskdalmuir (records from 1908) and Lerwick (records from 1923). The Natural Environment Research Council took over Eskdalemuir from 1968 (but Meteorological Office staff remained for meteorological work and to help, as required, with the seismological and geomagnetic work) and has, in 1969, provided some staff for the geomagnetic work at Lerwick. Kew has continued to be of some help to the other observatories in that the workshop facilities have been used to repair magnetometers and, in 1960–63, to make the required coils for the proton vector magnetometers for the observatories at Eskdalemuir and Lerwick.

General. Looking through the various documents in relation to Kew, one comes across a galaxy of names of famous persons in physics and meteorology who have been connected with the work. A tribute must, however, be paid here to the staff at Kew over the years who faithfully carried out work which, while important, must often have been tedious. Many of their names are recorded in the early annual reports (see general references). Mention is made here of E. Boxall, A. G. W. Howard and R. Relf (see Plate IX) who were all in their fiftieth year of public service when they retired at Kew (in 1941, 1955 and 1967 respectively), and T. W. Baker who retired in 1912 after 52 years' service, all at Kew.

Kew continues today as a full meteorological observatory making extra specialized measurements as required, its main investigational interests now being in relation to radiation³⁴ and in the study of fair-weather atmospheric electricity.

General references. *The Reports of the British Association for the Advancement of Science* 1842–1871 give statements regarding the work at Kew — from 1851 onwards they include the reports of the Kew Committee; the reports of the latter are continued in the *Proceedings of the Royal Society*, 1872–1900. Following this there are the *Reports of the Observatory Department of the National*

Physical Laboratory 1900-09, and the annual reports of the Meteorological Office from 1910 onwards. *The Observatories' Year Book*, 1922-67, and its predecessor give many details; several have plans and photographs. Howarth gives a general account of the BA days in *The British Association for the Advancement of Science: a retrospect 1831-1921*, published by the Association in 1922.

In the Archives of the Meteorological Office are the manuscript minutes of the Kew Committee 1849-1900, the manuscript Kew diary 28 August 1850-31 October 1851 and many letters and documents from about 1840.

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KEW OBSERVATORY AND THE NATIONAL PHYSICAL LABORATORY

By H. BARRELL, C.B.E.

National Physical Laboratory, Teddington, Middlesex.

Introduction. One of the aims of the British Association in taking over Kew Observatory in 1842 was to establish standard instruments for meteorology and geomagnetism there so that other instruments could be brought to Kew for comparison. This type of work began when the famous Regnault provided Kew, early in 1851, with a thermometer which he had calibrated himself; at the same time he arranged the supply of the apparatus for graduating thermometers generally, for the determination of the freezing- and boiling-points of water and for the marking of the divisions by a Perraux machine, and satisfied himself as to the accuracy of the whole equipment. A sub-committee of the main Kew Committee, consisting of Mr Gassiot, Dr Miller and Colonel Sabine supervised the initial installation of the equipment at Kew and reported on 11 April 1851 'that the Observatory may now be considered to possess a standard thermometer with which other thermometers designed to be used as standards may be advantageously compared'. Regnault himself visited the Observatory on 29 July 1851 and the Kew diary mentioned in general references (see page 170) records the useful advice he gave.

The work soon grew and instruments other than those for meteorology and geomagnetism were involved. Barometers and hydrometers (see Plates X and XII) were verified from 1853, magnetic instruments were considered from 1856 and later in the century anemometers, rain-gauges, sunshine recorders, theodolites, sextants, compasses, telescopes and binoculars, lenses, watches and chronometers and a miscellaneous collection including barographs, thermographs, air meters, artificial horizons and rain measures were added in turn. Standard charges were made from the beginning.

Chree¹ gives a concise review of the development of this Kew verification

TABLE I—NUMBERS OF INSTRUMENTS VERIFIED AT KEW DURING 1853-95

Self-recording magnetic instruments	21	Sunshine recorders	15
Magnetometers	117	Theodolites	78
Inclinometers (dip circles)	155	Sextants	3 847
Thermometers (except clinical)	68 727	Compasses	423
Clinical thermometers	183 057	Telescopes	2 731
Mercury barometers	6 673	Binoculars	2 574
Aneroid barometers	1 572	Watches	7 781
Hydrometers	9 430	Chronometers	221
Anemometers	206	Miscellaneous	3 363
Rain-gauges	228	Total 1853-95	291 219

TABLE II—GROWTH OF VERIFICATION WORK AT KEW (1853-95)

Period	Total number of verifications	Average annual number
1853-55	4 250	1 417
1856-65	8 347	835
1866-75	18 587	1 859
1876-85	71 756	7 176
1886-95	188 279	18 828

service in the individual categories of instruments and Tables I and II here give his analysis for the period 1853–95. Table I shows the total numbers of instruments in the various categories which were verified and Table II the growth of the work. Broadly speaking, the average annual number of verifications remained fairly constant until about 1870 and then started to climb rapidly, mainly because of the expansion of thermometry and especially after the inclusion of tests for clinical thermometers. In fact, clinical thermometers represent 63 per cent, and all other types of thermometers nearly 24 per cent, of the total number of verifications during 1853–95.

There follows a review of some items of the Kew verification service and the allied experimental work and investigations. The selection of items is limited to four categories of instruments — thermometers, barometers, sextants, and watches and chronometers — and a note on some experimental work with pendulums for world-wide gravity surveys is included. The achievements with these particular instruments are characteristic of those made during the years up to the end of the century when, as will be described below, the Observatory became 'the Observatory Department' of the newly formed National Physical Laboratory (NPL).

Thermometers. Following the initial help by Regnault, mentioned above, both calibration and construction of standard thermometers became an important activity at Kew and it is reported that by 1895 over 700 thermometers had been made, of which some 600 were issued to physicists and instrument makers, and also to other observatories, as standards. For instance, reference is made to a Kew standard mercury-in-glass thermometer by W. H. Miller,² one of the Commissioners appointed by Parliament to superintend the construction of new national standards of length and mass to replace the standards ruined in the great fire at the Houses of Parliament in 1834. This thermometer, designated *K* and bearing the inscription 'No 43, Kew Observatory, July 1853', was supplied by the Kew Committee and was used to verify other thermometers employed in the work of the Commissioners. It was constructed under the supervision of J. Welsh and was of range 0°C to 100°C divided to 0.2 degC (approximately 1-mm intervals of length upon the stem) and could be read by estimation to 0.1 division. When verified at Kew by a method employed by the Rev. S. Sheepshanks (another Commissioner), it was concluded that the graduation was correct throughout the scale to 0.02 degC.

Balfour Stewart carried out some interesting experiments with an air thermometer which were described in 1863.³ With the aid of a grant of £150 from the Royal Society he undertook the project to add a third fixed thermometer point — the freezing-point of mercury — to the ice and steam points for the calibration of thermometers. A constant-volume air thermometer was used containing dry air free from carbon dioxide. The result obtained for α (coefficient of increase of pressure of air at constant volume) was expressed in the form $(1 + 180\alpha) = 1.367\ 28 \pm 0.000\ 07$, for the range 32°F to 212°F, and the freezing-point of mercury determined by the air thermometer was -37.93°F . Regnault's value at that date for $(1 + 180\alpha)$ was 1.36657 and the modern value is 1.367 44; the value, -37.93°F , for the freezing-point of mercury is equivalent to -38.85°C and the modern value is -38.862°C — a striking testimony to the accuracy of a determination made at Kew over a century ago.

The earlier mentioned influx of clinical thermometers led to the need to install more sophisticated test equipment than had been provided initially. F. Galton (then a member and later chairman of the Kew Committee) designed apparatus which enabled rapid comparisons of batches of thermometers to be made at any specified temperature between the freezing- and boiling-points of water.⁴ The basic techniques thus introduced, using appropriately lagged and stirred water (or other liquid) baths, are much the same as those employed today in testing thermometers. For temperatures below the freezing-point of water, down to 12°F or lower, use was made of freezing mixtures, and minimum thermometers were tested at the freezing-point of mercury, attained with the aid of compressed carbon-dioxide gas. Deep-sea thermometers were tested, mainly for the Admiralty, under pressures equivalent to those attained at great depths, using a hydraulic press installed in 1878 to produce the controlled environment. In the same year the practice was introduced of etching the monogram of the letters K and O



on thermometers which passed the Kew specification of accuracy — an approval mark which was subsequently applied to other categories of satisfactory instruments and became as well known, both nationally and internationally, as the NPL monogram at a later date.

Barometers. The verification of mercury barometers commenced in 1853 and comprised tests of the ordinary patterns then available for use on land and at sea. Aneroid barometers began to be submitted for verification much later, thus accounting for the much lower numbers dealt with in relation to mercury barometers — see Table I. Welsh described in 1856⁵ the many attempts he had made earlier to prepare a satisfactory barometer tube of about 1-inch internal diameter, and then to fill it with pure mercury (Plate X). He gives an account of the techniques finally devised to produce standard instruments and also of equipment made for verifying barometers under test against a standard in a variable-pressure receiver. Reference is made in the paper to the lack, in many portable (marine) barometers received for test, of means for adjusting the mercury surface in the cistern to a constant level and of the need, therefore, to determine the correction for 'capacity', or the variation of the mercury level in the cistern corresponding to different heights of the mercury column in the tube. It is stated that this correction may be determined during construction of the barometer so that 'by reducing in the required proportion the lengths of the divisions it (i.e. the variation of zero point) may be allowed for in graduating the scale as has been done in the marine barometers made under the supervision of the Kew Committee by Mr P. Adie of London'. This appears to be the earliest reference to what is still known as the Kew-type barometer, in which the need to adjust the

mercury level in the cistern before taking a reading, as in the Fortin type, is eliminated by the method, outlined above, of using an appropriately contracted scale for reading the height of the mercury column.

G. M. Whipple described, in 1878,⁶ some intercomparisons of standard barometers at the Royal Observatory, Greenwich, and at the Kew Observatory, made as a result of some queries from foreign observers as to possible differences between the two standards. Four barometers of the Fortin type from Kew were used as transfer standards and were conveyed by carriage (hence the nickname of such transfer standards as 'hack' barometers) to and fro between Kew and Greenwich for comparisons with the standard barometers at the two stations. Three different sets of comparisons were made and the mean result came out to be: Greenwich - Kew = - 0.000 1 inch (- 0.003 mb).

Watches and chronometers. The rating of watches commenced in 1884 on a system of verification based closely on that used at the Geneva Observatory. Three classes of certificates were issued, namely *A* (the highest), *B* and *C*, according to the severity of the trial for which the watch was entered. The trial of a watch entered for Class *A* occupied 45 days (eight periods of 5 days each and 5 other days in which the watch was not rated); during the test the watch was rated when disposed in different positions and at three different temperatures. The Class *B* test occupied 31 days. The Class *C* tests were discontinued in 1897 because of a lack of demand for them.

Kew had several clocks and chronometers of the observatory type which were used as reference standards and which were checked by frequent observations of both solar and sidereal transits; however, two extra 'mean time' clocks, one being loaned by the Astronomer Royal (it was Dent 2011 and had originally been purchased for the Transit of Venus Expeditions of 1874), were acquired in 1884 for this extra work. On 22 January 1884 the first experiment on the use of the GPO telegraph, as a means of transmitting a time signal from the Royal Observatory, Greenwich, was undertaken, when a direct connection was made between Greenwich Observatory and the Richmond Post Office — two chronometers which were conveyed from Kew Observatory to Richmond Post Office showed, on comparison with the signal, a satisfactory agreement between the times as kept at the two observatories. By 1889, direct telegraphic connection had been established between the two observatories for the regular transmission of time signals; however there were some irregularities in the early years and Kew continued its solar and sidereal transit observations, on occasions, up to 1893. Two burglar-proof (and fire-proof) safes were installed, one for holding the watches while under test at ambient temperatures and the other for tests at either high or low temperatures, using gas heating for the former and ice cooling for the latter. A third rating safe was later obtained, so that temperatures near 40°F, 65°F and 90°F could be continuously maintained the year round.

At the request of watchmakers and others, a system for awarding marks to Class *A* watches was instituted in 1885 to indicate the degree of performance achieved during the rating tests, the marking scheme being similar to that already used at Geneva and Yale observatories. In it the number of marks awarded to a watch that only just succeeded in obtaining a Class *A* certificate

was zero, but to an absolutely perfect watch would be a 100 made up as follows: 40 for a complete absence of variation of daily rate, 40 for absolute freedom from change of rate with change of position and 20 for perfect compensation for effects of alteration of temperature. From 1890 onwards, watches receiving 80 marks and upwards had the legend 'especially good' added to the certificate. The highest mark achieved by any watch entered for the Class *A* certificate at Kew was 96.1 in 1912, the year during which the rating of watches and chronometers was transferred to the NPL, Teddington.

Rating tests were extended to marine chronometers in 1886. For these instruments the trial occupied 35 days (five periods of 6 days each plus 1 day at the commencement of each period when the chronometer was not rated). The tests were made in a symmetrical fashion at three different temperatures. Two classes, *A* and *B*, of certificates were issued according to the quality of performance achieved; the Class *B* certificate was abolished in 1905.

Sextants. In 1862 a simple means of testing the accuracy of the angular scales of sextants was set up by F. Galton in the Old Deer Park, near the Observatory. On each of four pillars, erected along a circular arc of $\frac{1}{2}$ -mile radius and subtending angles of 20° , 60° and 40° at the centre of the arc, was fixed a small mirror. At the centre, beside the observer and the sextant under test, were two mirrors for reflecting light from the sun towards two of the four distant mirrors. This light entered the telescope of the sextant when the mirrors at the centre were suitably inclined. An assistant beside the observer altered continuously the inclination of these mirrors to compensate for the sun's motion and also made the change from one combination of mirrors to another. Observations were made every 20° from 20° to 120° and the zero error was deduced by calculation. The angular distances between the mirrors fixed to the pillars were determined by means of a theodolite. Class *A*, *B* and *C* certificates were issued.

This original outdoor equipment, inconvenient in many ways, particularly because the tests could only be made during periods of steady sunshine, was replaced in 1866 by a more elaborate apparatus designed by T. Cooke, an optician; it is described by Balfour Stewart⁷ and was set up in the basement of the Observatory. The NPL built a similar equipment in 1912, to accommodate the testing of sextants when the Kew verification work was being transferred to Teddington, and a photograph of this is shown in Plate XI. The series of double-collimator units is very similar to that of the original apparatus at Kew (though the illumination is by small electric lamps instead of candles) and graticules with suitable matching patterns of transparent lines on an opaque background replaced the former crosswires; similar modifications had indeed already been introduced into the Kew apparatus before the work was transferred to Teddington. In the NPL equipment there are 13 double-collimator units arranged to subtend angles differing by 10° , 15° and 20° . The spacings provide angles in 5° steps from 0° to 180° , with a few exceptions, and many angles are duplicated. No provision was made originally at Kew to determine the errors of the dark shades used to screen the observer's eyes when the sextant is directed to the sun or moon. Errors occur because of non-parallelism and distortion of the faces of these

dark glasses, and also because of flatness errors in the surfaces of the sextant mirrors. Apparatus for examining these optical components of sextants was set up at Kew at the request of the sextant makers, and was described by G. M. Whipple.⁸

Pendulums for gravity surveys. Experiments were made at Kew in 1865 to determine the constants of two 'invariable' pendulums which were to be used for geodetic purposes in the Indian Trigonometrical Survey. A paper⁹ gives a full account of the work, describing how the number of vibrations made by each of the two pendulums in a mean solar day was ascertained in an evacuated enclosure. Mention is made in the Kew Committee Report for 1864-65 of Colonel (later General) Walker and Captain Basevi, who received instruction at Kew in the techniques of 'swinging' pendulums for the gravity survey of India. The results obtained at Kew served as the control and basis of reference for the subsequent work.

From time to time similar experiments with pendulums were undertaken at Kew and an interesting account of some of these was given by General Walker in 1890.¹⁰ The pendulum operations described were undertaken to determine the gravity connection between the Kew Observatory and the Royal Observatory, Greenwich, in order to establish the relationship between the series of pendulum observations made during the Indian Survey and other series, made in different parts of the world, which had been based on Greenwich as the reference station. The paper gives details of all the pendulums and experimental methods used.

Origins of the National Physical Laboratory. At the Norwich meeting of the British Association in 1868 Colonel Strange read a paper entitled 'On the necessity for state intervention to secure the progress of physical science'. To the Association, with the experience of its Kew Committee in managing the Observatory on a restricted budget and with the firm conviction that the work done at Kew was of considerable benefit to science and industry, this idea of governmental support for a purpose which had long been the objective of the Committee was evidently attractive. Further references to the subject were made at subsequent meetings of the Association, notably at Glasgow in 1871 by Lord Kelvin and at Cardiff in 1891 by Sir Oliver Lodge, the latter thereby arousing the interest of the Association's Secretary, Sir Douglas Galton.

Meanwhile, during the period 1883-87, the *Physikalische technische Reichsanstalt* had been established at Charlottenburg, near Berlin, as the national standards laboratory, the first of its kind set up under state auspices to assist national science and industry. In his presidential address to the Association at its Ipswich meeting in 1895, Galton, who had visited the German laboratory earlier in that year, urged the importance of establishing a similar laboratory in this country. A committee was appointed by the Association, with Galton as chairman and Lord Rayleigh (the third Baron) as another of its 14 members, to consider the establishment of a National Physical Laboratory for the more accurate determination of physical constants and for other quantitative research. This committee reported to the Liverpool

meeting of the Association in 1896. It recommended that the Royal Society be responsible for the definition of the proposed Laboratory's functions and for its management; estimates were made of the monies required for initial building and equipment and for annual maintenance of its work.

In 1897 the Government set up a committee of inquiry into the matter, with Rayleigh as chairman; the Chairman of the Kew Committee, F. Galton, and the Superintendent of Kew Observatory, C. Chree, gave evidence before this committee, which visited the Observatory early in 1898. The main conclusion of the report of the committee, made to the Lords Commissioners of Her Majesty's Treasury in July 1898, was that a National Physical Laboratory should be established under the control of the Royal Society and the four recommendations emanating from this conclusion were accepted by the Government. Of these four recommendations, it is germane to quote the first two :

- (i) That a public institution should be founded for standardizing and verifying instruments, for testing materials and for the determination of physical constants.
- (ii) That the institution should be established by extending the Kew Observatory in the Old Deer Park, Richmond, and that the scheme should include the improvement of the existing buildings and the erection of new buildings at some distance from the present Observatory.

The Royal Society agreed to co-operate in carrying the recommendations into effect, with financial aid voted by Parliament, and drew up a scheme for the organization of the Laboratory, which was officially approved. In accordance with this scheme the Kew Observatory was to be incorporated with the National Physical Laboratory and to become part of its organization from 1 January 1900, on which date the Kew Committee would cease to exist. The work at Kew was to proceed as hitherto and to be carried on by the existing staff of 19.

The scheme of organization included the founding of an Executive Committee to be the authority having the immediate management of the new Laboratory, and six members of the Kew Committee were nominated to its membership. The scheme also provided for the appointment of a Director who, subject to the authority of the Executive Committee, was to have sole control and direction of the staff of the Laboratory and of the work done within it. Dr R. T. (later Sir Richard) Glazebrook was appointed to the post as from 1 January 1900.

In accordance with the second recommendation of Rayleigh's Committee, a site of about 15 acres in the north-east corner of the Old Deer Park, Richmond, was chosen; however, difficulties arose because of objections of local inhabitants to siting the Laboratory in the Park; a question was asked in Parliament and a deputation of persons was sent to lay the reasons for objection before the Financial Secretary to the Treasury. Although the Executive Committee were unfavourable at first to considering other sites, agreement was eventually achieved, late in 1900, on Bushy House with its grounds, on the edge of Bushy Park, Teddington, as the acceptable alternative. Thus the NPL had its beginning, the British Association and the Royal Society being its progenitors and the Kew Observatory constituting 'the Observatory Department' of the new structure.

The Observatory Department of the NPL. The published annual *Reports of the NPL* for the years 1900 and 1901 relate entirely to the work done at Kew; thereafter, until 1909, the yearly account of the work at Kew Observatory appears in the Observatory Department part of the annual *Report of the NPL*. Table III, taken from the annual *Report of the NPL* for 1910 gives a continuation of the story of the verification work as shown by Tables I and II. It can be deduced from Table III that no less than 673 200 instruments had been tested since 1880. Information from the annual *Reports of the NPL* for 1911 and 1912 show that a further 76 770 instruments were tested at Kew during these years. An estimated figure of 58 700 for the period 1853-80 can be derived from the information given in Table II, so it would appear that, from the main start of the verification of instruments at Kew in 1853, the grand total is about 809 000.

TABLE III—GROWTH OF VERIFICATION WORK AT KEW SINCE 1880

Class of instrument	Average number of instruments tested per annum during each decade		
	1881-90	1891-1900	1901-10
Barometers			
Aneroid	81	124	168
Mercury	151	211	261
Hydrometers	390	323	500
Thermometers			
Clinical	8 462	16 502	19 909
Meteorological	1 801	2 823	3 940
Binoculars	68	475	1 054
Telescopes	26	632	3 601
Sextants	139	613	1 078
Watches	302	737	386
Marine chronometers	5	48	75
Inclinometers	6	6	10
Unifilar magnetometers	4	4	7
Others	1081	583	734
All instruments	12 516	23 081	31 723

In the Observatory Department period there was interesting work done on the comparison of the scale of the Kew standard mercury-in-glass thermometers with the hydrogen scale,¹¹ in which it was concluded that the departure of the Kew scale from the international hydrogen scale was very small at all temperatures within the range investigated, 0°C to 100°C. In 1901 an account was published¹² of the work on platinum resistance thermometers commenced at Kew in 1895; detailed examination was made of the various sources of error found in platinum resistance thermometers and the associated Callendar-Griffiths resistance bridge, the results obtained representing a notable contribution to the development and improvement of resistance thermometry at that date.

Concluding remarks. To conclude this NPL tribute to the achievements of the instrument verification service initiated at Kew over a century ago, it is of interest to remark very briefly on the history of this service since its transfer to Teddington in 1912-13. At that date the service became the responsibility of three sections of the Physics Department, namely Heat (thermometers), Metrology (barometers, aneroids, hydrometers and also watches and chronometers), and Optics (optical instruments). These sections

later became organized into separate Divisions of the Laboratory as a consequence of their increased responsibilities for research in the various specialist aspects of measurement science and to meet the corresponding development of diverse new requirements for verifications. In 1949, the NPL Test House was founded to relieve the Divisions of a major proportion of their routine and repetitive verification work, bringing it within a suitably planned unit to provide a comprehensive service for science and industry.

More recently it has become the policy of the Laboratory to pass certain categories of verification work to external organizations which are considered to have suitable staff and facilities to undertake the service. The first such transfer, of clinical thermometers, was to the British Standard Institution's Test House (Hemel Hempstead), which later undertook the verification of certain classes of meteorological and industrial thermometers, as well as hydrometers and other instruments. Previously, the average annual number of thermometers tested at Teddington was around 500 000, for the clinical type, and about 8000 for other types. Binoculars, telescopes and sextants are now inspected in laboratories within the Admiralty establishment, for which the major proportion of such instruments had been verified in the past at Kew and Teddington. The service for rating watches and chronometers is at present being maintained at the NPL; the Kew Class *A* test for watches, however, was discontinued in 1951, together with the system of allocating marks for superior performance, and was replaced by a Craftsmanship test designed to encourage the re-establishment of watch craftsmanship in this country.

The British Calibration Service set up in 1966 with headquarters in the Ministry of Technology will, in due course, considerably modify the organization of the instrument verification service in this country. Already several laboratories have been officially approved to provide a service for the certification of various categories of measuring instruments in return for fees. Laboratories in industry, research associations, universities or other educational institutions and government establishments may apply for approval. The NPL is associated with the scheme in an advisory capacity and participates in the procedure for the approval of laboratories. The Laboratory also provides, through its recently established Metrology Centre, the facilities for ensuring that the bases of reference for measurement in the approved laboratories are related to the national standards maintained at the NPL.

Acknowledgements are made to : Mr L. Jacobs, Meteorological Office, for much assistance in the preparation of this article; Cdr A. G. Thoday, Science Museum, for providing the illustration of Kew standard barometers (Plate X); and to Mr D. J. Bryden, Department of Technology, Royal Scottish Museum, for providing the illustration of hydrometers (Plate XII).

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SOME REMINISCENCES OF KEW OBSERVATORY IN THE TWENTIES

By F. J. SCRASE, O.B.E.¹

When I first joined the staff of Kew Observatory in 1920 as a Junior Professional Assistant (at a basic salary of £175 per annum plus a cost-of-living bonus which just doubled this figure), my first impression was that very little could have changed there since the time of George III, for whom the Observatory was built. Some reconstruction of the interior of the building had, in fact, taken place in 1913 soon after the section of the National Physical Laboratory (NPL) which had tested watches, thermometers, compasses and sextants there since 1900, was transferred to its permanent home at Teddington. The facilities for experimental work at the Observatory, however, compared unfavourably with those I had enjoyed at the Cavendish Laboratory under the guidance of J. J. Thomson, E. Rutherford and C. T. R. Wilson. The place had more the air of a rather musty museum with a large number of instruments of historic interest, and some jars of Queen Charlotte's natural-history collection on view in the glass-fronted cabinets in the octagonal North Hall where one entered the Observatory. Some armchairs, used by the senior staff, had probably survived since George III's time.

Inside the dome there was the photoheliograph installed in 1856 for sunspot observations, and on top of the dome was the massive Robinson-Beckley cup anemograph of about the same date and still working in 1920. In the Clinical House, so-called because it was where clinical thermometers used to be tested, the water-dropper electrograph set up in 1861 under the personal supervision of William Thomson (later Lord Kelvin) was still in operation. Other historic instruments continuing to be used in 1920, included John Welsh's standard



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PLATE I—PORTRAIT OF GEORGE III, FOUNDER OF KEW OBSERVATORY
King George III founded the Observatory (built 1768–69) primarily for the observation of the transit of Venus, which occurred on 3 June 1769. The portrait shows the king at about 1767 and now hangs in the National Portrait Gallery, London. See page 162.

Transit of Venus.

3: of June. 1769.

His most venerated Majesty King George the 3.
Her most sacred Majesty Queen Charlotte.
His Serene Highness Prince Edward of Mecklenburg-Schwerin.
His Serene Highness Prince George of Mecklenburg-Stralitz.

attended by.

Colonel Desaguliers
Edw. New. M. G. Wollaston.
Stephen Rigaud.
Justin Williams.
James Fishon.
Ben. Williams.
John Cust.
Doctor Stephen Demainbray.
present.

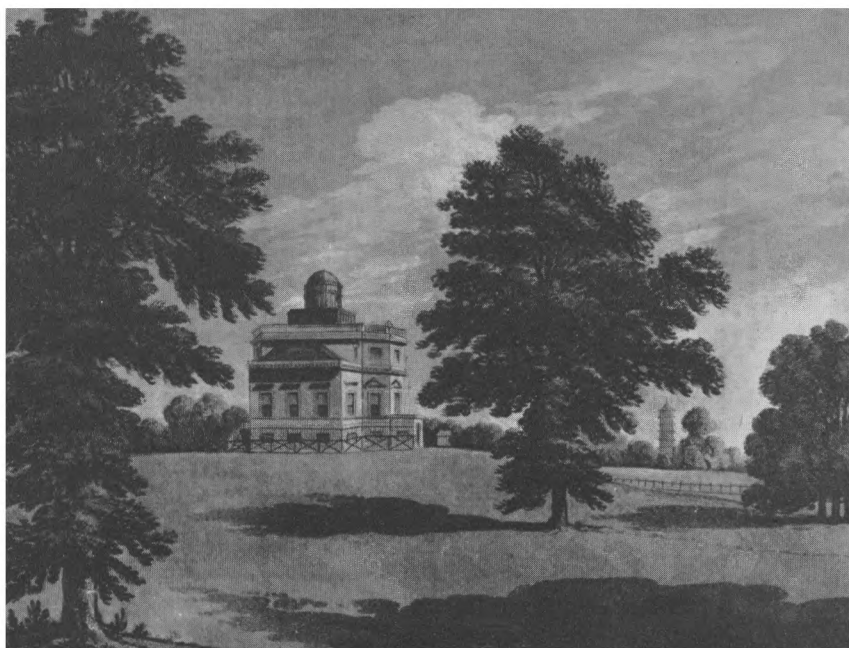
His Majesty the King who made his Observation
with a Most Reflecting Telescope, magnifying
Diameter 170 Inward, was the first who saw
the Penumbra of Venus touching the Edge of
the Sun's Disk.
The exact Mean Time (according to civil reckoning)
was attended to by Mr. Stephen Demainbray, appointed to
take exact Time by Mr. Thomas Reginald, previously
regulated by several Astronomical Observations.

Reproduced by courtesy of the Librarian of King's College, London

PLATE II—THE FIRST OBSERVATION FROM KEW OBSERVATORY —

THE TRANSIT OF VENUS ON 3 JUNE 1769

The account is by Dr Demainbray and page 1 shown here begins with a list of those present. The telescope and clock referred to are now in the museum of the planetarium adjacent to Armagh Observatory, Northern Ireland. The manuscript book (MS/1) is in the Library of King's College, London. See page 162.



Reproduced by courtesy of L. Jacobs

PLATE III—THE OBSERVATORY IN THE LATE 18TH CENTURY VIEWED FROM ABOUT
THE SOUTH-WEST

The plate is reproduced from a print ($8\frac{1}{2} \times 7$ inches), in the possession of L. Jacobs, which was published in 1792 by T. Cadell, Strand, London, and entitled 'The Observatory in Richmond Gardens'. The main telescopes were in the dome, the roof of which could be opened and moved. The facing room on the west, with four long windows visible, was used for routine transit observations, while the corresponding room on the far side of the building was used for quadrant observations. Not visible are tall obelisks in the Park still existing, one 300 yards away to mark north from the centre of the Observatory and two, 900 yards away, marking south from the transit and quadrant rooms respectively. As no ground was available outside for instrumental work until about 1856, the rain-gauge was placed on a pole near the southern edge of the flat part of the roof — it is clearly visible in the original print. The Observatory is built on an artificial mound. See page 166.



Photograph of the silhouette at Kew Observatory by courtesy of R. K. Pilsbury

PLATE IV—SILHOUETTE OF DR STEPHEN CHARLES TRIBOUDET DEMAINBRAY
He was the first King's Observer at Kew Observatory, 1769–1782. The original silhouette is at Kew Observatory to which it was presented by his great-grandson in 1882. See page 163.



PLATE V—THE OBSERVATORY TODAY — A CORNER OF THE ENTRANCE HALL
From left to right are the busts of S. P. Rigaud (1774–1839), E. Sabine (1788–1883), and J. P. Gassiot (1797–1877). See page 163.

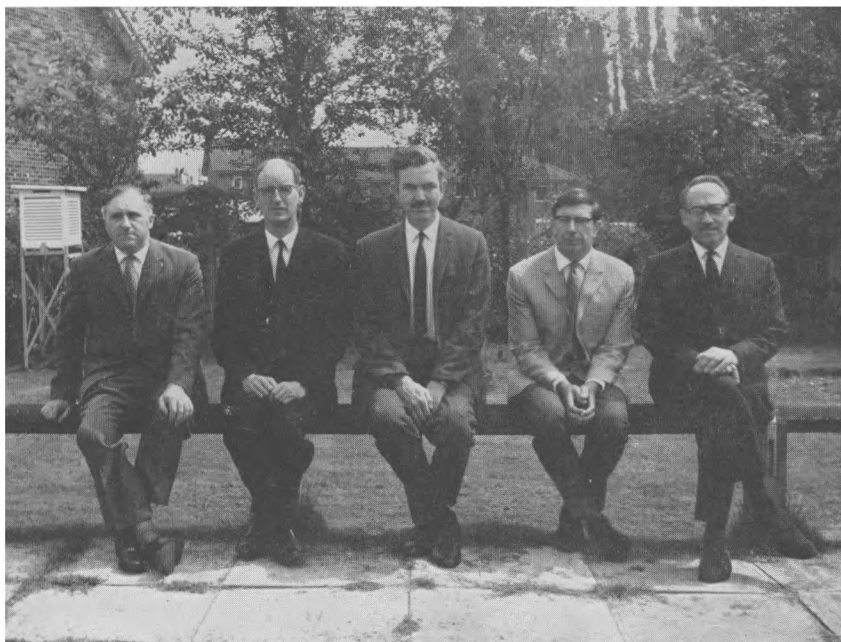


PLATE VI—THE SUPERINTENDENTS AT KEW 1947–1969

The photograph was taken at Bracknell on 22 July 1968. From left to right the superintendents with their dates of appointment are: 1947, George David Robinson; 1957, Kenneth Hope Stewart; 1960, Robert Henry Collingbourne; 1966, Richard Alexander Hamilton; 1968, Stanley Gershon Crawford.

A composite photograph of superintendents 1842–1939 is given in the *Meteorological Magazine* for July 1962, and in the issue for November 1954 there is a description of a memorial tablet at the Observatory giving a list of King's Observers and superintendents up to 1939 and their dates of appointment.

King's Observers :

- 1769 Stephen Charles Triboudet Demainbray
- 1782 Stephen George Francis Triboudet Demainbray

Superintendents :

- | | |
|----------------------------------|---------------------------------|
| 1842 Sir Francis Ronalds, F.R.S. | 1876 George Mathews Whipple |
| 1852 John Welsh, F.R.S. | 1893 Charles Chree, F.R.S. |
| 1859 Balfour Stewart, F.R.S. | 1925 Francis John Welsh Whipple |
| 1871 Samuel Jeffery | 1939 James Martin Stagg |
| 1939 Sir George Simpson, F.R.S. | |

Sir George Simpson (who had retired from the post of Director of the Meteorological Office on 2 September 1938 but had voluntarily resumed duty at Kew from September 1939) continued as Superintendent until 1946, when J. M. Stagg returned. The next Superintendent was G. D. Robinson, in 1947. See page 163.



PLATE VII—AN AERIAL PHOTOGRAPH OF THE OBSERVATORY

This view of the Observatory shows part of its six acres of grounds — and was taken in 1965 from the south at 500 feet. A plan and full details of the instrumental equipment are also given in the 1965 *Observatories' Year Book*; the main changes up to 1969 are the addition of several different types of evaporimeters in the right foreground and the cessation of the tethered balloon work. The Observatory itself is about 30 feet north-south and about 50 feet east-west and the head of the pressure-tube anemograph, on the top of the dome, is at about 80 feet above the general ground level. The northern obelisk (see caption to Plate III) is some 50 yards beyond the edge of the grass line to the north — many of the trees have now been cleared. See page 166.



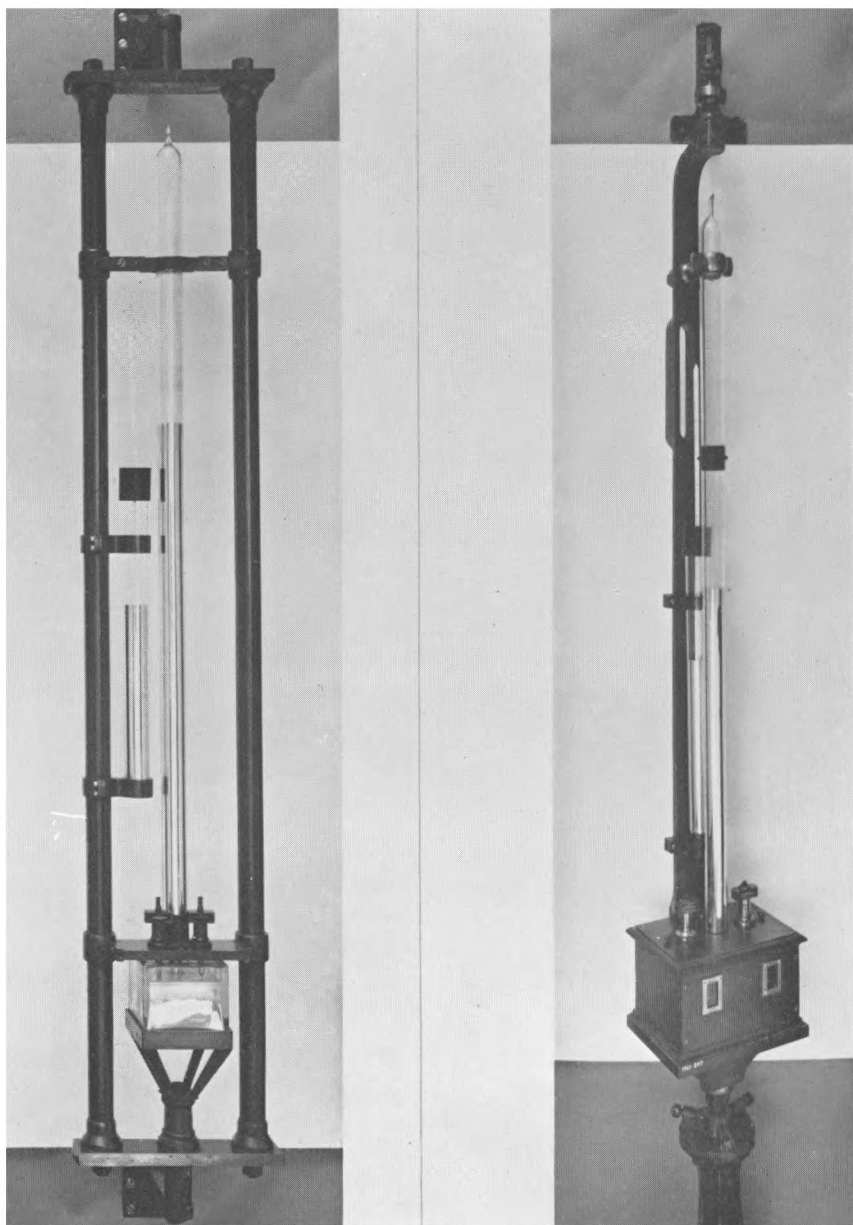
PLATE VIII—THE OBSERVATORY TODAY — VIEWED FROM THE NORTH

The ground-floor window to the left just above the balustrade is where the thermometers were exposed from January 1773 to October 1849; then a Glaisher screen was erected on top of the balustrade and this was replaced from 1 January 1854, by a Welsh (Kew) screen near the same place. The north-wall screen, seen on the right, came into use from October 1867 and was, in its turn, replaced by an aspirated psychrometer in the middle of the lawn from 1 January 1969 (see *Meteorological Magazine* for January 1969). The ground-floor window on the west side nearest to the north-wall screen is the site of the water-dropper photo-electrograph installed by W. Thomson (later Lord Kelvin) in 1861 (see note on page 184).



Photograph by courtesy of B. Shardlow

PLATE IX—THE PRESENTATION OF THE IMPERIAL SERVICE MEDAL TO MR R. RELF
The Director-General of the Meteorological Office (Dr B. J. Mason, F.R.S.) is shown with Mr and Mrs R. Relf at Bracknell on 18 December 1967, on the occasion of the presentation. Mr Relf retired from service at Kew, from April 1918, in July 1967; he was, from 1935, resident caretaker and his wife was resident housekeeper; in the 30 years up to 1965 Mr Relf's duties included 'such participation in the routine observations as the Superintendent may direct', and these observations were mostly made in the early morning, at night and over weekends. See page 169.



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PLATE X—EARLY KEW STANDARD BAROMETERS

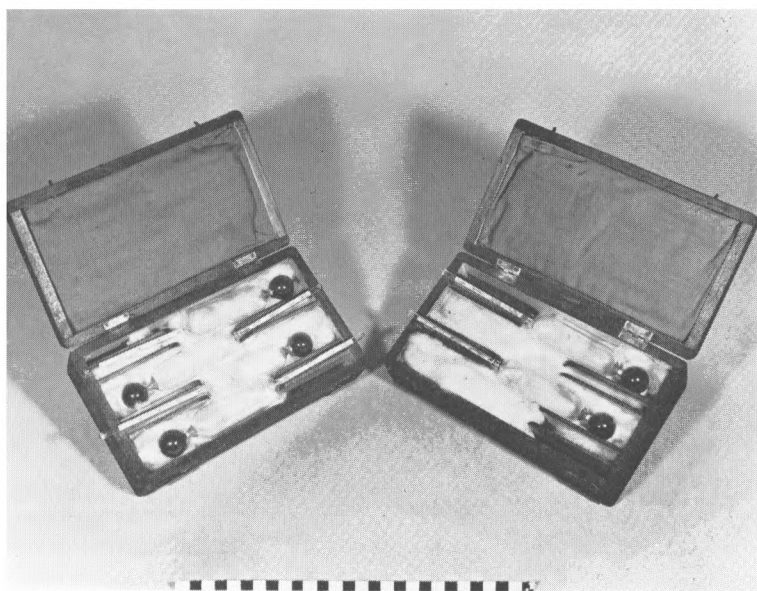
The barometer on the left was constructed in 1855 (Welsh) and the one on the right in 1860 (Stewart and Beckley following Welsh). The instruments were in use at Kew Observatory until 1953, then came into the custody of the National Physical Laboratory until 1966 and are now on permanent loan to the Science Museum. See pages 171 and 181.



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**PLATE XI—EQUIPMENT USED AT THE NATIONAL PHYSICAL LABORATORY FOR
VERIFYING SEXTANTS**

The design is based on that of the equipment set up at Kew in 1866. See page 175.



Reproduced by courtesy of the Director, Royal Scottish Museum, Edinburgh

PLATE XII—TWO SETS OF HYDROMETERS

These were made between 1854 and 1857, for the Admiralty or the Board of Trade, and are now in the Department of Technology, Royal Scottish Museum, Edinburgh. They were for use by naval and merchant vessels for measuring the specific gravity of sea water. The set on the right (two missing) was verified at Kew in July 1857. See page 171.

barometers with one-inch tubes (see Plate X), the photographic recording barometer, thermometers and magnetometers, all of which had been in operation some 60 years or more. Time signals for checking the Observatory standard clock were obtained by means of a Post Office telegraphic needle.

In 1920 the Superintendent was Dr Charles Chree, F.R.S. He had been appointed in 1893 and had established a world-wide reputation as an authority on terrestrial magnetism;² under his guidance the Observatory had attained a foremost position among the magnetic observatories of the world. He delighted in teaching new members of his staff and many workers from all parts of the world, the technique of magnetic observations and computations. His method of standardizing records of potential gradient led to Kew having a longer series of reliable observations of this element than any other observatory.^{3,4} Chree's needs for his own (mainly theoretical) researches were very modest and very little modern laboratory equipment was provided for experimental work. When G. C. (later Sir George) Simpson visited the Observatory soon after becoming Director of the Meteorological Office in 1920, he said he thought the laboratory facilities should be brought up to date and asked Chree to have a list of requirements prepared for this purpose. Simpson recorded later² that Chree's short list included four rings for a retort stand and a nest of four beakers. Chree scorned the use of a typewriter and wrote all his official letters in manuscript; duplicates were made on an old copying press.

One member of the staff in 1920 had been at the Observatory even longer than Chree. This was E. Boxall who was in charge of the computing room where data for the *Geophysical Journal*, precursor of the *Observatories' Year Book*, were prepared. Boxall recollected Chree's predecessor, G. M. Whipple,⁵ who had started as a boy at the Observatory in 1858, and when the Superintendent used to wear a frock coat and top hat and summon his staff back to work after their lunch-break by blowing a whistle on the front steps. Another 'old-timer' was B. Francis who was nominally the librarian and also acted as guide to the numerous visitors. His main interests, however, were phrenology and spiritualism. He pursued the latter to the extent of holding seances at the Observatory until someone discovered that objects which materialized during the seances were concealed in convenient places beforehand.

On the professional staff in 1920 were C. D. Stewart, who later became head of the meteorological service of the Federated Malay States, R. E. Watson and C. H. Kellett. Watson worked on Ångström pyrheliometer standardization,⁶ and later on comparison of the air-earth current at a height of 1 m and at ground level.⁷ For the latter measurement he crouched in a very small hole in the ground covered by a metal sheet. It was not until 10 years later that the first underground laboratory was built.⁸ Kellett was Resident Observer and subsequently went to Eskdalemuir Observatory, but died at an early age.

Most of my first year at Kew was spent in learning the observational techniques of terrestrial magnetism, atmospheric electricity and meteorology. Amongst other things I learned how to replace broken crosswires of instrument telescopes by spider web. I was later to find out what a great nuisance spider's

webs could be in atmospheric electrical work, in causing breakdown of insulation when moisture condensed on them. The only investigation to which Chree directed me was to determine the errors, due to self-heating, of the Callendar electrical resistance thermograph, an elegant instrument incorporating a self-balancing and recording Wheatstone bridge. It had been installed at the suggestion of Sir Napier Shaw some years earlier in the hope of its replacing the photographic method of recording temperatures of the large wet- and dry-bulb mercury thermometers which had been in use since 1867. Alas, the photographic method proved the more satisfactory in 1920 and, in fact, continued in use until the end of 1968.

I was fortunate in being allowed time off from my duties at Kew to attend the first course of lectures at the School of Meteorology, which was established at Imperial College in 1920 under Sir Napier Shaw, the first Professor of Meteorology in this country. In addition to Sir Napier's lectures on general and synoptic aspects of the subject, Captain (later Sir David) Brunt gave a course on physical and dynamical meteorology, which subsequently formed the basis of his well-known textbook.

It was not until I returned to Kew in 1926, after five years at Porton, by which time Dr F. J. W. Whipple had become Superintendent, that I started an interesting and enjoyable period of eleven years geophysical research. Whipple had close family connections with the Observatory, for not only had his father been Superintendent from 1876 to 1893, but his grandfather was Robert Beckley who had been assistant to earlier Superintendents John Welsh and Balfour Stewart. Whipple gave his staff every encouragement to pursue original work and had no hesitation in asking for the necessary equipment. His own interests covered a wide field, but he is best remembered for his work on the propagation of sound waves from gunfire and explosions,⁹ and his determination of the temperature structure of the atmosphere at heights beyond the reach of sounding balloons.¹⁰ One of his outside interests was the excavation of part of the Observatory paddock to reveal the foundations of the Carthusian priory founded by Henry V in 1414.

By 1926 all the geomagnetic work, which for some years had suffered disturbance by the electrification of the nearby railway, had been transferred to Eskdalemuir Observatory¹¹ and the Galitzin seismographs were brought from that Observatory to Kew,¹² On my return I took over the seismological work from J. M. Stagg and, with the help of the German translation of Prince Galitzin's classic textbook on the subject, I was soon involved in the complicated business of calibrating the instruments.¹³ When I came to study the records I was mystified by the occurrence from time to time of large isolated pulses which did not appear to be due to earth tremors. The seismograph pendulums were protected from draughts by large metal cases, but, at first, removal of these showed nothing untoward. Eventually I found that the pulses were caused by earwigs jumping or falling on the pendulums, and while the cases were being removed they scuttled under the bases of the instruments. The remedy was to seal the edges of the cases with grease.

Analysis of the records of earthquakes for the *Kew Seismological Bulletin* and the *International Seismological Summary* soon brought me into contact with H. H. Turner, Savilian Professor of Astronomy at Oxford, who was responsible for

the Summary, and with H. (later Sir Harold) Jeffreys at Cambridge. With their valuable help and the encouragement I received from Whipple, I was led to the study of deep-focus earthquakes¹⁴ and the recognition of the reflected waves associated with them.¹⁵ After a few years I handed over the seismological work to A. W. Lee¹⁶ who concentrated on the study of microseisms and published some important papers on the subject.¹⁷⁻²⁰

I took over the investigation of air-earth current from R. E. Watson and, in the course of the next few years, went on to various aspects of atmospheric electricity.^{8, 21-26} When, as an undergraduate, I attended C. T. R. Wilson's lectures on the subject, little did I think that it would ever provide me with a full-time job. Atmospheric electricity had a very long history at the Observatory, having started in 1843 when F. (later Sir Francis) Ronalds measured the electric potential with a lantern collector above the dome, using a straw electrometer.⁸ By the time I came on the scene we had at least advanced to the gold leaf of the Wilson 'Universal Portable Electrometer', and very soon substituted that excellent little instrument, the Lindemann electrometer, in this equipment. My atmospheric electrical work culminated in the collaboration with Sir George Simpson to develop the alti-electrograph for use on sounding balloons to detect the electric fields in and around thunderstorms.²⁵

In 1920 a good deal of attention had begun to be given to atmospheric pollution, following the setting up of an Advisory Committee on the subject under the chairmanship of Sir Napier Shaw. An automatic air-filter, invented by J. S. Owens, was installed at the Observatory. Owens also introduced his portable dust-counter which worked on the impaction principle. Some years later I used this instrument to investigate the dust content at various levels in the huge airship hangar at Cardington, where the ill-fated R101 was being built. It was thought that the presence of dust was causing difficulty in joining the gold-beater's skin used in making the gas bags. I became interested in atmospheric aerosols generally, and after resurrecting an old Aitken condensation nucleus counter, began to investigate the effect of dust and nuclei, charged and uncharged, on the electrical conductivity of the air.²⁶ H. L. Wright continued the work on aerosols but concentrated more on their effect on visibility.²⁷⁻³⁰

Many visitors were attracted to Kew Observatory; they ranged from parties of school children to the heads of geophysical observatories and meteorological services all over the world. There were also frequent training courses for meteorological observers. The annual meetings of the Gassiot Committee of the Royal Society often took place at the Observatory. Its task was to administer the Trust set up by J. P. Gassiot in 1871 for the purpose of assisting magnetic and meteorological observations with self-recording instruments, primarily at Kew Observatory. In the early twenties the chairman was Sir Joseph Thomson. The staff used to watch with great interest the arrival of the eminent scientists attending the meeting, especially Sydney Chapman, who could be seen speeding up the Observatory track on what appeared to be a racing bicycle. It was interesting to read in *The Times* of 29 July 1968, that although more than 80 years of age he was still riding a bicycle and even swimming half a mile a day; moreover, long after retirement

from his Oxford Professorship, he is still at work at the University of Alaska and at the U.S. National Center for Atmospheric Research at Boulder, Colorado.

Before the existence of London/Heathrow Airport and the building of the bypass across the Old Deer Park, life at Kew Observatory was very quiet and peaceful. Behind the Clinical House, the caretaker kept hens and on the surrounding golf course sheep grazed. At the beginning of the track leading to the Observatory there were stables and also a cottage where the famous professional golf champion J. H. Taylor lived; his two daughters worked in the Meteorological Office. A reminder that the peace of the place was temporarily shattered in the 1914-18 war was a bomb crater in the Observatory paddock. Another crater just outside was turned to useful purpose as a golf bunker.

One drawback associated with the site of the Observatory was the liability of the grounds to be flooded when the Thames overflowed its banks. One of the most serious floods occurred in 1928, when lives were lost at several places lower down the river. My own house near Kew Green was flooded to a depth of three feet, and amongst the many books which were damaged was an expensive new *Handbuch der Geophysik* which I had borrowed from the Observatory library. I persuaded the Superintendent to seek authority for it to be 'written off', and eventually the Finance Division of the then Air Ministry agreed, but warned that I should not let it occur again.

A description of the Observatory building given in the Kew Committee Report of 1859-60 includes the remark that 'the repose produced by its complete isolation is eminently favourable to scientific research'. This physical isolation of the building in the Old Deer Park did not, of course, mean that members of the staff lacked facilities for the exchange of ideas with other workers. Not only did the large number of visitors help in this respect, but every encouragement was given to the staff, particularly under Dr Whipple's direction, to attend meetings of the learned societies in London as well as the Monday evening scientific discussions of the Meteorological Office. Looking back after nearly 50 years since I first went to Kew Observatory, I think that the repose and the pleasant surroundings must have helped to make my 12 years service there the most productive and most enjoyable of my career.

Note : The photoheliograph, long unused, went to the Science Museum in 1927; the Robinson-Beckley cup anemograph was dismantled in 1929 and replaced by a pressure-tube anemograph; the necessary overlapping records were discussed in the 1931 *Observatories' Year Book*, pages 343-344. The photo-electrograph was originally set up by W. Thomson in 1861 with its boom projecting from the west side of the main observatory building (see Plate VIII); the siting at the adjacent Clinical House, which Scrase mentions here, occurred from 1915 to early 1940, when the instrument was returned to near the original site, where it still remains and records. The water-dropper was replaced by a radioactive (polonium) collector in 1931; there is also, from May 1958, a pen-record (valve voltmeter) from the Clinical House site. The John Welsh barometers are now in the Science Museum (see Plate X). The photobarograph is still in use. Of the magnetometers transferred to Eskdalemuir, the horizontal component and declination variographs are still recording.

The seismological work has, in the last few years, been entirely taken over by the Global Seismology Unit, Institute of Geological Sciences (IGS) (Natural Environment Research Council) Edinburgh. The Galitzin seismographs ceased operation at the end of 1964 and are now in the Science Museum; the Office has provided the IGS with microfilms of all available

seismograms from 1898 to 1964. Recording with the last seismograph at Kew short-period vertical) ceased at the end of March 1969 because the IGS then had another station providing coverage for southern England. The International Seismological Summary, which Scrase mentions as being established at Oxford, was given accommodation at Kew Observatory from 1947 to the end of 1967, when it disbanded on its function being taken over by the Global Seismology Unit, which then also took over the responsibility for publication of the seismological data for Eskdalemuir from 1968 onwards. The last issue of the *Seismological Bulletin* of the Meteorological Office was that for December 1967.

The full background story to the extra interest, from 1912, in the air pollution problem, which Scrase mentions, is given in the book by Sir Napier Shaw and J. S. Owens;²¹ here it is mentioned that F. J. W. Whipple acted as scientific consultant to the Atmospheric Pollution Committee. Records of pollution from Kew and many other stations were collected and studied — the task is nowadays that of the Warren Spring Laboratory, Ministry of Technology. The original Owens hourly recorder at Kew, in routine use from 1 January 1921, was replaced on 1 January 1962 by a new recorder, designed at the Warren Spring Laboratory, in which the optical density of the smoke stains is measured by a photo-electric reflectometer. The gradual implementation of the 1956 Clean Air Act is shown by the annual maximum hourly value of smoke pollution at Kew falling, after 1964, below 1000 microgrammes per cubic metre of air for the first time since recording began. However, with the decrease of smoke, increasing attention has to be paid to the measurement of sulphur dioxide and the daily values at Kew have been notified to Warren Spring since January 1961.

L. JACOBS

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THE BRITISH RADIOSONDE : ITS DEBT TO KEW

By D. N. HARRISON, O.B.E.¹

When I went to Kew Observatory as resident observer in December 1926, I was aware that L. H. G. Dines was calibrating meteorographs in a room at the south end of the Clinical House, having been in charge of this work since its transfer from his father W. H. Dines's home at Benson in 1923. My time at Kew was short, as I left for the Edinburgh Office in May 1927 and afterwards went on to Lerwick Observatory, but, as will be seen below, I was much concerned, from 1937 onwards, with the new radio methods being used for upper air measurements.

Crucial decisions. The development in other countries of radiosondes to replace the meteorograph during the 1920s is described in the *Handbook of meteorological instruments, Part II.*² The initiation of such a project in this country is recorded in the *Report of the Director of the Meteorological Office* for the year ending 31 March 1937, which states that 'the development work has been entrusted to the National Physical Laboratory, who are working in close collaboration with the Meteorological Office. Although the experimental stage has not been passed, very satisfactory progress towards the design of a suitable instrument has been made during the year'. It was decided that, in addition to measuring pressure (P), temperature (T) and humidity (U), radiosonde signals should be used to measure upper winds by direction-finding (DF), and my first contact with this work was in the autumn of 1937, when I was sent from the Instruments Branch by J. S. Dines, Superintendent, brother of L. H. G., to visit H. A. Thomas and H. G. Hopkins at the National Physical Laboratory (NPL) to be briefed on the requirements for DF sites.

After prospecting in the flat country of Essex with C. E. Britton of the Meteorological Office, Shoeburyness, I looked at sites on Salisbury Plain, where it was decided to set up a station at the Meteorological Office, School of Artillery, Larkhill.

Before the end of 1937 it was agreed that the instrumental work of the Office on the development of radio sounding should be based on Kew Observatory, the Upper Air Section, with L. H. G. Dines in charge, being combined with the Observatory work under F. J. W. Whipple, Superintendent. I had no further contact with the work until I went to Larkhill in February 1940.

The first British radiosonde was designed by H. A. Thomas;³ the preliminary testing of sondes took place at Kew in December 1937, when the workshop was making calibration apparatus, and the first experimental ascent was made in April 1938. These sondes, known as the NPL Mark 1, were not successful, and were soon followed by Mk 2 and Mk 3. Meanwhile supplies of sondes and ground equipment were obtained from Professor V. Väisälä of Helsingfors, Finland, where A. J. Lander, of Kew, spent two weeks learning the technique. The first ascent with these sondes at Kew was made on 31 March 1939, and routine soundings began in the Isles of Scilly on 18 February 1940, under Lander's guidance. Sondes of the Bureau type were sent from France and, after trials at Kew under instruction from a French army sergeant, were used on routine ascents at Lerwick Observatory from 10 April 1940, again with initial help from Lander.

The supply of Väisälä and Bureau sondes was soon exhausted, on account of the war, and they were replaced by the NPL Mk 3.

The Kew sonde. After the Mk 3 had been used for a time at these stations and at Larkhill, the design was found to be faulty and a new sonde was developed by E. G. Dymond, from Edinburgh University, and H. Carmichael, from Cambridge, who had come to Kew towards the end of 1939. This, known as the Kew Mk 1, came into routine use in June 1941, replacing the NPL Mk. 3.⁴ The NPL remained, however, responsible for the DF equipment and methods used by the Meteorological Office.

Kew was responsible for the supply, testing and calibration of all sondes. Up to the time of introduction of the Kew Mk 1 sonde, Kew made the meteorological units and commercial firms supplied the complete transmitter; subsequently, with further manufacture of parts, Kew's work was confined to dealing with the actual meteorological elements (for *P*, *T*, and *U*).

In addition to the work on sondes and calibration plant, certain important ancillary equipment was developed at Kew by Dines and Lander, notably the cone and gear for launching balloons in strong winds, 'unwinders', which allowed the long suspension string to be carried on a spool and unwound after the launch, and parachutes. There was also the invaluable radiosonde training machine due originally to E. H. Myer of Larkhill and developed and manufactured (from 1942) at Kew, which simulated mechanically the *P*, *T* and *U* changes normally experienced by a radiosonde in flight. Machines were issued to all stations for the training of operators. The work at Kew had by now increased greatly and there was a small very busy 'factory', a new Calibration House being built early in 1942; this work continued for the rest of the war and up to July 1946, when the staff and the work were transferred to the Instrument Branch at Harrow. (There was a similar transfer from Larkhill — see p.188 — in April 1947).

The development of upper wind observations by DF went on from 1938, first at Larkhill and later at other stations. This has already been described⁵ and need not be dwelt upon here.

Growth of network. The network of stations was built up until by August 1942 Larkhill, Fazakerley (near Liverpool), Downham Market (near King's Lynn) and Lerwick were operating as combined radiosonde and radio-wind stations. Penzance replaced Scilly, with radiosonde only, in October 1940. The number of ascents was increased until by March 1944 the routine consisted of four a day.

This meant that the work of calibration was greatly increased, and in July 1942 a complete calibration plant, made at Kew, was installed at Larkhill, in order to ensure the supply of sondes in case of enemy action against Kew (which fortunately never occurred), and this was followed by a second one in January 1943.

It should be recorded that, during the war, valuable help was given by the United States Army Air Force, which ran radiosonde and radio-wind stations with their own equipment, and also provided staff at Larkhill for calibration and for routine soundings.

Technical changes. The Kew sonde has continued in use as the standard Meteorological Office sonde with only minor modifications (which will be mentioned later) until the present, but methods of reading have changed greatly. At first the audio frequency, from which P , T and U are found by means of calibration curves, was measured by comparison with a variable oscillator, the adjustment being made originally by matching the signals by audible beats, later by a 'magic eye', finally on a cathode-ray tube; much later still this manual method of observation was superseded by an automatic counter and recorder,⁶ which gives a graphical record of the period, instead of the frequency.

The calibration work at Harrow was taken over by the Instrument Development Branch on its formation in 1948 (I came to Harrow in 1947 and became Head of the upper air section of this new Branch in 1948 and remained in the Branch until my retirement in 1962). A very effective mass-production plant was designed by H. L. Pace and H. E. Painter;⁷ this, with modifications, is still in use.

Over the years certain changes have been made in Dymond's design. In 1946 the layout was redesigned for mass production;⁸ this model became known as the Meteorological Office sonde Mk 2. Later, in order to lessen the risk of short-circuiting power lines, the half-wavelength aerial was replaced by one of a quarter-wavelength, a modification which required changes in the circuitry, and at the same time the stability of radio and audio frequencies against changes of temperature and battery voltages was improved; this modification, in 1950, was called the Mk 2B. An unforeseen result of this was that the third harmonic of the radiosonde signal interfered with the frequency-modulation radio-telephones used by some of the county police forces; to remedy this filters were incorporated into the radiosonde.

Army radar sets (GL3) superseded direction-finding for wind measurement after the war, and these proved to be so accurate that they could be used as a check on the heights above ground calculated from the radiosonde observations of P , T and U . A great deal of valuable information on pressure errors has been obtained in this way. Further information has been provided by 'twin' soundings, in which two sondes are carried by the same balloon. These methods are indirect and incomplete, but they are the only methods of any value for investigating the errors of the sondes, since there is no instrument of higher accuracy against which to compare the sonde in flight; tests on the ground do not give enough information. Much has thus been learnt about the variability of sondes one from another,⁹ but very little about the systematic errors which are common to all sondes of one type at one time and the way in which these vary over long periods. The twin sounding method was extended at international trials in Switzerland, in which many different sondes were compared, sometimes half a dozen or more simultaneously being carried by the same bunch of balloons, but the difficulties of organization and technique and the unrepresentative nature of the conditions have meant that the results have been of little value.

Recent developments. The first radar sets employed manual following, that is to say, the operators kept the aerial pointing at the target by watching the reflected signal and recorded the indicated range, azimuth and elevation. Later, automatic following methods were introduced, and these enabled the rates of change of the co-ordinates to be computed automatically. The Meteorological Office, with the help of the Ministry of Supply (later Ministry of Aircraft Production), undertook in 1950 a project to apply radar pulse techniques to a combined sounding (P , T , U) and wind-measuring equipment to be known as the Radar Sonde Theodolite.¹⁰ The development and basic design work of the radar sonde were carried out under F. E. Jones at the Telecommunications Research Establishment (now the Royal Radar Establishment) Malvern. Engineering and pre-production development was done by Mullard Research Laboratories. Much progress was made and a working prototype was produced in which all the results (P , T and U , and wind speed and direction) were recorded graphically or digitally; but the equipment, especially the airborne transponder, became so complicated and expensive that the project was abandoned in 1957. (The wind-finder portion was used for research purposes until the supply of transponders had been consumed.)

It was then decided that a fresh beginning should be made, and a new sonde and separate radar-wind equipment developed. This has been done. The new sonde, Mk 3, uses the same principle of audio-frequency-modulation as the Thomas sonde, but the frequencies are in the range $3\frac{1}{2}$ –7 kc/s instead of 700–1000 c/s. The sensing elements are an improved aneroid capsule with greatly reduced temperature coefficient for pressure, giving significant results to at least 30 km, and our old friend gold-beater's skin for humidity, both actuating ferrite-cored inductors; but for temperature a fine tungsten-wire resistor, coiled as in a lamp filament and supported on a plastic frame, is used instead of the bimetal element. The time-constant and heating by

solar radiation are greatly reduced, and these wire elements have the additional advantage that they can be standardized and therefore need not be calibrated with their individual sondes, (as is necessary with the bimetal elements); the resistance varies from 950 ohms at 20°C to 500 ohms at - 100°C. The incorporation of a resistance element, especially one of such a comparatively low value, along with the inductors of the *P* and *U* units, has only been made possible by recent advances in transistor circuit design. The three units are switched into circuit by a battery-operated motor instead of a windmill, and the design of the switch allows the programme of readings to be changed easily.

It is expected that the new sonde will be in routine use in about two years' time.

Since the war, changes have been made in the upper air network and the stations are now at :

United Kingdom : Aughton, Camborne, Crawley, Hemsby, Lerwick, Long Kesh, Shanwell, Stornoway.

Overseas : Cyprus, Gan, Gibraltar, Malta, Masirah, Muharraq, Tobruk, and four Ocean Weather Ships on stations in the North Atlantic.

And so the work done at Kew Observatory 30 years ago, on the foundation laid by the NPL, still endures, and its influence can be traced through successive generations of radiosondes. We can confidently expect that the latest member of the family will prove to be the best.

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AIR-LAND INTERACTION, FOG, ATMOSPHERIC OPACITY — A MISCELLANY

By G. D. ROBINSON¹

No one who has worked for any length of time at Kew Observatory regards the published record as an adequate source for a history of the ideas discussed and experiments conducted there: this article treats a miscellany of work, some of it recorded only in internal reports and in manuscript, and by some standards unsuccessful, but memorable enough to the participants and enlightening to them if not to the scientific world.

Investigations of fog and atmospheric opacity at Kew have for the most part been aimed at the specific and immediate problems. In the late 1920s M. G. Bennett, known for his work on railway signalling systems, spent some time at Kew perfecting an instrumental method for measurement of visibility. The resulting 'nephelometer'² operated on the extinction principle; obscuring screens were introduced in front of the eye until the distant light or object could not be seen. There is little documentation of this work, and no indication why the instrument was not adopted — it operated on the same principle as the Gold visibility meter³ later put into general use in the Meteorological Office — though it lacked the continuous scale made possible by use of the optical wedge.

A few years later, systematic counts of Aitken nuclei and the large ion content of the air were begun at Kew. This was part of the comprehensive investigation of atmospheric electricity initiated by Sir George Simpson⁴ and F. J. W. Whipple⁵ and, amongst others, H. L. Wright took part in the measurements^{6,7} during his term of service as Resident Observer. Some years later when working with the Naval Weather Service and faced with problems of visibility at sea, he remembered the Kew nucleus counts, and returned to the Observatory to make the analysis of land and coastal visibility observations,^{8,9} work for which he was awarded the Buchan Prize of the Royal Meteorological Society.¹⁰ He used these results to clarify the influence of Aitken nuclei and sea-salt nuclei on atmospheric opacity.^{11,12,13}

The next attack on problems concerned with opacity was a more substantial effort in the mid-1950s. It resulted from a fusion of two lines of research — a study of airfield visibility problems,^{14–17} particularly at the smoke-affected London/Heathrow Airport, six miles from Kew, and the study of ground-fog formation,¹⁸ which had begun as an off-shoot of the energy-balance investigations to be described later. This investigation brought together the remarkable, if disparate, talents of A. J. Lander and K. H. Stewart; it has had an influence more pervasive than would be suspected by those who count success in terms of published pages and it was certainly a pleasure to be associated with it. A feature of this activity was the examination by Stewart of methods of determining the size-distribution of the particles responsible for atmospheric opacity in haze and fog. He made a thorough analysis of the shortcomings of impaction techniques standard at the time, and particularly of the possibilities of evaporation within the impactor, and began work on optical methods of size-distribution determination. The need for some kind of controlled foggy atmosphere became apparent, and Lander designed and built a well-insulated 3-metre cube with various experimental facilities, in which it proved remarkably difficult, but not impossible, to maintain a stable fog long enough to allow size-distribution determinations. Stewart worked on small-angle scattering methods within this chamber, and with optical and infra-red transmission in the open. Being of a thrifty disposition, and having no great faith in the routine utility of methods involving inversion of an integral equation, he scorned the temptation to spend money on expensive and fashionable equipment. The infra-red detector was a thermopile with filters, borrowed from the solar radiation programme. Two infra-red sources were respectively a domestic electric boiling ring, and a kettle in which water was being boiled. The kettle, in fact, served a dual

role in the investigation; it was also part of the humidifier of the fog chamber. The results of this work are recorded only in unpublished reports^{19,20} to the Meteorological Research Committee; reports which repay study both of the methods used and the conclusions reached. They contain, amongst other things, an analysis of opacity in fogs at Kew in relation to size-distribution of the particles, stressing the importance of very small particles which make little contribution to the suspended mass, and the design of an efficient cascade impactor. There is a published discussion²¹ of artificial fog clearance with suggestions for improvement of the hygroscopic-drop method of Houghton and Radford.²²

Investigations of energy and momentum transfer at the surface at Kew grew naturally out of the radiation programme described by R. H. Collingbourne in the July 1969 issue of the *Meteorological Magazine*: the incident solar energy and the returning radiation from the ground were being measured; what happened to the balance of the energy absorbed by the ground? The investigation at first followed well-established methods with measurements of the profiles of temperature, humidity and wind speed accompanying determination of the radiation balance at the surface; if there was any improvement over prior investigations of the same kind it was in the precision of the radiation measurements and, in the realization of the role of direct radiative heating and cooling of the lower layers of air. It was realized from the start that the site at Kew was far from ideal for comparison with theories of the boundary layer over an extensive uniform surface, but the investigators had in mind that such sites are exceptional and hoped to make a contribution of more general value, a hope which was not fully realized. Results are contained in internal reports; one published paper²³ summarizing the investigation deserves the attention of the student of the history of micro-meteorology. Some observations taken immediately before the formation of ground fog are particularly interesting, with a near-linear wind profile and a temperature profile probably consistent with local radiative equilibrium.

At an early stage of this programme, it was decided to supplement the profile observations with measurement of the heat and momentum fluxes by the correlation methods which were being developed elsewhere, particularly in Australia by W. C. Swinbank and his colleagues. For this purpose experience in hot-wire anemometry was required, and this aspect was enthusiastically pursued by A. J. Lander who soon acquired skill in the construction of crossed-wire anemometers and built a small wind tunnel for calibration purposes in the laboratory still known as the Clinical House. Analogue computing aids were a common feature of similar laboratory investigations at the time, but it was decided not to employ these 'in the first instance', as it was felt that more insight would be gained into the nature of the processes involved if records of the fluctuations of temperature and the components of wind were available for inspection. This expectation was certainly borne out: the investigators associated with this programme over a period of about five years learnt a great deal about the lower layers of the atmosphere; the most memorable feature being a mistrust of the value of the correlation method for determination of fluxes, particularly of momentum, and particularly when measurements are made at only one point. The site of the field measurements was moved from the restricted area at Kew, first to a more open area

at Cardington, Bedfordshire, and then to a little-used airfield at Graveley, near Huntingdon, where a long fetch over flat treeless land was available for all wind directions. Many records were obtained. The scale of phenomena measured was set by the free period of the galvanometers used for recording: periods of 1/50 second, 1/10 second and 2 seconds were available, and records were taken for periods which allowed more than 2000 independent points to be measured. On most occasions independent methods of measuring heat or momentum flux were attempted, and the energy-balance method in use for the heat flux required a cloudless sky if the radiation measurements were to be made with sufficient accuracy. Waiting for such conditions was frustrating and the investigators often thought enviously of the climatic advantages of Australian workers in the field, but the envy was tempered when the day did arrive and work began in the green moderation of a perfect English summer day. N. E. Rider, A. J. Lander and H. E. Painter were associated with this work, and I am grateful to them for hard work which may well have greatly increased their appreciation of the complexity of the atmosphere but which brought them little immediate scientific recognition. Only one published paper commemorates this work and that is on a side issue,²⁴ but several unpublished reports were made.²⁵⁻²⁹ So far as flux determination by the correlation method was concerned, the general experience was that this method (applied at a single sampling point) and the energy-balance method usually gave results which agreed within a factor of two for heat flux. Momentum flux, compared with the results of drag-plate techniques, was much less consistently determined, and spectral analysis often showed curious anomalies. A feature observed on more than one occasion was an apparent upward flux of momentum in the direction of the mean wind associated with the components of frequency a few cycles per hour. An attempt was being made, in collaboration with H. Charnock to operate over an extensive water surface (a reservoir at Kempton Park) when staff changes, and in particular the end of my own long stay at Kew, interrupted the work. It was not resumed: the pause allowed what would now be called a cost-benefit analysis, with discouraging conclusions.

It is interesting to note that at the same time as the Kew work was in progress at Cardington and Graveley, staff from the Meteorological Office Research Unit at the School of Agriculture, Cambridge, were investigating, using the same field sites, drag/profile relationships³⁰ and the factors affecting natural evaporation from grass.³¹

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DEVELOPMENT OF ROCKET AND SATELLITE EXPERIMENTS AT KEW OBSERVATORY, 1959-61

By K. H. STEWART

Kew has been the home of many pioneering investigations. One of the most recent began on 1 October 1959 when D. E. Miller arrived to study, in consultation with the Superintendent (K. H. Stewart), the feasibility of measuring ozone from an artificial earth-satellite. The United States generously offered to build and launch satellites carrying experiments designed and made in other countries, and the Meteorological Office was anxious to provide one of the experiments in an early satellite of what became the ARIEL series. Dr G. D. Robinson, Deputy Director (Physical Research) had been a member of the party which accompanied Professor H. S. W. Massey to the U.S.A. in June 1959, to negotiate the agreement by which British experiments would be mounted on these American-launched satellites, and it resulted from this that D. E. Miller was sent to Kew and became the first member of the High Atmosphere Branch which was officially established, at the Meteorological Office, Harrow, at the end of February 1960.

The early work at Kew covered a wide range of subjects from the properties of satellite orbits to the design of filter and prism systems and the practical details of data storage and telemetry. It soon became clear that measurements of useful accuracy and with a satisfactory geographical coverage ought to be practicable from the rather simple satellite that was envisaged, and by early 1960 definite plans for the satellite experiment were put forward.

The principle of the experiment was to measure the attenuation of ultra-violet sunlight by the ozone in the atmosphere at times when the satellite was just entering or leaving the earth's shadow, and the sun's rays had to pass tangentially through the atmosphere to reach the satellite. The crucial point of the design was the devising of sensor systems that would measure light of the selected wavelengths. In the end two systems were chosen, one very simple, relying on the inherent photo-electric response of a suitable metal (thorium) to produce a signal from a broad band of wave-lengths in the ozone absorption region, and the other more elaborate, using a prism spectrometer which would scan the sun's ultra-violet spectrum as the satellite rotated. In order to test and measure the components of these systems and to calibrate the complete units when made, an ultra-violet monochromator was obtained, together with various other ultra-violet sources and a collection of electronic measuring equipment, and was set up, for lack of another suitable darkroom, inside the 'fog chamber' that had been built a few years earlier in the wooden hut previously used for radiosonde calibrations.

The group at Kew, now under the new High Atmosphere Branch, expanded rapidly during 1960 to include K. H. Stewart, G. P. Carruthers, D. G. James and one or two assistants, and work went ahead on many fronts at once. An essential preliminary to the satellite experiment was the testing of equipment (and of the operation of the experiment generally) in a rocket flight, and the most pressing task became the construction and testing of sensor

units and electronics for this flight. The spectrometer units were designed and assembled at Kew, the mechanical parts being made in the workshops at Harrow; the 'broad band' units were entirely made at Kew, using the staff and resources of its workshop. Assembly, testing and calibration were done in the old 'calibration' hut, and many relics of earlier work at Kew were pressed into service to fill gaps in the equipment available. In particular, an old brass dip-circle which originally came from Falmouth became the main mounting device for the calibration of spectrometers at different angles of incidence. Besides this practical work, much planning went on for the incorporation of the experiments into the satellite, and elaborate studies were made of mathematical methods of handling the data to be expected so as to derive the ozone concentrations, not an easy matter, since the quantities observed would depend on ozone amounts integrated over large regions of the atmosphere both vertically and horizontally.

By early 1961 construction of the rocket equipment was more or less complete and a series of visits to the Royal Aircraft Establishment (RAE), Farnborough, began, for the final testing of equipment and its assembly and testing in the instrument bay of the rocket. In these last months at Kew the group was joined by D. W. S. Limbert and D. S. Hamilton. In July, as the Meteorological Office's first rocket experiment left Kew for the RAE and its long journey to Australia and thence into the upper atmosphere, the High Atmosphere Research Unit moved from its nursery at Kew to a new home at Bracknell.

This first SKYLARK rocket was launched in November 1961 and was technically successful, though the information yielded was not very precise. It has been followed (to date) by seven further SKYLARKS carrying equipment of gradually improving accuracy and reliability, which has given good measurements of ozone at heights between 40 and 80 km.¹ An unexpected by-product has been the measurement of the large amount of dust injected into the atmosphere by the eruption of Mount Agung (Bali) in 1963.² The satellite version of the experiment was launched in ARIEL 2 in March 1964, and operated with fair success over the next six months.³ In more recent years the same basic technique has been used for the measurement of molecular oxygen at greater heights, 100–250 km, both from rockets⁴ and from the ARIEL 3 satellite.^{5,6}

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REVIEWS

Die Wissenschaft vom Wetter, by H. Reuter. 185 mm × 120 mm, pp. viii + 146, illus., Springer-Verlag, 1 Berlin 33, Heidelberger Platz 3, Berlin-West, 1968. Price: DM 7.80.

This little book is one of a series entitled *Comprehensible science*. The author is Professor of Theoretical Meteorology at the University of Vienna. He writes in the preface that his aim has been to bring the results of research by meteorologists to a wider circle of readers in exact but generally comprehensible form with special attention to progress since the publication before the last war in the same series of von Ficker's book *Wetter und Wetterentwicklung*.

The book provides a very readable non-mathematical account of many aspects of meteorology. The main subjects covered are the general structure of the atmosphere, radiation, general circulation and jet streams, cloud and precipitation, hydrological cycles, atmospheric circulations from tornadoes to large-scale pressure systems, present methods of observation (satellite cloud pictures, radar) and weather forecasting. A notable absentee is atmospheric diffusion. Particular care, as is proper to a writer in Vienna, is given to a good clear account of the sources of the energy of the wind. The account of numerical forecasting is not good. The methods used in most countries based on the solution of the equations of motion of a model atmosphere adjusted to agree at certain levels with current observations are not mentioned; the author merely says that numerical forecasting depends in principle on the determination of an 'influence function' at each point of the grid.

The reproduction of the diagrams and half-tones, notably the satellite cloud photographs, is excellent.

The book is written in a simple clear style and would give good reading practice in German to English-speaking meteorologists.

G. A. BULL

Der Aufbau der Erdatmosphäre, by H. Faust. 235 mm × 165 mm, pp. viii + 307, illus., Vieweg and Sohn, Brunswick, 1968. Price: DM 56 (112s.).

Most books of meteorology, apart from a brief mention of noctilucent clouds, meteor trails and auroral displays, confine their attention to the troposphere and the stratosphere up to about 30 km. There are, of course, plenty of books about the ionosphere and magnetosphere, but as far as I know this is the first fairly comprehensive treatment of the atmosphere as a whole. In this ambitious attempt the author, writing in a very individual way, has made a notable and very interesting contribution to meteorological literature.

A main theme running through the book is the layered nature of the atmosphere starting from the peplosphere (friction layer) and the troposphere, into the stratosphere, mesosphere and ionosphere. He refers repeatedly to the importance of 'null layers', i.e. layers through which the meridional gradient of temperature changes sign. The lowest of these is at about 10 km

where the normal polewards fall of temperature of the troposphere gives way in some latitudes to a rise. He claims that in the mean the vertical velocity changes sign at a null layer but it is not easy to see quite what importance this bestows on the layer. His other claim that the west winds are supergeostrophic at this null layer has as a consequence a flux of mass towards south, thereby providing a mechanism for the maintenance of the subtropical belt of high pressure against the dissipating effect of friction. He recognizes another null layer at the level of the mesospheric wind maximum at about 60 km, and, in the winter hemisphere, he claims that the level of minimum west wind between 20 and 25 km also represents a null layer. This, he says, represents a separating layer (*Trennschicht*) between the circulation arising from the heat supply at the earth's surface and that arising from the heat supply at the ozonosphere. However, other workers do not recognize a change in sign of the vertical motion at this level. This 'null layer' concept of Faust does not in the ten or so years since it was put forward seem to have received much attention by meteorologists outside Germany.

Despite this stress on null layers (some of which are explicitly termed separating layers), Faust claims that we must bear in mind the possible interactions of the various layers of the atmosphere. For example, if changes in the ozonospheric circulation due to variations in the ultra-violet part of the solar radiation affect the tropospheric circulation, then this will have important implications in long-range forecasting. Despite his concept of a separating layer at 20–25 km Faust presents the possibility of a frictional coupling which would produce such an interaction.

To go back to the beginning, the treatment of tropospheric conditions (about the first third of the book) is fairly standard but enlivened by a markedly individual approach which here and there pulls one up sharply. Such as, for example, when he says that the friction layer prevents cloud base falling to the surface in bad weather and that near fronts the friction layer is destroyed by the turbulent motions !

The next third of the book deals with the wind and temperature distribution from the tropopause to the limit of the homosphere, i.e. the region with a nearly constant composition which he puts at about 100 km. He describes how measurements from rocket ascents at Ascension from October 1962 to early 1965 indicate decreasing easterly components in the winds at levels above 40 km. It appears from these measurements that in the upper part of the ozonosphere the 26-monthly oscillation of the zonal wind is no longer present. Several other very interesting mesospheric circulations revealed by these rocket soundings, are also discussed.

This section of the book ends with an ambitious chapter on 'The homosphere as a whole', in which he discusses the inherent predictability of atmospheric processes and presents the views of some meteorologists that the large-scale variations in weather cannot be understood without taking account of what is happening in the greater part of the homosphere — up to about 70 km anyway.

The book finishes with an account of those regions in which ions are present in significant numbers so that magnetodynamical terms have to be taken account of in the equations of motion.

In the final chapter he discusses conditions at the levels where space craft operate, speculating on the kind of space-weather briefing they may require to avoid hazards such as proton storms.

This monograph is not written primarily for meteorologists, but for geophysicists who may wish to gain a picture of the atmosphere as a whole. It is very well produced and with one or two exceptions the diagrams are clear and helpful. References to the literature (listed under authors' names) are abundant (438 in all) but naturally enough well over half are to writings in German.

There is one misprint in this list of references (which will greatly amuse the author concerned); E. Gold's classic paper of 1909 on the stratosphere is given the date 1009 !

M. K. MILES

Seasonable weather, by L. P. Smith. 250 mm × 190 mm, pp. 146, *illus.*, George Allen and Unwin Ltd, Park Lane, Hemel Hempstead, Herts., 1968. Price: 50s.

A brave man is he who dares to unravel the vagaries of our British climate ! Certainly there is no one better qualified for this unenviable, yet fascinating task than Mr Smith, whose earlier book *Weatherwise gardening* is unique and whose wide experience in the field of agrometeorology needs no mention.

Seasonable weather, comprising 146 pages and numerous plates, is virtually two books in one. With Mr Smith's own illuminating survey of our last century of weather is incorporated a reprint of a superb series of photographs from an earlier book, *Weatherwise*, by the late Mr J. H. Willis. These span a period of no less than 29 years and faithfully record the state of growth on fixed annual dates of the same clumps of snowdrops and daffodils and the same branches of chestnut and beech. It is to someone's credit that this excellent opportunity has been taken to republish them.

Mr Smith examines methodically the behaviour of our weather during the hundred years 1850–1949. Detailed records of this period are condensed into simple tables as each season is 'cross-examined' in its turn. Subsequently the weather for the years 1950–67 is first described and then compared with the general trends of the previous century. From this, the outstanding feature is the almost continuous series of warm autumns since the last war (and 1968 has proved no exception). Generally, however, there is confirmation, if any were needed, of our weather's sheer inconsistency and one begins to wonder if, indeed, there is such a thing in these islands as a normal season.

The investigation into certain weather lore — indeed the whole book — is full of interest and reasoned interpretations. Perhaps, however, the most heartening single fact to emerge from *Seasonable weather* is its defence of our much maligned climate '... it does not run to insufferable excesses ... most of all a good climate for growing things ... the countryside is always green'. How very true !

E. J. GILBERT

CORRECTION

Meteorological Magazine, October 1951, p. 297. The date for the transit of Venus should read June 3, 1769.

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THE SUMMER WEATHER OF 1968: RELATED ATMOSPHERIC CIRCULATION AND SEA TEMPERATURE PATTERNS

By R. MURRAY and R. A. S. RATCLIFFE

Summary. In the British Isles the summer of 1968 showed some unusual weather features. These features are described and related to the large-scale circulation patterns both in the preceding spring and in summer. Atlantic sea surface temperature anomalies were also very unusual; the formation of the very large area of negative temperature anomaly which dominated the Atlantic pattern from June to November is described and a possible relation to the high-summer pressure pattern near the British Isles is discussed. A search through past records for a similar summer achieved only limited success. Other factors which might have had some relevance to the unusual summer, such as the biennial oscillation and the position in the solar cycle, are also considered. It is concluded that all the relevant factors taken together might have led to a fairly satisfactory forecast of the pressure anomaly pattern, but the weather associated with this pattern was most unlikely to have been predicted.

Weather and synoptic types over the British Isles. The main synoptic feature of the summer of 1968, particularly in July and August, was the degree of blocking near the British Isles and the unusually frequent occurrence of easterly and northerly winds over the United Kingdom. Progressive synoptic types predominated in June, apart from anticyclonic blocking from the 9th to the 16th. In the normal year there is generally a notable increase of progressive synoptic types in July and August but on this occasion an outstanding reversal of the normal trend took place. Indeed blocking, as measured by negative values of the *P*-index of Murray and Lewis,¹ reached the extreme (since 1873) figure of -63 units for the period July to August. Moreover, the northerly bias in high summer was also very pronounced (*S*-index = -27 units). For the most part anticyclonic centres north of about 55°N were the main feature but occasionally cyclonic centres south of 55°N were more significant. One such centre which moved north-east across England and Wales on 9-10 July brought at least 75 mm of rain in 24 hours to a broad area from Dorset to Lincolnshire.

The weather in the summer of 1968, particularly in high summer, was highly anomalous over the British Isles with an inverted pattern of weather.

The normally dull and wet north-western seaboard had long fine spells, whereas eastern parts of England were unusually cool, dull and wet. Although it was very cool in July in south-eastern districts, a brief hot spell culminated with a temperature of 33°C in London on the 1st. On the same day fine dust from Spain and northern Africa was deposited in heavy thundery rain in many places and record hailstones (7 cm in diameter) fell at Glamorgan/Rhoose Airport near Cardiff. For the rest of the summer the weather in the eastern half of England was dismal for the most part, despite a mainly dry spell from about 18 July to 6 August when dull, cool weather was associated with persistent north-easterly winds.

The geographical variations of mean daily maximum temperature and mean sunshine are shown in Figure 1. The marked difference between

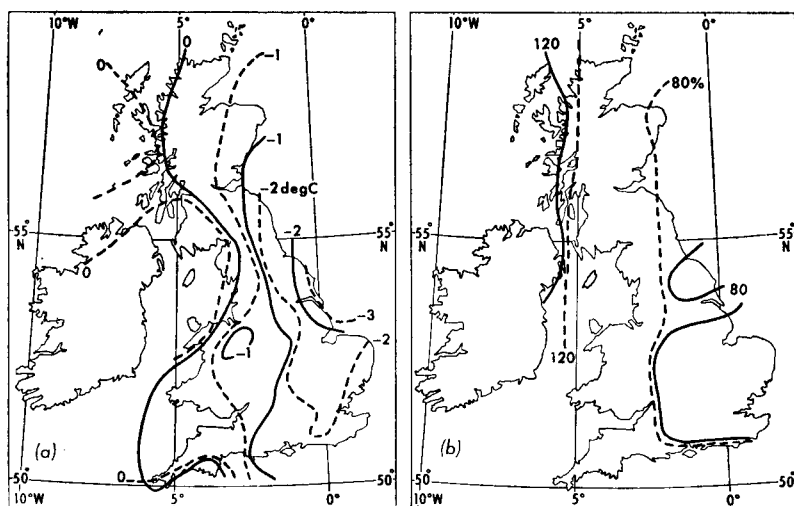


FIGURE 1—(a) ANOMALIES (degC) IN 1968 OF DAY MAXIMUM TEMPERATURE FROM THE 1931-60 NORMAL (b) SUNSHINE IN 1968 AS PERCENTAGES OF THE 1931-60 NORMAL

———— Summer (June, July and August) - - - High summer (July and August)

eastern England and the area west Scotland-Northern Ireland is striking. The sunshine contrast in high summer is particularly noteworthy—mean sunshine ranged from less than 70 per cent of normal in many places from the Thames to Yorkshire (mostly less than four hours per day) to over 130 per cent in the Hebrides (about seven hours per day). Rainfall had a similarly abnormal spatial distribution, as may be seen from Figure 2, which presents information on rainfall amounts and rain-days. Both these rainfall measurements have excesses in the eastern parts of England and deficiencies in Northern Ireland and western Scotland. A useful summary of the overall character of the summer is given in Figure 3 which shows the departure from average of the Summer Index of Davis.³ This Summer Index combines sunshine, rainfall and daily maximum temperature. Broadly speaking, negative anomalies signify 'poor' weather and positive anomalies 'good' weather. The negative anomaly centre near the Wash and the major positive centre in

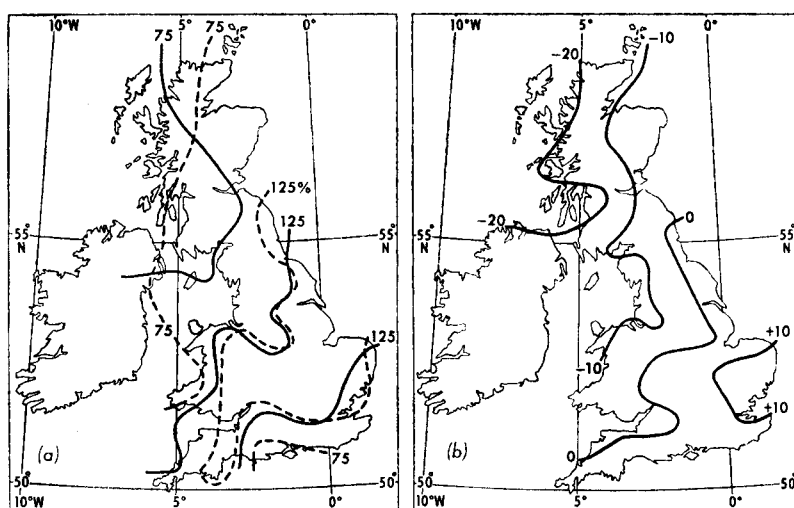


FIGURE 2—(a) RAINFALL IN 1968 AS PERCENTAGES OF THE 1931-60 NORMAL
(b) ANOMALIES IN 1968 OF RAIN DAYS FROM THE 1931-60 NORMAL
—— Summer (June, July and August) - - - High summer (July and August)

west Scotland are each equal to about 2.2 times the standard deviation of the Summer Index in each locality. Considered separately each anomaly centre might be expected to occur in the same position with the observed intensity once or twice per 100 years. The correlation between the indices in the south-east and north-west of Britain is small, so that the combination shown in Figure 3 must be extremely rare.

Broad-scale circulation. The seasonal circulation patterns in spring and summer at the surface and 500 mb are shown in Figures 4 to 9. The following discussion is largely centred on the anomalies which are shown as continuous lines.

The main features of the spring surface patterns in Figure 4 are the anomalously deep low-pressure systems near the Arctic coast of Russia and the area of above average pressure in the North Atlantic. Between these two anomaly centres the anomaly pattern corresponds to an anomalous component of flow from north-west to north over the British Isles. The associated 500-mb patterns are shown in Figure 5, in which the shift of the polar vortex towards the Russian Arctic is clearly in evidence.

The summer surface patterns (Figure 6) appear to show continuity with the spring patterns (Figure 4). There is evidently persistence in the negative anomaly centre in the Russian Arctic, and in the areas of below average pressure near the Pacific (about 160°W) and America (about 100°W). The main changes from spring to summer are the shift of the positive centre from the Atlantic to north-east of Scotland and the formation of a negative anomaly in the Atlantic. The July to August patterns are depicted in Figure 8, which shows most of the features of the whole summer, but the positive anomaly centre near the Shetlands exceeds 8 mb and the anomalous east to north-east component in the flow is pronounced over Britain. The corresponding 500-mb

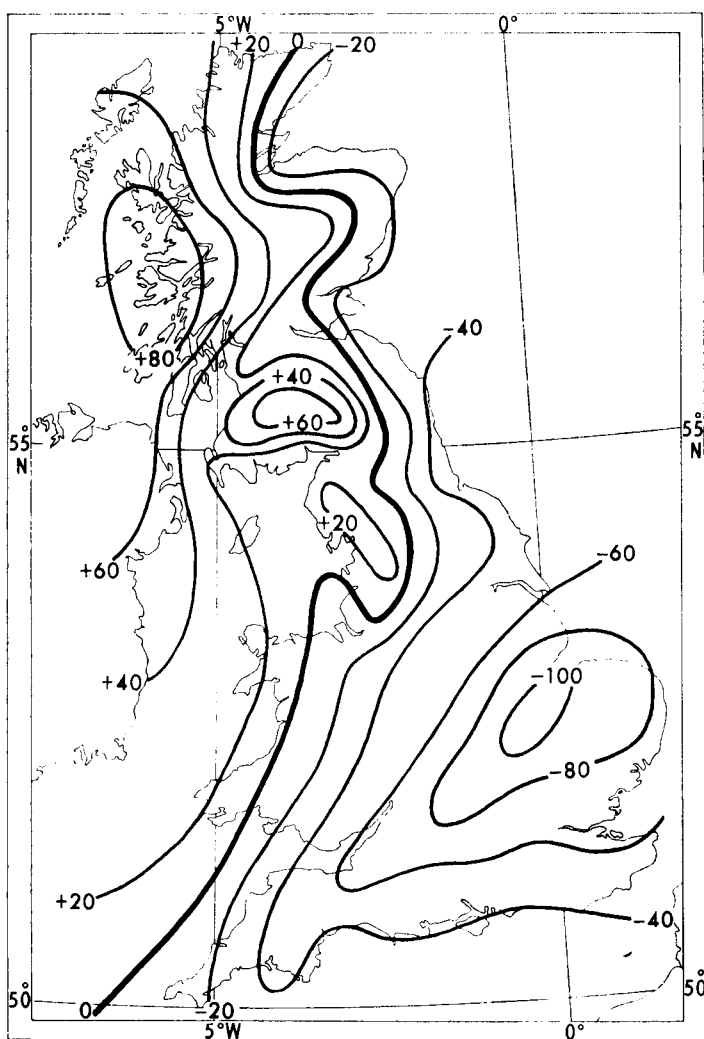


FIGURE 3—DEPARTURE IN 1968 FROM THE AVERAGE OPTIMUM SUMMER INDEX OF DAVIS²

maps are shown in Figures 7 and 9. The marked blocking in the north-east Atlantic is most clearly shown in high summer by the large positive anomaly centre between Iceland and Scotland in Figure 9.

Sea temperature anomalies. Over the Atlantic Ocean, one of the most noticeable features of the 1968 summer was the development of very large negative anomalies of sea surface temperature over a huge area covering thousands of square miles and centred to the south-east of Newfoundland near ocean weather station (OWS) 'D' (44°N 41°W).

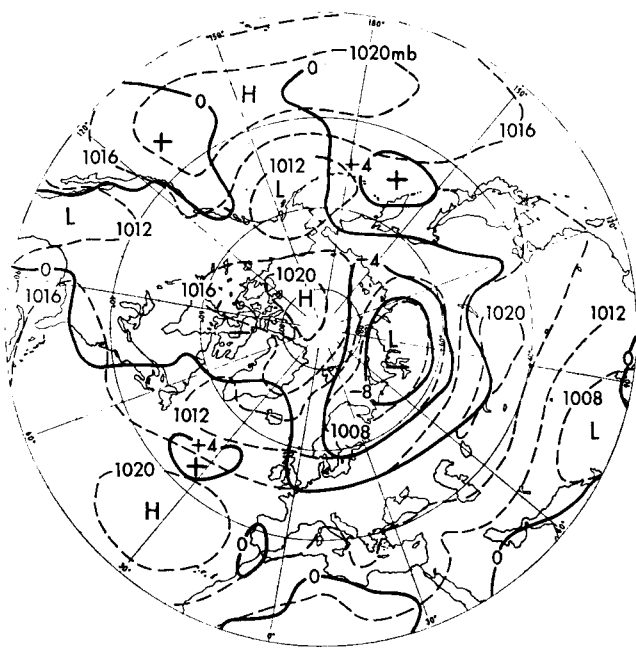


FIGURE 4—MEAN SURFACE PRESSURE AND PRESSURE ANOMALIES IN SPRING 1968
- - - Surface pressure ——— Pressure anomalies
Isopleths at 4-mb intervals



FIGURE 5—MEAN 500-MILLIBAR CONTOURS AND ANOMALIES FOR SPRING 1968
- - - Mean 500-mb geopotential heights at intervals of 120 gpm
——— 500-mb anomalies at intervals of 60 gpm

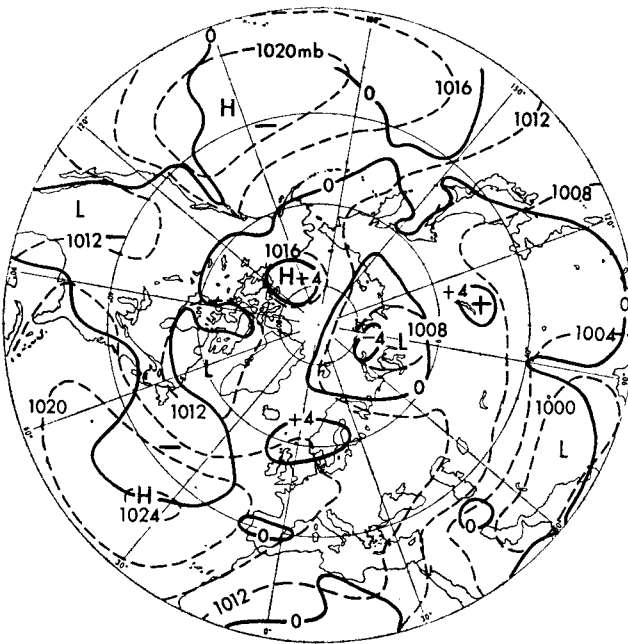


FIGURE 6—MEAN SURFACE PRESSURE AND PRESSURE ANOMALIES IN SUMMER 1968
 - - - Surface pressure ——— Pressure anomalies
 Isopleths at 4-mb intervals

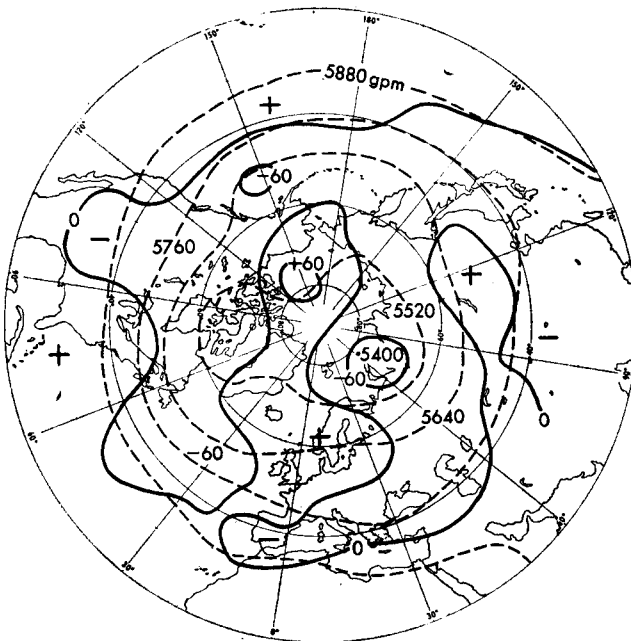


FIGURE 7—MEAN 500-MILLIBAR CONTOURS AND ANOMALIES FOR SUMMER 1968
 - - - Mean 500-mb geopotential heights at intervals of 120 gpm
 ——— 500-mb anomalies at intervals of 60 gpm

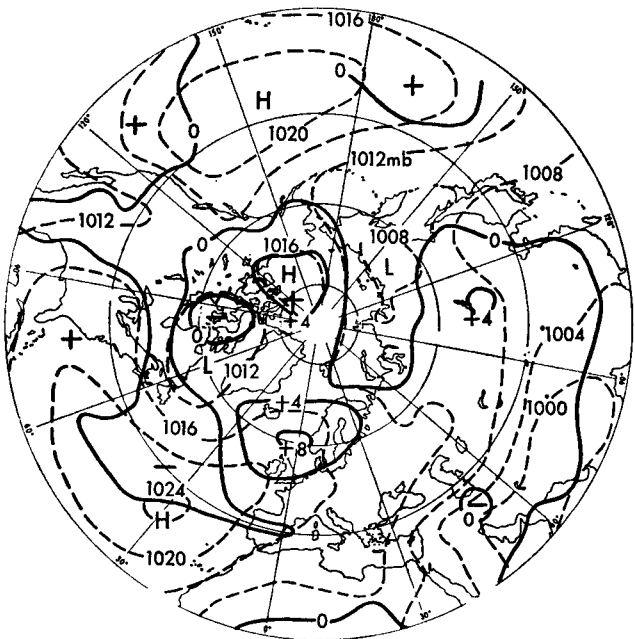


FIGURE 8—MEAN SURFACE PRESSURE AND PRESSURE ANOMALIES IN JULY AND AUGUST 1968
--- Surface pressure ——— Pressure anomalies
Isopleths at 4-mb intervals

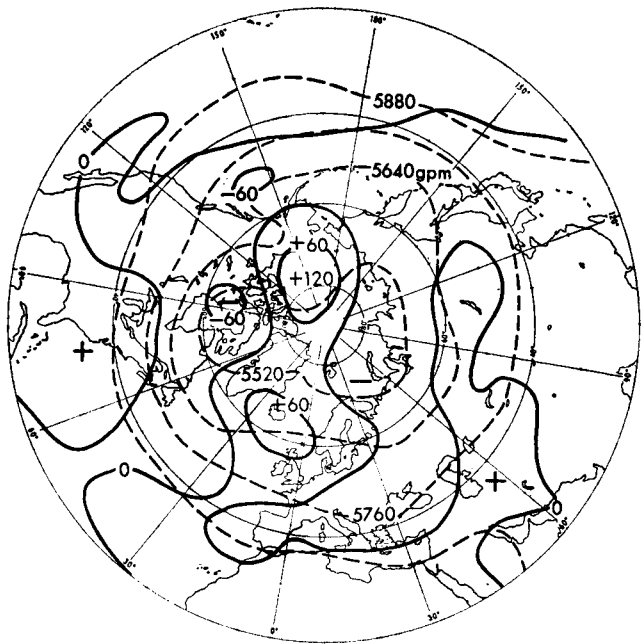


FIGURE 9—MEAN 500-MILLIBAR CONTOURS AND ANOMALIES IN JULY AND AUGUST 1968
--- Mean 500-mb geopotential heights at intervals of 120 gpm
——— 500-mb anomalies at intervals of 60 gpm

Figure 10 shows the variation of sea surface temperature anomaly along a line from 43°N 55°W to 53°N 20°W over the period from October 1967 to August 1968. It shows that the pattern of anomalies underwent a complete reversal over the period and, further, that the negative anomaly near OWS 'D' began to develop in late May reaching its peak (equal to about two-thirds of the annual variation) in August. There was some sign of a negative anomaly developing from February onwards but the main large anomaly did not appear until June.

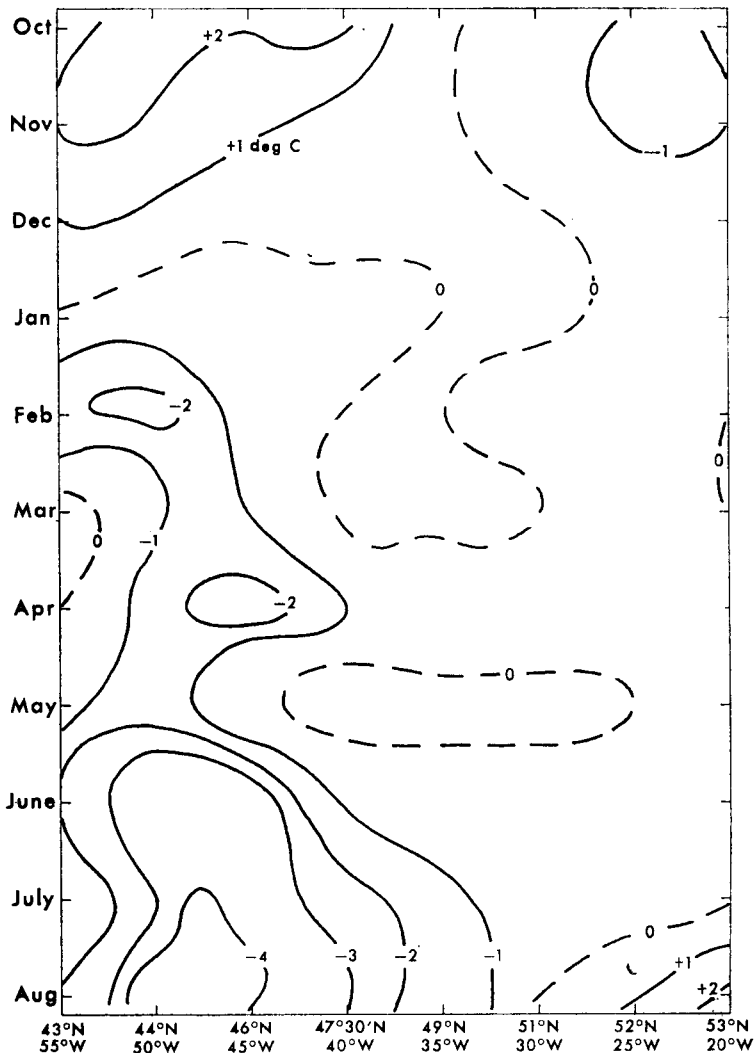


FIGURE 10—SEA SURFACE TEMPERATURE ANOMALIES (degC) FROM OCTOBER 1967 TO AUGUST 1968 BETWEEN 43°N 55°W AND 53°N 20°W
Data extracted from maps of the U.S. Fleet Numerical Weather Facility, Monterey, California.

Hay (personal communication) considers that the formation of this large area of negative anomaly was mainly due to upwelling following persistent cyclonicity in the area. The surface winds of such a quasi-stationary cyclone must react on the ocean through frictional Ekman stresses to produce divergence of the surface waters, as described by Bjerknes.³ The resulting upwelling of water near the cyclone centre would clearly bring cooler water from below and result in negative sea temperature anomalies at the surface. Support for this theory largely accounting for the formation of the negative sea surface temperature anomaly on this occasion is shown in Figure 11. The lower part of this figure shows that, over a big area near OWS 'D', the 1000-mb (approximately surface pressure) anomaly was very consistently negative from the second pentad in May until the end of July. The predominance of negative 1000-mb anomaly in Figure 11 is a rough measure of enhanced cyclonic activity. Independent confirmation of enhanced cyclonic activity near OWS 'D' in May 1968 was obtained by counting the number of days with centres of depressions in the area 40° – 55° N, 35° – 55° W; in this area depressions were

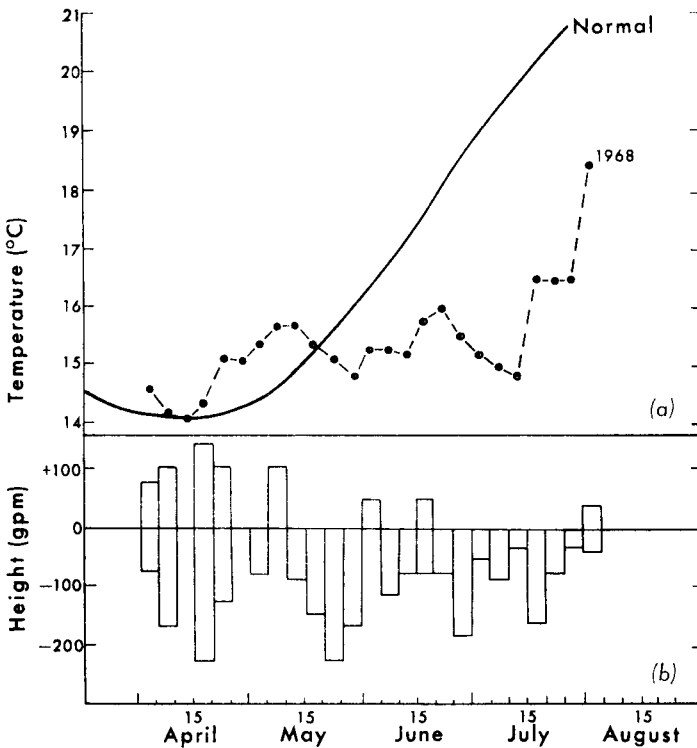


FIGURE 11—(a) PENTAD-MEAN SEA SURFACE TEMPERATURES IN 1968 AND THE 1944-61 AVERAGE AT OCEAN WEATHER STATION 'D' (b) HISTOGRAM OF INTENSITIES OF POSITIVE AND NEGATIVE PENTAD-ANOMALY CENTRES AT 1000 MILLIBARS WITHIN THE AREA 35° – 55° N, 60° – 20° W

--- Sea surface temperatures ————— 1944-61 averages
Based on a figure supplied by R. F. M. Hay in a personal communication.

almost 40 per cent more frequent and anticyclones nearly 50 per cent less numerous than the normal values for May as given by Klein.⁴ The upper part of Figure 11 shows how the sea surface temperature at OWS 'D', which was above normal until about mid-May, reacted to this unusual cyclonic activity and fell well behind the normal seasonal warming for the rest of the summer. However, it is unlikely that upwelling accounted for the whole of the observed anomaly; Figure 12 shows that at OWS 'D' mean cloud amount was consistently and increasingly above normal from May to August 1968, and this situation would clearly help to create a negative anomaly of sea surface temperature by reducing incoming solar radiation. How the isotherms of sea temperature and their anomalies were distributed in depth is illustrated

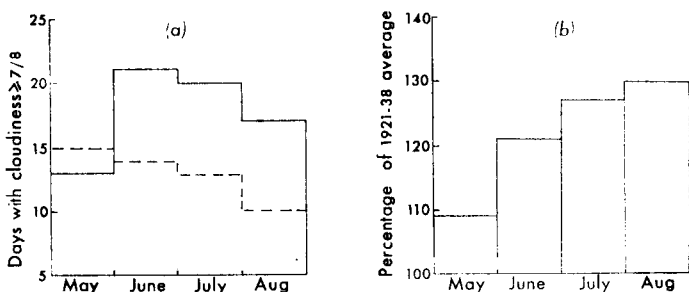


FIGURE 12—CLOUDINESS AT OCEAN WEATHER STATION 'D', MAY TO AUGUST 1968
 (a) FREQUENCY OF DAYS WITH 7/8 CLOUD COMPARED WITH THE 1921-38 AVERAGE
 (b) MEAN CLOUD AMOUNT EXPRESSED AS A PERCENTAGE OF 1921-38 AVERAGE
 ——— Days with cloud $\geq 7/8$ - - - 1921-38 average

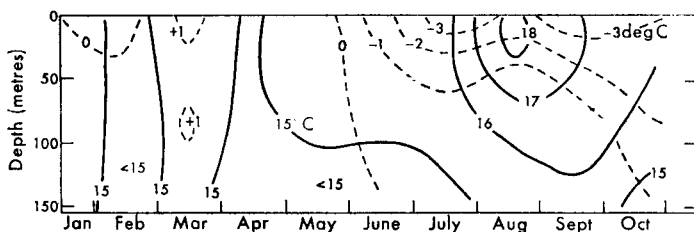


FIGURE 13—VARIATIONS OF SEA TEMPERATURE AT THE SURFACE AND IN THE TOP 150 METRES AT OCEAN WEATHER STATION 'D' FROM JANUARY TO OCTOBER 1968
 ——— Isotherms - - - Anomalies

in Figure 13 for OWS 'D'. It is interesting to note that negative anomalies of more than 1 degC were confined to about the topmost 50 m until the end of the summer, but in autumn the anomaly increased notably at depths between 50 and 150 m. Figures 14 and 15 show the large-scale pattern of sea surface temperature anomalies over the Atlantic and Pacific Oceans in May and August 1968. The main features to note are the development of the big negative anomaly in the Atlantic, already referred to, and a negative area almost as large in the Pacific near 40°N 160°W: significant areas of positive sea temperature anomaly also existed in August in both oceans, notably south of Iceland and near 30°N 130°W in the Pacific.

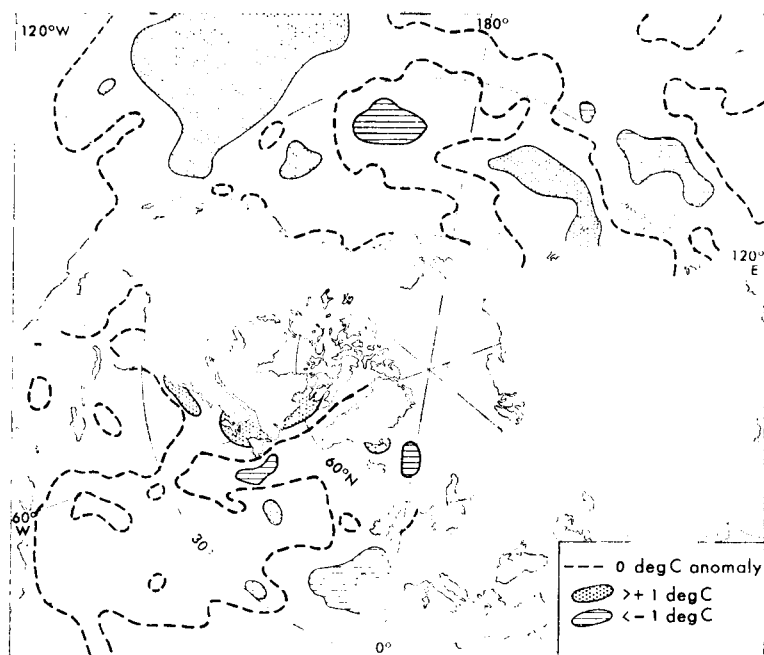


FIGURE 14*—MEAN MONTHLY SEA SURFACE TEMPERATURE ANOMALY IN MAY 1968
After U.S. Fleet Numerical Weather Facility, Monterey, California.

After the unusual sea surface temperature anomaly pattern over the Atlantic in the summer of 1968 had been noticed, other years in the past with similar sea temperature distributions were studied. Data exist in the long-range forecasting section of the Meteorological Office for most of the last 80 years, but it was immediately apparent that 1968 was the most extreme example of colder than normal water over such a wide area in the Atlantic in summer. Well-marked sea temperature patterns are quite persistent, the average length of time for which a well-defined pattern persists being at least three to four months. In fact the pattern established in June 1968 persisted until December. Because of this persistence and also because the input of heat and moisture to the lower layers of the atmosphere is largely controlled by the state of the underlying surface, several writers, e.g. Sawyer⁵ and Namias,⁶ have suggested that the patterns of sea surface temperature anomaly are probably important from the point of view of forecasting on the monthly time scale. It was therefore decided to see if Junes in the past which had an Atlantic sea surface temperature anomaly pattern similar to June in 1968 were followed by Julys which had any recognizable similarities. There were 11 Junes of this type (excluding 1968) with a mean anomaly over the sample of about -1.5 degC near OWS 'D'. The mean sea-level pressure map for the 11 Julys following showed positive

* Note : Small positive area near east Greenland to be ignored.

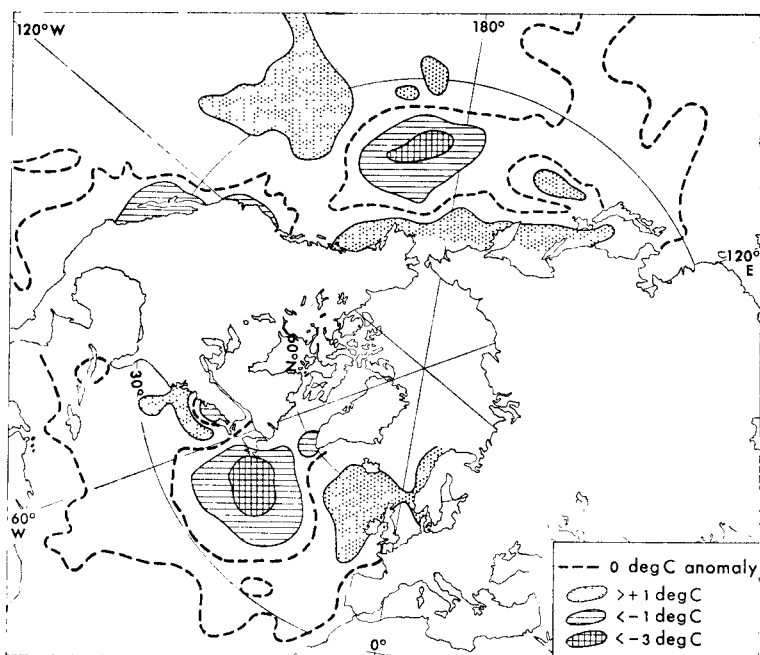


FIGURE 15—MEAN MONTHLY SEA SURFACE TEMPERATURE ANOMALY IN AUGUST 1968

After U.S. Fleet Numerical Weather Facility, Monterey, California.

anomalies of about $1\frac{1}{2}$ mb in the area from Greenland to north of Scotland and negative anomalies of the same order near the Azores. Eleven June's with the opposite sea temperature anomaly pattern proved to have approximately the reverse mean pressure anomaly in July. Figure 16 shows the difference between the mean July pressure maps averaged for each of the 2 samples of 11 years. It shows that the occasions with colder than normal ocean to the south-east of Newfoundland in June, tend to be associated in July with higher than normal pressure to the north of Scotland and with lower than normal pressure near the Azores. Statistical tests show that this pattern is almost certainly significant, the areas of more than ± 2 mb representing areas where the anomaly of pressure is between two and three times the standard deviation of random samples about the mean. The similarity of pattern between Figures 16 and 8 is striking; if it is borne in mind that the 1968 sea temperature anomaly pattern was more extreme over a wider area than in any other year, it strongly suggests that the sea temperatures played a part in determining the weather of July and August in Britain in 1968.

Some analogues. An attempt was made to find analogues on the basis of the broad-scale surface pressure patterns in spring and summer (most weight being given to the sector from America to Europe), and the monthly sea temperature anomaly patterns in the Atlantic from April to June. No good analogue was apparent, especially when the inverted weather distribution in the summer over Britain was also taken into account. The year 1899 was probably the best broad-scale circulation analogue for both spring and summer,

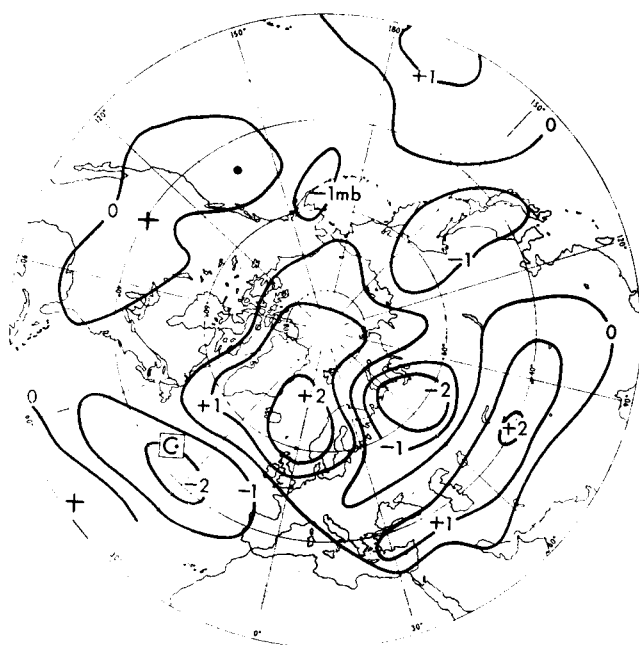


FIGURE 16—DIFFERENCE BETWEEN (a) JULY MEAN PRESSURE ANOMALIES (MILLIBARS) AFTER JUNES WITH COLD SEA SURFACE SOUTH-EAST OF NEWFOUNDLAND AND (b) JULY ANOMALIES AFTER JUNES WITH WARM SEA SURFACE

- Note (i) Each July mean pressure anomaly is a mean of 11 years.
(ii) The mean anomaly centre for the cold sea surface is about -1.5 degC at position 'C'.

and the sea temperature patterns in the Atlantic were also like those in 1968, although not so strong. Figure 17 shows the spring (dashed lines) and summer (full lines) anomaly patterns superimposed. The spring patterns of 1899 and 1968 (Figure 4) each show blocking over the Atlantic, negative pressure anomalies over north Russia consistent with displacements of the tropospheric polar vortex to the Russian side of the Arctic, enhanced zonal flow between 40°N and 60°N over Asia, some similarity of pattern in the Pacific and finally an anomalous component from north-west to north in the flow over the British Isles. The summer patterns in Figures 17 and 6 are clearly similar in the east Atlantic and west Europe. Nevertheless the summer in 1899 was dry and warm over Britain.

The spring of 1968 resembled 1885 over the Atlantic and western Europe but had little resemblance elsewhere (sea temperature comparisons were not possible). The summer pattern in 1885 showed positive anomalies of $+4$ mb over Scotland and south Norway with anomalous easterly flow over England and France, quite like 1968. However, in 1885 the summer was dry over England and Wales unlike 1968, although the temperature in central England was below normal as in 1968.

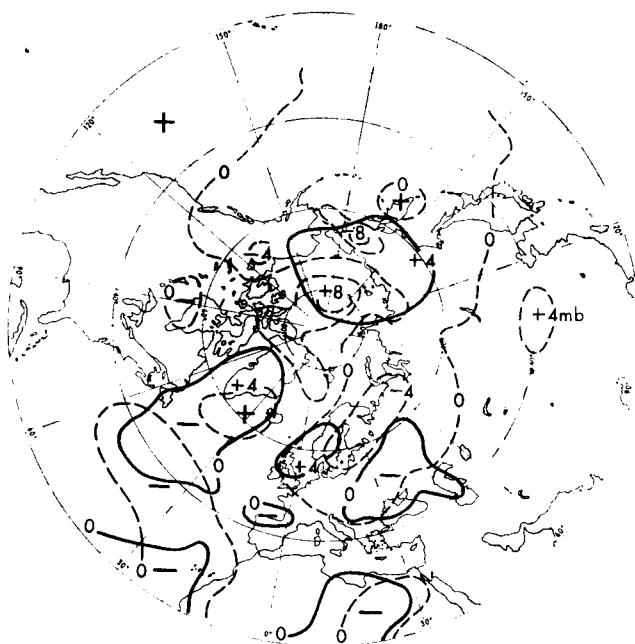


FIGURE 17—SEASONAL MEAN SURFACE PRESSURE ANOMALIES (MILLIBARS) IN 1899

--- Spring ——— Summer
Isopleths at 4-mb intervals

The circulation in the spring of 1902 was very like that in 1968 only over the Atlantic where sea temperature patterns were also fairly similar. The anomaly pattern in the summer of 1902 certainly indicated blocking in the north-east Atlantic with east to north-east winds over the British Isles, but the main positive anomaly centre was in the Arctic instead of near north Scotland although pressure was somewhat above normal over Scotland. In the summer of 1902 the rainfall was below normal over Scotland and near normal over England and Wales, and it was very cool over central England. There was a general contrast in weather, including sunshine, between the south-east and north-west of Britain although the inverted pattern was not so extreme as in 1968.

The pressure pattern over the British Isles in the summer of 1955, especially in high summer, resembled that of 1968. The pressure anomaly in high summer of + 8 mb off north-east Scotland and the anomalous east to north-east wind over most of Britain and France (see Figure 18) were very like the anomalies in 1968 (see Figure 8), but the weather on these two occasions was quite different. It must be said that the atmospheric circulation in spring and the sea temperature pattern in 1955 were not analogues of 1968. Moreover, the high-summer circulation in 1955 away from the British Isles and adjacent areas, particularly over the Greenland-Iceland area, was quite unlike that of 1968 (compare Figures 18 and 8). Despite the close similarity of surface



FIGURE 18—SEASONAL MEAN SURFACE PRESSURE ANOMALIES (MILLIBARS) IN 1955

--- Spring ——— Summer
Isopleths at 4-mb intervals

pressure patterns over the British Isles, examination of the upper air temperature fields clearly indicates that considerably more subsidence took place over the British Isles in 1955 than in 1968. In the earlier year a south-westerly mean jet stream just south of Iceland in high summer was both anomalously strong and in unusually high latitudes over the North Atlantic and Norwegian Sea; pronounced subsidence on the right side of the jet stream, that is, over the British Isles, was dynamically reasonable and consistent with the fine weather over the whole country.

It is of interest that in five other years in the period back to 1874 the summer rainfall was simultaneously above average (tercile 3) over England and Wales and below average over Scotland (tercile 1), as in 1968. In two of these years, namely 1878 and 1909, the actual England mean temperature was much below average (quintile 1) and in the other years, 1880, 1936 and 1939, it was about average (quintile 3); these may be compared with a mean summer temperature of quintile 2 in 1968. In terms of weather there was some rough similarity. However, only 1878 showed any real resemblance to 1968 in broad-scale circulation in spring and summer. The sea temperature patterns in 1909 were roughly analogous to those in 1968, but in the other four years they were poorly defined or not known.

These examples show that it was not possible to find analogues acceptable at the same time in terms of broad-scale circulation in spring and summer, sea temperature pattern and weather over the British Isles in the period with reasonably complete synoptic records.

Other factors of possible relevance.

(i) *Excessive sea ice near Iceland.* Pack ice was exceptionally abundant in the spring off east Greenland and around Iceland, as has been pointed out by Marshall.⁷ A rather cursory examination of the summer weather over Britain, and pressure anomalies at selected points in Greenland and western Europe following 10 other springs with heavy ice, did not suggest that the existence of abundant ice near Iceland and east Greenland was materially important in determining the summer weather or pressure pattern over the British Isles.

(ii) *Biennial oscillation.* The existence of a quasi-biennial oscillation has been noted by many authors and Davis⁸ has stressed its importance in relation to summer weather, particularly mean daily maximum temperatures in summer. Briefly, since 1880 summers in odd years tend to be warmer and drier than in even years. Over England and Wales the summer of 1967 was rather warm and dry; the deterioration in 1968 was undoubtedly in agreement with the tendency expected with the biennial oscillation.

(iii) *Date of change-over to summer circulation at 50 mb.* Ebdon⁹ has suggested that 'good' summers in south-east England do not occur when the change from winter to summer type circulation at 50 mb over the British Isles is late. Figure 19 shows that the change-over from west to east winds at Shanwell was certainly not early. However, Ebdon's criterion does not enable a positive prediction of 'poor' weather to be made, since an average type of summer would still satisfy the condition that the summer was not 'good'.

(iv) *Blocked/northerly springs over the British Isles.* Blocked/northerly springs, like that of 1968, may be classified synoptically by the P - and S -indices of Murray and Lewis¹ as those in which each index is either quintile 1 or quintile 2 (i.e. P_1 or P_2 and S_1 or S_2). There appears to be a tendency for rather cool and wet summers over England and Wales to follow blocked/northerly springs. Table I shows the frequency distribution for England and Wales rainfall and central England temperature.

TABLE I—SUMMER RAINFALL OVER ENGLAND AND WALES AND SUMMER TEMPERATURE OVER CENTRAL ENGLAND FOLLOWING BLOCKED/NORTHERLY (P_{12} S_{12}) SPRINGS

Frequency	Rainfall (terciles)			Temperature (quintiles)				
	R_1	R_2	R_3	T_1	T_2	T_3	T_4	T_5
	3	3	8	3	7	1	2	1

In all but one case the summers were more northerly (i.e. S_{12}) or more cyclonic (i.e. C_{45}) than usual.

(v) *Solar cycle.* In order to see if there was any systematic difference between mean July pressure just before the sunspot maximum (as in 1968) and mean July pressure just before the sunspot minimum, all such years for which pressure data were available were analysed by computer, the earliest year being 1878. There were nine Julys in the first class and eight in the second. Mean pressure maps were formed for each class for each grid point in the Atlantic area and the two means were subtracted. The result is shown in Figure 20. The significance of this figure is difficult to estimate owing to correlation between pressure at adjacent grid points, but the high value in high latitudes and the low value in low latitudes are both equal to



Photograph by courtesy of Dr. H. A. Lang

PLATE I—NOCTILUCENT CLOUD OBSERVED FROM NEWTON STEWART, WIGTOWN-
SHIRE, ON THE NIGHT OF 28-29 JUNE 1968 AT 0151 UT

See page 221



Photograph by courtesy of Dr H. A. Lang

PLATE II—NOCTILUCENT CLOUD OBSERVED FROM NEWTON STEWART, WIGTOWN-
SHIRE, ON THE NIGHT OF 28-29 JUNE 1968 AT 0200 UT

See page 221

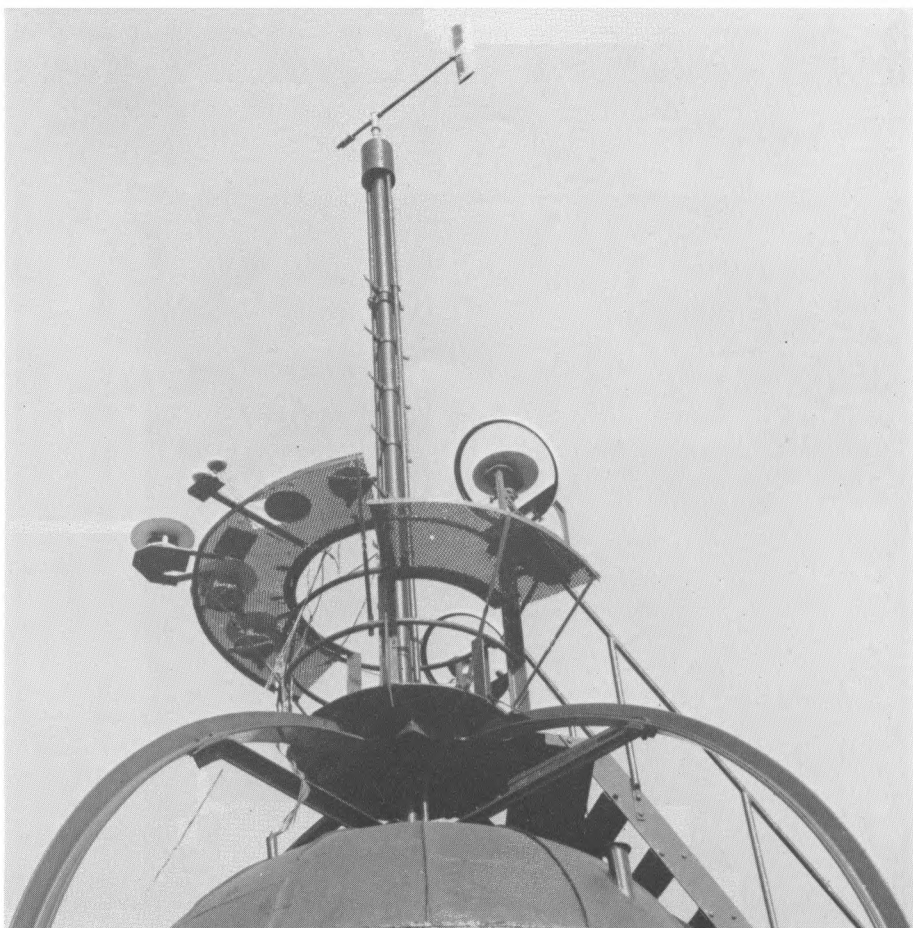


PLATE III—THE MAIN RADIATION RECORDING INSTRUMENTS

The site of the main radiation recording instruments on top of the dome, accessible by a ladder, seen in the background, from the Observatory roof. In the centre is the head of the pressure-tube anemograph. On the platform to the left of the picture are the solarimeters for measuring global solar radiation, the daylight illuminator and a number of other radiation instruments exposed for experimental purposes. On the platform to the right is the solarimeter for measuring diffuse solar radiation. Behind the pressure-tube anemograph mast is the illuminator for measuring diffuse illumination — this is only partly visible. Other radiation instruments are on the roof below. For recording equipment see Plate IV. (See page 225.)

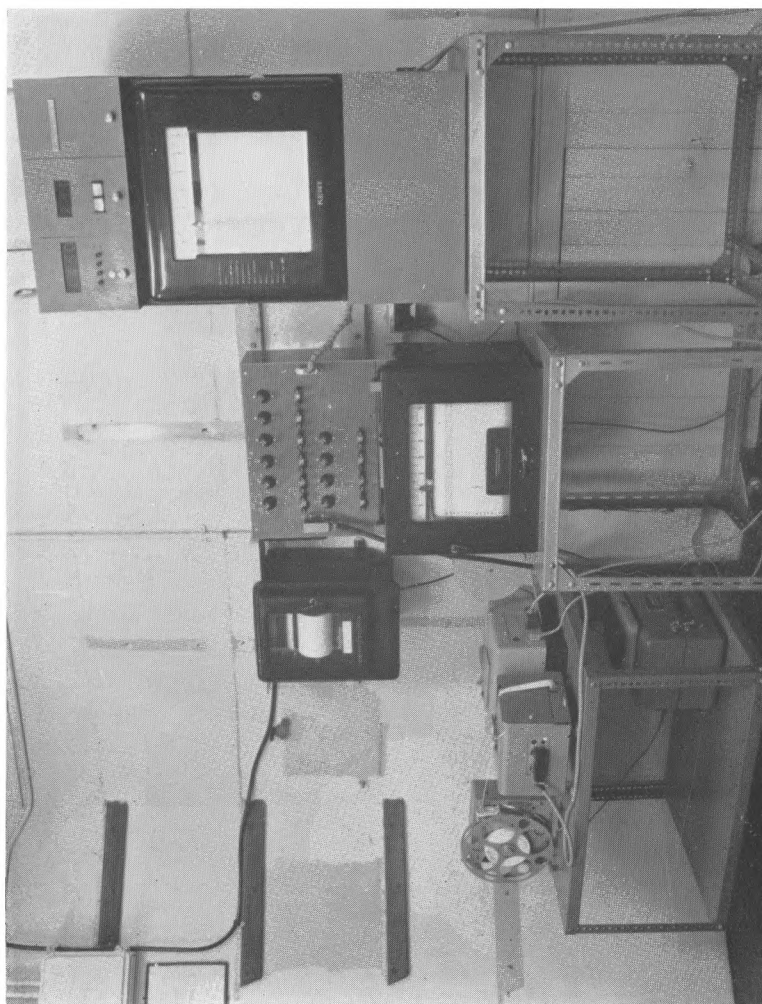


PLATE IV—THE METEOROLOGICAL OFFICE DATA LOGGING EQUIPMENT (MODLE)
FOR RADIATION INSTRUMENTS.

This equipment is now in the basement at the Observatory. On the right, on the stand, is the MODLE and on the far left is the paper-tape punch. In the centre are two standby recorders (See page 226.)

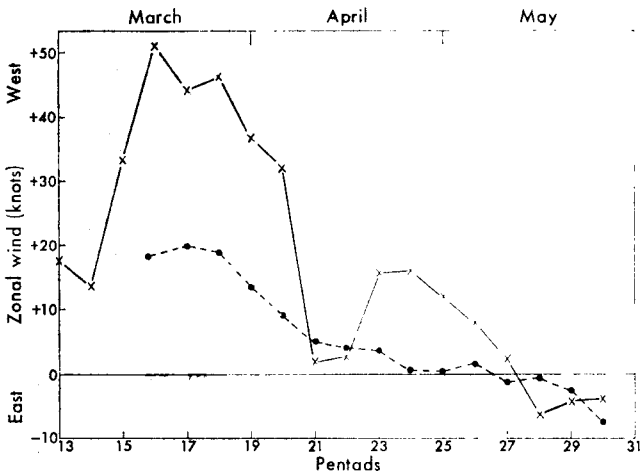


FIGURE 19—PENTAD-MEAN ZONAL WIND COMPONENTS AT 50 MILLIBARS AT SHANWELL
—— 1968 - - - 1957-68 average

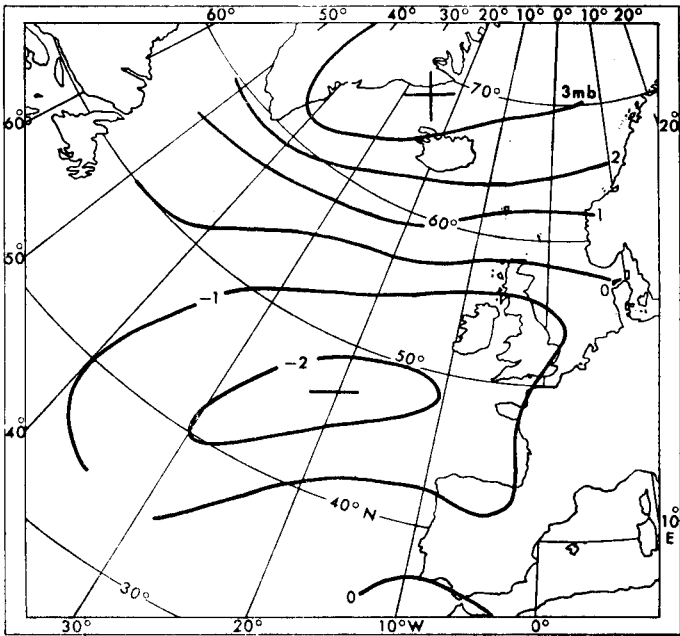


FIGURE 20—DIFFERENCE BETWEEN JULY MEAN PRESSURES (MILLIBARS) IN ACTIVE AND QUIET SUN YEARS (EIGHT SOLAR CYCLES)

about twice the standard deviation. It would thus appear that Julys near the solar maximum are likely to have pressure above normal to the north of the British Isles with lower than usual pressure near the Azores.

(vi) *April 500-mb trough position and summer weather.* In a recent paper Ratcliffe and Collison¹⁰ have shown that there is some association between the longitude of the European trough on the April 500-mb mean chart and the rainfall in England and Wales in the following summer. If the April trough is definitely west of 10°E a wet summer is unlikely — out of 22 years with this type of trough only 5 had wet summers. Nevertheless in 1968 the April trough was in this category and the summer was wet. This highlights the unusual type of summer in 1968; it is probable that Ratcliffe's rule indicates that Aprils similar to 1968 are usually followed by upper ridges near Britain much of the summer, a situation satisfied in 1968 (see Figure 6), and normally not resulting in a wet summer. The year 1968 thus appears as an exceptional case of this rule also.

Concluding remarks. In this article certain facts have been recorded concerning the unusual weather and circulation patterns. Clearly no satisfactory explanation can be given for the abnormal developments. The empirical evidence on pressure anomalies associated with cold sea surface temperature patterns over the west Atlantic suggests that positive pressure anomalies were likely near and north of Britain. The fact that the negative anomaly near OWS 'D' was much larger in extent and intensity in 1968 than in the other years with broadly similar sea surface temperature patterns might suggest that the associated pressure anomaly in the north-east Atlantic should be appreciably larger than the 1 or 2 mb indicated by the mean map, and so could account for a considerable part of the large positive pressure anomaly which was a feature of the high summer of 1968 in the north-east Atlantic.

There is also the tendency for above average surface pressure to occur in high latitudes in Julys in active sun years; on this account positive pressure anomalies were to be expected in 1968 in the north-east Atlantic.

Another feature which could be invoked to aid the tendency for positive pressure anomalies in high latitudes was the existence of the cold vortex in the Russian Arctic in spring and early summer. Associated with the vortex was an extensive snow cover over northern Europe in April. The snow limit gradually retreated north-eastwards until it was confined to the Arctic coast of north-east Siberia at the end of June, leaving a cold waterlogged surface over northern Russia and north-west Siberia. The importance of this feature is not known, but it may have been a contributory factor. Certainly a source of anomalously cold air was available in these areas, and cold outbreaks to the south readily occurred in the summer. These conditions are at least consistent with the occurrence of higher pressure than usual farther west over Scandinavia and the Norwegian Sea, although it is recognized that cause and effect cannot be specified.

The cumulative effect on surface pressure anomalies associated with the cold sea temperature pattern, the position in the solar cycle and the slow-moving cold tropospheric vortex near Novaja Zemlja, could well have gone quite far towards predicting the large positive pressure anomaly in high

latitudes over the north-east Atlantic as occurred in the high summer of 1968. There would still have remained the difficulty of predicting the actual weather, since the pressure pattern which occurred in 1968 would normally be associated with fine weather over Britain, as in 1899 or 1955. Indeed, the summer under study highlights the great difficulty of forecasting the seasonal weather even when the mean pressure map is correctly predicted by whatever means. Fortunately this type of inconsistency between pressure anomaly and weather is fairly unusual, and in most cases correct prediction of the pressure anomaly pattern implies a satisfactory forecast of summer weather.

Acknowledgement. Permission to publish the maps shown in Figures 14 and 15 has been kindly given by the U.S. Fleet Numerical Weather Facility, Monterey, California, who are also responsible for the data on which Figure 10 is based.

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NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1968

By J. PATON

A list of displays of noctilucent clouds (NLC) observed from western Europe during 1968 is contained in Table I. The first three columns give the night of the display, the period of time during which the NLC were observed, and details of the cloud forms and progress of the display when these are available; when observations permit the location of the southern boundary of the clouds, this is given in the notes.¹ The last four columns contain observations from selected stations, giving latitude and longitude to the nearest half degree, universal time, the maximum elevation above the northern horizon and the limiting azimuths of the NLC. Nights when the sky is sufficiently clear of ordinary clouds at many stations to permit the decision that no NLC are present, are noted. When tropospheric clouds prevailing at most stations make it impossible to decide whether or not NLC are present, 'cloudy' is entered in the notes.

The frequency of occurrence of the clouds was not significantly different from that of previous years but many of the displays were much brighter than during 1967.² As is usual, the clouds first appeared early in June and receded northwards during the first week in August to be last visible from northern Scotland on 5 August. The most spectacular displays occurred on the nights of 19–20, 23–24 and 28–29 June and 23–24 July.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1968

Date-night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths
31 May–1 June		No NLC.				
1–2 June		Cloudy.				
2–3		No NLC seen over British Isles. Weak display reported from Denmark.	55°N 15°E	0020–0030	8°	360°–045°
3–4		Cloudy.				
4–5		No NLC.				
5–6		No NLC.				
6–7		No NLC.				
7–8		Cloudy.				
8–9	2310–0110	Faint veil and bands.	56°5N° 7°W 56°N 4°5°W 55°N 4°5°W	0050 2310 0010 0058	 15° 23° 10°	 020° 340°–020° 010°–045° 020°–070°
9–10		No NLC.				
10–11		No NLC.				
11–12		No NLC.				
12–13		No NLC visible from British Isles but very weak display seen from near Kiel, Germany, and from aircraft over western and mid-Atlantic between 0200 and 0400 h.				
13–14 June	2140–0110	Faint veil and bands. Whirls seen from Denmark.	57°5N 7°5°W 57°N 2°W 56°5°N 3°W 55°5°N 1°5°W 55°N 15°E	0020 0040 0001 0100 2324 0106 2350 2140	10° 10° 12° 15° 7° 7° 12° No elev. given.	320°–020° 340°–020° 360°–012° 308°–320° 320°–340° 340°–360° 330°–010° 045°–090°
14–15	2300–0010	Faint veil.	55°5°N 4°5°W	2300	7°	360°–020°
15–16		No NLC.				
16–17		No NLC.				
17–18		No NLC.				
18–19	2345–0154	Moderately bright veil, bands and billows.	56°5°N 3°5°W 55°5°N 7°5°W 54°N 4°5°W 53°N 1°5°W	2345 0042 0035 2300	12° 16° 7° 6°	330°–020° 360°–045° 340°–030° Hidden by cloud.
19–20	2200–0305	Cloudy north of 53°N. Clear in south. Bright veil, bands, billows and whirls, bluish white in colour, and visible down to northern horizon. Detailed observations from Plymouth, St Mawgen, Exeter and Chivenor indicate that just after 0245 h 'streaks' were seen to extend to the southern horizon. So the southern boundary of the clouds was probably at least as far south as 45°N.	52°N 1°5°W 51°5°N 1°W 50°5°N 5°W 50°5°N 4°W 50°5°N 3°5°W	2305 2230 2230 2230 2200 2225 0230 0245	15° 15° 9° 5° 8° 35° 12° 27° 34°	330°–050° 350°–360° 300°–030° 360°–030° 328°–006° 270° 288°–029° 331°–049° 310°–027°
20–21		No NLC.				
21–22		No NLC.				
22–23	2350–0250	Moderately bright veil, and bluish-white bands. The southern boundary of the clouds was about 52°N.	58°N 6°5°W 57°5°N 7°5°W	0115 0145 2350 0100 0220 0240–0250 0145 0245	17° 70° 11° 14° 90° 135° 12°5° 32°	360°–090° 340°–120° 030°–060° 010°–080° 300°–130° 135° 350°–083° 350°–085°
23–24	2110–0208	Veil, bands and billows, very bright around 2120 h and again at 0100–0130 h.	55°N 15°E 52°5°N 1°E	2120 0150 0208	35° 13° 35°	045° 055° No record.
24–25	2200–0201	Veil and bands.	58°N 6°5°W 56°5°N 3°W	2305 0046 0201	90° 7° 15°	No record. 020°–040° 340°–010°
25–26		Cloudy.				
26–27		No NLC.				

Date— night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths
27-28	2245-0107	Very faint veil and bands seen from aircraft over northern Scotland at height of 36 000 feet and from Leuchars.	58°N 3°W 56·5°N 3°W 55°N 4·5°W	0030 0100 2245	70° 10° 20°	360°-060° 040°-060° 020°
28-29	2345-0255	Spectacular display of veil, bands, billows and whirls seen from Shetland to northern England and north of Ireland. Cloudy elsewhere. The predominant feature of the early part of the display was a sharply defined long and persistent band extending from north to north-east at an elevation of 7° above the northern horizon as observed at Malin Head and about 19° seen from Kinloss. As dawn approached, the cloud became visible in the southern sky in fine filaments resembling condensation trails and patches like dense cirrus. The southern boundary of the clouds was probably about 53°N.	58·0°N 6·5°W 57·5°N 3·5°W 56·5°N 7°W 55·5°N 3°W 55·5°N 7·5°W 55·5°N 1·5°W 55°N 4·5°W 55°N 3°W	0019 2350 0115 0230 0001 0200 0015 0105 0027 0220 0230 0240 0030 0150 0157 2345 0100	18° 30° 110° 167° 14° 70° 10° 20° 12° 80° 100° 135° 20° 135° 120° 10° 14°	350°-040° 340°-080° 300°-120° 180°-210° 315°-045° 315°-090° 360°-030° 350°-050° 315°-060° 310°-100° 295°-110° 340°-030° 315°-135° 340°-120° 360°-045° 340°-070°
29-30	2250-0145	Bright greenish bands seen from Denmark and northern Germany. Low cloud widespread over the British Isles but NLC seen from Abingdon, Berks.	56°N 12·5°E 54°N 10°E 51·5°N 1·5°W	2300 0030 No time given. 0100 0145	8° 30° 12° 5° 6°	360° 360°-020° 350°-045° 350°-010° 350°-360°
30 June- 1 July		No NLC.				
1-2 July		No NLC.				
2-3		No NLC.				
3-4		No NLC.				
4-5	2315-0225	Bands. Southern boundary about 55°N.	55·5°N 3°W 55°N 3°W 54°N 6·5°W	2330 0010 0100- 0200 2315	45° 90° 90° 28°	310°-060° 360°
5-6		NLC reported from Uppsala, Sweden. No details given. Mainly cloudy over western Europe.				
6-7	2130-0145	Faint veil and bands.	55°N 4·5°W	0115	5·5°	360°-045°
7-8	2350-0230	NLC seen from north of Ireland.		No details.		
8-9		No NLC.				
9-10		No NLC.				
10-11		Mainly cloudy.				
11-12	2228-0230	NLC seen from Shetland, two aircraft over North Sea and from southern Yorkshire. Bands.	60°N 1°W 56·5°N 1°W 56·5°N 0° 53·5°N 0° 55°N 4·5°W	2312 0010 0030 2240 0100	47° 20° 20° 9° 6°	200°-270° 350°-070° 360°-080° 310°-360° 340°-070°
12-13	2200-0115	Faint veil and band.				
13-14		Cloudy.				
14-15		Low cloud prevalent but NLC bands seen at Tiree (56·5°N 7°W) and Harlov, Sweden (57°N 14·5°E).		No details.		
15-16		Cloudy.				
16-17	0050	NLC seen through low cloud at Tiree.	56·5°N 7°W	0050	9°	020°
17-18	0045-0150	Thin band seen through low cloud.	58°N 6·5°W 56·5°N 7°W 55·5°N 1·5°W	0045 0050 0100	— 6° 5°	070°-090° 050° 010°-020°
18-19		No NLC				
19-20 July		Cloudy.				
20-21	0030	NLC seen in Denmark.	56°N 12·5°E	0030	7°	360°
21-22		Cloudy over British Isles.				
22-23		Cloudy.				
23-24	2110-0130	NLC seen from ship in Skagerrak, and from Denmark and Scotland.	59°N 10°E 56°N 10°E	2200 2130 2230	40° 10° 8°	020° 045° 045°
24-25	2235-0100	Very bright blue-green bands and billows 0030-0045 h.	55°N 4·5°W 56·5°N 1°W 56·5°N 3°W	0110 0045 0045	8° 12° 9·5°	010°-070° 360° 357°-003°
25-26	2115-2225	Blue bands and billows seen at Uppsala, Sweden, from an aircraft over the North Sea and from Scotland.				
26-27		Very faint bands seen from Uppsala and Denmark. Not visible from British Isles though skies clear at some stations.	56°N 10°E	2115	8°	045°
		Cloudy.				

Date— night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths
27-28	2330-0250	Moderately bright bands and billows. Southern boundary of display about 59°N.	58°N 6.5°W 57.5°N 3.5°W	0050 0140 0215 0250	10° 10° 23° 25°	350° 350°-035° 340°-035° 350°-020°
28-29		NLC seen from Kinloss (57.5°N 3.5°W) through gaps in low cloud.	57.5°N 7.5°W 56.5°N 7°W	2350 2330 0250	12° 4° 12°	— 340° 340°-040°
29-30		Cloudy.				
30-31		Bands seen at Uppsala, Sweden. Cloudy over British Isles.				
31 July- 1 Aug.		NLC seen at Uppsala, Sweden, and from aircraft over western Atlantic between 53°N 53°W and 55°N 45°W (0300-0330 h). Cloudy over British Isles.		No details.		
1-2 Aug.	2315-0200	Veil and bands seen from Lerwick and Benbecula and from aircraft over Atlantic. Southern boundary about 63°N.	60°N 1°W 57.5°N 7.5°W 57°N 45.5°W	2315 0100 0120 0200	13° 5° 5° 5°	350°-020° 340°-010° 340°-020°
2-3		No NLC.				
3-4		No NLC.				
4-5		No NLC.				
5-6		NLC seen from Kinloss (57.5°N 3.5°W) through gaps in low cloud.				

A feature of the displays of 1968 was the large number that extended far southwards. The southern border of the majority of displays observed from the British Isles is situated to the north of these islands, but on at least eight nights during 1968 (June 19-20, 22-23, 23-24, 24-25, 27-28, 28-29, July 4-5 and 27-28), the clouds were overhead over some part of the British Isles. On the first of these nights, 19-20 June, observers in the south-west of England observed NLC bands before dawn close to the southern horizon, so that the southern border of the display may have been as far south as latitude 45°N. If the NLC consist of ice crystals, as has been indicated by rocket experiments, then the formation of the clouds will be largely controlled by the temperature at the mesopause. The NLC may therefore provide a visible indication of the meridional extent of the region of abnormally low temperature at the level of 80 kilometres, where they are situated.

Observations in Poland show that NLC were visible there on the nights of 21-22 and 29-30 July, when it was cloudy over western Europe, and on the nights of 30 June-1 July, 9-10 July and 4-5 August when no NLC were visible from western Europe.

The assistance of the large number of observers who, by providing visual observations, photographs and sketches, have made this analysis possible, is gratefully acknowledged. These synoptic studies will continue and observers are invited to send observations to the Balfour Stewart Auroral Laboratory, The University, Drummond Street, Edinburgh 8. A general account of NLC appeared in the *Meteorological Magazine*, Vol. 93, 1964, pp. 161-179, and notes on observations in the *Meteorological Magazine*, June 1967, p. 189.

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KEW — THE NATIONAL RADIATION CENTRE

By R. H. COLLINGBOURNE

This paper describes the work carried out at Kew Observatory, or by staff intimately connected with the Observatory, in the field of solar and atmospheric radiation measurement.

Early work. Attempts to measure the 'sun's heat' or 'amounts of sunshine' have always been important to scientists interested in the atmosphere, and so it was natural that this task should be included in the work of Kew from an early stage. The first serious instrument was that of Campbell; in its original form a water-filled hollow glass sphere was supported at the centre of a wooden hemispherical bowl so that in clear conditions an image of the sun was formed on the bowl's inner surface, charring the wood. Because the rotation of the earth causes the sun's image to trace out a line, it was possible to see from the charring when the sun was 'shining'. A fresh wooden bowl was placed in position at each summer and winter solstice (21 June and 21 December); because of the sun's changing declination, the lines traced on successive days by the centre of the solar image did not overlap. It was possible in this way to form a general picture of the pattern of sunshine during the six-month period and an estimate of the total sunshine was found by measuring the volume of wood which was charred. A discussion of 20-years record (1855-74) obtained with this instrument (after a few years the water-filled globe was replaced by a glass sphere) in the centre of London, is given by Roscoe and Balfour Stewart.¹ In 1874 this instrument was transferred to Kew and operated in this form for several years. The limitations of the crude six-month record were, of course, recognized and, both at Kew and at the Royal Greenwich Observatory, experimental records were made with cards which were clipped or fastened into the appropriate place on the inner surface of a hemispherical bowl.^{2,3} The modern form of card holder with three sets of slots (for summer, equinoctial and winter cards respectively), was described by Stokes⁴ in 1880 and was soon brought into general use.

As would be expected from its function as the Central Observatory of the Meteorological Office (from 1867) all the important radiation instruments at this time were tested at Kew. A new pattern of the Jordan sunshine recorder was compared with the Campbell-Stokes instrument for one month in 1887,⁵ and there is still at Kew a specimen of the Macleod sunshine recorder which was also tested.⁶

Instruments designed to measure the intensity of solar radiation, rather than its duration, were also examined and tested. There are still at Kew two specimens of the Hodgkinson actinometer,⁷ and Balfour Stewart's instrument⁸ may also be mentioned; although neither of these instruments came into widespread use, their basic principle of operation is similar to that later adopted for the well-known Abbot silver-disc secondary standard pyrheliometer.

Commencing about 1875, observations were also made with 'solar-radiation thermometers' or 'black-bulb thermometers in vacuo'; these were maximum thermometers with their bulbs painted black, or made of black glass, enclosed in an evacuated glass tube and freely exposed to solar radiation. The difference between the maximum temperature recorded by these thermometers and the maximum true air temperature was considered to be proportional to the maximum intensity of solar radiation. It was, however, early shown that different specimens of this type of instrument could not be made to give concordant results, and in a later study⁹ it was shown that the temperature difference must depend on other important factors besides radiation.

The gradual development. A great step forward in the international field of solar radiation measurement was made in Europe by the development of the Ångström pyrheliometer for measuring the intensity of direct solar radiation, i.e. solar radiation falling on a surface placed perpendicular to the direction of the sun. Following its adoption by the International Meteorological Congress at Innsbruck in 1905 as a standard instrument, specimens were obtained for use at the British observatories at Kew and at Eskdalemuir. Observations were made regularly at Kew from 1907, usually within half an hour of noon whenever the weather was clear. Results were published in the *British Meteorological and Magnetic Year Book*; this publication was later superseded by the *Observatories' Year Book*. A specimen of the Abbot silver-disc pyrheliometer was also obtained and one of the early comparisons of these two instruments and thus of the Ångström and Smithsonian scales was carried out at Kew.¹⁰ As a natural development, following on from this, continuous records of direct solar radiation have been made at Kew from July 1932 using a Górczynski pyrheliograph.

Measurements of long-wave (thermal) radiation emitted by the atmosphere were started at Kew when the W. H. Dines differential radiometer (comparing radiative temperatures of the sky and of a tank of water) was transferred to Kew from Dines's home at Benson; an irregular series of observations covering the period 1930-40 was published in the *Bulletin Actinometrique International*.*

The modern scene. Up to the 1939-45 war, the measurement of radiation was a relatively minor part of the varied geophysical work at Kew Observatory, but in 1946 the emphasis was changed, and from then on radiation measurement and research became a major interest. It is convenient to sub-divide the discussion of this later phase into five parts, which follow.

Development of instruments. The recording of global solar radiation and diffuse solar radiation on a horizontal surface (the diffuse radiation is the component coming from the sky and clouds and not direct from the sun) began at Kew in 1946 using Moll-Górczynski solarimeters made in Holland. These instruments have been carefully investigated in the laboratory at Kew and the measurements have been repeated with gradually increasing precision, as successive improvements have been made in the instrument by the manufacturers. Apparatus has now been built at Kew to enable the deviations of the response of any particular solarimeter from the cosine law to be measured using a stationary artificial light source, and using an intensity

* Observatoire Léon Teisserenc de Bort, Trappes.

which is not much less than that of the sun on a clear day (about 50 milliwatts per square centimetre is usually used). The solarimeter is kept in its normal horizontal position. In addition, reliable measurements have been made of the linearity of the solarimeter output, up to full solar radiation intensity, and of the solarimeter temperature coefficient. It is hoped that these results will be published soon.

Soon after the start of the recording of global solar radiation it was decided to record as well the corresponding intensity of daylight illumination; this is the intensity of solar radiation evaluated in proportion to its ability to stimulate the average human eye. Suitable instruments were not available commercially and, after taking advice from the National Physical Laboratory about suitable cells and correcting filters, experimental instruments were built at Kew and these were followed by improved versions.¹¹ Development has continued and, in particular, it has proved necessary to keep a continual check on the spectral response of the cells and the transmissions of the correcting filters. Recording at Kew has been continuous since 1947.

During this period also, a much improved version of the Robitzsch bimetallic actinograph was built¹² and this has been made commercially in London. The instrument naturally requires regular recalibration against a standard instrument.

It had long been realized that measurements should also be made of the long-wave radiation exchange. A long series of measurements of down-coming atmospheric radiation was made with the Dines radiometer and the Linke-Fuessner actinometer,¹³ but these instruments are not suitable for continuous recording, and it was decided to concentrate further developments on the construction of a radiation balance meter, an instrument for the measurement of the difference between the downward and upward streams of radiation. An early Kew instrument, based on the type originally built in America by Gier and Dunkle has been described by MacDowall.¹⁴ In an international comparison of radiation balance meters (organized by the World Meteorological Organization (WMO) during the period 1964-67), specimens of the latest version of this instrument compared well with the three other types in routine use; however, the need for some improvement in all the types became evident.

The equipment in general use at Kew and at other Meteorological Office stations recording solar radiation in 1961 has been described by Jacobs;¹⁵ a view of the main solar radiation instruments is in Plate III.

Instruments for special investigations have also been devised. An important project has been the measurement of a spectral distribution of solar radiation on a routine basis. This has involved the development of complex equipment using a set of 15 narrow-band interference filters and has been described in general terms by Collingbourne.¹⁶

A major improvement in the facilities at Kew, in 1966, was the installation of an integrating sphere for the inter-comparison of solarimeters. This enables three solarimeters to be inter-compared. The measurements take about half an hour; previously the inter-comparison had to be done outdoors and required several days of fine weather.

Short, *ad hoc*, investigations were also undertaken which occasionally

required special instrumentation. One such was the operation for about a year of an extra-sensitive illuminometer to investigate the daylight intensity around sunrise and sunset.

Development of recording methods. The continuous records from the radiation instruments were originally made on the type of recording galvanometer in which the trace appears in the form of a series of dots. These records had to be hand-scaled, and this is a tedious task which cannot be performed accurately when the record is fluctuating. It was natural therefore that a search should be made for ways of recording which would both save labour and, if possible, be more accurate.

The first improvement that was adopted involved the use of a low-inertia electric motor of which the speed of rotation is accurately proportional to the applied voltage over a large range of inputs. If such a device is coupled to a counter so that the number of revolutions of the motor can be indicated, then the difference in counter readings between the beginning and end of any period of time is proportional to the integral of the applied voltage, which is just what is required for hourly or daily mean values. A description of the system used has been given by Blackwell.¹⁷ This method, however, had a number of drawbacks, notably the necessity for careful maintenance of the brush contacts on the motor. A major step forward was the production of the Meteorological Office Data-Logging Equipment (MODLE) as a combined effort by Kew, the Instrument Development Branch of the Meteorological Office and the manufacturers. The first prototype was received in June 1961 and this was brought into routine use from 1 January 1962. With this equipment the outputs from up to 12 different instruments can be converted into digital form on a scale from 0 to 999 and punched on to paper tape for subsequent analysis and processing by an electronic computer. The introduction of this equipment was foreshadowed by Jacobs.¹⁸ The output in each channel is sampled at the rate of once per minute, and subsidiary experiments at Kew have shown that this rate of sampling is adequate for the calculation of hourly mean values even when the radiation is very variable.

The computer programmes to enable the Meteorological Office computer to produce hourly and daily totals of the radiation components, and to ensure that faulty data are not used, were written by Kew staff. A chart record is also obtained to safeguard against faults in the paper-tape output. An improved version of MODLE was produced in 1964 (see Plate IV) and is now in routine use at Kew and 10 other Meteorological Office stations.

With the first Meteorological Office computer it was possible to obtain only a printed output of processed data, but, following the introduction of the second Meteorological Office computer, the data are now stored on magnetic tape as well as being printed out. A series of computer programmes has been written so that data on magnetic tape can be added to, amended or modified in any necessary way, and so that any required tabulation can be prepared automatically. The time saved by this application of automation is available for a critical examination and analysis of the data.

This data-processing system, based on the widespread use of automatic data-logging apparatus, pioneered and largely devised by the staff at Kew

Observatory, is at present unique in the Meteorological Office and perhaps in the world. It has been favourably commented on by Filippov.¹⁸

A future planned development for MODLE is the replacement of the paper-tape punch by a magnetic-tape recorder, because this should lead to increased reliability. On the same general lines a simple magnetic-tape recording system has been designed for recording the output of a single solarimeter (e.g. on ships) and some instruments of this type have been tested.

The organization of a radiation network. Observations of solar radiation prior to 1939 at Meteorological Office stations other than Kew were sparse. Occasional observations with the Ångström pyrheliometer were made at Eskdalemuir from 1909 to 1939, and a continuous record of solar radiation on a horizontal surface was made, with a Callendar radiograph, at South Kensington from 1911 to 1939.¹⁹

After the 1939-45 war, however, it was decided, partly in connection with research work being started in agricultural meteorology, that solar radiation should be measured at other stations, and a network was gradually built up. In 1951-52 measurements of global and diffuse radiation were started at Lerwick and Eskdalemuir and by 1957 had been extended to Aberporth, Cambridge and central London (Victory House). Illumination measurements were started in central London in 1950, and in 1958 at Lerwick and Eskdalemuir. Measurements of radiation balance started at Lerwick and at Eskdalemuir in 1964.

The International Geophysical Year (IGY) (July 1957-December 1958) proved to be a stimulus in this field of activity, as in so many others, and, as one of its contributions, the Meteorological Office decided to set up radiation measuring equipment at Malta, Aden and Stanley (Falkland Islands), measuring global and diffuse solar radiation, and radiation balance, and also to equip the four British Ocean Weather Ships with equipment for measuring global solar radiation and radiation balance. All this equipment was installed by June 1957. In addition to these Meteorological Office stations, help was given to the observatories at Halley Bay and Argentine Island. Later, in 1965, routine recording of solar radiation was started at Bracknell.

This large expansion of radiation recording threw a correspondingly large and continuing burden of extra work on to the staff of Kew Observatory. All the solarimeters and illuminometers had to be calibrated at Kew, advice and instructions on recording and tabulating procedures had to be given, the radiation balance meters had to be constructed in the workshop and then calibrated, and the routine of regular recalibrations had to be built up. Many visits of inspection have been made to stations both at home and overseas. Since this extra work was also coincident with a reduction of Scientific Officer staff, it was inevitable that there had to be a shift from the more fundamental experimental investigations of 1947-55 to the more routine, but still very necessary, calibration and investigation of routine instruments of the later years.

In parallel with this development of the radiation network using official Meteorological Office stations, there was an effort to encourage those non-Meteorological Office stations desirous of making solar radiation observations

for their own purposes to use solarimeters calibrated at Kew (or calibrated against solarimeters which have themselves been calibrated at Kew), and to collect such data in a uniform manner. It was planned to store all the radiation data on punched cards and this has now largely been carried out.

The completed tabulation forms have all been sent to Kew for critical scrutiny, and thus Kew Observatory has truly developed into the National Radiation Centre. Since about 1956, an effort has also been made to obtain solar radiation measurements on ships making regular voyages. Solarimeters and potentiometric chart recorders have been installed on a number of naval survey ships, British Antarctic Survey (BAS) ships and research vessels (so far six in all) and later, when the magnetic-tape recorders, mentioned above, are proved to be satisfactory, it is intended to extend this scheme.

There have also been close links between Kew Observatory and the radiation measurements undertaken by the Meteorological Research Flight (MRF). The solarimeters and illuminometers of the MRF are regularly calibrated and every assistance is given in the instrumental problems encountered.

The analysis of the collected data. It is not possible here to do more than indicate the main feature of this work. The first major discussion on the radiation data collected at Kew was by J. M. Staggs⁹ who analysed some 14 years of direct solar radiation data. At about the same time Robinson¹³ produced his important papers on atmospheric radiation.

This was followed by Blackwell's papers on the first five years of global and diffuse radiation²⁰ and of daylight illumination.²¹ These summarized the main instrumental factors and produced average values for various conditions. Using these records and the first records of the radiation balance, it was found possible to estimate the reflection and absorption of solar radiation in a cloudless atmosphere,²² and the magnitude of the various terms of the local energy balance of the atmosphere.^{23,24} These studies showed the value of the radiation observations it was proposed to make during the IGY.

Robinson²⁵ further developed this work by using the surface observations to estimate the absorption of solar radiation by atmospheric aerosols. It was shown fairly conclusively that this was often appreciable but there were some curious features about the results that were further brought out in a paper by Hamilton and Collingbourne.²⁶ It now seems probable that the small discrepancies reported were due in part to a wrong application of previous results on aerosol scattering, and in part to small errors in the cosine response of the solarimeters. A direct result of the radiation measurements is to show the increase of solar radiation received in central London,²⁷ following the 1956 Clean Air Act.

A summary of the much larger amount of data now available for stations covering much of the United Kingdom is obviously a much larger problem than the use of data from one or two stations only. A start has been made by Day,²⁸ and Lumb²⁹ has analysed data from Ocean Weather Ships but a more ambitious publication is now planned.

Many inquiries concerning radiation problems have been answered over the years. One particular item may perhaps be cited; a study of the one year's record with a sensitive illuminometer at Kew has produced a valuable

summary of the illumination around sunrise and sunset which has been of help to engineers concerned with street lighting, and to construction engineers and animal physiologists.

International comparisons and work. There is a great need to ensure that the measurements of radiation made in different countries are concordant. Kew Observatory has always kept several Ångström pyrheliometers which are inter-compared with each other. From the early days there has been a series of recalibrations against the Swedish standard. The comparison of the Smithsonian and Ångström scales by R. E. Watson,¹⁰ already mentioned, and a similar later comparison by Eldridge³⁰ showed agreement with such comparisons elsewhere. That the accuracy was being maintained was confirmed by further measurements at Davos, Switzerland, in 1959 and 1964 when a Kew representative took one of the Ångström instruments to join in the international comparison of standard pyrheliometers organized by WMO. Since 1957 the measurements at Kew have been expressed in the International Pyrheliometric Scale (IPS), recommended by WMO. This is an attempt to assess the true pyrheliometric scale based on the estimated errors in both the Smithsonian and Ångström scales. At the same time, however, a close contact has been kept with the independent scale of radiation maintained by the National Physical Laboratory (NPL). It seems likely that the difference between the IPS and the NPL scales is less than one per cent.

The staff at Kew Observatory have always played their share in the work of international organizations, in close consultation with the Headquarters Branch which since 1957 has been Met. O.14. The international representation at present is by Met.O. 14 members; L. Jacobs is a member of the Working Group on Radiation Climatology, WMO Commission for Climatology, while R. H. Collingbourne is a member of the WMO Commission for Instruments and Methods of Observation Working Group on radiation instruments and methods of observation for general use, and of the Regional Association (RA) VI (Europe) Working Group on Radiation.

Kew Observatory, because of its equipment and facilities, was designated one of the European regional radiation centres by RA VI in 1965, i.e. it is recognized as being competent to calibrate instruments and supervise radiation observations.

The future. The staff and facilities at Kew Observatory over the years have played a major part in the recording of solar radiation in the United Kingdom, at certain overseas stations and at sea. There is a slight shift of emphasis now as the data processing provided by the Meteorological Office Headquarters becomes more important, but the facilities of the Observatory and the expert knowledge of its staff will be required for many years to come.

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Note : In the June *Meteorological Magazine*, Vol. 98, p. 165, line 1, the term 'House Guards' has been quoted. Although it appears in the original journal of 1882, there is no doubt that the reference is to the well-known Horse Guards.

REVIEW

Graphical rational patterns, a new approach to graphical presentation of statistics, by Roberto Bachi. 170 mm × 245 mm, pp. xvii + 243, *illus.*, Israel Universities Press, Jerusalem, 1968. Price: 80s. (Distributors, H. A. Humphrey Ltd, 5 Great Russell Street, London, W.C.1.)

The author, who is Professor of Statistics and Demography at the Hebrew University of Jerusalem, has suggested a new solution to the problem of presenting statistical material in graphical form. In essence this consists of representing numbers relative to a fixed base (such as percentages) by the proportion of a standard area which is printed in black (or other colour). If, say, the base is 100, then 1 per cent is represented by a just visible black dot, the 10, 20 and 30, etc. percentages correspond to one or more black areas of respectively 10, 20 and 30, etc. times the unit size, arranged more or less like the pips on a playing card, with a space for any odd units, while for 100 per cent the whole area is black. Patterns are suggested for bases of 10, 40, 100 and 1000; in the last case, the total pattern measures just over one inch square. This method of graphical representation is used in many variants through 13 chapters, typical examples being the distribution of average income in each province in Italy, or the percentage distribution of population in Sweden by quinquennial age-groups for the period 1850 to 1950. One or more graphical rational patterns are shown in each subcell, and the reader will understand these as soon as he has learned the appropriate code.

The idea is well presented, and well executed, although I find many of the resulting graphs rather heavy and unsightly in areas of high percentages. However, the reader will ask what advantages these patterns have over the more familiar graphical patterns for conveying numerical information, the ordinary Arabic numerals. Certainly the amount of information contained in an ordinary weather observation, plotted around the station circle, far exceeds what could be conveyed in the same time by these graphical rational patterns.

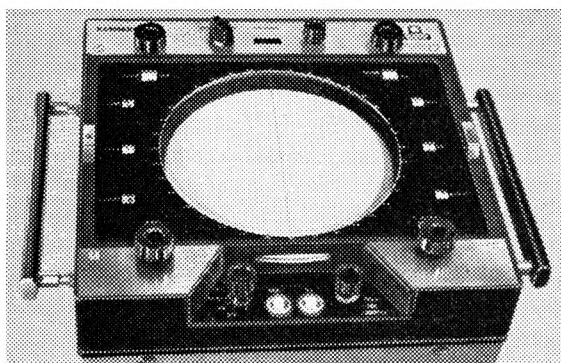
The book is easy reading, although Figure 12.5B is puzzling until the reader looks at it in a mirror. Meteorologists, however, will probably share the feeling that in many problems the advantages claimed for this idea can be obtained more simply by the judicious use of ordinary numerals, and some isopleths.

J. M. CRADDOCK

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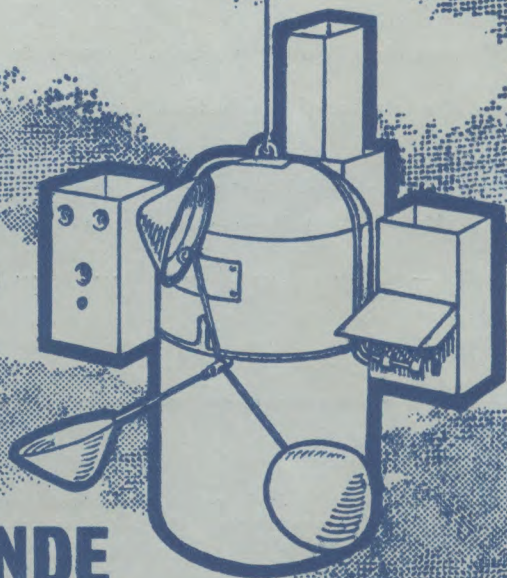
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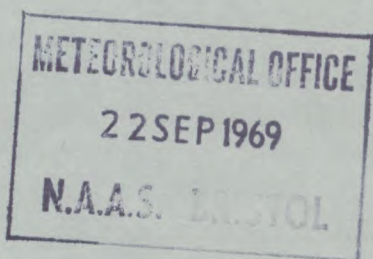
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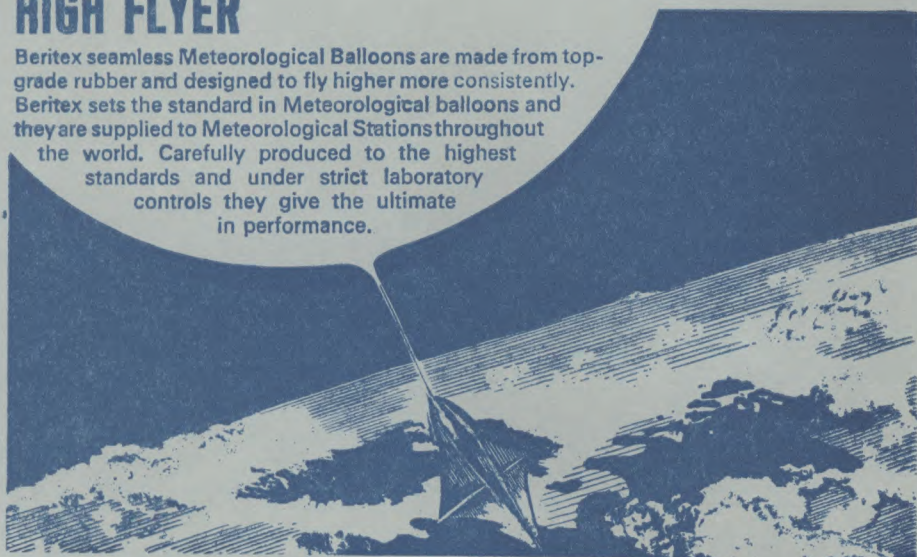


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THE LAG OF THE HUMIDITY SENSOR IN THE BRITISH RADIO- SONDE

By J. F. R. McILVEEN and F. H. LUDLAM,
Imperial College, London

Summary. Glückauf's laboratory measurements of the behaviour of gold-beater's skin as a function of temperature and relative humidity are summarized. A similar behaviour of the humidity sensor of this material in the British radiosonde is shown by an analysis of some soundings. The response of the sensor in the lower troposphere is satisfactory, and even in the low temperatures of the high troposphere is better than is sometimes thought: in particular, the recordings may show saturation with respect to ice even without correction for lag. It is recommended that the relative humidity indicated there should be corrected for lag, and that values should be reported up to the tropopause, and not, as in present practice, to the -40°C level.

Introduction. In the study of atmospheric soundings it is often desired to establish the presence and height of layers of cloud. Although these should be revealed by the reported relative humidity, it is well known that the sluggishness of the sensors used makes this an unreliable indicator, especially at low temperatures. Nevertheless, since the development of an improved sensor sufficiently inexpensive for routine use still cannot be foreseen, it is useful to have some estimate of the performance of those now employed, and we here review that of the gold-beater's skin in the British radiosonde, particularly to assess whether it can be expected to give a good indication of layers of air nearly saturated with respect to ice, or containing ice clouds, in the high troposphere, where in our latitudes the temperature is about -40°C or less.

The behaviour of gold-beater's skin in the laboratory. Glückauf¹ found that the response of gold-beater's skin to small instantaneous changes of relative humidity in a wind-tunnel could be described satisfactorily in terms of the diffusion of water vapour through a particular boundary-layer configuration. Though a complicated exponential and logarithmic function of time, this response differs little from a simple exponential function of time of the form

$$dh/dt = -(1/T_e) (h - h_e) \quad \dots (1)$$

where h is the relative humidity indicated by the gold-beater's skin (with respect to saturation over liquid water),

h_e is the ambient relative humidity,

t is time

and T_r is the response time of the gold-beater's skin, defined as the time taken for the difference between the indicated relative humidity and a constant ambient value to decrease by the factor $1/e$. T_r is given by Glückauf's theory as a function of the temperature and pressure, and certain skin parameters (Figure 2* and Appendix), and is subsequently called the Glückauf response time T_G .

Two factors which complicate the behaviour of the skin are described by Glückauf :

- (i) T_G is a function of h , being a minimum for relative humidities of about 55 per cent. The continuous line in Figure 1(a) represents an average of a number of curves presented by Glückauf and indicates the magnitude of the variation, though the variation of the response with relative humidity is itself a function of temperature. The response is effectively at its optimum at relative humidities between 30 and 80 per cent.
- (ii) After indicating relative humidities below 30 per cent the gold-beater's skin exhibits hysteresis. If the skin has been calibrated in successively drier atmospheres, subsequently indicated relative humidities below about 70 per cent are too low. Figure 1(b) represents Glückauf's laboratory measurements of this effect at a temperature of 12°C (Glückauf, Figure 3¹), Glückauf states that similar curves, in some cases almost identical, have been obtained at temperatures down to -29°C. Figure 1(b) presents the discrepancy in relative humidity as a function of an indicated relative humidity which increases from each of four minimum values. Since the routine calibration of the humidity element of the British radiosonde uses a succession of decreasing standard humidities, it follows that if a minimum relative humidity below 30 per cent is reported subsequent uncorrected values may be too low by as much as 10 per cent.

The effect of hysteresis will be greatest after a sonde has passed through a dry layer sufficiently deep to allow the skin to indicate very low relative humidities. Although this may happen in the middle troposphere, it is probably most frequently associated with low-level subsidence inversions and rather high temperatures which permit rapid response by the hygrometer. The relative humidity (with respect to liquid water) corresponding to saturation with respect to ice is 70 per cent at -36.5°C, and so the skin will rarely recover its calibration if a relative humidity below 30 per cent is reported in the middle troposphere.

It appears appropriate to correct indicated relative humidities first for the effect of hysteresis, which depends only on the state of the skin, and then for lag. A simple correction for hysteresis, which is always an increase of reported humidity, may be found by interpolating between the curves on Figure 1(b).

The gold-beater's skin in the British Mk 2B radiosonde. The exposure of the gold-beater's skin in the wind-tunnel in Glückauf's experiments differed considerably from that in a radiosonde in flight. In the laboratory the plane of the skin was parallel to the airflow, while in the radiosonde it is perpendicular to it and the skin lies downstream of a rain-shield. However,

* Figures 1-7 appear on pages 237-240.

in the radiosonde the response of the skin to a change in relative humidity probably still has an exponential form, and the variation of the response time T_e with temperature in both kinds of exposure is likely to be dominated by that of the saturated water-vapour density with temperature (see Figure 2). Accordingly, the response time of the skin in the radiosonde may be expected to differ from that determined in the laboratory only by a small increase associated with somewhat poorer ventilation.

The original records of some two dozen soundings from Crawley in 1967 were selected and used to estimate values of T_e for the gold-beater's skin from equation (1), introducing the observed values of h and dh/dt and estimates of h_e . Equivalent values at 1000 mb, assuming the pressure dependence to be that of the Gluckauf response time (given in the Appendix), are plotted in Figure 2. In estimating values for T_e in the troposphere, a part of the original record showing a marked change of indicated relative humidity was assumed to have resulted from a discontinuous decrease in the ambient humidity to the value asymptotic to the recorded trend. In this way a maximum value of T_e was obtained.

Because of the greater variability of indicated humidity in the lower troposphere, the time intervals used in the computations were generally shorter there than in the upper troposphere. If, however, gradients of relative humidity had similar magnitudes throughout the troposphere, the effect on the computed lag of assuming these to be infinite (i.e. of assuming a stepped humidity profile) would be greater in the lower troposphere. Since the assumption of discontinuous changes in the ambient humidity can result only in values of T_e which are too large, the tendency to overestimate T_e can be expected to be more noticeable in the lower troposphere.

Some estimates of the response time were made also from the records obtained in the lower stratosphere. The air in the stratosphere was assumed to be completely dry, and T_m , (the maximum value of T_e) computed from equation (1) was then found to have a minimum on each sounding at a level some 50 mb above the tropopause (as shown for example in Figure 7). Such minimum values provided the points shown at the lowest temperatures in Figure 2. Measurements of frost-points from aircraft² show that the average relative humidity 50 mb above the tropopause is less than 4 per cent, so that the assumption of a value of zero should lead to reasonable results, but it is possible that at these levels the air close to the gold-beater's skin is significantly contaminated by the evaporation of water vapour from the balloon or the structure of the radiosonde itself, so that the computed values of T_m may still be too large.

From Figure 2 it appears that the estimated values of T_e and T_m deviate from those of T_G in the manner anticipated. Values obtained from the middle and upper troposphere are in closest agreement with T_G , and suggest that the latter correctly represents the response time of the humidity element of the Mark 2B radiosonde to within a factor of about two. Values of T_e in the troposphere were computed from fifteen soundings, seven of which each provided at least three points on Figure 2. Response times computed at different levels from the same sounding often showed a consistent bias away from the axis of the bulk of the values, which may be due to variations in the characteristics of individual samples of the gold-beater's skin.

Figure 3 displays T_G as a function of height or pressure in the International Civil Aviation Organization (ICAO) atmosphere. The discontinuity in its gradient at the tropopause results from the change in lapse rate there; in the isothermal stratosphere T_G is simply proportional to the square root of the air pressure.

The response of the idealized humidity sensor. The behaviour of the idealized gold-beater's skin is described by Figures 1 and 2. We may consider the response of such a sensor in a radiosonde which rises with the typical speed of 6 m/s using the following four simple models of the vertical profile of the relative humidity in the atmosphere.

(i) A completely dry layer lies above one in which the gold-beater's skin has reached equilibrium under a relative humidity of 60 per cent; the model atmosphere is isothermal.

In Figure 4, curve A shows the response of the gold-beater's skin as a function of the time after the sensor enters the dry layer (the scale of the abscissa is made non-dimensional by dividing the time elapsed by the minimum response time, i.e. T_G at relative humidities of about 50 per cent; T_G varies with indicated relative humidity according to the continuous line in Figure 1(a). For comparison, the curve B represents a purely exponential response, T_G remaining fixed at the minimum value. The increasing difference between the two curves for values of the parameter (time/minimum T_G) greater than unity results from the rapid increase of T_G with decreasing relative humidity when the latter is below 30 per cent (Figure 1(a)).

When the gold-beater's skin is indicating a measurable rate of change of relative humidity, the Glückauf response time T_g defined by Figures 2 and 1(a) can be used in a finite difference form of equation (1) to estimate the true ambient humidity h_e . We have

$$h_e = T_G(h_2 - h_1) / \Delta t + (h_1 + h_2) / 2 \quad \dots (2)$$

where h_1 and h_2 are respectively the reported humidities at the beginning and end of the time interval Δt , and the response time T_G is appropriate to the conditions mid-way through the time interval.

Figure 4 contains values of the ambient humidity computed in this way using humidities read from curve A and values of T_G /minimum T_G from Figure 1(a). The scatter in the values is a measure of the accuracy with which the curves can be read, though the value marked E is significantly above zero because the linear relationship of equation (2) is not accurately applicable to the non-linear curve A when the time interval ΔT is greater than T_G . Since intervals between successive observations of relative humidity by the radiosonde may be as large as 30 seconds, correction for lag is justified only at temperatures below about -20°C (above the 500-mb level), when the Glückauf response time is greater than 30 seconds.

From equation (1) it is apparent that if the correction $(h - h_e)$ which is applied to the indicated humidity is in error only because of the value used for the response time, then the fractional error in the correction is just the fractional error in the response time (estimated from Figure 2 as likely to be as much as 0.3).

When the minimum response time is less than about 1.5 minutes, corresponding to temperatures above -33°C , the gold-beater's skin has indicated

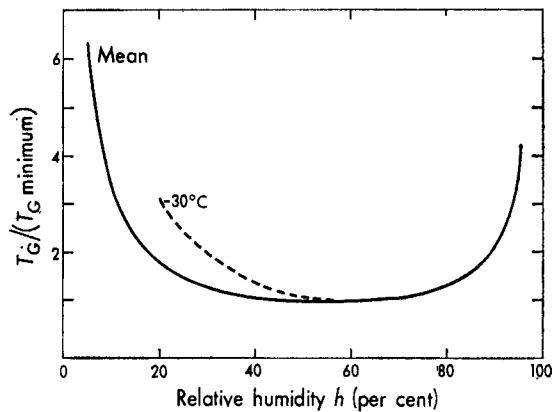


FIGURE 1(a)—VARIATION WITH INDICATED RELATIVE HUMIDITY h OF THE GLÜCKAUF RESPONSE TIME T_G DIVIDED BY THE MINIMUM VALUE AT THE SAME TEMPERATURE

The continuous line represents the mean of Glückauf's observations over a range of temperatures from -30°C to 18°C , and the pecked line represents his observations at -30°C .

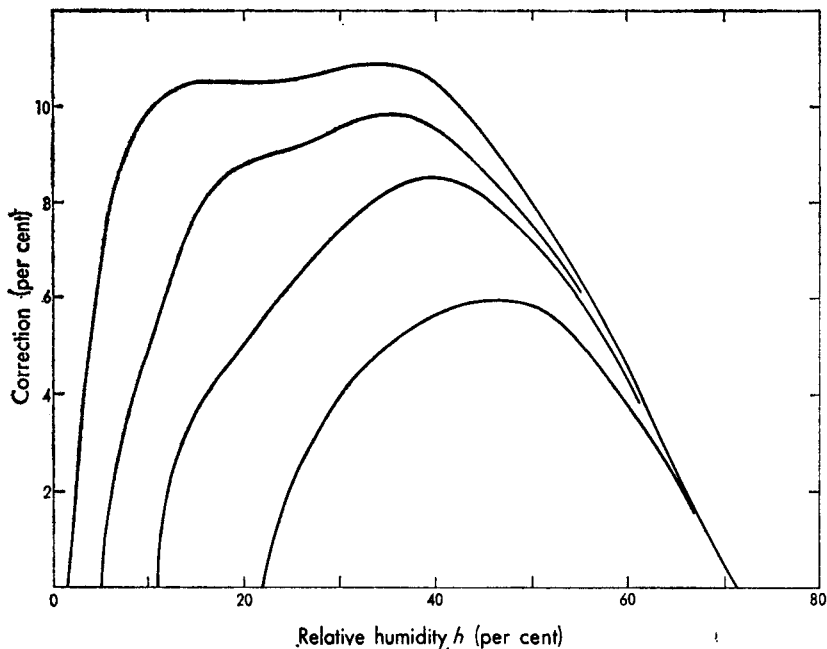


FIGURE 1(b)—THE EFFECTS OF HYSTERESIS ON THE RELATIVE HUMIDITY INDICATED BY GOLD-BEATER'S SKIN IN THE LABORATORY (FIGURE 3¹)

Each curve shows the correction to be applied to any indicated relative humidity after a certain minimum value has been indicated. Corrections needed following the indication of minimum relative humidities other than 1.7, 5, 11 and 22 per cent can be found by interpolation between the curves.

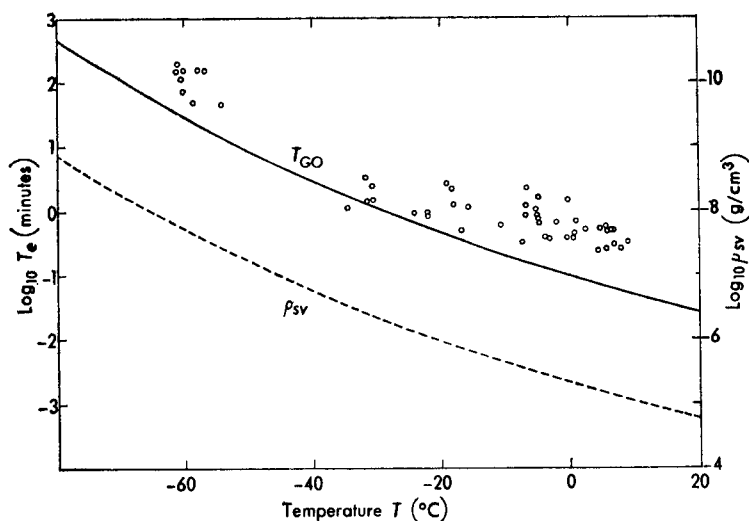


FIGURE 2—VARIATION WITH TEMPERATURE T OF THE GLÜCKAUF RESPONSE TIME (SEE P. 234 AND APPENDIX)

The continuous line is $\log_{10}(T_{GO})$, where T_{GO} is the Glückauf response time at a pressure of 1000 mb and is related to the response time T_G at a pressure of p mb by $T_G = T_{GO}(p/1000)^{\frac{1}{2}}$. Response times T_e computed from radiosonde ascent records were reduced to equivalent values at a pressure of 1000 mb using the same relation. The density of vapour saturated with respect to liquid water, ρ_{sv} , is included for comparison (pecked line).

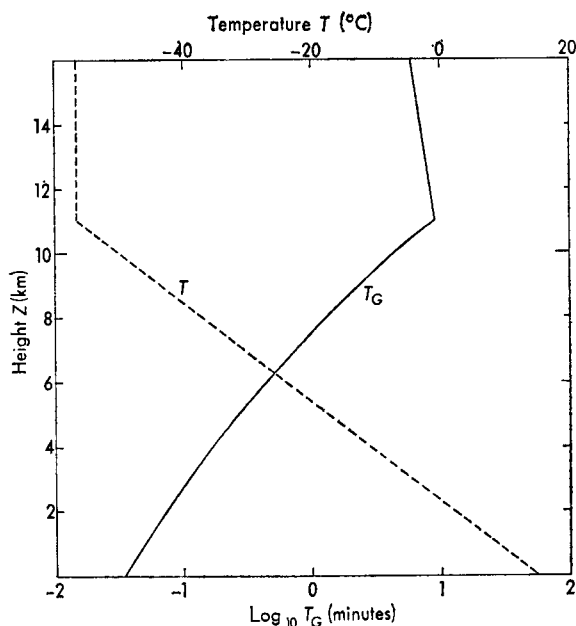


FIGURE 3—THE GLÜCKAUF RESPONSE TIME T_G AND AIR TEMPERATURE T AS A FUNCTION OF HEIGHT Z IN THE ICAO STANDARD ATMOSPHERE

— T_G - - - T

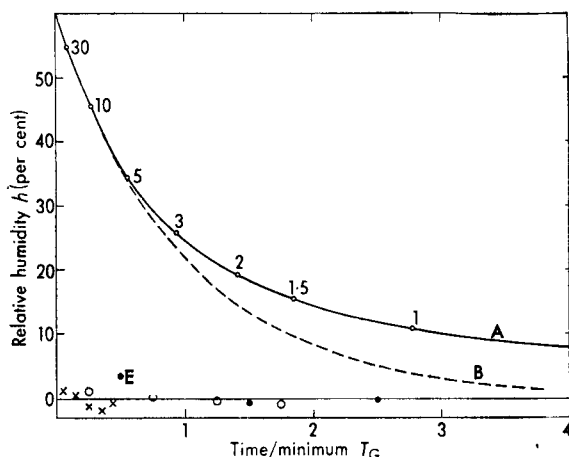


FIGURE 4—THE RESPONSE OF A HUMIDITY SENSOR AFTER ENTERING A COMPLETELY DRY ISOTHERMAL LAYER

The initial indicated relative humidity is assumed to be 60 per cent; the subsequent response is represented by a curve A when the response time varies with indicated relative humidity according to the continuous line on Figure 1(a), and by curve B when the response time is constant. The ordinates at the points on the curve A marked by the numbers N show the relative humidity indicated 1 km above the base of the dry layer by a sensor with a response time of N minutes (the sensor rises at 6 m/s). Ambient relative humidities computed using equation (2), with half-minute time intervals, and curve A, are marked respectively by full circles, open circles and crosses when the response times are 0.5, 1 and 5 minutes.

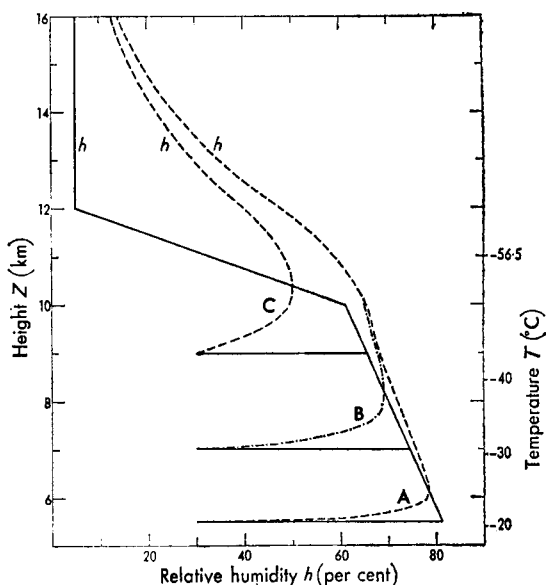


FIGURE 5—THE RESPONSE OF HUMIDITY SENSORS, WITH RESPONSE TIMES DEFINED BY FIGURE 2, DURING AND AFTER PENETRATION OF DAMP LAYERS (SATURATED WITH RESPECT TO ICE) IN THE HIGH TROPOSPHERE OF THE ICAO ATMOSPHERE. Curves A, B and C respectively represent the response when the relative humidity rises from 30 per cent to ice saturation at heights of 5.5, 7 and 9 km, and subsequently falls above 10 km to a constant value of 5 per cent in an isothermal atmosphere as shown by the continuous lines. The rate of change of indicated relative humidity with height (or time) is zero when the sensor indicates the true relative humidity.

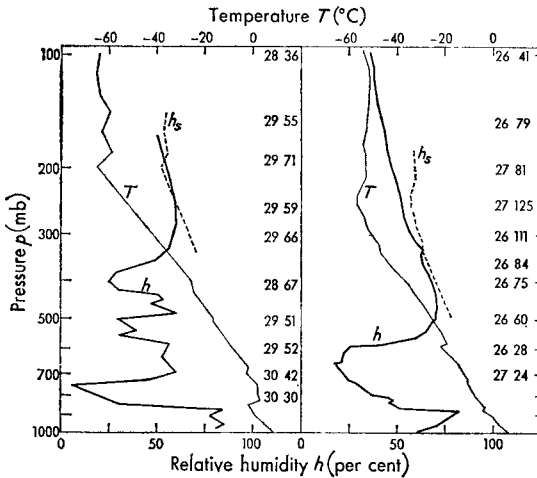


FIGURE 6—THE SOUNDINGS FROM CRAWLEY AT ABOUT 1200 GMT (a) ON THE LEFT, 12 NOVEMBER 1967, AND (b) ON THE RIGHT, 12 MARCH 1967

The profiles of relative humidity h and temperature T , represented respectively by thick and thin continuous lines, were taken from the original record of the ascent. The pecked line is the relative humidity h_s corresponding to ice saturation at the indicated temperatures. The reported winds in tens of degrees and knots are included on the right-hand side of each diagram.

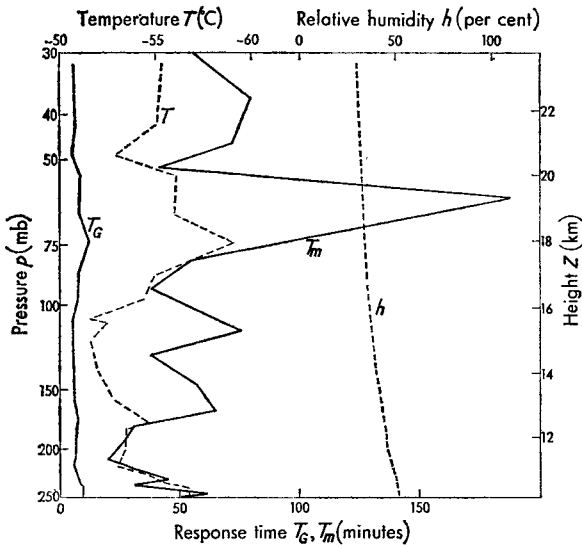


FIGURE 7—SOUNDING THROUGH THE LOWER STRATOSPHERE FROM CRAWLEY AT ABOUT 1200 GMT, 12 MARCH 1967

Temperature T , the Glückauf response time T_G , the maximum response time T_m (the value of T_e satisfying equation (1) when h_s is zero), and the relative humidity h indicated by the sensor are shown as functions of height Z , or of pressure p .

most of the change in the ambient relative humidity after penetrating 1 km into the dry air (that is after about 3 minutes). Because of desiccation, however, the response time at this level has risen to many times the appropriate minimum value and the instrument will very rarely indicate relative humidities as low as 5 per cent, since this would require the existence of a very dry layer many kilometres deep. This is consistent with the experience that radiosondes seldom indicate relative humidities much below 10 per cent in subsided air in the low troposphere, although values as low as 1.5 per cent occur, as shown for example by observations of frost-point from balloons³ and aircraft,⁴ and by inference from the frequently observed radar-ducting in the Caribbean.⁵

When the minimum response time is of order 10 minutes, corresponding to temperatures below -50°C , the idealized gold-beater's skin grossly misrepresents features of the stratification of relative humidity having vertical dimensions of about 1 km, though they may be reconstructed from the indicated values.

(ii) A cloud layer 300 m thick, saturated with respect to liquid water, lies above a layer in which the sensor has reached equilibrium under a relative humidity of 50 per cent. The model atmosphere is isothermal.

The relative humidity indicated by the sensor was computed as a function of time using a form of equation (1), values of T_G appropriate to temperatures of 5°C and -5°C and the indicated relative humidity (the continuous curve on Figure 1(a)). At a temperature of 5°C the sensor indicated a relative humidity of 96 per cent 90 m above the cloud base, while at -5°C 91 per cent was indicated at the same level. In each case the value indicated at the top of the saturated layer exceeded 97 per cent.

This performance seems impressive in view of the common experience that soundings usually fail to find saturated or nearly saturated layers on occasions when altocumulus clouds are reported, although shallow layers with distinct maxima of relative humidity are usually indicated (as shown for example in Figure 6(a) at about 650 and 470 mb, when medium-level cloud $C_M=3$ was reported by most stations in southern England). However, on such occasions the proportion of saturated air at the cloud levels may be smaller than it seems, considering the frequently patchy distribution of cloud, the presence of much thinner cloud or even clear spaces between individual cloud elements, and the effect of perspective in obscuring gaps at low elevations.

(iii) The relative humidity decreases linearly at the rate of 40 per cent per kilometre in an isothermal atmosphere.

The difference between reported and true ambient humidities is given by

$$h - h_s = -w(\partial h_s / \partial z) T_G (1 - \exp(-t/T_G)) + \Delta h_0 \exp(-t/T_G) \quad \dots (3)$$

where w is the vertical speed of the sensor,

$\partial h_s / \partial z$ is the vertical gradient of relative humidity and

Δh_0 is the initial value of $(h - h_s)$. The value of $(h - h_s)$ approaches the limit $-w(\partial h_s / \partial z) T_G$ with increasing time; the values of this limit are given below for three values of T_G .

Response time T_G in minutes	0.2	1	5
Corresponding temperature in $^{\circ}\text{C}$	-9.5	-29	-45
$-w(\partial h_s / \partial z) T_G$ percentage R.H.	2.9	14.4	72 (54)

When the response time is 5 minutes ($h - h_e$) approaches the limiting values of 72 per cent so slowly that when the ambient relative humidity has reached zero the value of the first term on the right of equation (3) is only 54 per cent. The treatment assumes the response time to be constant, ignoring the larger values associated with extremes of relative humidity.

Thus the comparatively modest response time of 1 minute leads to considerable over-estimation of relative humidity when this has a large negative vertical gradient. The correction for lag, using equation (2) is, of course, still applicable.

(iv) Layers of various thicknesses, saturated with respect to ice, lie in the high troposphere of an ICAO atmosphere, above a layer in which the sensor has reached equilibrium under a relative humidity of 30 per cent with respect to liquid water. The relative humidity decreases linearly with height through a layer 2 km thick centred on the tropopause and remains constant at 5 per cent up to a height of 16 km. This profile is a simple model of conditions commonly observed on the anticyclonic side of polar-front jet streams.

Figure 5 presents the profiles of relative humidity indicated by the idealized gold-beater's skin when rising at 6 m/s and entering the ice-saturated layers at heights of 5.5, 7, and 9 km. The response time is determined by the ambient temperature and pressure, using Figure 2. The effects of desiccation of the sensor are ignored, but from Figures 1(a) and 5 can be seen to be unimportant at heights below 13 km. Equation (3) is used to compute the indicated relative humidity as a function of time and thus of height, since between heights of 5 and 10 km in the ICAO atmosphere the relative humidity with respect to liquid water at saturation with respect to ice is a nearly linear function of height. In all three cases the sensor over-estimated the relative humidity in some regions, especially in the stratosphere. It appears that the vertical gradient of relative humidity associated with ice saturation in the high troposphere, together with the appropriate values of response time, is sufficient to account for the occasional indications of supersaturation with respect to ice found on routine soundings (see, e.g., Figure 6(a)).

When the saturated layer is encountered at a temperature of -20°C (curve A of Figure 5) the height of its lower boundary is over-estimated by 0.6 km, whereas when it is encountered at temperatures of -30°C (curve B) and -40°C (curve C) it is respectively over-estimated by 1.2 km and over 2 km. Evidently it may commonly happen that saturated layers are insufficiently thick for ice saturation to be indicated.

The smooth profiles of humidity indicated in the stratosphere are qualitatively typical of routine soundings and though the magnitudes of the computed gradients are rather too large (see Figure 7) this can be explained, in part at least, by the neglect of the increase in the response time caused by desiccation.

Observed humidity and temperature profiles. Figure 6 contains the humidity and temperature profiles of two soundings from Crawley. At the time of the first, 1200 GMT on 12 November 1967, nearly every station in the British Isles south of a line from the Wash to Malin Head reported high cloud ($C_H = 2$), and most stations in southern England reported middle cloud ($C_M = 3$). The strongest wind at the 300-mb level was observed at

Stornoway (134 kt from 280°); thus Crawley lay well to the south of the axis of the jet stream. The extensive shield of dense cirrus is represented on the midday sounding (Figure 6(a)) by the damp layer above the 350-mb level. The value of 5 per cent for the relative humidity reported at about 750 mb is unusually low.

At the time of the second, 1200 GMT on 12 March 1967, near Crawley the sun was completely obscured by an overcast of altostratus with mamma; there was no lower cloud. The cloud-filled layer, saturated with respect to ice, is clearly indicated on Figure 6(b) and probably had a lower boundary at about 550 mb.

It is confirmed by Figure 6 that deep layers of damp air in the upper troposphere are represented with useful accuracy even by the uncorrected readings of the routine radiosonde. It is therefore unfortunate that the present practice is to cease reporting relative humidity when the temperature falls below -40°C . The synoptic report from the sounding represented by Figure 6(a) therefore omitted humidity data above the 308-mb level, and the very clear evidence of a deep cloud layer in the high troposphere was effectively lost. Because of the smoothing effect of the large lag of the gold-beater's skin, only a few more values would be needed to provide a sufficiently complete record up to the tropopause.

Relative humidities indicated in the lower stratosphere. Using radiosonde observations of humidity and equation (1), maximum values for the response time of the gold-beater's skin (T_m) were computed assuming the ambient humidity to be zero. Five of the routine soundings made from Crawley early in 1967 were chosen because, in each, a marked rise of indicated humidity towards ice saturation in the high troposphere showed that the sensor had not become unresponsive because of excessive desiccation or some other reason. Figure 7 presents the vertical profiles of temperature and humidity from one sounding, together with the profiles of T_m and the Gluckauf response time T_G (as defined by Figure 2 and the pecked line on Figure 1(a)).

Although the vertical gradients of humidity indicated in the stratosphere are small, they vary sufficiently in the vertical to produce considerable variations in T_m . Three features of this structure in Figure 7 are common to the five soundings examined.

- (i) There is a decrease of T_m in the first 50 mb above the tropopause, showing that the ambient relative humidity is decreasing upwards and is not yet negligible.
- (ii) A minimum of T_m occurs some 50 mb above the tropopause. In Figure 7 this is 3.1 times the appropriate Gluckauf value, and Figure 2 shows that there were similar discrepancies on all the soundings examined. In Figure 7 the observations of humidity at the level of the minimum lag would be consistent with the value of T_G if the true ambient relative humidity were 32 per cent. However, frost-point measurements in the lower stratosphere^a show that the average value of relative humidity 50 mb above the tropopause over southern England is about 4 per cent, and although a higher value may be more appropriate to the type of sounding considered here, 32 per cent is probably unrealistically high. It is possible that at these

levels the processes determining the response of the gold-beater's skin differ from those considered by Glückauf, but it seems more probable, particularly since in these instances the radiosondes had previously indicated high relative humidities in the upper troposphere, that the environment of the gold-beater's skin was being contaminated by water vapour escaping from the structure of the sonde. This phenomenon is known to be important with other techniques at low pressures.³

- (iii) At lower pressures T_m increases, though the magnitude and nature of the increase differs considerably from one sounding to another. As in Figure 7, magnitudes and amplitudes of fluctuations of T_m show some correlation with temperature and are much greater than those of the Glückauf response time. Contamination probably occurs but, to explain the maxima of T_m , it would be required to occur preferentially at temperature minima.

The amount of water necessary to contaminate the environment of the gold-beater's skin sufficiently to reduce the average magnitude of T_m to that of the Glückauf response time can be estimated. Depending on whether the cross-section of the airflow being contaminated is about 4 cm², corresponding to the region close to the gold-beater's skin, or is about 10⁴ cm², corresponding to the wake of the balloon, the amounts of water required to saturate the 11-km layer between 180 mb and 30 mb are respectively 6×10^{-2} g and 140 g. Both values seem unrealistically large, and make significant contamination seem doubtful, but no other explanation of the observed behaviour can be suggested.

Conclusion. The humidity sensor of gold-beater's skin on the British radiosonde has a satisfactory response at the temperatures typical of the lower troposphere, and the indicated values can mostly be accepted without correction for lag as appropriate to the layers a few hundred metres or more deep which are effectively sampled by the technique adopted for routine soundings. However, a substantial increase in the response time as the indicated relative humidity decreases below 10 per cent or increases above 90 per cent (with respect to liquid water) hinders the recording of such extremes.

The response time of the sensor increases with decreasing temperature; it exceeds 1 minute at temperatures below about -30°C and 15 minutes at temperatures below about -60°C . The accurately recorded trend of the indicated value offers the possibility of making corrections to obtain true relative humidities in the upper troposphere, although the correction is complicated by the uncertain effects of hysteresis after exposure to very low humidities in the lower troposphere and, perhaps, of variations in the characteristics of individual sensors, apart from some doubt about the effect of the exposure and ventilation in the radiosonde, which differ from those in the one series of laboratory studies which have been made. Nevertheless two examples of soundings are given in which the sensor responded well in ice clouds in the high troposphere, even after previously passing through layers of very low relative humidity. In layers of ice cloud the relative humidity probably hardly ever exceeds that corresponding to saturation with respect to ice, at which the relative humidity with respect to liquid water (to which the sensor responds) is usually between about 50 and 80 per cent, where the sensor

has its best performance. The present arbitrary practice is to cease reporting the relative humidity at air temperatures below -40°C , and to make no corrections for lag or hysteresis. This practice might well be reviewed and humidities reported at levels up to the tropopause, particularly when soundings are evaluated by computer rather than by hand, since it sometimes fails to indicate the presence of saturated layers in the high troposphere, which are important in some kinds of investigation.

In the stratosphere the trend of the indicated relative humidity is generally still measurable, but an analysis suggests that it cannot usefully be corrected, because of irregular behaviour which can probably be attributed to a significant contamination of the air near the sensor with water vapour derived from the balloon train.

Appendix

The theoretical lag coefficient. On the assumption that the interchange of water vapour between gold-beater's skin and the atmosphere is determined by diffusion through a turbulent boundary layer, Glückauf¹ derives a relationship

$$(h - h_e)/(h_o - h_e) = F(kt/\sqrt{l}) \quad \dots (4)$$

- when F is a complicated exponential and logarithmic function,
 h is the relative humidity reported by the gold-beater's skin,
 h_e is the steady ambient relative humidity which changed instantaneously from h_o at zero time t ,
 l is the length of skin along the airflow,
 and k is a parameter whose dependence on pressure and temperature is described by Glückauf's theory.

Equation (4) agrees very closely with measurements made in a wind-tunnel by Glückauf, but, as is apparent in the following table, differs considerably from the simple exponential relationship

$$(h - h_e)/(h_o - h_e) = \exp - 2(kt/\sqrt{l}) \quad \dots (5)$$

only for values of $X = (kt/\sqrt{l})$ greater than 1, i.e. when the gold-beater's skin has practically reached equilibrium with the changed environment.

X	$F(X)$	$[\exp(-2X)]/F(X)$
0.1	0.725	1.13
0.2	0.579	1.16
0.4	0.390	1.15
0.8	0.199	1.01
1.6	0.063	0.65

Thus the response of the gold-beater's skin is effectively exponential in time and has a definite response time T_G , where T_G is $\sqrt{l/2k}$.

Glückauf derives an expression for k in which T_G in seconds is given by

$$T_G = 1.125(aA_o/D\rho_s) (\nu/u)^{\frac{1}{2}}$$

where A_o is the mass per unit area of the gold-beater's skin, which averaged $1.07 \times 10^{-3} \text{ g/cm}^2$ in a sample of 2000 cm^2 supplied by the Meteorological Office.

a is defined by $dA/dh = aA_o$, relating the fractional change in weight per unit area of skin to a change in relative humidity. Glückauf's value of 2×10^{-3} is taken to be correct. Note that this represents the maximum sensitivity of the skin at

intermediate relative humidities; at larger and smaller relative humidities a is larger, giving a greater response time.

- D is the diffusivity of water vapour in air; it may be written as $D_0(T)(1000/p)$, where $D_0(T)$ is the diffusivity at 1000 mb and is a function of temperature T only.⁶
- ρ_s is the density of water vapour saturated with respect to liquid water at the air temperature and is effectively a function of temperature only.^{6,7}
- ν is the kinematic viscosity of air and may be written as $\nu_0(T)(1000/p)$, where $\nu_0(T)$ is a function of temperature only (Smithsonian Tables, p. 394).
- u is the ventilation speed of the gold-beater's skin, which is arbitrarily assumed to be 300 cm/s, half the average vertical speed of a radiosonde, to allow for obstruction of the airflow near the skin by the rain shield.
- l is the length of the gold-beater's skin in the direction of flow and is taken to be 1.5 cm, though in fact the skin in the Mark 2B radiosonde is exposed with its surfaces perpendicular to the incident airflow.

The expression for the Glückauf response time is then

$$T_G = T_{GO}(T) (p/1000)^{\frac{1}{2}} \quad \dots (6)$$

and from numerical values of the above parameters T_{GO} has been computed to be the function of temperature represented by the continuous line on Figure 2.

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ESTIMATES OF THE DURATION OF SHORT-PERIOD RAINFALL RATES BASED ON CLOCK-HOUR VALUES

By J. BRIGGS and J. A. HARKER

Summary. Data were examined from special recording gauges in operation at Winchcombe during moderate or heavy rain (mainly showery type), and a distribution was obtained of the two-minute rainfall intensities associated with various ranges of clock-hour totals. A graph was then produced to show the percentage of two-minute intensities which equalled or exceeded various multiples of the clock-hour rainfall. This graph (or conversion factors obtained from it) can be used to obtain estimates from clock-hour data of the number of hours per year with rainfall intensities equalling or exceeding specified values, and examples are given to show how these estimates compare with estimates made by other methods.

Introduction. Estimates of the probability of instantaneous rainfall rates exceeding certain critical values are of importance for a number of design problems. Unfortunately there is little direct evidence available from short-period measurements of rainfall, and so to meet the questions posed by designers it is necessary to calculate the chances of short-period rainfall of high intensity from data more commonly to hand. For many stations there are now several years of 'clock-hour' rainfall totals and these are often used to produce tabulations of the occurrences of specified rainfall rates. The 'clock-hour' total is simply the amount of rain to fall in a given clock-hour; the rain may have accumulated fairly evenly throughout the hour but, at the other extreme, it may have fallen in one minute or less. In general the clock-hour total will include a variety of instantaneous rates but, over a large sample, it may be possible to determine the average distribution of instantaneous rates about the clock-hour total, and so to derive factors which can be used to estimate the probabilities of short-period rain intensities from the available clock-hour statistics. An analysis of this kind was made by H. E. Bussey¹ and he obtained figures for the duration of one-minute rates of rainfall for the vicinity of Washington.

Distribution of two-minute falls for specified ranges of clock-hour rainfall. Bussey's figures do not examine the variation of the distribution of short-period rates about the clock-hour total as this clock-hour total is varied. It seemed desirable to examine this variation and, at the same time, to provide data for this country which might be compared with Bussey's figures. An opportunity to do this was provided by the results of Meteorological Office experiments with a network of recording rain-gauges at Winchcombe. These experiments were similar to those at Cardington which have been described by Holland.² In the Winchcombe experiments the rain-gauges were sited in a small valley in the Cotswolds. Up to 24 rain-gauges were in use at one time and individual gauge totals were recorded at intervals of two minutes. The experiments were mostly in the months of March to October and were limited to the years 1962 to 1967. Analysis was restricted to those occasions in which the maximum two-minute fall in any gauge of the network was 0.5 mm or more. This restriction essentially limited the analysis to occasions of moderate or heavy rain and so basically to showery type rain, though the location of the network was such that orographic effects tended to intensify frontal rains and some frontal rainfall was included in the analysis.

From the recorded Winchcombe data all occasions were next selected when any particular gauge was working throughout any given clock-hour and the distribution of two-minute falls was noted for that gauge and hour. The results were then sorted according to the clock-hour value so that any systematic variation of the distribution with change of clock-hour value would show up. Table I presents the results of this sorting.

Table I shows that 2748 clock-hours were included in this analysis. Many of these represented multiple observations of a particular shower but, since the effect of any shower varied considerably across the network, depending on the location of each gauge in relation to the shower, it is considered that the best representation of average distributions will be obtained by using

TABLE I—NUMBER OF OCCASIONS OF TWO-MINUTE RAINFALL AT GIVEN INTENSITIES FOR SPECIFIED RANGES OF CLOCK-HOUR RAINFALL

Clock-hour rainfall mm	Two-minute rainfall (mm)							Number of two-minute occasions*		
	<0.3	0.3-0.9	1.2-5.1	5.4-9.9	10.2-24.9	25.2-50.1	50.4-75.0		75.3-99.9	≥100
<5	25 413	15 669	20 663	4 131	2 294	395	14	1	0	68 550 (2 285)
5-9.99	1 824	1 377	4 098	2 286	1 796	506	75	8	0	11 970 (399)
10-14.99	329	91	290	221	293	177	55	12	2	1 470 (49)
15-19.99	47	8	82	103	60	48	29	8	5	390 (13)
20-24.99	9	4	14	3	11	9	8	2	0	60 (2)
									Total	82 440 (2 748)

*Figures in brackets are equivalent clock-hours

all the gauge values. Two-minute rain totals were not read to better than 0.01 mm; this accounts for the column headings of Table I, i.e. to the nearest 0.3 mm/h.

Table I was next used to obtain Figure 1, which shows the percentage of two-minute intensities which exceeded various multiples of the clock-hour intensity, R , shown as ordinates on the figure. The different ranges of R of Table I are represented by separate curves on Figure 1. Inspection of the figure reveals close agreement between the distributions associated

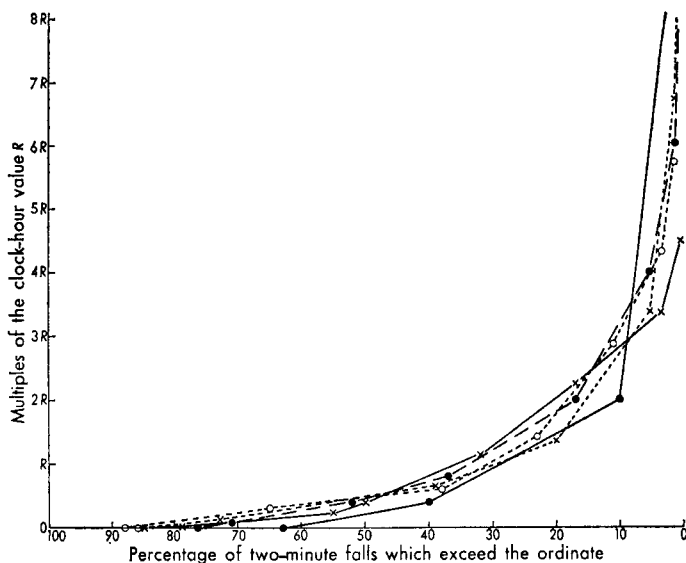


FIGURE 1—DISTRIBUTION OF TWO-MINUTE FALLS ABOUT THE CLOCK-HOUR VALUE

..... R in range < 5 mm/h
 R in range $10-14.99$ mm/h
 x — — — x R in range $5-9.99$ mm/h
 o — — — o R in range $15-19.99$ mm/h

with the different clock-hour ranges, but two minor discrepancies require some comment. Firstly, the lowest range of R has a considerably higher percentage of short-period falls shown as trace or no rainfall than have the other ranges. This is an effect of the detection limit of the rain-gauges, for with a low value of R a relatively high fraction of R is needed to ensure detection. Secondly, the curve corresponding to the highest range of R has a somewhat lower percentage of short-period falls at high multiples of R than have the other ranges. In this instance it must be noted that the sample is limited to only two clock-hours and this can hardly provide an adequate selection of the high multiples of R .

The original selection of data introduced a bias towards showery-type rain, since rains in which a rate of 15 mm/h was not reached by at least one gauge in any two-minute period were excluded. Nevertheless, Table I shows that by far the highest number of clock-hour totals, 2285, corresponded to intensities of below 5 mm/h. Bearing in mind the two discrepancies already discussed, it is thought that the curves of Figure 1 are sufficiently close to

permit the substitution of an average curve as representative of the distribution of short-period means about the clock-hour total for all ranges of that total. Moreover, it is thought that the bias against frontal rains will not introduce any serious errors when this average distribution is used to assess durations of high-intensity short-period rains.

Figure 2 presents the average curve based on Figure 1. In reaching this average there is a self-contained check which has been used. Over a long period the average curve must show the relative distribution of short-period rainfall rates for the average clock-hour with rainfall amount R . Thus the

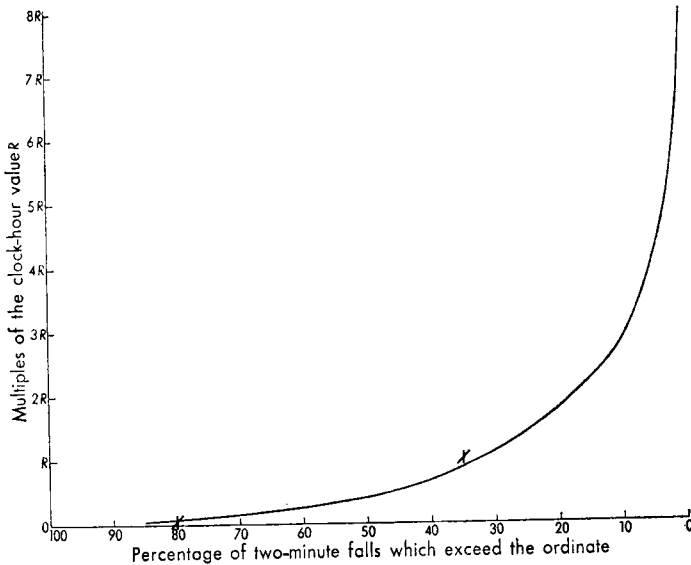


FIGURE 2—AVERAGE DISTRIBUTION OF TWO-MINUTE FALLS ABOUT THE CLOCK-HOUR VALUE (R)
 X = Bussey value

abscissa corresponding to a given ordinate of Figure 2 must indicate the percentage of the average clock-hour for which the short-period rate exceeds the value of the ordinate. Thence the total area under the curve of Figure 2 is a measure of the amount of rain to fall in the average hour, but this amount is R , and so the area under the curve must equal that below the ordinate R taken over the whole hour (100 per cent of the time). Also shown on Figure 2 are crosses representing two values quoted by Bussey, namely that about 20 per cent of each hour corresponded to 'trace' or 'zero' rain and that rainfall exceeded R for about 35 per cent of each hour. Bussey also noted that values of $5R$ to $6R$ were exceeded fairly commonly for a few minutes each hour. It is difficult to represent this last statement adequately on the figure, but it is quite clear that there is very good agreement between the Winchcombe and Washington average distributions, and this suggests that Figure 2 may be generally applicable except possibly for light frontal-type rains.

Estimates of two-minute intensities from clock-hour data. If clock-hour data are available for any particular station for a sufficiently long period, then Figure 2 can be used to give estimates of the percentages of the two-minute falls which occurred with intensities at or above specified values.

In practice it is more convenient to use the figure to produce conversion factors which can be applied directly to the clock-hour totals. Table II presents these factors as percentages.

TABLE II—PERCENTAGES OF THE CLOCK-HOUR DURING WHICH THE TWO-MINUTE RAINFALL INTENSITY EQUALS OR EXCEEDS SPECIFIED VALUES. PERCENTAGES ARE GIVEN FOR A SELECTION OF CLOCK-HOUR TOTALS

Clock-hour total (mm)	Intensity (mm/h)								
	0.1	1	5	10	20	25	50	75	100
					percentages				
0.1	32	0	0	0	0	0	0	0	0
1	80	32	02	0	0	0	0	0	0
2	85	45	12	02	0	0	0	0	0
3	85	53	21	08	01	0	0	0	0
4	85	60	27	12	02	01	0	0	0
5	85	65	32	17	05	02	0	0	0
6	85	70	35	21	08	04	0	0	0
7	85	75	38	24	10	06	01	0	0
8	85	77	41	27	12	08	01	0	0
9	85	79	43	30	14	10	02	0	0
10	85	80	45	32	17	12	02	0	0
11	85	81	47	34	19	14	03	01	0
12	85	82	49	35	21	16	04	01	0
13	85	82	51	37	22	18	05	01	0
14	85	82	52	39	24	19	07	02	0
15	85	83	53	40	26	21	08	02	0
16	85	83	54	41	27	22	08	03	01
17	85	84	56	42	28	24	09	04	01
18	85	84	57	43	30	25	10	04	02
19	85	84	59	44	31	26	11	05	02
20	85	85	60	45	32	27	12	06	02
21	85	85	61	46	33	28	13	07	03
22	85	85	62	47	34	29	14	08	03
23	85	85	63	48	35	30	15	08	04
24	85	85	64	49	36	31	16	09	04
25	85	85	65	50	36	32	17	09	05
30	85	85	70	53	40	35	21	12	07
35	85	85	73	57	43	38	24	15	10
40	85	85	75	60	45	41	27	18	12
45	85	85	78	63	48	43	30	21	15
50	85	85	80	65	50	45	32	23	17
75	85	85	83	75	58	53	40	32	26
100	85	85	85	80	65	60	45	37	32

The factors of Table II were applied to clock-hour figures for Mildenhall, Suffolk, for the period 1949-66 and to figures for Changi, Singapore Island, period 1958-61 plus 1964, and Freetown, Sierra Leone, period 1944-47. Table III presents the results and compares them with durations obtained directly from clock-hour data.

In the absence of adequate short-period measurements of rainfall rate it is not possible to check directly on the estimates presented in Table III, but in the case of Changi separate estimates had been made for the year 1961 using autographic records and a model shower profile as described by Briggs.³ Table III shows that for the high-intensity rainfall the two estimates for 1961 were in very good agreement and so supports the reliability of both methods of making these estimates. Table III also clearly shows how the direct analysis of clock-hour data can underestimate the probability of occurrence of high-intensity rainfall.

TABLE III—DURATION OF RAINFALL INTENSITIES EQUALLING OR EXCEEDING SPECIFIED VALUES

Place and period of data	Method of obtaining duration	Intensity (mm/h)							
		1	5	10	20	25	50	75	100
<i>hours per year</i>									
Mildenhall (1949-66)	(a) Directly from clock-hour data	124	9.9	1.1	0.2	0.1	0	0	0
	(b) Using estimated two-minute rainfall rates	206	33.1	8.2	1.3	0.8	0.12	0.03	0.01
Changi (1958-61) plus 1964)	(a) Directly from clock-hour data	241	100	56	22	16	1.9	0.3	0.1
	(b) Using estimated two-minute rainfall rates	208	79	44	21	16	6	2.5	1.3
	(c) Using estimated two-minute rainfall rates (1961 only)	—	—	36	—	13	5	—	1.3
	(d) Estimates for 1961 using autographic records and assumed shower profile ³	—	—	46	—	15	5	—	1.1
Freetown (1944-47)	(a) Directly from clock-hour data	445	187	99	35	25	4.1	1.0	0.3
	(b) Using estimated two-minute rainfall rates	380	137	81	39	29	11	4.9	2.8

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DISTRIBUTION OF PRECIPITATION AND THE VARIATION OF VISIBILITY IN PRECIPITATION

By W. D. SUMMERSBY

Summary. In this investigation the area considered extends from the eastern and northern extremities of the Baltic across the British Isles to include the ocean weather stations (OWS) 'I' and 'J'. A selection of observations for 13 stations spanning this region are examined to show how precipitation varies in type and intensity across it and, using the observations nearest midday, how visibility varies in precipitation. Interest is mainly confined to coastal and sea areas rather than to inland stations.

Distribution of precipitation. In describing the weather of a region it is relevant to state what forms of precipitation occur, how frequently they occur at various places within the region, and how these frequencies compare with one another, both from place to place, and from one type of precipitation to another. Figure 1 shows the region considered, extending from Leningrad in the east and Lulea-Kallax near the northern end of the Gulf of Bothnia, across the North Sea and the British Isles to include OWS 'I' and 'J' in the west; it also shows the positions of the 13 stations from which data were taken.

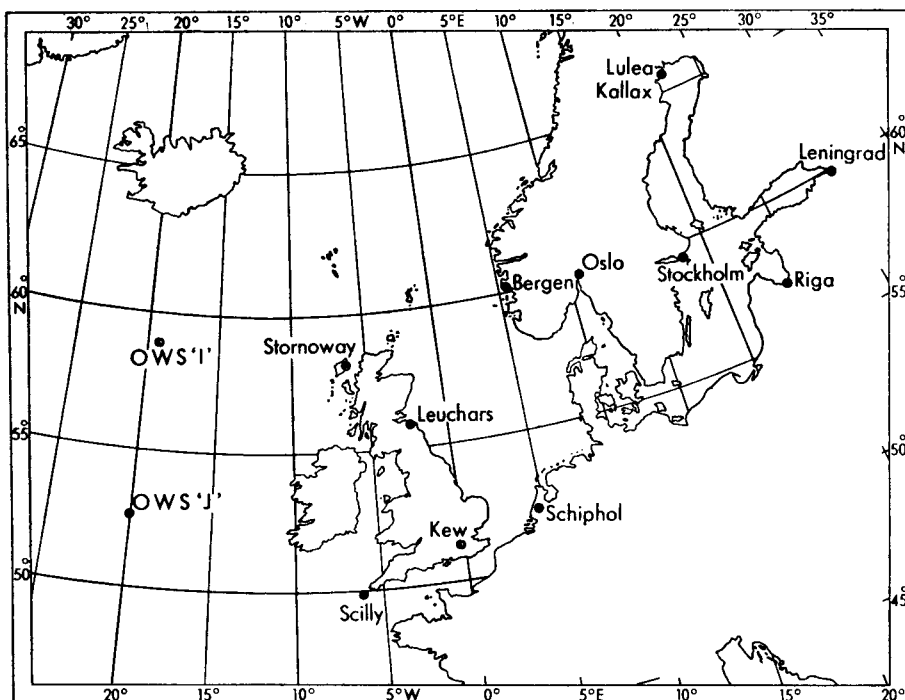


FIGURE 1—MAP SHOWING POSITION OF OBSERVING STATIONS

The approximate percentage of observations having precipitation of various types and intensity and of no precipitation is shown in Table I. Account is taken of the fact that the present-weather code has changed over the years and that sometimes the definition of a present-weather code figure includes more than one form of precipitation. While a homogeneous selection of years and times of day would have been preferable, the restricted published data available made it necessary to use the various times and periods quoted in Table I. Use of a longer, or a different but equally short, period would bring slightly different results, but as far as is known the periods selected were not abnormal. Just under 3000 observations were considered for each station, though for the region as a whole the proportion of daylight observations exceeds that of observations made at night.

Nearly all forms of precipitation occur from time to time throughout the region, but their relative frequencies both compared with one another and from place to place vary considerably. For example, the frequency with which precipitation falls as rain over the open sea (see OWS 'I' and 'J') far outstrips that of any other form. Only at Leningrad and Lulea-Kallax does the total of the rain and drizzle frequencies not exceed that of the sleet* and snow. The figures of Table I summarize the frequencies for a whole year, and in deriving them monthly and seasonal frequencies became available. It

* In the United Kingdom the term sleet is used to denote precipitation of snow and rain (or drizzle) together or of snow melting as it falls, but it has no agreed international meaning.

TABLE I—PERCENTAGE FREQUENCY OF OCCASIONS OF DIFFERENT TYPES OF PRECIPITATION OR OF NO PRECIPITATION

Type	Precipitation Intensity	Leningrad	Riga	Oslo	Bergen	Lulea-Kallax	Stockholm	Schiphol	Scilly	Stornoway	Leuchars	Kew	OWS 'I'	OWS 'J'
Drizzle	Slight	1.1	1.2	1.3	1.7	1.1	1.5	1.9	2.2	3.0	1.9	1.6	2.8	3.7
	Moderate	0.4	X	X	0.3	0.1	0	0	0.4	0.1	0.1	0.3	0.2	0.2
	Heavy	0	0	0	0.1	0	0	0	X	0	X	X	0	X
Rain	Total	1.5	1.2	1.3	2.1	1.2	1.5	1.9	2.6	3.1	2.0	1.9	3.0	3.9
	Slight	3.6	3.4	4.9	7.6	3.5	4.4	6.7	4.7	6.3	6.5	6.5	8.6	8.3
	Moderate	1.6	1.2	1.1	2.4	0.6	0.4	0.6	3.2	2.7	1.6	2.0	1.1	1.4
	Heavy	0.1	0.2	0	0.1	0	0	0	0.1	0.5	0.5	0.1	0.1	0.1
	Sit shower	0	0	1.5	3.2	0.7	1.5	3.1	0.3	3.1	1.3	0.6	4.7	3.3
Total	Mod/hvy shower	0.1	0.4	0.2	1.4	0.2	0.3	0.7	0.4	0.7	0.2	0.5	0.7	0.5
	Total	5.4	5.2	7.7	14.7	5.0	6.6	10.6	8.7	13.3	10.1	9.7	15.2	13.6
Sleet*	Slight	0	0	0.8	0.5	0.6	0.6	0.1	0	X	0.1	0.1	0.1	0
	Mod/hvy	X	X	0.2	0.1	0	0.1	0	X	X	0.2	0.1	0	0
	Sit shower	0	0	X	0.4	X	0.1	0	X	0.1	X	0	0.1	X
Snow	Mod/hvy shower	0	0	X	0.2	0	0	0	0	0.1	0	0	X	X
	Total	X	X	1.1	1.2	0.6	0.8	0.1	X	0.3	0.3	0.2	0.2	0.1
	Slight	6.7	2.7	5.9	1.2	7.8	4.2	0.4	X	X	0.2	0.2	0.1	0
	Moderate	2.9	0.9	0.9	0.4	2.2	0.9	0.1	0	X	0.1	0	X	0
	Heavy	0.3	0.2	0	0	0.1	0.2	0	0	0	0	0	0	0
Total	Sit shower	0	0	0.2	0.9	0.1	0.8	X	0	0.2	0.3	0.1	0.3	0
	Mod/hvy shower	0.1	0.1	0	0.2	0	0.4	0	X	0.1	0.1	X	0.2	0
	Total	10.0	3.9	7.0	2.7	10.2	6.5	0.5	0.1	0.4	0.7	0.3	0.6	0
Hail		X	0.1	0	X	0	0	0	0.1	X	0	0	0.2	0.1
No precipitation		83.0	89.5	82.9	79.3	83.0	84.6	86.9	88.6	83.0	86.9	87.9	80.9	82.4
Total showers (all types) and hail		0.2	0.6	1.9	6.3	1.0	3.1	3.3	0.8	4.3	1.9	1.2	6.2	3.9

*In the United Kingdom the term sleet is used to denote precipitation of snow and rain (or drizzle) together, or of snow melting as it falls, but it has no agreed international meaning. Note: Values less than 0.005 per cent are shown as 0 and values from 0.005 to less than 0.05 per cent as X. Where necessary slight moderate and heavy have been abbreviated to 'slt, mod and hvy'. Several values of X totalling 0.05 per cent or more are allowed for in the column totals.

Notes on data and sources: Leningrad—Russian daily weather reports 1936–37 at 0100, 0700, 1300 and 1900 GMT daily.

Riga—North German weather reports and charts 1942–43 at 0200, 0800, 1400 and 1900 GMT daily.

Stockholm, Oslo, Bergen and Lulea-Kallax—*U.S.A. synoptic weather maps—Part II* 1956–62 at 1200 GMT daily.

Schiphol—Synoptic and upper air observations in the Netherlands 1960–61 at 0000, 0600, 1200 and 1800 GMT daily.

Scilly, Stornoway, Leuchars, Kew, OWS 'I' and 'J'—Manuscript data held in the Meteorological Office 1957–60 at 0000, 0600, 1200 and 1800 GMT daily, but Kew limited to 0600, 1200 and 1800 GMT daily.

Details of observing stations: Bergen—Frederiksberg, 60°24'N, 5°19'E, 144 ft above MSL to 1956 and Fiestand 60°17'N, 5°14'E, 164 ft above MSL from 1 Jan 1957. Lulea-Kallax 65°33'N, 22°08'E, 52 ft above MSL.

became evident that while the liquid forms of precipitation are the most frequent over most of the region, snow is normal in winter within the area of continental climate. Table I also shows that at sea the frequency of drizzle is about one third that of rain (excluding showers), and the frequency of slight showers is slightly greater than that of drizzle of all intensities (OWS 'I' and 'J' together). These proportions remain substantially unchanged along the western seaboard of the British Isles, but in the only slightly more sheltered situation at Bergen there are only about one fifth as many occasions of drizzle as of rain (even excluding showers), though the total percentage frequency of rain combined with that of drizzle remains little less than at the ocean weather stations.

The whole region has snow from time to time, though infrequently in the south-west. Reporting errors arise during snow because in periods of drifting it is almost impossible to say if more snow is falling or not. Table I also shows that sleet is of greater frequency in the north than in the south and that it is relatively infrequent both in the coldest and in the warmest parts of the region. For example, OWS 'I' has a frequency of all intensities of sleet of 0.2 per cent, while OWS 'J' has only 0.1 per cent and this is limited to showers. Leningrad and Riga both with less than 0.05 per cent (none in the form of showers) are outstanding in the east. Distinctly more sleet is reported from places intermediate between the coldest and warmest parts.

Rain falling from shower cloud is often more intense than continuous rain, and Table I shows more slight rain showers at OWS 'I' and 'J' than at any of the land stations, though Bergen, Schiphol and Stornoway, all having maritime climates, are not much less affected. The Table also shows that, at sea, about one quarter of the occasions of precipitation reported are showers (OWS 'I' and 'J' together), and that OWS 'I' has nearly twice as many showers as OWS 'J', whereas in the east (Leningrad and Riga together) the proportion of occasions with showers is much less (about $1/34$). Seasonally there is a summer maximum on the continent, and Summersby¹ has shown that there is a winter maximum at sea for all types of showers combined. The geographical position of Bergen gives it the highest frequency of showers (all types) in Table I, probably because the showers are caused by instability in maritime air, by orographic action nearby and by convection over land heated by day in summer.

When convective activity is vigorous and deep, hail may form within cumulonimbus cloud and may reach the ground. No clear geographical distribution emerges beyond the greater frequency of hail at sea and at stations well exposed to maritime influences. Bilham² gives the hail frequency inland in Britain as varying from about 3 to 25 occasions per year, there being no obvious association with high ground. In winter, low temperature and moisture content successfully inhibit hail in the east of the region, though during the summer hail forms over the continent more often than over the ocean. Table I shows less frequent hail at OWS 'J' than at OWS 'I', and this is a reflection of the greater frequency with which deep cold air overruns the north-west of the region.

Visibility in precipitation. The forecasting of visibility in precipitation presents some difficulty because the degree of obscurity found is fairly varied for a given intensity of precipitation. Analyses of the distribution of visibilities

in precipitation of varying types and intensities have been produced by Jefferson³ for a region well to the north of Britain and by Ross⁴ for Kinloss. The present analysis is of interest in that it covers an area further south than the earlier ones and extends considerably on each side of the line usually taken as dividing oceanic from continental climates. The general agreement between this and the earlier analyses is reassuring.

Wright,⁵ Poljakova,⁶ and Poljakova and Tret'jakov⁷ have attempted calculations of the obscurity to be expected from precipitation in which the concentration of scattering particles is known and the drop sizes are also known. Such attempts give only rough estimates, because it always has to be assumed that the precipitation intensity and drop-size spectrum as measured at a point is constant throughout the area spanned when measuring the visibility. A fair spread of visibility values should be expected in precipitation of a given intensity when it is remembered that the given intensity can occur with a large number of small drops, or a small number of large drops or a mixture of the two. The drop-size spectrum may or may not distinguish rain from drizzle, but for calculation of visibility this is immaterial. Richards's⁸ work in Canada, though directed at assessing the expected accretion of snow from the visibility reported during its deposition, shows a good deal of scatter in the visibilities reported for given rates of accretion. Particle size plays a part in determining visibility, in that visibility on occasions of equal concentration of particles is more restricted when the particles are large than when they are small. Snowflakes are much larger than the raindrops they form on melting, so that the physical state of the precipitation also plays a large part in determining visibility. Thus, for a given water content of precipitation, visibility in snow is likely to be less than in other forms of precipitation.

Reference to the footnote of Table I shows that observations at about midday were the only ones common to all 13 stations used. Therefore the second part of this descriptive work used only the observations nearest to midday. Snow and sleet were considered together. It was found that for the more intense forms of precipitation, there were insufficient occasions at individual stations to obtain a representative distribution of visibility. Table II therefore gives the percentage distribution of visibility code figures for the general weather headings: no precipitation, drizzle, rain, snow and sleet, and showers of all types, all being irrespective of intensity. Those few occasions when more than one type of precipitation is included by a single present-weather code figure were equally shared between the types of precipitation involved. For these reasons it is not possible to calculate percentages of occurrence in Table I from the various parts of Table II.

The largest percentage for each line of Table II is printed in bold type: a general reduction can be seen in visibility in precipitation compared with that in no precipitation. Scandinavian places stand out as a group where visibility without precipitation was particularly good, and Leningrad, Schiphol and Kew are places clearly affected by industrial and domestic pollution. It is possible that at some stations difficulty arises when reporting visibility because of the lack of good visibility points at great distances. This difficulty is most marked at the ocean weather stations where the horizon is about 11 km distant, though there is good agreement between OWS 'I', OWS 'J' and Stornoway.

TABLE II—PERCENTAGE FREQUENCY OF VISIBILITY CODE FIGURES AT ABOUT MIDDAY IN VARIOUS TYPES OF PRECIPITATION AND IN NO PRECIPITATION

Type of pptn	Station	Visibility code figure									Number of cases	
		0 <50 m	1 50-200 m	2 200-500 m	3 500-1000 m	4 1-2 km	5 2-4 km	6 4-10 km	7 10-20 km	8 20-50 km		9 ≥ 50 km
No pptn	Leningrad	0	X	X	1	1	5	40	52	1	X	523
	Riga	X	1	1	1	1	4	12	20	37	23	573
	Oslo	0	X	1	X	1	3	6	10	34	45	2044
	Bergen	X	X	X	X	X	X	4	8	39	49	1980
	Lulea-Kallax	0	X	X	1	X	1	6	6	20	66	2070
	Stockholm	0	0	X	X	1	1	6	12	30	50	2112
	Schiphol	X	X	X	X	2	8	26	30	33	1	627
	Scilly	X	X	1	1	X	2	22	25	47	2	1303
	Stornoway	0	0	X	X	X	1	5	21	63	10	1188
	Leuchars	0	X	X	1	2	4	14	23	47	9	1264
	Kew	X	X	1	1	5	7	25	25	32	4	1270
	OWS 'I'	0	X	X	X	X	1	4	19	67	9	1055
	OWS 'J'	0	X	X	1	1	2	5	20	63	8	1106
Drizzle	Leningrad	0	0	0	6	18	6	70	0	0	0	17
	Riga	0	9	0	0	18	9	37	18	0	9	11
	Oslo	0	0	9	4	18	30	18	13	4	4	46
	Bergen	0	0	0	2	5	18	58	15	1	1	87
	Lulea-Kallax	0	0	0	5	19	16	25	14	16	5	37
	Stockholm	0	0	0	0	9	25	39	23	4	0	56
	Schiphol	0	0	6	13	6	31	38	6	0	0	16
	Scilly	0	0	0	10	32	27	31	0	0	0	41
	Stornoway	0	0	0	0	2	11	62	21	4	0	57
	Leuchars	0	0	3	3	6	25	35	22	6	0	36
	Kew	0	0	0	7	18	14	46	11	4	0	28
	OWS 'I'	0	0	0	2	6	27	40	19	4	2	48
	OWS 'J'	0	0	0	0	10	26	47	10	6	1	70
Rain	Leningrad	0	0	0	0	5	24	58	13	0	0	38
	Riga	0	0	0	0	18	11	29	28	14	0	28
	Oslo	0	0	1	2	5	18	38	21	11	4	179
	Bergen	0	0	0	0	1	5	29	32	30	3	275
	Lulea-Kallax	0	0	0	0	4	8	30	18	28	12	121
	Stockholm	0	0	1	1	5	10	30	29	20	4	138
	Schiphol	0	0	0	0	2	13	57	26	2	0	47
	Scilly	0	0	1	3	5	13	49	22	7	0	103
	Stornoway	0	0	0	0	2	2	39	45	12	0	121
	Leuchars	0	0	0	2	2	16	40	31	8	1	127
	Kew	0	0	0	2	16	16	41	20	5	0	128
	OWS 'I'	0	0	1	1	2	9	33	40	14	0	128
	OWS 'J'	0	0	0	1	2	5	28	45	17	2	110
Snow or sleet	Leningrad	0	1	4	5	14	33	40	3	0	0	79
	Riga	0	0	0	15	32	17	24	6	6	0	34
	Oslo	0	0	0	4	19	32	30	11	4	0	169
	Bergen	0	0	0	10	10	17	34	19	10	0	41
	Lulea-Kallax	0	0	0	3	16	28	33	8	11	1	253
	Stockholm	0	0	0	4	15	14	43	13	11	0	131
	Schiphol	0	0	0	0	17	33	50	0	0	0	6
Showers (all types)	Leningrad	0	0	0	0	0	4	48	44	4	0	25
	Riga	0	3	0	3	3	3	19	22	41	6	32
	Oslo	0	0	0	0	0	5	18	21	33	23	62
	Bergen	0	0	0	1	1	3	20	30	40	5	166
	Lulea-Kallax	0	0	0	0	0	0	16	40	44	25	25
	Stockholm	0	0	0	1	1	11	19	30	27	11	75
	Schiphol	0	0	0	0	0	0	30	37	33	0	33
	Scilly	0	0	0	0	8	0	46	15	31	0	13
	Stornoway	0	0	0	1	3	2	13	48	33	0	91
	Leuchars	0	0	6	0	10	0	26	39	19	0	31
	Kew	0	0	0	0	3	3	28	17	49	0	29
	OWS 'I'	0	0	1	0	0	2	13	35	49	0	84
	OWS 'J'	0	0	0	0	0	6	22	35	37	0	54

X = <0.5 per cent. The values quoted are correct to the nearest one per cent. Bold figures represent the largest percentage for each station.

When it was drizzling, most stations (11 out of 13), reported visibility in the range of code figure 6 (4-10 km) more often than in the range of other code figures. Oslo (Gardemoen) differs from many other places in that it is higher above sea level, while at Scilly visibilities were rather worse than at any of the other stations.

In rain, as well as in drizzle, most places (9 out of 13) reported visibility code figure 6 more often than other code figures. However, those places not reporting this code figure most frequently, reported code figure 7 (10–20 km), whereas in drizzle, those places not reporting code figure 6, most frequently gave code figures 4 (1–2 km) or 5 (2–4 km). It is probably significant that the places having code figure 7 as the most frequent in rain are all well removed from sources of pollution and include OWS 'I' and 'J'. Except for OWS 'J' they also lie in the northern parts of the region, where polar and arctic air are commoner.

Stations in the central and western parts had insufficient snow at midday for the percentage distributions here calculated to be representative, and are therefore omitted from Table II if they had five occasions or less of snow and sleet. The infrequency of snow in these parts is commented upon in discussing Table I. The more north-easterly stations had distributions of visibility code figures in snow rather similar to those in drizzle, visibility tending to be slightly worse than in rain.

Showers mostly occur in polar and arctic air masses, in which visibilities are otherwise normally good over the region. The limited horizontal extent of showers enables objects at a distance to be viewed partly through precipitation and partly through clear air. The visibilities reported in showers are therefore not so much reduced as they would be were the precipitation more widespread and continuous, and of the same intensity as often occurs in showers. The distribution of the most frequently occurring visibility code figures is rather more scattered than in other forms of precipitation, lying in the range code figures 6–9 inclusive, but code figures 7 and 8 (covering 10–50 km) were those most frequently occurring across the region as a whole.

Since reasonable consistency was found from station to station, percentage frequencies of reported visibility code figures in varying intensities of precipitation were combined for the 13 stations regarded as representative of the region as a whole, and Table III gives the results. The maximum percentage in each intensity and type of precipitation is marked with an asterisk. In addition Table III shows in bold figures the three consecutive visibility code figures which together have the biggest combined percentage.

TABLE III—PERCENTAGE FREQUENCY OF VISIBILITY CODE FIGURES REPORTED IN PRECIPITATION OF DIFFERENT INTENSITIES, AND IN NO PRECIPITATION

Visibility code figure	No precip- itation	Type and intensity of precipitation										Showers (all types)	
		Drizzle			Rain			Snow/sleet					
		A	B	C	A	B	C	A	B	C	A	B/C	
0	X	0	0	0	0	0	0	0	0	0	0	0	
1	X	X	0	0	0	0	0	X	1	0	X	0	
2	1	1	0	0	X	X	0	0	2	8	0	2	
3	1	3	2	8	1	1	4	1	14	54*	0	2	
4	1	9	23	46*	4	7	8	11	40*	15	1	5	
5	2	20	36	8	8	19	29	25	31	15	2	9	
6	11	45*	37*	38	32	50*	46*	40*	10	8	17	31*	
7	17	16	0	0	33*	17	13	12	1	0	32	30	
8	38*	5	0	0	19	6	0	10	1	0	40*	20	
9	29	1	2	0	3	0	0	1	0	0	8	1	
No. of cases	17 115	481	56	13	1218	301	24	570	145	13	555	165	

A = slight, B = moderate and C = heavy. X = <0.5 per cent. The three consecutive code figures which give the biggest combined percentage have their percentages printed in bold and the maximum is marked with an asterisk. The whole region is represented by 13 stations and the values quoted are correct to the nearest one per cent.

A general tendency for visibility to decrease with increasing intensity may be seen, the least effect on visibility occurring in showers and the most in snow or sleet. It should be appreciated that the divisions between slight and moderate, and moderate and heavy precipitation occur when the rates of accretion in recording rain-gauges reach critical values of 0.5 mm per hour and 4.0 mm per hour respectively. At stations, including the ocean weather stations, that are not equipped with such gauges, the decision whether precipitation is slight, moderate or heavy is subjective, and errors stemming from this are impossible to eliminate. However, reasonable consistency is found and these results are in general agreement with similar investigations in the past.^{3,4}

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NOTES AND NEWS

Cloud physics research in Czechoslovakia

Dr J. Podzimek, the Director of the Institute for Atmospheric Physics of the Czechoslovak National Academy of Sciences, who was visiting England as the guest of the Royal Society, led a colloquium at the Meteorological Office Headquarters at Bracknell on 20 March. The subject chosen was the current programme of cloud physics research in his department. The main laboratories employ a staff of 22 and, in addition, the department runs a mountain research laboratory equipped with a 3.2-cm weather radar, and hopes to make use of a field observatory with a tower 80 metres high, instrumented for electric-field measurements. For three years the 21 stations throughout Czechoslovakia have made atmospheric-chemistry observations with a frequency greater than that of the rest of the European network.

Much of the research programme has been in the field of air pollution. Routine observations of the concentrations of large numbers of contaminants, made both from the surface and from aircraft, show that the atmosphere is very highly contaminated, particularly in the industrial regions. The average sulphate content in rain-water is approximately 10 times greater than the average of 6 mg/l in the non-industrial areas of Britain, and the maximum values found are considerably in excess of any measured regularly in Britain. The size spectrum of sulphate and chloride particles has also been measured, the number n with radius r being found to obey the law $n = Ar^2 \exp - (Br)$ where the constants A and B depend on the origins of the air mass. As regards the production of aerosols, the department has been studying various types of burners with particular reference to the production, on the ground, of silver iodide aerosols for cloud seeding.

A number of theoretical and experimental studies have been made of the growth of cloud particles in mixed clouds (containing both water and ice) of the stratiform type. A mathematical model of such a cloud has been set up, and the growth rates of both drops and various-shaped ice crystals calculated. This involved the use of electrical analogues in order to solve the equations of sublimation on non-spherical particles. Ice crystals grow by sublimation by the transfer of molecules from the vapour to steps on the crystal faces. These steps advance across the crystal, the rate of growth of the crystal being determined by the rate of advance of these steps. The growth by the advance of steps on the base plane of ice crystals has been calculated and the results found to differ from those of other workers in that there was no peak in the growth rate at a temperature of -11°C . In an attempt to see how the airflow around a falling particle would affect its growth, exact solutions of the Navier-Stokes equation have been found for the flow around a cylinder.

The motion of ice crystals of various shapes falling through the air, and the way in which they cluster together, has been investigated in model experiments using high-speed photography. Some work has also been started on the separation of electric charge by the thermo-electric effect in ice, both pure and doped with atmospheric contaminants.

The discussion following this talk, which was enjoyed by all those present, was concerned mainly with the possible origins of the atmospheric contaminants, many of which are still uncertain. Dr Podzimek answered several questions on this subject and also on some details of the cloud model which he was using in his calculations. As chairman of the colloquium, Dr Mason, the Director-General of the Meteorological Office, thanked Dr Podzimek for his very stimulating account of cloud physics in Czechoslovakia.

P. R. JONAS

REVIEWS

The measurement of environmental factors in terrestrial ecology, British Ecological Society Symposium Number Eight, edited by R. M. Wadsworth. 220 mm \times 140 mm, pp. x + 314, *illus.*, Blackwell Scientific Publications, 5 Alfred Street, Oxford, 1968. Price: 55s.

The increasing application to biological field work of instruments and techniques developed largely by physicists and engineers, induced the British Ecological Society to devote a Symposium (held at the University of Reading in March 1967) to the problems involved. The published record consists of 21 papers (pp. 1-254), a valuable 37 pages describing the extensive display of working equipment on show to participants, with the addresses of manufacturers, personal details of the 400 or so attending, a subject index and one of all authors whose names are quoted anywhere in the text.

A deliberate aim was to concentrate as much upon exactly what is to be measured, as upon how the objectives may be reached. Whilst these twin aims were explicit in all contributions, the papers may be conveniently divided into: ten on mainly instrumental topics, six with an ecological bias and five giving roughly equal weight to both aspects.

I. F. Long (pp. 1-32) and J. S. G. McCulloch (pp. 205-212) give critical reviews of some existing or reasonably developed systems. Others deal with: measuring conditions in food stores (F. L. Waterhouse and T. G. Amos pp. 34-46); the use of infra-red techniques (S. D. Smith, G. E. Peckham and P. J. Ellis pp. 83-90); radio-telemetric devices (J. Bligh and S. G. Robinson pp. 225-234); the measurement of radiant energy (G. Szeicz pp. 109-130), of CO₂ (G. E. Bowman pp. 131-140), and of soil aeration (M. H. Martin pp. 181-190). M. J. Blackwell and M. R. Blackburn (pp. 213-224) stress the need for a 'systems engineering' approach to data acquisition, recognizing that a decision on equipment and processing at any one stage from sensor to eventual computer output, depends upon and influences decisions at all other stages; ready access to a qualified technician is also necessary — advice implicitly underlined by J. K. Brookhouse (pp. 243-254) when discussing computer processing.

The first of the 'ecological' papers (A. Macfadyen pp. 59-68) examines 'climate' mainly in soils and surface litter. J. W. Sibborn (pp. 91-96) asks what should be measured, whilst L. Leyton, E. R. C. Reynolds and F. B. Thompson (pp. 97-108) examine the special difficulties of measuring rainfall-interception under trees and moorland vegetation. Two contributors (E. J. Winter pp. 147-160 and D. R. Gifford (pp. 175-180) concentrate on soil water, and M. B. Alcock, J. V. Lovett and D. Machin (pp. 191-204) examine relationships between environmental factors and pasture production. All reveal, *inter alia*, the structure of biological systems to which the physical measuring systems must be matched.

The contributors to the remaining group are D. B. Idle (pp. 47-58) on surface temperature measurements; J. M. Caborn (pp. 69-81) on the measurement of wind; P. R. Newell (pp. 141-146) on light and temperature at the surface; V. I. Stewart and W. A. Adams on soil moisture (pp. 161-174), and finally A. I. Fraser (pp. 235-242) on the forest environment.

Another reviewer would classify and would evaluate the papers differently; accordingly comparisons are invidious. However, for meteorologists first entering the biological field, the six ecological papers may be recommended as 'required reading'. Predictably as in all symposia proceedings, browsing is rewarding. The last sentence of the penultimate paragraph on p. 11 seems incorrect, and would be improved by substituting 0.5°C for 0.05°C. The sentence similarly situated on p. 99 concerning the exposure of rain-gauges, also needs some elaboration to be acceptable.

R. W. GLOYNE

Exploring the atmosphere. Second edition, by G. M. B. Dobson. 225 × 145 mm, pp. xv + 209, *illus.*, Clarendon Press, Oxford University Press, Ely House, 37 Dover St, London, W.1, 1968. Price: 42s. (paperback 21s.).

This is not yet another textbook on meteorology, but a book written with the intention of presenting a general and interesting account of the earth's atmosphere to the scientifically minded public. The author has not made the mistake of making the book too comprehensive: it is of sensible length — *circa* 200 pages — and being light in weight and well printed can be regarded as easy reading: occasionally explanation tends to be rather long but this is the fault of nature, not of Dr Dobson who has the facility of explaining processes in a clear and concise manner.

The book does not touch on the dynamics of the atmosphere, and is free of mathematics and equations: the author's aim is to describe the physical properties of the atmosphere — in the first brief chapter he gives a general picture of the atmosphere, its temperature, ionization and composition. The next two chapters are concerned mainly with the temperature of the atmosphere from the surface up to great heights, with solar and atmospheric radiation, and with methods of measurement.

In the fourth and fifth chapters the reader is brought again to ground level to learn about familiar matters such as cloud, rain and thunderstorms. Chapter six deals with atmospheric ozone, a subject in which Dr Dobson has played a major role though, with characteristic modesty, his name is not mentioned. A little more might have been said about the importance of ozone in controlling the temperature and circulation of the upper stratosphere.

The atmosphere so far described has been neutral — but above the stratopause we enter the region of the atmosphere where our main interest is in its state of excitation and ionization and for which an understanding of solar activity and sunspots, which are described in a short chapter seven, is necessary. The last four chapters give a clear description of the ionosphere, aurora, airglow, the magnetosphere and the methods by which these high levels of the atmosphere are studied.

The author has adopted the familiar lecture-room style of 'we will now . . .', but in reading the book one feels that Dr Dobson is taking only the reader himself on his journey of exploration through the atmosphere from the ground to its outer limits. Though it flags somewhat in the middle chapters, the enthusiasm of the author for everything they meet on their travels must affect all but the dullest of readers. Though there are no photographs, the numerous excellent diagrams help to explain various methods and results discussed in the text. The author has not wasted time on historical reviews, but has kept in mind his single purpose of providing a contemporary description of the atmosphere, and in this he has been eminently successful. This is a sensible and readable book, and should be on the shelves of school and county libraries, and will be well read.

R. A. HAMILTON

Statistics in the computer age, by J. M. Craddock. 195 mm × 126 mm, pp.x + 214, illus., English Universities Press Ltd, London, 1968. Price: 35s. (paperback 22s.).

This book has been written with two objectives in mind. The first is to give the general reader of appreciable mathematical attainment an account of current methods of drawing conclusions from statistics with special reference to the revolution brought about by the advent of the electronic computer with its ability to do arithmetic on a scale previously inconceivable so that the statistician can, if he wishes, 'correlate everything with everything'. The second is to encourage professional statisticians to use the computer and to give them guidance in doing so.

The author covers a large field in his fifteen chapters from fundamentals in the theory of probability to the analysis of time-series. The basic ideas, mathematical parameters and frequency distributions used in statistics, are defined and described from histogram, mean, and percentile to the normal distribution, chi-square, Student's 't', Snedecor's 'F' and Sherman's 'ω'. Mode is an elementary term which is not mentioned.

The generation of random numbers and their use in determining values of statistical parameters applicable to random distributions for subsequent comparison with values computed from observations in statistical inference work are given prominence.

A particularly strong feature of the book is the account of ways in which a statistical parameter such as a correlation coefficient or chi-square can be used to test a hypothesis. The meaning of significance levels and the problems of the use of samples in this work are described in detail.

In a chapter on statistics and the electronic computers, the author gives advice out of his long experience to the statistician new to the use of these machines as well as giving much information to the general reader on methods of input and output and programming.

The analysis of time-series is one of the author's major professional interests, so it is given particularly full consideration. It starts with an account of the ways in which time-series can be generated, and the correspondingly appropriate methods of analysis for purposes of prediction of the future course of those which can be supposed to be of a stationary type. The prediction of the course of non-stationary time-series, to which class most important meteorological ones are stated to belong, is still a matter for the future. The account covers the construction of appropriate trigonometric multiplying functions — 'filters' — for the amplification of the amplitude of oscillations of specific frequencies and their application to the construction of the power spectrum of the time-series. This is probably the simplest available introduction to the power spectrum concept.

This is not an impersonal textbook. It is based on the author's personal experience and written with some fervour in areas about which the author has strong views he wishes to bring home to his readers.

The examples are naturally meteorological from the author's own work. Chi-square, for example, is used to test for a connection between the five-day temperature means of mid-August and mid-September.

No first edition is free from error, obscurity, or misprint. The contingency table of the mean monthly temperatures of February and March for central England contains two incomplete cells and one cell has an error; a more thorough explanation of this table could usefully have been given. A quantity θ_n appears without explanation on page 168. There are some slips in indices and suffixes in the mathematical formulae. A table of symbols and their meanings could usefully be added. The index is adequate.

G. A. BULL

AWARD

We note with pleasure that the International Meteorological Organization Prize for outstanding work in meteorology and international collaboration has been awarded for this year to Professor Erik Herbert Palmén (Finland) by the Executive Committee of the World Meteorological Organization during its 21st session.

CORRECTIONS

Meteorological Magazine, May 1969, p. 148.

For Figure 2 please see correct Figure 2 below.

P. 149 line 3 'For increase' read 'decrease'.

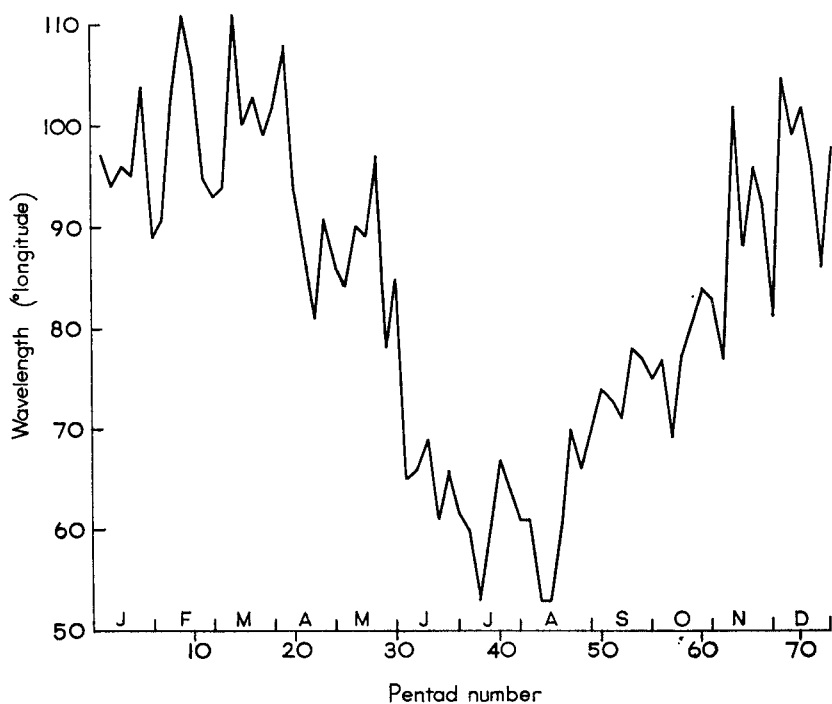
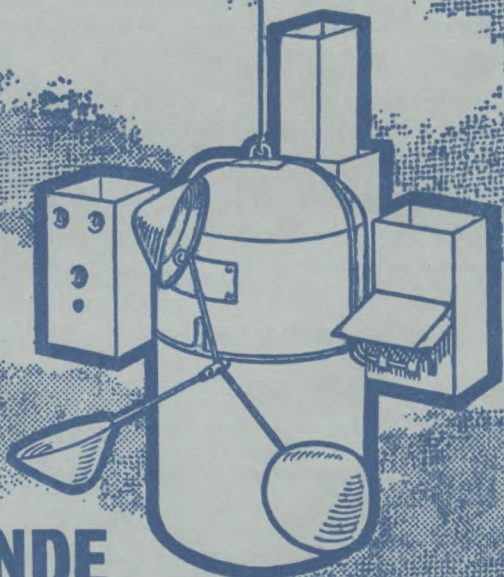


FIGURE 2—AVERAGE WAVELENGTH ACROSS ASIAN RIDGE (500 mb) AT 50°N.
PERIOD 1949-64

Meteorological Magazine, July 1969, Plate III, title, lines 4 and 6.

For 'illuminator' read 'illuminometer'.

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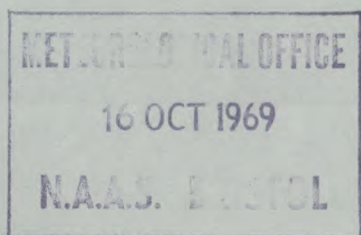
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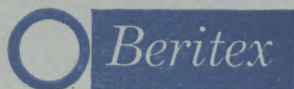
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THE METEOROLOGICAL MAGAZINE

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SUNSHINE AND SOLAR RADIATION IN SINGAPORE

By CHIA LIN SIEN

Department of Geography, University of Singapore

Since 1929 the Singapore Meteorological Service has maintained observations of the duration of bright sunshine using a Campbell-Stokes sunshine recorder. Observations were started on 1 January 1929 at Mount Faber. The meteorological station was shifted to the Kallang Aerodrome in June 1934. Observations were interrupted during the period January 1942 to April 1949 by the war in the Pacific. In August 1955 the station was shifted once more when the new Paya Lebar International Airport was opened. The British Meteorological Office also maintained Campbell-Stokes sunshine recorders at Seletar, starting in February 1957, and at Tengah, monthly totals for which are available for 1951 to January 1957. The locations of these stations are shown in Figure 1.

Solar radiation as measured by the Casella bimetallic actinograph has been recorded by the Singapore Meteorological Service since January 1961 at the Paya Lebar station. Also, Webb¹ carried out a two-year period of solar radiation observations using a Kipp solarimetric thermopile at the University of Singapore from April 1952 to March 1954.

This paper summarizes the available data of these two related climatic elements. The relationship between solar radiation and the duration of sunshine is also examined.

Sunshine

Total annual sunshine. Dale,² in his map of mean annual hours of sunshine for Malaya, shows the southern tip of Johore and the island of Singapore as areas receiving less than 2100 hours of sunshine per year. However, Table I shows that there are appreciable differences in the mean

TABLE I—MEAN ANNUAL SUNSHINE AMOUNTS FOR FIVE STATIONS IN SINGAPORE

Station	Co-ordinates	Height above MSL <i>feet</i>	Period of observations	Mean annual sunshine <i>hours</i>
Mount Faber	01°16'N, 103°49'E	296	Jan. 1929–May 1934	2183.6
Kallang	01°18'N, 103°53'E	7	Jan. 1934–Dec. 1941 and May 1949–July 1955	2077.8
Paya Lebar	01°21'N, 103°54'E	25	Sept. 1955–Mar. 1968 1958–1967	1977.1 1994.8
Seletar	01°25'N, 103°52'E	29	Feb. 1957–Mar. 1968 1958–1967	1971.3 1971.3
Tengah	01°23'N, 103°43'E	25	Jan. 1950–Mar. 1968 1958–1967	1849.2 1863.5

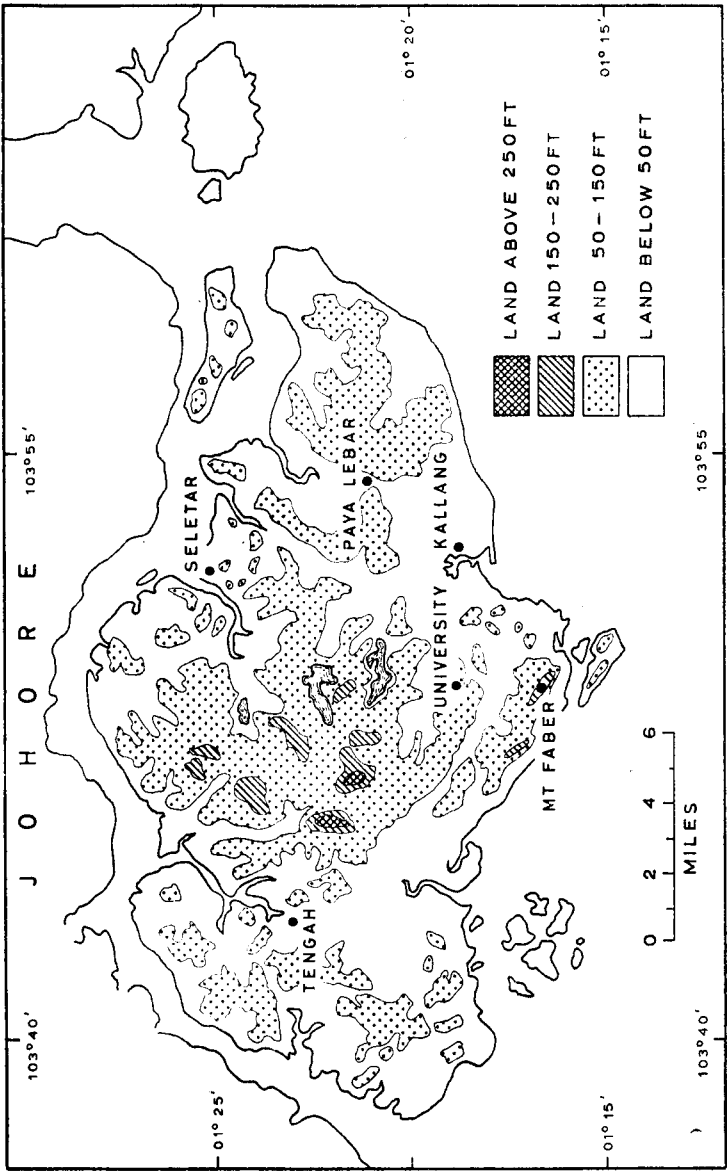


FIGURE I—STATION LOCATION MAP, SINGAPORE

total sunshine per year received by the five stations in Singapore. Mount Faber and Kallang receive the most sunshine with 2183.6 and 2077.8 hours per year respectively. Paya Lebar and Seletar receive slightly less with 1977.1 and 1971.3 hours respectively. Tengah has the least, with only 1849.2 hours. The mean annual total sunshine hours appear therefore to decrease from the southern coast inland to the north-west of the island.

Figure 2 attempts to show the secular changes in the total annual sunshine amounts using all available data. There appear to be two sunshine peaks in 1930 and 1940 with lower amounts in between. The amounts of sunshine received prior to the war in the Pacific seem to be generally higher than in the post-war years. After the war, peaks are shown for the years 1951 and 1958. The period 1954-56 appears to be especially gloomy. The trend in the sunshine amounts received after 1958 is a downward one generally with very regular biennial fluctuations from 1960 until 1966. Note also that Seletar which received higher sunshine amounts between 1958 and 1960 than Paya Lebar has been receiving less than Paya Lebar since then. The generally less sunny conditions over Tengah are clearly shown in the diagram.

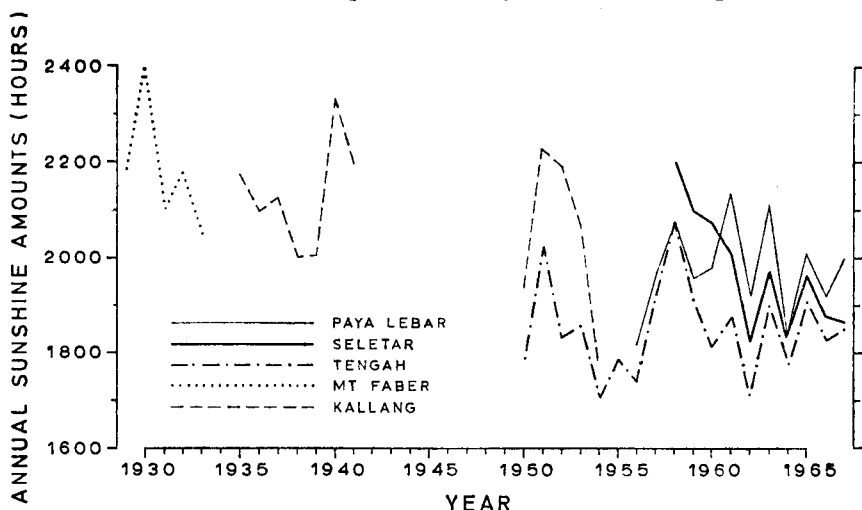


FIGURE 2—ANNUAL SUNSHINE AMOUNTS FOR FIVE STATIONS IN SINGAPORE

Seasonal variations. Variations of monthly average sunshine per day for the five stations are shown in Figure 3. The graphs for Paya Lebar, Seletar and Tengah have been drawn for the same period, 1958-67, to allow for direct comparisons. These three stations show very similar patterns of seasonal variations with two peaks in April/May and July and a low minimum in December. Generally, sunshine amounts are higher from February to September and lower for the rest of the year. The amounts of sunshine received at Tengah are consistently lower than those of Paya Lebar and Seletar throughout the year. Kallang exhibits generally higher amounts of sunshine received than Paya Lebar, Seletar and Tengah although the variations seasonally are similar. Mount Faber is anomalous in that there are three peaks of sunshine occurring in February, March and August, the August peak being the highest; sunshine during the rest of the year is much

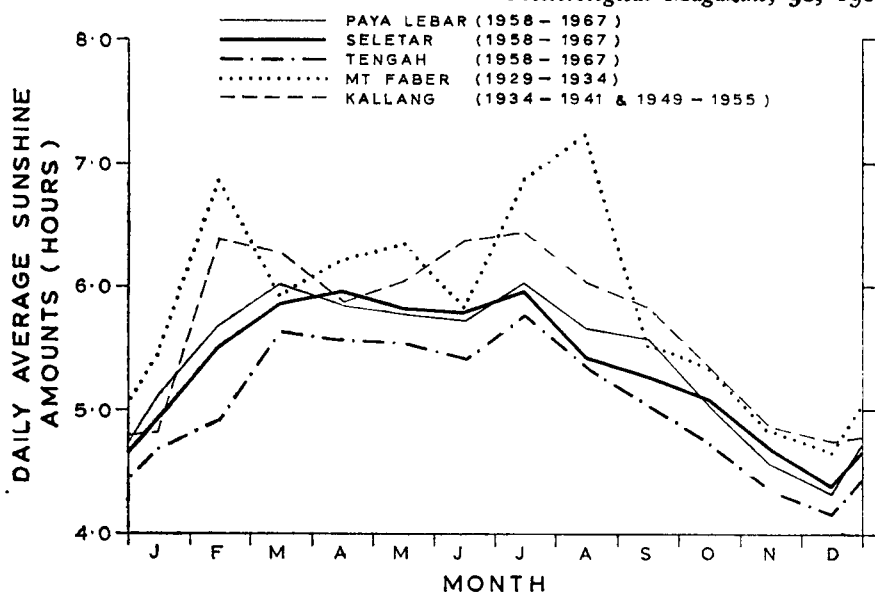


FIGURE 3—SEASONAL VARIATIONS OF SUNSHINE FOR FIVE STATIONS IN SINGAPORE

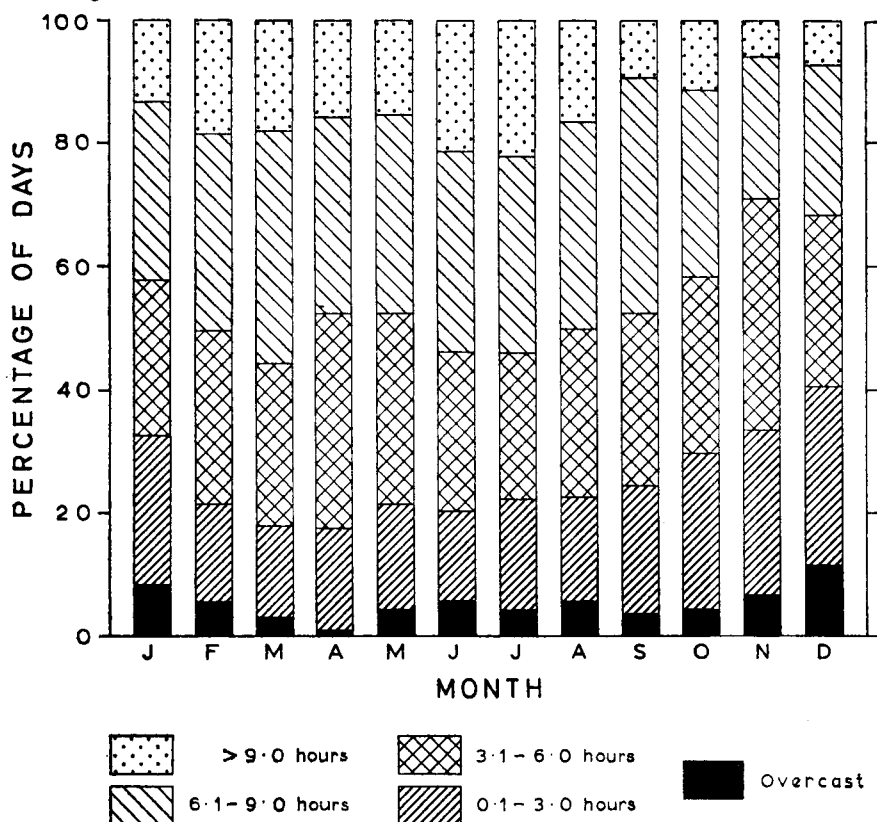


FIGURE 4—SEASONAL VARIATIONS OF THE PERCENTAGES OF DAYS WITH VARIOUS AMOUNTS OF SUNSHINE FOR PAYA LEBAR, 1956-67

the same as that of Kallang. It must be remembered that Kallang and Mount Faber cannot be compared with one another or with the other three stations directly owing to the difference in the period of observations.

Seasonal variations in the percentage of days with various amounts of sunshine are shown in Figure 4. June and July have relatively higher percentages of sunny days while the period September to December has smaller percentages of days with high sunshine hours. Overcast days without sunshine are most frequently experienced in December with January a close second, and their incidence decreases to a minimum in April. July and August have relatively larger percentages of days without sunshine. It is to be noted that February, June, July and August, which have high percentages of days with more than 9.0 hours of sunshine, also have significant percentages of overcast days.

Diurnal variation. Diagrams showing the diurnal variation of sunshine for all five stations have been constructed. However, only that for Paya Lebar is presented here (Figure 5) as most of the features showing differences among the five stations can be inferred from discussions in the previous sections. The seasonal variation of sunshine amounts for Paya Lebar is clearly

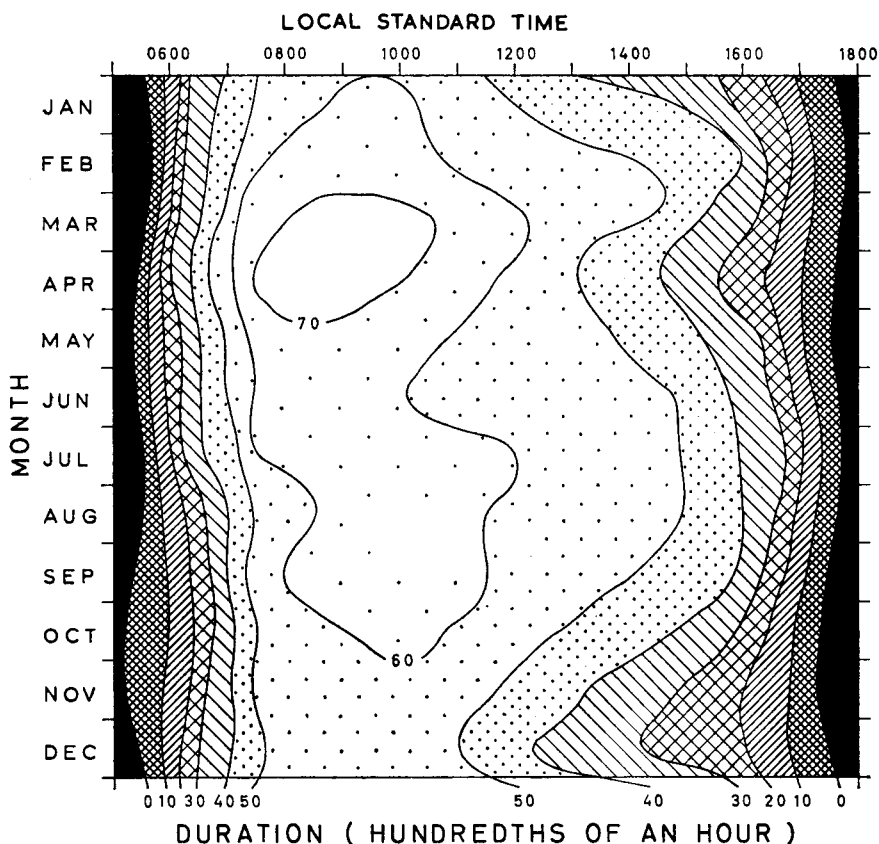


FIGURE 5—DIURNAL VARIATIONS OF SUNSHINE FOR PAYA LEBAR, 1958-67

seen from the diagram. The zero isopleth has been constructed from the times of sunrise and sunset. The rapid increase in amounts of sunshine from the time of sunrise to the period of maximum sunshine applies throughout the year. Thereafter average sunshine amounts decrease unevenly during the year.

Figure 6 shows the variation of the time of maximum duration of sunshine for the five stations in Singapore. In general, maximum sunshine is received between 0900 and 1000 local standard time. This variation may be compared to that of the University of Malaya, Kuala Lumpur (Chia³), where the time of maximum duration of sunshine occurs at least an hour later than in Singapore. Still further inland, Dale,² shows that the maximum duration of sunshine occurs around the noon period in Temerloh, Pahang, in the Malayan Peninsula. Examination of Figure 6 indicates that Kallang and Mount Faber, the two stations near the south coast, have a slightly different régime from the other more inland stations. The time of maximum duration of sunshine is later for these two stations from about April to June than for the other three stations. During the rest of the year, however, the times are much the same. Other peculiarities are that Seletar, in December and January, experiences maximum sunshine one to one-and-a-half hours later than the other stations. Tengah, on the other hand, experiences its time of maximum sunshine during July and August with about the same time lag relative to the other stations. Variations of this nature are related to the seasonal disposition of cloudiness over the island.

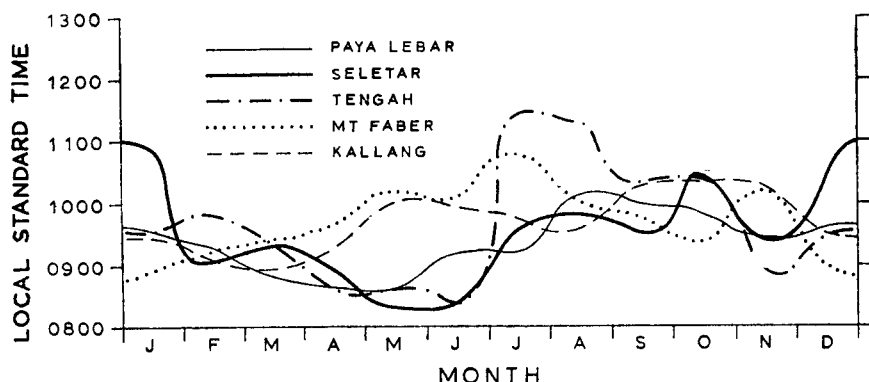


FIGURE 6—SEASONAL VARIATIONS OF THE TIME OF MAXIMUM SUNSHINE FOR FIVE STATIONS IN SINGAPORE

Solar radiation. Observations of total solar radiation incident on a horizontal surface as measured by the Casella bimetallic actinograph are available from January 1961. In 1965 a new actinograph was acquired and simultaneous measurements of incoming solar radiation revealed large discrepancies between the two sets of data. The first actinograph was sent to the manufacturer for recalibration and was subsequently reinstalled. The second actinograph has since been stored and taken out every six months for comparative readings. The procedure adopted by the Singapore Meteorological Service for correcting the records made prior to the purchase of the

second actinograph is as follows. Records for days under clear-sky conditions for the first actinograph were selected from the period of comparative readings. The charts for the same days or one day on either side from the previous years were taken out. Envelopes were drawn on the charts to represent the traces for clear-sky conditions and the areas were planimetered. From the results a single factor for each year was chosen and applied to the daily readings.

The mean annual total incoming radiation at Paya Lebar is 147 750 cal/cm². The highest was in 1965 with 157 183 cal/cm² and the lowest in 1962 with 141 980 cal/cm² (see Table II). The values obtained by Webb¹ for the University of Singapore for the period June 1952 to March 1954, included in Table II, are generally much lower. The total for 1953, 112 474 cal/cm², is 24.5 per cent less than the mean annual total for Paya Lebar. However, values obtained by Tan Beng Cheok⁴ also for the University of Singapore for the period March to August 1962 compare well with those of Paya Lebar. Both Webb and Tan used Kipp solarimeters for their observations although the latter had the advantage of using a more sensitive solarimeter as standard.

The seasonal variations of incoming solar radiation show a maximum in March and a secondary maximum in September, and a minimum in December and a secondary minimum in July. The seasonal pattern follows the changes in the solar radiation receipts over Singapore assuming a completely transparent atmosphere. The low amounts of solar radiation received in November and December are due to greater cloudiness during the period.

Diurnal variation of solar radiation receipts over Paya Lebar is shown in Table III. Solar radiation increases generally rapidly in the morning after sunrise under the clearer morning skies and declines more gradually during the afternoon. Maximum solar radiation receipts are experienced between 1100 and 1200 local standard time in most months except for May and July which show maximum receipts between 1200 and 1300. Thus maximum radiation occurs some two to three hours after the time of maximum duration of sunshine. This is to be expected as the intensity of solar radiation increases to a maximum at noon assuming complete transparency of the atmosphere. Thus, in spite of increasing cloudiness after about 1000 the actual intensity of solar radiation received continues to increase until the noon period.

Relation between solar radiation and duration of sunshine. The relationship between solar radiation and duration of bright sunshine at Paya Lebar was obtained using the formula :

$$Q/Q_A = a + bn/N$$

where Q and Q_A are the observed incoming solar radiation and the incoming solar radiation incident upon a horizontal surface, respectively, assuming a completely transparent atmosphere; n and N are the actual and maximum possible hours of sunshine, respectively; and a and b are constants. Daily values of Q_A were obtained by interpolation of the values given in the Smithsonian Meteorological Tables (List⁵) using 2.00 cal/cm² min as the solar constant.

TABLE II—INCOMING SOLAR RADIATION AT THE UNIVERSITY OF SINGAPORE* AND PAYA LEBAR†

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
<i>University of Singapore</i>							<i>cal/cm²</i>						
1952													
1953	317.9	327.3	327.3	321.3	263.8	340.0	245.2	280.3	384.2	397.8	303.4	341.2	—
1954	310.1	389.3	367.7			316.2	273.7	317.0	300.1	304.1	294.0	337.1	112 474
1962			389	402	406	354	364	352					—
<i>Paya Lebar</i>													
1961	409.6	443.3	456.5	408.1	395.4	400.6	420.5	430.2	443.3	395.8	379.6	335.3	149 507
1962	319.9	448.2	388.5	408.1	419.0	374.8	378.7	367.2	416.1	409.1	379.5	305.3	141 980
1963	364.2	397.0	492.5	521.6	421.7	392.1	427.6	411.0	390.5	369.8	376.5	309.7	148 228
1964	427.7	382.2	436.8	397.7	400.0	407.8	341.6	462.7	381.4	379.6	379.2	311.1	143 609
1965	466.7	472.8	468.6	448.5	394.1	415.8	448.2	439.5	443.6	394.2	416.1	363.5	157 183
1966	396.4	475.7	436.6	435.0	413.4	420.2	405.0	396.6	446.2	407.5	351.7	336.0	149 447
1967	355.5	400.2	494.3	392.0	384.0	386.6	369.3	411.5	416.7	401.6	340.7	332.7	144 295
Mean	391.4	431.3	453.4	430.1	403.9	399.7	398.7	417.0	419.7	393.9	374.8	336.2	147 750

* Values for the University of Singapore taken from Webb¹ (1962 from Tan⁶)

† Corrected values used for the period Jan. 1961 to Mar. 1965

1 cal/cm² = 4.19 × 10⁴ joules/m²

TABLE III—MEAN HOURLY VALUES OF INCOMING SOLAR RADIATION AT PAYA LEBAR, APRIL 1965 TO MARCH 1968

Month	06-07	07-08	08-09	09-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
							<i>cal/cm²</i>							
Jan.	2.4	14.6	29.3	41.6	50.3	55.3	50.8	47.2	37.8	29.1	17.8	6.7	0.2	0.0
Feb.	2.2	16.2	32.8	46.3	59.1	65.3	58.9	59.1	47.0	35.5	22.4	9.2	0.3	0.0
Mar.	3.3	18.8	35.6	48.5	58.5	61.8	59.4	57.0	45.5	33.7	20.6	7.5	0.3	0.1
Apr.	5.5	22.2	37.6	48.3	55.3	59.2	56.9	48.5	37.1	28.5	16.8	6.4	0.1	0.0
May	5.4	19.3	34.2	44.2	48.2	52.9	55.2	49.2	39.2	28.4	16.1	4.8	0.2	0.0
June	5.0	18.5	33.1	43.4	50.8	54.9	52.2	49.7	44.1	31.3	18.7	6.1	0.0	0.0
July	4.1	18.4	32.3	44.7	51.7	55.5	55.6	48.6	39.1	31.9	19.6	6.9	0.1	0.0
Aug.	3.8	17.4	31.3	42.9	52.7	56.5	56.2	49.7	43.8	34.2	20.2	11.1	2.3	0.0
Sept.	5.5	20.5	35.3	48.5	57.6	61.0	57.2	52.2	42.7	31.5	18.1	5.5	1.7	0.0
Oct.	7.2	22.8	35.6	47.6	57.3	58.6	52.1	44.9	33.8	24.6	13.0	3.4	0.1	0.0
Nov.	7.6	22.1	35.3	44.7	50.3	53.2	50.1	41.2	30.7	20.7	10.9	2.8	0.0	0.0
Dec.	4.1	15.3	28.2	39.6	47.3	49.4	45.3	39.0	33.0	24.0	13.7	4.0	0.1	0.0
Mean	4.7	18.8	33.4	45.0	53.3	54.8	54.2	48.9	39.5	29.5	17.3	6.2	0.5	0.0

1 cal/cm² = 4.19 × 10⁴ joules/m²

Table IV presents for each year from 1961-67 values of the constants a and b in the above formula using the method of least squares, and the values of $a + 0.45b$. Corrected values for the period January 1961 to March 1965 were used when the older actinograph was in operation prior to the purchase of the second actinograph. Except for 1967, the value of $a + 0.45b$ increases slightly. There is a similar increase in the values of a and $a + b$, though not as clearly seen. These imply that there is a small systematic error in the radiation measurements which the correction factor has failed to eliminate.

TABLE IV—VALUES OF COEFFICIENTS a AND b AND $a + 0.45b$ FOR VARIOUS PERIODS FOR PAYA LEBAR

Period	a	b	$a + 0.45b$	Remarks
1961	0.245	0.460	0.452	
1962	0.234	0.493	0.456	
1963	0.235	0.474	0.448	Corrected values
1964	0.245	0.494	0.467	
1965	0.266	0.485	0.484	
1965 (Apr.-Dec. only)	0.260	0.485	0.478	
1966	0.274	0.471	0.486	Uncorrected values
1967	0.238	0.467	0.459	
1961-64	0.240	0.478	0.455	Corrected values
1965-67	0.260	0.472	0.472	Uncorrected values

Monthly regression coefficients were obtained and the results are presented in Table V. Values of a vary from 0.231 in April to 0.284 in August, while values of b range from 0.411 in August to 0.506 in April. There is generally an inverse relationship between a and b . There does not appear to be any consistent trend in the values of either of the constants over the year.

TABLE V—MONTHLY VALUES OF COEFFICIENTS a AND b FOR PAYA LEBAR, 1961-67

Month	a	b	Month	a	b
Jan.	0.245	0.497	July	0.259	0.451
Feb.	0.266	0.473	Aug.	0.284	0.411
Mar.	0.280	0.440	Sept.	0.252	0.459
Apr.	0.231	0.506	Oct.	0.241	0.468
May	0.250	0.464	Nov.	0.256	0.437
June	0.259	0.456	Dec.	0.236	0.486

Values of coefficients of the regression formula of stations near the equator obtained by various workers are presented in Table VI. Values obtained here are close to those obtained by Tan⁴ for the University of Singapore. However, Tan's coefficients were obtained from a period of five months' observations, although the correlation coefficient found was 0.91. The values for Kabete, Kenya and those of Trinidad are also similar except that the value of b for Kabete is much higher than that of Paya Lebar. The high value of b for Kabete may be expected as the station is some 6000 ft above MSL.

TABLE VI—VALUES OF COEFFICIENTS FOR STATIONS NEAR THE EQUATOR

Station	Latitude	a	b	Authority
University of Singapore	01°19'N	0.23	0.46	Tan ⁴
Trinidad, West Indies	11°N	0.27	0.49	Smith ⁷
Kabete, Kenya	01°16'S	0.26	0.57	Glover and McCulloch ⁸
15 stations in Kenya, Tanzania and Uganda	5°N - 10°S	0.23	0.53	Woodhead ⁹
Djakarta, Tjibodas and Bandung	6°11'S - 6°54'S	0.29	0.29	Black <i>et alii</i> ⁹

Under cloudless conditions values of Q/Q_A should be higher, and this will result in a higher value for the slope of the regression line. The values obtained by Black, Bonython and Prescott⁶ for the three stations Batavia (now Djakarta), Tjibodas and Bandung are anomalous in that the value of b is only 0.29. This is much lower than those for the other stations. This could only occur if there is a high percentage of days with thin high clouds which will still allow the sunshine recorder to burn a trace on the card although the amount of solar radiation at the surface is reduced. There is, however, no reason to believe that such a condition exists over Indonesia. The results must therefore be viewed with suspicion.

Conclusion. Variations of climatic elements with distance from the coast and over islands in the tropics have been noted elsewhere. In Singapore, variations in time and space of wind, cloudiness, temperature and sunshine are commonly observed. The paper illustrates the rapid transition of the amounts of sunshine and solar radiation with distance from the open sea surface.

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SOME RELATIONSHIPS BETWEEN THE 100-MILLIBAR CHART AND SURFACE WEATHER

By N. E. DAVIS

Summary. Ridges at 100 mb are highly persistent and slow moving. Each ridge at 100 mb may be associated with a succession of surface highs, most of which are found on the eastern side of the 100-mb ridge.

The rainfall pattern at the surface is such that a deficiency of rain occurs under the eastern side of a 100-mb ridge and an excess of rain under the eastern side of a 100-mb trough.

As the 100-mb pattern is persistent and slow moving, it can on many occasions be forecast for a long time ahead and hence it is possible to make a general forecast of the precipitation distribution and of anticyclonic areas at the surface.

Introduction. In a previous paper¹ the author showed that north and north-west winds at 100 mb were associated with dry weather at London/

Heathrow Airport. An earlier paper² showed the possibility that stratospheric flow had some effect on the subsequent surface developments. Labitske³ pointed out that sudden warmings in the stratosphere in winter were generally followed by a blocking in the troposphere. Boville,⁴ Charney and Drazin,⁵ Sun Chu Ching and others⁶ have made mathematical calculations of the interactions between stratosphere and troposphere. The present paper attempts a statistical investigation of the relationship between the stratosphere and the surface, in particular the relationships between ridges at 100 mb and highs at the surface and between the ridge-trough pattern at 100 mb and rainfall.

In addition the persistence of ridges at 100 mb over the America-to-Europe area is examined and the speed of movement of such ridges compared with the speed of movement of surface features. Ridges at 100 mb are highly persistent. Their average life is some 14 days and their mean speed is only 4 knots from west to east. Surface highs move with a mean speed of about 15 knots and the mean west-to-east component of their motion is about 8 knots, i.e. about twice the speed of the ridge at 100 mb. Surface highs have a mean persistence of about four to five days, i.e. about one-third of the persistence of the upper ridge so that each ridge at 100 mb is associated with a succession of surface highs. The speed of the surface high is greatest in the upper south-westerlies on the western side of the 100-mb ridge and least within 10 degrees of longitude east of the axis of the upper ridge.

As the majority of surface highs are to be found on the eastern side of the 100-mb ridge, a further examination of the rainfall pattern in relation to the positions of the 100-mb ridges and troughs was made and this showed a highly significant connection.

These relationships would suggest that the 100-mb chart could be used as an aid in extended forecasting, and a possible line of attack is appended.

Speed of movement of ridges at 100 mb. The 100-mb charts for 0000 GMT for each day of the period January to December 1962 were examined for ridges between 50°N and 55°N and the longitude positions of the ridges at latitude 52°30'N were listed. All ridges between about 50°E and 130°W, i.e. over Europe, the Atlantic and North America, were included. There were normally two or three ridges in this half of the northern hemisphere.

Table I gives the frequency of the distances moved by the ridges in 24 hours, expressed in terms of the number of degrees of longitude in latitude 52°30'N.

TABLE I—NUMBER OF RIDGES AT 100 mb IN VARIOUS RANGES OF 24-HOUR MOVEMENT IN LATITUDE 52°30'N IN 1962

	Degrees westward			24-hour movement		Degrees eastward			
	>10°	6-10°	1-5°	Stationary	1-5°	6-10°	11-15°	16-20°	>20°
No. of ridges	23	67	164	88	215	166	55	27	18
Percentage of total	3	8	20	11	26	20	7	3	2

The mean speed of the 823 ridges was 2.6 degrees of longitude from west to east in 24 hours which equals 4 kt (in latitudes 50°N-55°N). The mean speed irrespective of direction was about 6 degrees in 24 hours, 57 per cent moving 5 degrees or less in 24 hours (8 kt or less) and 85 per cent 10 degrees or less (16 kt or less).

Persistence of ridges at 100 mb. The charts were further examined and the number of days each ridge persisted was determined. Table II gives the number of ridges which persisted for certain specified numbers of days (grouped in 5-day classes).

TABLE II—NUMBER OF RIDGES AT 100 mb PERSISTING IN 1962 FOR VARIOUS PERIODS GROUPED IN 5-DAY CLASSES

Number of days	1-5	6-10	11-15	16-20	21-25	26-30	>30
Number of ridges	12	14	17	5	6	3	5
Percentage of total	19	23	27	8	10	5	8

The average number of days the 62 ridges persisted at 100 mb in 1962 was between 13 and 14, i.e. the total number of ridge days (823) divided by the number of ridges grouped as persisting (62).

The general history of a particular ridge is progression for a day or two after formation, then a longer period in which the ridge progresses slowly or remains oscillating slightly about a fixed longitude, followed by a final period of more rapid progression for a day or two as it collapses.

The large amount of westward motion (retrogression) — more than 30 per cent — in Table I, is due to ridges tending to oscillate about a fixed position rather than to some third of the ridges having a long period of retrogression whilst the other two-thirds move eastward. About 19 situations were noted in which retrogression continued for more than 48 hours. These examples involve about 80 of the 823 ridges in Table I (equivalent to a frequency of about 10 per cent of the total) and as there were 254 westward-moving ridges in Table I it can be deduced that only one-third of these retrogressed for more than 48 hours.

As the mean speed is 2.6 degrees of longitude to the east in 24 hours, ridges on the average will move some 35 to 40 degrees of longitude eastward in their life span of 14 days. Indeed, as a closer consideration of the percentage frequencies in Table I shows, for 12 per cent of the time the ridge moves east at a speed greater than 10 degrees of longitude per day (and this relatively fast speed occurs generally at the beginning and end of the life of a ridge), for 20 per cent of the time it moves east at 6 to 10 degrees per day, and for the remainder of the time the ridge is stationary or oscillating slightly at a relatively slow speed; so that on average a ridge will move east about 15 degrees on the first day, another 10 degrees in the next day and a half, remain more or less stationary for the next nine days and finally move away eastward with increasing speed in the final two and a half days.

In short, ridges at 100 mb are stationary or oscillating slightly for more than half their life.

Distribution of surface highs relative to 100-mb ridges and speed of movement of surface highs. Surface charts for the period January to December 1962 were examined and the positions of all surface highs between 50°E and 50°W and north of 40°N at 0000 GMT were determined and compared with the longitudinal position of the nearest ridge at 100 mb (in the same latitude as the surface high). In Figure 1, if H is the position of the surface high, AA', BB', CC', etc. the contour lines at 100 mb, and EFG the axis of the ridge where E, F, and G are the most northerly points of the

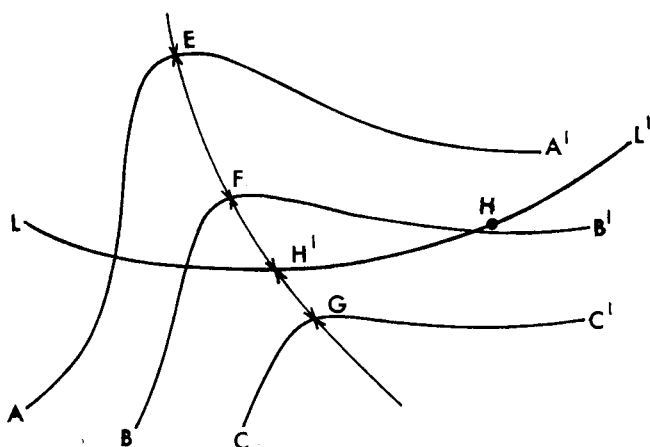


FIGURE 1—DISTANCE OF SURFACE HIGH (H) FROM RIDGE (EFG) AT 100 mb

contours AA', BB' and CC', then the distance of the surface high from the axis of the 100-mb ridge is the longitudinal distance HH' where H' is the point where the latitude circle LL' through H cuts EFG.

As this note is concerned with the moving highs of temperate latitudes (especially those between 50°N and 55°N), it was considered that the semi-permanent high of subtropical latitudes (the Azores-Bermuda high) should be excluded. Furthermore as there are only three upper air stations in the Atlantic south of 40°N (Bermuda, ocean weather station 'E' and Lajes in the Azores), it was frequently difficult to fix the position of the ridge at 100 mb south of 40°N. (Even so, the centre of the subtropical high was nearly always associated with winds from the north-west quarter at 100 mb.)

Only surface highs north of 40°N were therefore considered in compiling Tables III, IV and V.

Table III gives the number and percentage frequency of the surface highs at various longitudinal distances from the axis of the ridge at 100 mb (in the same latitude as the surface high).

TABLE III—FREQUENCY OF SURFACE HIGHS NORTH OF 40°N IN 1962 GROUPED ACCORDING TO DISTANCE FROM THE AXIS OF THE 100-mb RIDGE IN THE SAME LATITUDE

	Degrees west of 100-mb ridge		Coincident with axis	Degrees east of 100-mb ridge		
	> 10°	1-10°		1-10°	11-20°	> 20°
Number of surface highs	22	31	19	161	94	69
Percentage frequency	5	8	5	40	24	18

Table IV gives the frequency of the distance moved by the surface highs (in degrees of longitude) in 24 hours irrespective of amount of latitudinal change.

The mean speed of the 408 surface highs is 5.2 degrees of longitude from west to east in 24 hours which equals 8 kt in latitude 50°N-55°N.

TABLE IV—NUMBER OF SURFACE HIGHS NORTH OF 40°N IN VARIOUS RANGES OF 24-HOUR MOVEMENT IN 1962

	Degrees westward			24-hour movement		Degrees eastward			
	>10°	6-10°	1-5°	Stationary	1-5°	6-10°	11-15°	16-20°	>20°
Number of surface highs	9	18	54	20	111	90	62	29	15
Percentage frequency	2	4	14	5	27	22	15	7	4

Persistence of surface highs. Table V gives the number of surface highs which persisted north of 40°N for a certain specified number of days (grouped in 5-day classes).

TABLE V—NUMBER OF SURFACE HIGHS NORTH OF 40°N PERSISTING IN 1962 FOR VARIOUS PERIODS GROUPED IN 5-DAY CLASSES

Number of days	1-5	6-10	>10
Number of surface highs	84	19	9
Percentage frequency	75	17	8

The average number of days surface highs persisted in 1962 was about four.

In compiling Tables III, IV and V only surface highs north of 40°N were considered. These tables are to be taken as applying to moving highs of temperate latitudes and not to the semi-permanent subtropical high. This is especially so in the case of Table V.

Deductions from tables.

(i) From Table II, the 100-mb ridge is highly persistent, 58 per cent lasting more than 10 days. From Table I, it is often slow moving, 57 per cent being stationary or moving 5 degrees or less in 24 hours.

(ii) From Table III, the association between the 100-mb circulation and the surface features is such that surface highs are more frequently found under the eastern side of the 100-mb ridge and seldom under the western side. The normal wavelength at 100 mb is between 70 and 180 degrees (with two to five ridges and troughs round the northern hemisphere) so that a quarter wavelength is normally between $17\frac{1}{2}$ and 45 degrees. Table III shows that 64 per cent of surface highs are found under the eastern side of the 100-mb ridge and within 20 degrees of the axis of the ridge. Hence the majority of surface highs are found under the eastern (forward) side of the ridge at 100 mb.

(iii) Tables I and II are not strictly comparable with Tables IV and V as the 100-mb ridges were examined over the section 130°W to 50°E, whilst the surface highs were examined over the section 50°W to 50°E, but the mean speed of ridges over the sector 50°W to 50°E was only slightly higher than the mean speed over the whole sector 130°W to 50°E (2.9 degrees instead of 2.6 degrees in 24 hours). Hence the relative persistence and speed of surface highs and 100-mb ridges indicate that each ridge at 100 mb may be associated with several successive surface highs. Surface highs appear to form from the intensification of surface ridges under the south-westerly flow to the west of the 100-mb ridge, then move rapidly to a position just east of the 100-mb ridge axis, become slow moving and finally are absorbed by the next surface high or move away south-east with increasing speed.

Relationship between rainfall and 100-mb features. As it had already been shown by the author that north to north-west winds at 100 mb are associated with dry weather at London/Heathrow Airport and Table III shows that anticyclones are associated with the eastern (forward) side of 100-mb ridges where winds would be north-west, a more detailed examination of the relationship between rainfall and the 100-mb features was undertaken.

The position of the trough and ridge nearest to Heathrow ($51^{\circ}29'N$ $00^{\circ}27'W$) at 0000 GMT was noted and every day was classified as FT, RR, FR or RT according to Figure 2.

Suppose T_1T_1' , R_1R_1' , and T_2T_2' are the axes of a trough-ridge-trough system at 100 mb, cutting the latitude circle (LL') of Heathrow at A, C and E respectively. Further, let B be the mid-point of AC and D the mid-point of CE. Then a day was classified FT (forward, i.e. east, of trough) if W (the position of Heathrow) was between A and B. A day was classified RR (rear, i.e. west, of ridge) if W was between B and C. Similarly a day was classified FR (forward, i.e. east, of ridge) if W was between C and D and it was classified RT (rear, i.e. west, of trough) if W was between D and E.

The rainfall was that measured at Heathrow between 0600 GMT on the day in question and 0600 GMT on the following day. If no rainfall or a trace was recorded the day was classified as O; if the rainfall was 0.1 to 0.9 mm the day was classified as *r* and if 1.0 mm or more it was classified as R.

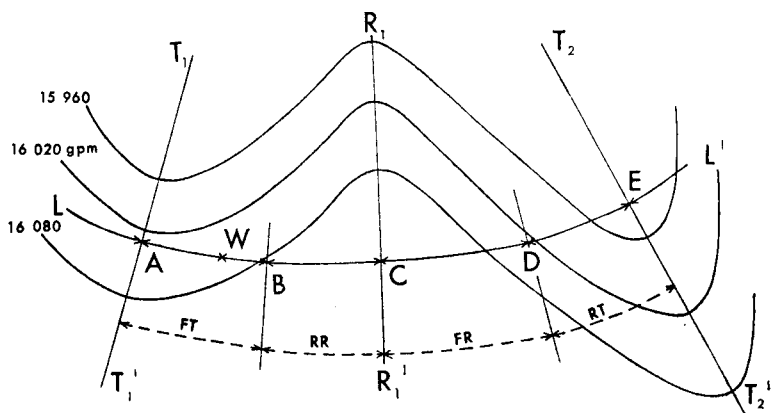


FIGURE 2—100-mb TROUGH-RIDGE-TROUGH SYSTEM AND DEFINITION OF FT, RR, FR AND RT

Tables VI, VII and VIII give the 3×4 contingency tables relating rainfall to 100-mb trough-ridge pattern. Table VI gives the actual values (*A*) for the year 1962. Table VII gives the expected values (*E*) with the given total number of days, FT, RR, FR and RT and the given total number of days of O, *r* and R on the basis that there was no correlation between the precipitation and the 100-mb pattern, i.e. on the basis that the 206 days

with rainfall O were distributed between the classifications FT, RR, FR, RT in the proportions 69:55:122:119, which were the frequencies of occurrence of FR, etc. in 1962.

Table VIII gives the actual minus expected values $A - E$.

TABLE VI—FREQUENCY TABLE OF DAYS OF FT, RR, FR AND RT WITH DAYS OF O , r AND R (ACTUAL VALUES IN 1962)

Rainfall amount	Circulation type				Total
	FT	RR	FR	RT	
O	24	29	85	68	206
r	14	6	23	21	64
R	31	20	14	30	95
Total	69	55	122	119	365

TABLE VII—CONTINGENCY TABLE SHOWING EXPECTED VALUES, E , DERIVED FROM THE TOTALS IN TABLE VI

Rainfall amount	Circulation type				Total
	FT	RR	FR	RT	
O	38.94	31.04	68.86	67.16	206
r	12.10	9.64	21.39	20.87	64
R	17.96	14.32	31.75	30.97	95
Total	69	55	122	119	365

TABLE VIII—CONTINGENCY TABLE SHOWING ACTUAL VALUES, A , MINUS EXPECTED VALUES, E

Rainfall amount	Circulation type			
	FT	RR	FR	RT
O	-14.94	-2.04	+16.14	+0.84
r	+1.90	-3.64	+1.61	+0.13
R	+13.04	+5.68	-17.75	-0.97

The value of $\chi^2 = \Sigma (A - E)^2 / E$ is 33.12 which with 6 degrees of freedom is very highly significant (the 0.1 per cent level is 22.46). There is thus a very distinct relationship between precipitation and trough-ridge pattern at 100 mb. Table VIII shows this is mainly due to the fact that there is an excess of occasions of moderate to heavy rain associated with the forward trough position and a deficiency of occasions of no rain, and the reverse in the case of the forward ridge position.

Table IX gives the total of the 24-hour rainfall amounts at Heathrow for the year 1962 for each type of trough-ridge position preceding the 24-hour period in the manner described.

TABLE IX—RAINFALL TOTALS AT HEATHROW OVER THE 24-HOUR PERIOD FOLLOWING VARIOUS 100-mb CIRCULATION TYPES IN 1962 COMPARED WITH FREQUENCY OF TYPES

Rainfall (mm)	Circulation type				Year	(86% of long-term average)
	FT	RR	FR	RT		
	238.4	106.1	47.2	135.0	516.7	
Percentage of 1962 rainfall	45	20	9	26		
Frequency of type (days)	69	55	122	119	365	
Percentage of year	19	15	33	33		
Mean fall per day (mm)	3.46	1.93	0.39	1.13	1.44	

Table IX shows that FT occurs for only 19 per cent of the year but accounts for 45 per cent of the total rainfall, while FR occurs for 33 per cent of the year but accounts for only 9 per cent of the total rainfall. Also the mean fall per day in 1962 to the east of a 100-mb trough was nearly nine times the mean fall to the east of a 100-mb ridge.

As Heathrow is in one of the drier parts of the U.K. an examination was made of the rainfall data for Eskdalemuir ($55^{\circ} 19' N$ $03^{\circ} 12' W$, elevation 749 ft) where the mean annual rainfall is 1581 mm, two and a half times that at Heathrow. A similar classification was adopted and the value of χ^2 was 27.92 (very highly significant — the 0.1 per cent level is 22.46 as before). The largest contribution to this value comes from a deficiency of occasions of no rain in FT conditions and an excess of occasions of no rain in FR conditions.

Rainfall, at least over the U.K., is highly correlated with the position of the troughs and ridges at 100 mb. Dry days are a feature of the weather under the forward (eastern) side of a ridge at 100 mb whilst wet weather is generally under the forward (eastern) side of a trough at 100 mb.

Use in extended forecasting. As ridges at 100 mb are very persistent and slow moving, it is frequently possible to forecast their position for a long time ahead. If the U.K. lies under the forward side (FR) (see Figure 2) of the upper ridge, the weather will generally be anticyclonic with below normal precipitation; but if the U.K. lies under the forward side (FT) of the upper trough, weather will generally be wet and unsettled. In winter, anticyclonic weather generally implies below normal temperatures, and unsettled weather implies above normal temperatures. In summer, the opposite occurs; anticyclonic weather implies above normal temperatures and unsettled weather below normal temperatures. As long as the position of the troughs and ridges at 100 mb can be forecast with any confidence so can a general statement be made about the expected surface weather.

The pattern at 100 mb can be used as a guide and aid in constructing extended prebaratics. If there is no ridge at 100 mb over the forecast area and no ridge is expected to move in, any surface highs which would appear to be moving into the forecast area are likely to weaken and collapse. On the other hand, if there is a stationary ridge at 100 mb over the forecast area, a surface anticyclone would be expected to persist on the forward side of such a ridge or a second anticyclone would be expected to develop and move north-east to a position on the forward side of the 100-mb ridge absorbing the previous high.

Examples of 100-mb charts and corresponding surface charts. Figures 3–7 show the 100-mb contour charts for 0000 GMT for 27 and 28 February 1961 and 1, 2 and 5 March 1961.

Figure 3 shows a ridge at 100 mb developing east of Newfoundland. It would be expected to move east fairly quickly at first as it intensified (following the normal development) and then to become slow moving (or to oscillate). Figures 4 and 5 show its steady motion across the Atlantic. As it intensifies over the U.K. it flattens and destroys the previous ridge that has been lying across western Europe. Figure 6 shows the ridge slowing up as it crosses the U.K. and Figure 7 shows the position three days later on 5 March with the ridge oscillating over the U.K.

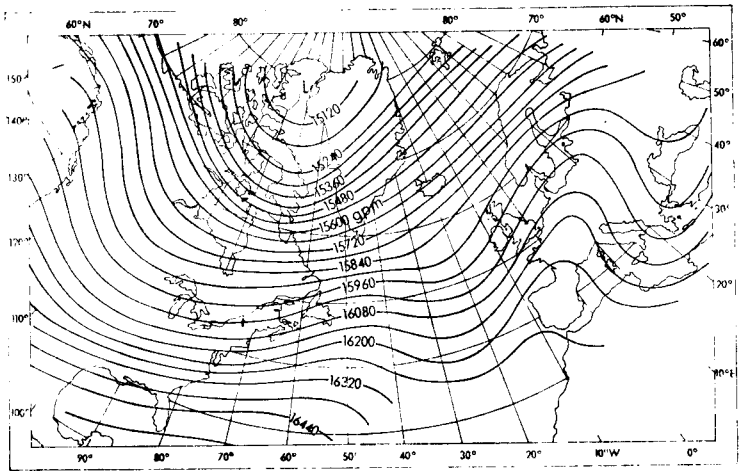


FIGURE 3—100-mb CONTOUR CHART, 0000 GMT, 27 FEBRUARY 1961

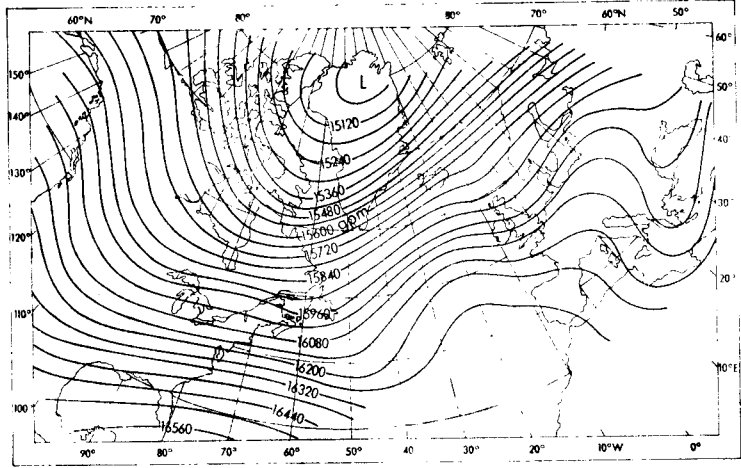


FIGURE 4—100-mb CONTOUR CHART, 0000 GMT, 28 FEBRUARY 1961

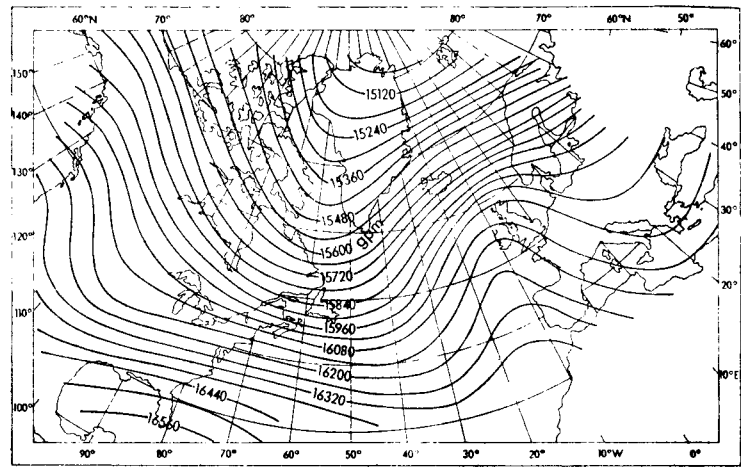


FIGURE 5—100-mb CONTOUR CHART, 0000 GMT, 1 MARCH 1961

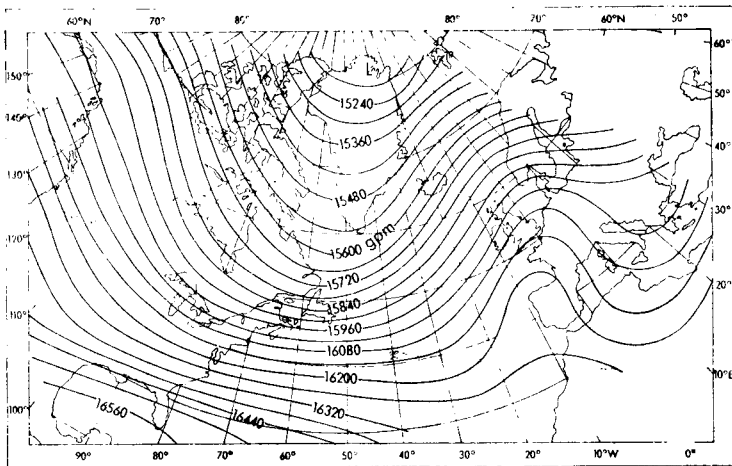


FIGURE 6—100-mb CONTOUR CHART, 0000 GMT, 2 MARCH 1961

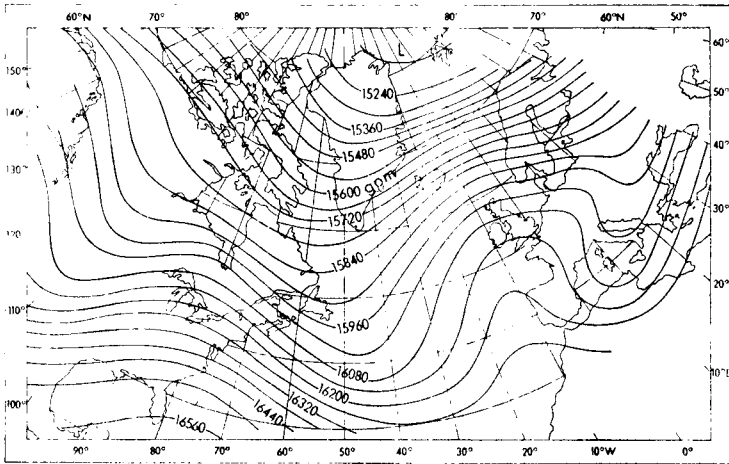


FIGURE 7—100-mb CONTOUR CHART, 0000 GMT, 5 MARCH 1961

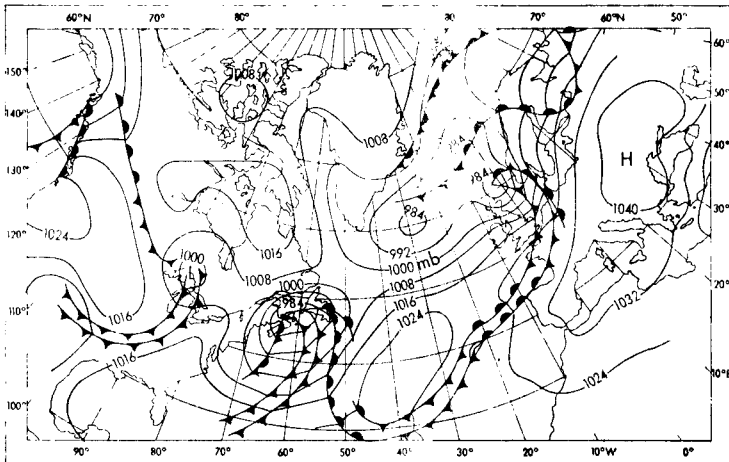


FIGURE 8—SURFACE CHART, 0000 GMT, 27 FEBRUARY 1961

Figure 8 shows the surface chart for 0000 GMT on 27 February 1961. Comparing this with Figure 3, the three major surface highs, viz. those north of the Black Sea, in mid-Atlantic and over the Pacific coast of the U.S.A., are centred just forward of a ridge at 100 mb. A fourth high over the north Hudson Bay region is centred a long way from any ridge. It disappears in 24 hours.

The anticyclone north of the Black Sea has been drifting southwards and intensifying slightly (central surface pressure rising from 1044 to 1047 mb over the previous 30 hours).

Figures 9 and 10 show the surface charts for 0000 GMT on 28 February and 1 March 1961. As the upper ridge which was over western Europe on the 27th is destroyed by the upper ridge advancing into the U.K., so the associated surface anticyclone collapses with the surface pressure north of the Black

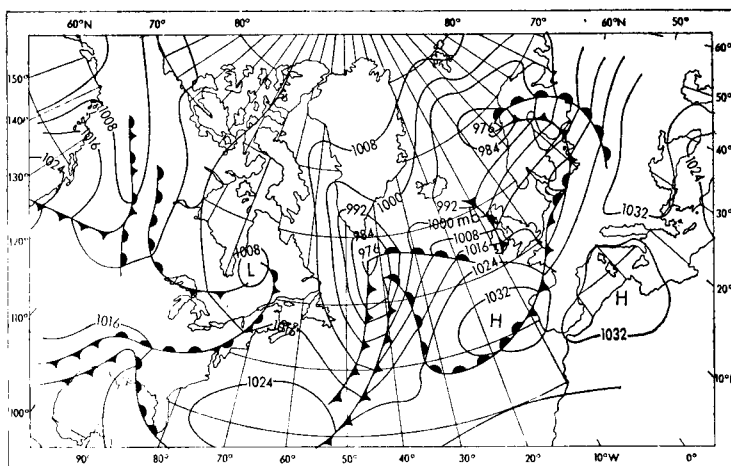


FIGURE 9—SURFACE CHART, 0000 GMT, 28 FEBRUARY 1961

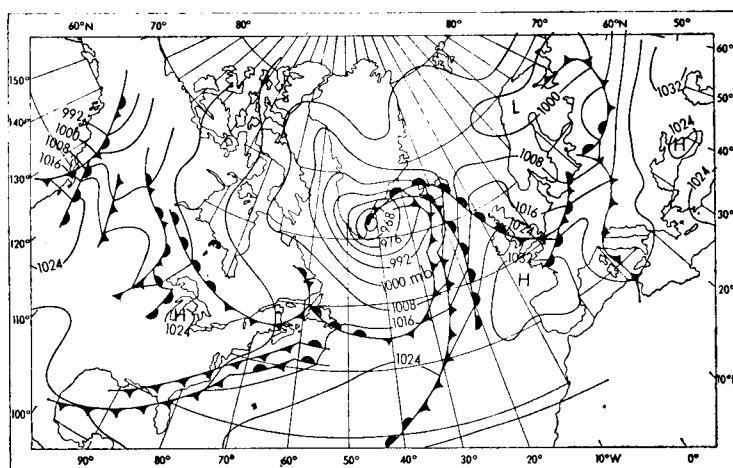


FIGURE 10—SURFACE CHART, 0000 GMT, 1 MARCH 1961

Sea falling by more than 20 mb. Furthermore, as the upper ridge advances into the U.K., the surface high in mid-Atlantic accompanies it into the Bay of Biscay and a large rise of surface pressure takes place over the U.K. amounting to more than 30 mb at 60°N 0°.

Figure 11 shows the surface chart for 0000 GMT on 2 March 1961 with the surface anticyclone slowing down over northern France. Figure 12 shows the surface chart for 0000 GMT on 5 March with a stationary high over western Europe (forward of the upper ridge over the U.K.). A long dry spell commenced on 2 March with no measurable rain at Heathrow until the 18th.

On the continent, precipitation mostly occurred ahead of the 100-mb trough which advanced from a position about 20°W on 27 February across the U.K. on the 28th and joined with the trough from the Black Sea to Cyrenaica to produce a slow-moving trough over the central Mediterranean on 2 March.

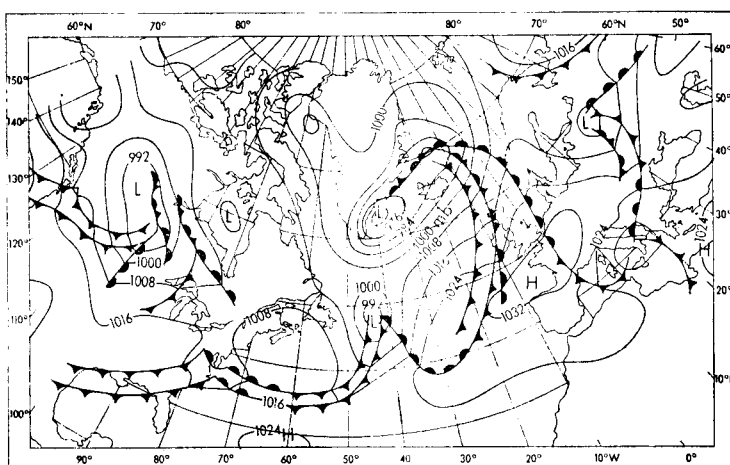


FIGURE 11—SURFACE CHART, 0000 GMT, 2 MARCH 1961

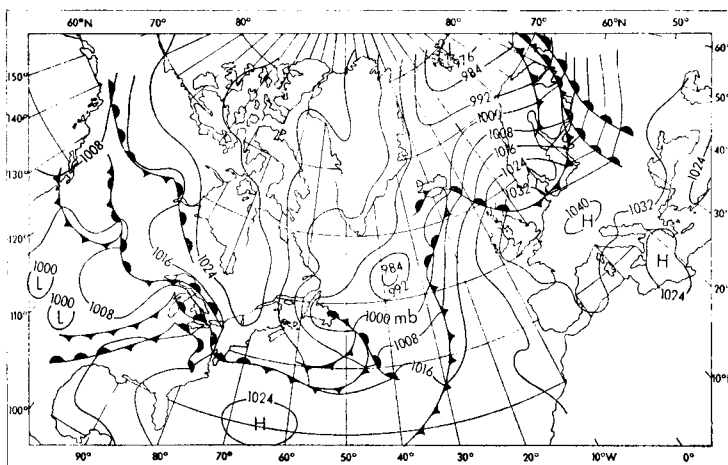


FIGURE 12—SURFACE CHART, 0000 GMT, 5 MARCH 1961

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551.509:323:625.7

MINIMUM ROAD TEMPERATURES

By G. E. PARREY

Summary. Over a period in 1967-68 readings were taken at Watnall of a minimum thermometer whose bulb was in contact with a concrete road surface. Air minimum temperatures were also read and the individual differences between air minimum and road minimum were plotted against the date over a seven-month winter period. A smoothed curve drawn through the individual differences showed a remarkable similarity to the curve giving the number of hours each day between sunset and sunrise i.e. the differences depended largely on the length of time available for outgoing radiation. An appropriate regression equation was constructed so that forecasts of air minimum could be used as a basis for forecasting road minimum.

Attempts to correlate road minima with other variables gave no useful results but a brief account is given of the trials.

Introduction. In an attempt to produce an aid for the forecasting of minimum road temperatures and hence the likelihood or otherwise of ice formation on road surfaces, an experiment was begun at Watnall in February 1967, whereby readings were taken of a grass-minimum thermometer which had been exposed overnight on a concrete road surface. The area of road selected for the experiment had to be free of both pedestrian and vehicular traffic and the best site that could be found was approximately 80 yards from the standard thermometer screen. The road itself and the surrounding land was horizontal and almost flat. The nearest obstruction was a small petrol installation about 5 feet high and 12 feet away from the thermometer site. The thermometer was placed horizontally with the bulb in contact with the road, a piece of wire about five inches long being looped round the end opposite the bulb to prevent the instrument from rolling.

The readings cover the periods February to the end of April 1967 and October 1967 to mid-May 1968. There was a break of about 10 days at the end of October 1967 due to the breakage of the thermometer.

Results. Attempts were made to find a correlation between the minimum road temperatures and various other variables, including the grass-minimum temperature, the mean cloud amount and geostrophic wind overnight as well as the general weather conditions. A comparison was made with the one-foot earth temperatures recorded daily at Nottingham Castle, five miles from Watnall.

It soon became apparent that the one relationship which was both significant and useful as a forecasting tool was the relationship between the date and the difference: minimum screen (or 'air') temperature minus minimum road temperature, ($M_A - M_R$). Figure 1 shows the values $M_A - M_R$ plotted against the date for the seven-month winter period October 1967 to

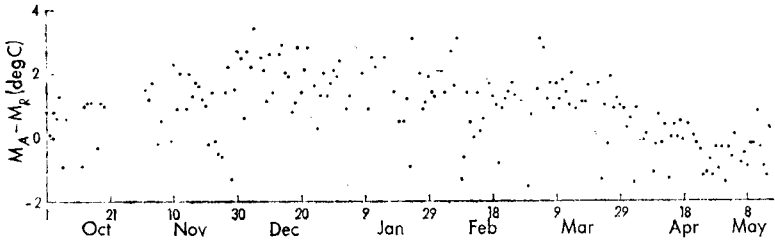


FIGURE 1—DIFFERENCE BETWEEN AIR TEMPERATURE, M_A , AND ROAD TEMPERATURE, M_R , AT WATNALL, OCTOBER 1967–MAY 1968

April 1968. To assist in drawing a smooth curve through these points, 31-day running means were calculated and plotted in Figure 2. Root-mean-square deviations of the individual daily values from the smoothed curve were calculated for each of the 10-day periods 1–10 October, 11–20 October and so on (see Table I).

TABLE I—ROOT-MEAN-SQUARE DEVIATIONS* FOR 10-DAY PERIODS 1 OCTOBER 1967–28 APRIL 1968

October			1967 November			December		
1–10, 0·7	11–20, 0·7	21–30, —	31–9, 1·0	10–19, 0·6	20–29, 1·4	30–9, 1·0	10–19, 0·8	20–29, 0·7 degC
January			1968 February			March		
30–8, 0·9	9–18, 1·0	19–28, 1·2	29–7, 0·9	8–17, 1·3	18–27, 0·7	28–8, 1·4	9–18, 0·7	19–28, 1·0 degC
			29–7, 0·7	8–17, 0·7	18–28, 0·6 degC			

* Evaluated from the smoothed curve of Figure 2.

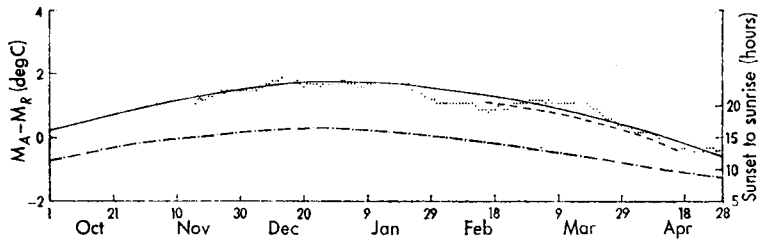


FIGURE 2—GRAPHS OF (a) DIFFERENCE BETWEEN AIR TEMPERATURE, M_A , AND ROAD TEMPERATURE, M_R , (31-DAY RUNNING MEANS) AND (b) NUMBER OF HOURS FROM SUNSET TO SUNRISE

- (a) $M_A - M_R$: Plotted points are 31-day running means, Oct. 1967–April 1968
Smoothed curve for Oct. 1967–April 1968 —————
Smoothed curve for Feb. 1967–April 1967 - - - - -
- (b) Number of hours from sunset to sunrise

Although the individual differences $M_A - M_R$ for the period February to April 1967 are not shown, an additional smoothed curve, obtained by taking 31-day running means, is drawn for this period in Figure 2 and is seen to be in close agreement with the curve for the following year. Also drawn in Figure 2 is a curve showing the number of hours, each day, between sunset and sunrise. The similarity between the two curves is remarkable.

It is interesting to note that the results obtained at Watnall are somewhat similar to those obtained in 1925 by N. K. Johnson and E. L. Davies.¹ Only monthly means are given in their paper for a plot of tarmac 15 cm deep and 1 m square, with an ordinary minimum thermometer set 1 cm below the surface. The values are given in Table II (converted to degrees Celsius for comparison) :

TABLE II—A COMPARISON OF MEAN TEMPERATURES IN AIR (SCREEN) AND IN TARMAC, FROM READINGS MADE IN 1925¹

Month	Mean air minimum temperature	Mean tarmac minimum temperature <i>degrees Celsius</i>	Difference
October	6.0	6.5	-0.5
November	1.2	0.0	1.2
December	—	—	—
January	1.7	1.3	0.4
February	0.8	0.3	0.5
March	-0.2	-0.2	0.0
April	1.7	2.3	-0.6

As previously mentioned, attempts to correlate the minimum road temperatures with other variables proved abortive but a brief account of these trials will be given.

Values of $M_R - M_G$ (where M_G is grass-minimum temperature) were plotted against the date. There appeared to be some relationship between the temperature difference and the date, or length of night, but in the opposite sense to that shown by $M_A - M_R$. However, the dispersion about the mean was too great for the relationship to have practical value.

It may be objected that the deviations of the individual values of $M_A - M_R$ from the mean curve are too great for practical value. Some of the occasions when departures (both positive and negative) from the curve were great were therefore examined in more detail to see if any consistent reason for the departure could be found.

TABLE III—A SELECTION OF OCCASIONS WHEN DEPARTURES FROM THE MEAN CURVE OF $M_A - M_R$ WERE LARGE

Date	Departure from curve	Mean cloud amount	Overnight weather	Mean geostrophic wind knots
$M_A - M_R > \text{curve}$				
13 November 1967	2.0	7	drizzle	22
5 December 1967	1.8	5	drizzle	37
14 January 1968	1.7	8	rain and drizzle	31
16 January 1968	1.7	7	rain	31
$M_A - M_R < \text{curve}$				
15 April 1967	1.3	obscured	fog	15
6 October 1967	1.3	8	rain	25
21 November 1967	1.5	8	drizzle	8
23 November 1967	1.5	8	drizzle	9
24 November 1967	1.9	8	drizzle	6
25 November 1967	2.0	8	rain	8

On most of the occasions in Table III there were seven or eight oktas of cloud accompanied by precipitation. There was also a predominance of strong winds when the difference $M_A - M_R$ was greater than would have been expected from the smoothed curve, but it has already been noted that there is little correlation between $M_A - M_R$ and wind speed. It was therefore decided to examine all occasions when there was (i) complete cloud cover throughout the night with some precipitation and (ii) complete cloud cover and no precipitation. Both exercises proved inconclusive because there were many occasions when one or other of the above conditions was satisfied and yet $M_A - M_R$ fell close to the curve.

To establish whether or not there is a relationship between the minimum road temperature and the one-foot earth temperature, the daily differences $M_A - M_R$ recorded at Watnall were compared with the daily differences between the air minimum and the one-foot earth temperatures recorded at Nottingham Castle over the same period. The correlation coefficient was 0.08. The daily values of one-foot earth temperature at Nottingham Castle were compared with the Watnall $M_A - M_R$ values and the correlation coefficient was found to be 0.28.

Results show that the minimum road temperature is influenced by both cloud amount and wind speed — as indeed is the minimum air temperature. The correlation coefficient between $M_A - M_R$ and mean cloud amount was 0.09. The correlation with wind speed was not calculated but a comparison of the appropriate plotted values indicated no significant relationship.

It was thought that perhaps the day temperatures (at screen level) over, say, the previous two days might have some bearing on the night-time depression of the road temperature below air temperature. The correlation coefficient in this case, however, was only -0.38.

The predominant fact remains that, for a given road, the depression of the road temperature at night below the air temperature at four feet depends largely on the length of time available for outgoing radiation; the correlation coefficient for the 300 pairs of observations was 0.59. In the Watnall experiment, negative values were obtained especially when the time between sunset and sunrise fell below about 10 hours. The relationship between $M_A - M_R$ in degrees Celsius and the time between sunset and sunrise in hours (t) is given by the regression equation :

$$M_A - M_R = 0.28t - 2.9$$

This indicates that negative values of $M_A - M_R$ are to be expected when the time between sunset and sunrise falls below about 10 hours, although the scatter of the individual points about the curve is such that some of the daily values are negative at almost any time of the year.

Discussion. The night minimum temperature of a given road surface will depend upon (i) the amount of outgoing radiation, which in turn depends on the temperature of the ground surface and the length of night, (ii) the back radiation, which depends upon the water vapour content of the air, the cloud amount and thickness, (iii) any evaporation or condensation at the road

surface and (iv) conduction to, or from, lower layers of the ground. Geiger² shows that there are further contributions due to conduction and convection from the overlying air. Knighting³ and Lake⁴ both suggest that the latter contributions can be important under certain conditions. Most successful methods of forecasting the minimum air temperature take some account, in an empirical way, of factors (ii) and (iii). By taking the date, and hence the length of night, into consideration allowance is made for (i) and to some extent (iv).

One would also expect the minimum temperatures of the roads in a particular locality to vary with the type of material used in their construction, their colour and thickness and with the local topography.

The multiplicity of variables involved, and the difficulty in estimating them, make the direct mathematical approach to forecasting the road minimum temperatures almost insuperable. It is for this reason that the Watnall findings seem to offer a more practical, indirect approach. The air minimum temperature, given a good estimate of overnight cloud amount and geostrophic wind speed, can usually be satisfactorily forecast using one of several published methods. A single value may then be subtracted from, or added to, the forecast M_A to give a reasonable estimate of M_R according to the length of night.

One and a half winter seasons is of course too short a time in which to expect conclusive results from an experiment of this kind, but in view of the urgency and importance of the problem, this note is presented rather as an interim report than as a final solution. Readings from the original site at Watnall are continuing and it will be particularly interesting to compare these with the 'concrete minimum temperatures' which were introduced officially on 1 December 1968 using a standardized concrete slab in the screen enclosure.

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551.509.314:551.509.323

FORECASTING NIGHT MINIMUM AIR TEMPERATURE BY A REGRESSION EQUATION

By J. GORDON, J. D. PERRY and S. E. VIRGO, O.B.E.

Summary. A regression equation for forecasting night minimum air temperatures at Mildenhall was derived from data for 1967 and tested by using data for 1966 and 1968. The root-mean-square errors obtained were similar to those obtained by using McKenzie's tables or by using methods based on the cooling curves of Saunders. In practice there is little to choose between the results obtained by any of the methods based on carefully constructed tables, cooling curves or regression equations.

Craddock and Pritchard¹ developed a regression equation as a means of forecasting night minimum screen temperatures in eastern England. Based on observations from 16 stations it is appropriate to a general area rather than to

a particular place. It was therefore decided to derive a regression equation for one particular place, Mildenhall, and to compare the results of forecasting night minimum air temperatures by this method with those obtained by McKenzie's method² based on a table also worked out specifically for Mildenhall.³

To accord as nearly as possible with the way in which Craddock and Prichard selected their cases it was decided that the criteria should be that the change in dew-point should be 2 degC or less at Mildenhall, that no noticeable front should have passed during the period and that nights when fog formed should be excluded. Like Craddock and Prichard the present authors chose to relate the forecast minimum temperature with the 1200 GMT temperature (T_{12}) and dew-point (D_{12}).

Two regression equations were worked out using data for 1967, one based on 50 observations and the other based on a further 46 observations, making 96 in all. There was very little difference in the root-mean-square error. There was however a difference of about 0.4 in the numerical constant as measured in degrees Celsius. This gives some indication of the number of observations needed to construct a regression equation applicable to a single station.

Craddock and Pritchard used a single regression equation for the whole year but Tinney and Menmuir,⁴ in an investigation of the Saunders method of forecasting night minimum temperatures^{5,6} at several stations, including Mildenhall, divided the year into two seasons: summer from April to September and winter from October to March. Two regression equations were therefore constructed, one for each season, and the forecast minima compared with those from a single equation for the whole year. Extreme values of T_{12} and D_{12} were inserted in the three equations and, as the value of T_{min} obtained from a seasonal equation did not differ by more than 0.7 degC from T_{min} obtained from the equation for the year as a whole, it was decided that a single equation would suffice.

When the regression equation for the year as a whole was finally worked out, it was found that there was no significant difference between the coefficients of T_{12} and D_{12} . In the equation the same coefficient could therefore be assigned to T_{12} and D_{12} ; this was very convenient as it enabled the equation to be presented to forecasters by means of a simple table. The equation for Mildenhall is

$$T_{min} = 0.395 (T_{12} + D_{12}) - 1.334$$

Temperatures are in degrees Celsius. The correlation between T_{min} and $(T_{12} + D_{12})$ was 0.87 and the root-mean-square error was 2.34 degC.

Craddock and Pritchard worked out a correction table to allow for variations in mean gradient wind speed and cloud amount during the night. Although this was based on observations at 15 other stations besides Mildenhall the corrections are generally so small that the table has been accepted as applicable to Mildenhall alone without calculating afresh.

The working papers from a previous investigation,³ including forecasts of cloud amount and wind speed, were available, so that the equation could be tested on a whole year's data from 13 January 1966 to 12 January 1967.

The following were the root-mean-square errors :

McKenzie	2.09 degC
Regression equation	2.20 degC

A subsequent test on current data for the period 16 January 1968 to 15 January 1969 gave the following root-mean-square errors :

McKenzie	2.14 degC
Regression equation	2.30 degC

Although the difference between the results by McKenzie's method and by regression equation is statistically significant at the 5 per cent level, there is little to choose between them in practice as no forecaster is interested in differences of less than 0.2 degC. Moreover the regression equation was based on 96 cases but the McKenzie table was based on 704 cases; it is therefore possible that the difference may be in some measure a reflection of the quantity of data used in obtaining the table and the equation respectively.

Gordon and Virgo³ found a root-mean-square error of 2.16 degC for Mildenhall for the first period (13 January 1966 to 12 January 1967) by the method of Saunders. It is therefore fair to conclude that there is very little to choose between the results obtained by any of these three methods in practice, provided that sufficient trouble is taken to establish a reliable basis (in the form of a table, a regression equation or a set of cooling curves) for whichever method the forecaster intends to use.

Acknowledgement. The authors thank the forecasters at Mildenhall for carrying out the test.

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HONOURS

The following awards were announced in the Queen's Birthday Honours List 1969:

I.S.O.

Mr. J. K. Bannon, Assistant Director (Public Services) Meteorological Office.

B.E.M.

Mr W. T. Newman, the officer in charge of the HMSO unit at Bracknell.

NOTES AND NEWS

551.5:92

Retirement of Commander C. E. N. Frankcom, O.B.E.

Commander Frankcom retired from his post as Marine Superintendent of the Meteorological Office on 27 June 1969. He was appointed to this post in January 1939. During the past three decades, therefore, his career has spanned some of the most momentous years in meteorology and he has been closely associated with all major developments concerned with maritime meteorology, including the organization of observations by the voluntary observing fleet and by ocean weather ships.

Commander Frankcom was born in Wiltshire in 1903 and at the age of 15 he joined H.M.S. *Conway* for training and subsequently served an apprenticeship with the Royal Mail Lines Ltd. He obtained his Second Mate's certificate in 1924 and became an Extra Master six years later. In 1933 he transferred to the Bristol City Line and in a short while was appointed Master of the *New York City* which operated on the North Atlantic trade. From the early days of his career Commander Frankcom has also served in the Royal Naval Reserve and has gained much experience in submarines.

In 1935 Commander Frankcom was appointed a Nautical Surveyor and Examiner in the Board of Trade and held this post until January 1939 when he joined the Meteorological Office as Marine Superintendent and Editor of the *Marine Observer*. An important undertaking during his early years in the Office was the preparation of climatic atlases of the oceans, using the data assembled from ships' logs since the early 19th century. This work was interrupted, however, in November 1940 when Commander Frankcom went on active service with the Royal Navy and was appointed Commodore of coastal convoys. For these duties he was made an Officer of the Most Excellent Order of the British Empire. From 1943 onwards he was engaged in combined operations in the Mediterranean and at the end of the Second World War he left the Royal Navy and resumed his post as Marine Superintendent in the Meteorological Office.

At the end of the war there were two major tasks in marine meteorology — the reorganization of the voluntary observing fleet and the establishment of the North Atlantic Ocean Station System. Commander Frankcom played a leading part in all this work and from 1946 until 1956 he was President of the World Meteorological Organization (WMO) Commission for Maritime Meteorology. From 1954 until his retirement he was Chairman of the Advisory Committee of European Operating States on North Atlantic Ocean Stations. Commander Frankcom has also represented the World Meteorological Organization at many meetings of other international organizations including the Inter-Governmental Maritime Consultative Organization and the International Load Line Convention.

Commander Frankcom is a member of the Honourable Company of Master Mariners, a Fellow of the Institute of Navigation and a Member of the Challenger Society and of the Society of Underwater Technology. He has written numerous articles concerning ocean networks, ocean currents, meteorological problems of ships' cargoes, and the weather routing of ships.

In meteorology, national or international, we have come to regard Eddie Frankcom as an immense figure. Well known in many international organizations besides WMO, he has earned respect and admiration for his enthusiasm, his spirit of co-operation, and his ability to appreciate what was required for maritime meteorology and to organize its fulfilment. In a lifetime of unending activity in his profession, he nevertheless found time to join in a host of social and cultural pursuits which are so important in the corporate life of large organizations. In sport, amateur dramatics, and in many other ways Eddie Frankcom has given much by his leadership, his enthusiasm and his sense of fun. In 1968 he was awarded the Sutton Rose Bowl as the one who had done most for the social and sporting life of the Meteorological Office. He has had a splendid career and both meteorology and meteorologists owe much to him. His impact remains and will be lasting.

We all wish Eddie and his wife a long and happy retirement.

P.J.M.

REVIEWS

The weather business, by Bruce W. Atkinson. 140 mm×215 mm, pp. 192, illus., Aldus Books Ltd, 17 Conway Street, London, W.1., 1968. Price: 16s.

This book is a very comprehensive review of the weather business. The first chapter deals with the effect of weather on the human body and on agriculture, transport and industry. The second chapter deals with routine observations and then discusses three types of non-routine observations: those designed for the United States National Severe Storms Project, aircraft reports and cloud photogrammetry. The third and fourth chapters deal in detail with analysis of surface and upper air charts and short-range forecasting by the human forecaster; they also deal with numerical prediction and long-range forecasting. The fifth chapter reviews the possibilities of modifying the weather and climate, and the last looks to the future under the title 'Prospect'.

The author has obviously read widely and is well informed about recent developments. He has organized his facts and presentation well, and the book is well produced in clear type and lavishly illustrated with coloured diagrams and photographs. These are right up to date; they include photographs of an automatic chart plotter, a zebra chart drawn by computer and pictures from weather satellites. The diagram of the vertical cross-section through a warm and a cold front on page 64 therefore comes as a shock. The cloud sequence ahead of a typical warm front is well known, starting with cirrus and ending with a bank of nimbostratus of considerable vertical extent; but the cloud in the diagram bears no relation to this sequence. Furthermore, it is questionable whether the zone of transition from moist to dry air above the cold frontal zone is a vertical column as shown in the diagram. The warm front in the diagram seems to be derived from a model of cyclonic development in a continuous baroclinic fluid. This is a research tool which, it is hoped, may lead to a clearer understanding of the dynamical meteorology of a cyclone, but something has yet to be done to the model to make it yield the cloud

formation which actually occurs. This is not made clear in the book. Moreover, on the middle of the three figures higher up on the same page there is an inexplicable kink in one of the isobars.

Although the reviewer enjoyed reading the book, it is difficult to envisage the reader for whom it is intended. There is too much detail about station plotting models, tephigrams, hodographs and the like to interest the general reader. Moreover, on page 86 the reader is suddenly confronted with wet-bulb potential temperature without explanation and on page 122 he meets 'the partly filtered nongeostrophic model'. Even with the explanation which follows the general reader might find this somewhat abstruse. If, however, the book is intended as background reading for practising meteorologists, details of codes and plotting models and elementary analysis are superfluous as they will have learnt about these elsewhere. Perhaps (as the author is a lecturer in geography at Queen Mary College, London University) it is intended for students of geography.

Although the book is from an English publisher, it has a mid-Atlantic flavour: 'center' and 'sulfate' appear in the text. The author also gives the concentration of silver iodide particles under certain circumstances in cloud-seeding experiments as $10^{12.7}$ per gram — an unusual index! 5×10^{12} would be easier to understand.

S. E. VIRGO

Climate and weather, by Hermann Flohn. 190 mm × 130 mm, pp. 253, *illus.*, World University Library, Weidenfeld and Nicolson, 5 Winsley Street, London, W.1, 1969. Price: 30s. (paperback, 18s.)

This is the English translation by B. V. de G. Walden of Professor Flohn's recently published book in the World University Library series. Professor Flohn is of course well known for his fine work in climatology and synoptic meteorology, particularly with reference to low latitudes. The book is intended primarily as an introduction to the subject for university students and the general reader.

As suggested by the title, the book covers a very wide range of topics, including radiation, cloud physics, atmospheric circulation, climatic variation and weather modification. Despite the nearly complete absence of mathematics the general treatment is essentially rigorous. The scientific basis of all aspects of climate and weather is emphasized and the discussion throughout is liberally supported with appropriate climatological statistics and numerical estimates of physical quantities. This thorough approach is evident right from the start in the first chapter on 'Radiation and the heat budget'. Here is a wealth of information on the physical processes in the atmosphere arising from the emission of solar radiation. This long first chapter certainly gets down to the basic physics and contains a very useful summary for most meteorologists, but it may be rather heavy going in places for the general reader for whom the work is mainly intended; however, he would be well advised to persevere because the chapters which follow tend to become more readable and, at least to the reviewer, more interesting.

Synoptic meteorology and forecasting are presented as problems in mathematical physics which depend for their practical solution primarily on

modern technology and on a much improved observational network, but Professor Flohn wisely leaves in a caveat on our present lack of knowledge of the limits of predictability.

The very informative chapter on 'Climate and climatic zones' should present no difficulty to the general reader. Here in particular the reviewer gained the impression that most of the places so aptly and refreshingly referred to for illustrative purposes were indeed personally known to Professor Flohn.

The chapter on 'Climatic variations' makes adequate reference to the work of three British meteorologists, C. E. P. Brooks, G. Manley and H. H. Lamb. The ground covered is fairly well-worn, but the chapter should make interesting reading to the non-specialist, covering as it does such topics as temperature and rainfall variations from instrumental records, the observations of the retreat and advance of glaciers, the possible effects on radiation and circulation of dust thrown into the atmosphere by volcanic eruptions, the dating of tree rings and fossilized pollen by radio-carbon techniques. The final chapter on 'Weather and climate modification' naturally follows. The themes are mainly the activity in cloud seeding in the past 20 years, the modifications in microclimates, for example, by planting trees and hedges and possible influences on the macroclimate by various means, for example, by reducing the albedo of snow and ice in May, but clearly the ultimate effects of man's intervention, especially on the scale of the macroclimate, are far from certain.

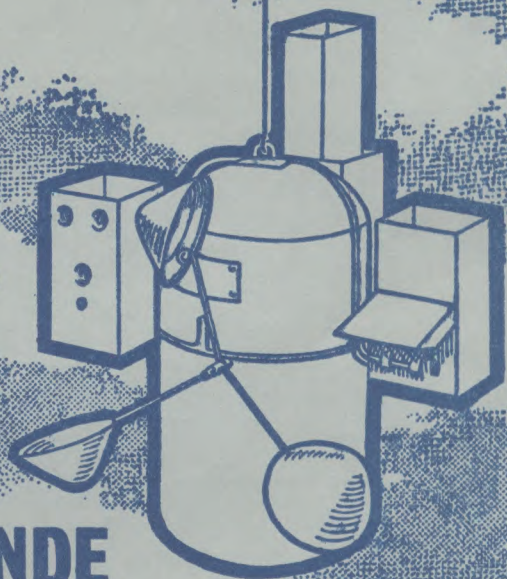
This book is undoubtedly very good value for money. It should prove helpful to the professional meteorologist as well as to the general reader for whom the book is primarily intended.

R. A. MURRAY

CORRECTION

Meteorological Magazine, July 1969, p. 215. In the caption to Figure 18, for 'Summer' read 'High summer' (July–August).

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'for Meteorological Magazine.'

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NIGHT MINIMUM TEMPERATURES AT OR NEAR VARIOUS SURFACES

By W. G. RITCHIE

Summary. Minimum temperatures were obtained over the period October 1967–September 1968 at Wyton for thermometers in contact with concrete and with bitumen-covered concrete. The differences were small and the lower reading was taken as ‘road minimum’ and found to be generally higher than the minimum over grass and slightly higher than the minimum over bare soil.

Readings from two concrete sites and from two grass sites showed that the concrete (or road) minimum temperatures were less erratic spatially than the grass minimum temperatures.

The daily values of air minimum minus road minimum were found to be dependent on the length of night from sunset to sunrise. In winter the daily values were always within 2 degC of the curve fitted to the observed depressions of road minimum below air minimum.

No useful results were obtained from readings of a thermometer whose bulb was 2 inches below the concrete surface.

Purpose of the investigation. For a great many years it has been standard meteorological practice to expose a grass minimum thermometer nightly on a lawn of short grass between 1 in and 2 in above the ground and in contact with the tips of the grass blades.¹ The results are used mainly for forecasting ground frost over grassland, but forecasters are also required to predict frost on roads and runways, and no comparable measurements have been taken as a routine over surfaces of this kind. Indeed very little is known about minimum temperatures over concrete and how they compare with corresponding measurements over grass. An experiment was therefore set up in an open exposure on the airfield at Wyton, Huntingdonshire, in an attempt to increase our knowledge of this subject, and this paper reports the results of the first year’s observations from October 1967 to September 1968.

Comparison of grass minimum temperatures at neighbouring sites. One question which must be asked is: What is the order of accuracy of a grass minimum temperature and what is the standard deviation between the readings of two grass minimum thermometers exposed a short distance apart on a flat grass surface? To answer this question two identical grass minimum thermometers were exposed nightly in open exposures on a flat sward 30 yards apart. Thermometer A was the thermometer in the enclosure and thermometer B was set up specially for this experiment. Monthly mean values of (A – B) and standard deviations in degC are given in Table I. (Tables I–V appear together overleaf.)

TABLE I — COMPARISON OF GRASS MINIMUM TEMPERATURES AT NEIGHBOURING SITES A AND B

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Year
Monthly mean (A - B)	+0.4	-0.4	-0.7	-0.7	-1.1	-0.5	-0.8	-0.7	-0.4	-0.3	+0.2	0.0	-0.4
Standard deviation	0.7	0.9	0.6	0.7	0.8	0.7	1.2	0.9	0.8	0.8	0.6	0.7	0.9

TABLE II — COMPARISON OF MINIMUM TEMPERATURES AT BITUMEN-COATED AND PLAIN CONCRETE SURFACES

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Year
Monthly mean*	+0.1	0.0	0.0	+0.1	+0.1	+0.3	-0.2	-0.2	-0.4	-0.4	-0.3	-0.1	-0.1
Standard deviation	0.3	0.3	0.4	0.3	0.3	0.4	0.3	0.2	0.3	0.4	0.3	0.3	0.4

* of plain concrete minimum temperature - bitumen-coated concrete minimum temperature

TABLE III — MONTHLY MEAN DIFFERENCES BETWEEN ROAD MINIMUM TEMPERATURES AND BARE SOIL MINIMUM TEMPERATURES

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Year
Mean*	+0.7	+0.2	+0.3	+0.2	0.0	+0.7	+1.8	+1.5	+1.8	+1.3	+0.7	+1.5	+0.9
Standard deviation	0.4	0.5	0.8	0.4	0.4	0.8	1.0	0.6	0.9	1.0	0.6	0.9	1.0

* of road minimum temperature - bare soil minimum temperature

TABLE IV — MONTHLY MEAN DIFFERENCES BETWEEN ROAD MINIMUM TEMPERATURES AND GRASS MINIMUM TEMPERATURES

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Year
Mean*	+1.7	+1.3	+0.9	+0.9	+1.4	+1.7	+2.8	+2.3	+2.7	+2.2	+1.1	+1.5	+1.7
Standard deviation	0.8	1.1	0.6	0.8	0.9	1.1	1.2	1.3	1.2	1.5	0.9	0.9	1.2

* of road minimum temperature - grass minimum temperature

TABLE V — MONTHLY MEAN DIFFERENCES BETWEEN AIR MINIMUM TEMPERATURES AND ROAD MINIMUM TEMPERATURES

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Year
Mean*	+1.2	+1.1	+1.8	+1.4	+1.0	+1.3	0.0	-0.6	-0.7	-0.8	-0.2	+0.2	+0.5
Standard deviation	0.5	0.9	0.6	0.8	0.7	0.7	0.9	0.9	1.2	0.9	0.7	0.7	1.2

* of air minimum temperature - road minimum temperature

The graph of frequency of occurrence of values of (A - B) together with the normal frequency distribution curve for a standard deviation of 0.9 and 358 observations (8 observations were missed) are shown in Figure 1. The distribution is not normal for values of (A - B) within 0.8 degC of the mean, and this range includes 72 per cent of the cases. The seasonal variation was statistically significant at the 1 per cent level. The differences are thought to be due to the slightly different exposures, A being a little more open than B, and to differences in the grass. For the rest of this paper the readings of the thermometer outside the instrument enclosure have been used as the grass minimum temperatures because this thermometer is close to those on the concrete.

Method of exposure of thermometers on the various surfaces. It is not easy to measure the temperature of a surface. Robinson² exposed a grass minimum thermometer directly on close-cut grass and concluded that the surface behaved like a black body radiating at the temperature shown by the thermometer. On this basis it was decided to expose grass minimum thermometers resting with the bulbs in contact with the various surfaces and to assume that they would give the minimum temperatures of the surfaces. Figure 2 is a sketch plan of the site showing the positions of the thermometers.

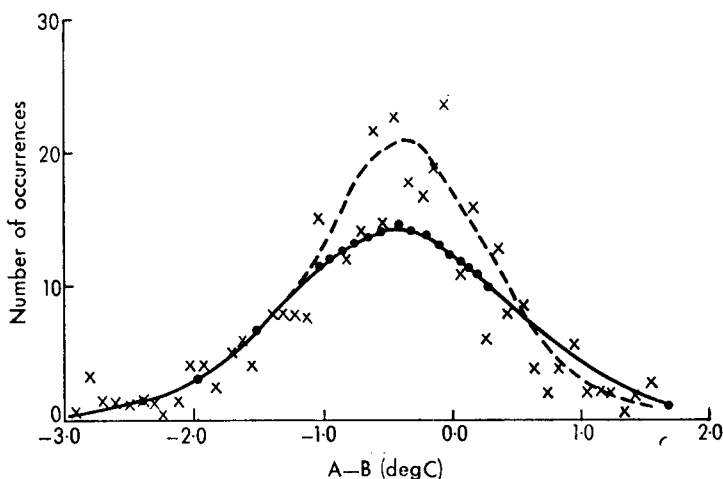


FIGURE 1 — DISTRIBUTION OF THE DIFFERENCES BETWEEN TEMPERATURES AS MEASURED BY TWO GRASS MINIMUM THERMOMETERS

x — — — x number of occurrences of values of A - B
 · — — — · normal frequency distribution curve

All thermometers other than the grass minimum thermometers were resting on the surface with the bulb in contact with the surface. The top ends of the thermometers were inserted in strips of wood four inches long; this tilted the thermometers slightly and kept the bulbs in contact with the surface and also prevented rolling. All thermometers except number 5 are minimum thermometers. The positions of the thermometers are as follows:

Minimum thermometer 1 : At the centre of the signal square which is made of concrete 6 inches thick and is painted at least once a year with a thick coat of black bituminous paint. The sides of the square are 30 feet and the nearest side is 66 feet from the control tower which is the nearest building.

Minimum thermometer 2 : At the centre of the strip of concrete which was separated from the signal square by 24 feet of grass. The concrete is 6 inches thick and 24 feet wide.

Minimum thermometer 3 : A grass minimum thermometer conveniently supported at the centre of the grass strip and in line with thermometers 1 and 2.

Minimum thermometer 4 : At the centre of a 3-foot square patch of bare soil near the middle of the grass strip.

Thermometer 5 : A 2-inch bent-stem thermometer embedded in mortar in a crack in the centre of the concrete strip.

It was necessary to protect each thermometer from accidental damage without appreciably affecting the exposure of the ground to the night sky. The protection consisted of a framework of angle-strip aluminium (1/10 in thick, 1/2 in wide) in the form of an open 2-ft square with a 2-ft leg at each corner (see Figure 3).

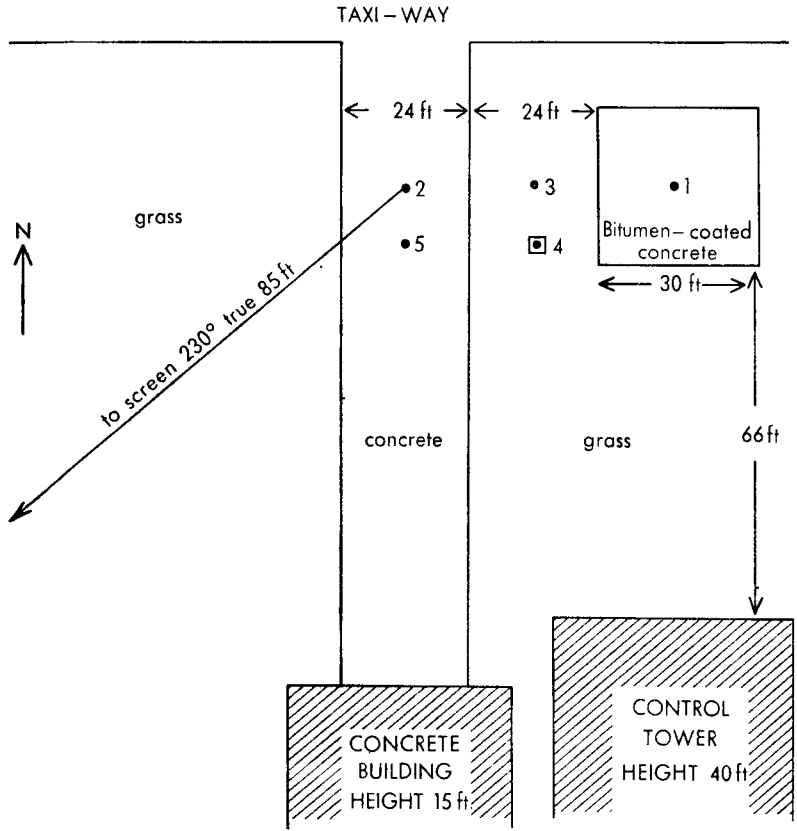


FIGURE 2 — PLAN OF SITE

- 1 = Minimum thermometer on bitumen-coated concrete
- 2 = Minimum thermometer on concrete
- 3 = Minimum thermometer on grass
- 4 = Minimum thermometer on bare soil
- 5 = 2-inch bent-stem thermometer in concrete

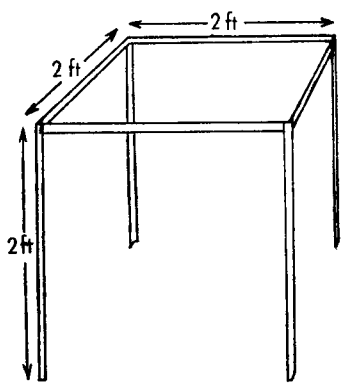


FIGURE 3 — THERMOMETER PROTECTION

The base of each leg, over concrete and tarmacadam, was inserted into a piece of lead piping about 2 inches long to prevent movement by wind. The thermometer was arranged so that the bulb was centrally placed beneath the framework.

Thermometers 1 to 4 were read at 09 GMT and thermometer 5 at 12 GMT.

Comparison of minimum temperatures at two concrete surfaces 300 yards apart. For reasons unconnected with the experiment it was necessary to transfer minimum thermometer 2 to another piece of concrete at the end of the year. Concrete minimum temperatures were read at both sites from 1 June till 30 September 1968. The standard deviation of the differences was 0.4 degC. The standard deviation of the differences between two grass minimum temperatures (Table I) for the same period was 0.8 degC. The standard deviation of the differences of the concrete minimum temperature was thus only half that of the differences between the grass minimum temperatures, even though the 'concrete' thermometers were much farther apart. Dight (personal communication) obtained a similar result at Edinburgh/Turnhouse.

Comparison of minimum temperatures at bitumen-coated and plain concrete surfaces. Monthly mean values and standard deviations of plain concrete minimum temperature minus bitumen-coated concrete minimum temperature are given in Table II. This shows that minimum temperatures were slightly lower at the bitumen-coated surface from October to March, and slightly lower at the plain concrete surface from April to September. These differences are smaller than had been expected in view of the different colours of the surfaces. The distribution of the differences between plain concrete and bitumen-coated concrete minimum temperatures is shown in Figure 4. The distribution differs from a normal distribution in the

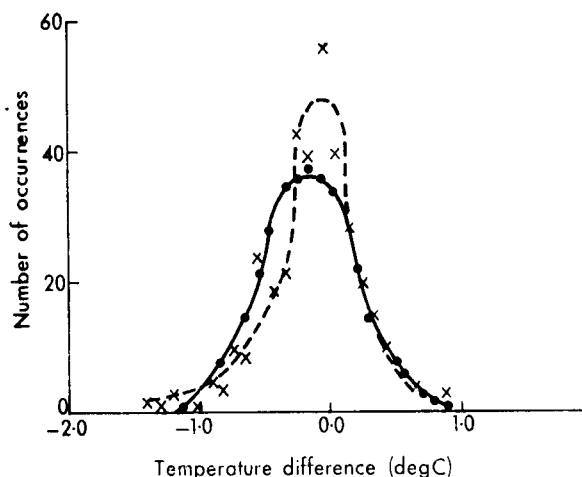


FIGURE 4 — DISTRIBUTION OF THE DIFFERENCES BETWEEN MINIMUM TEMPERATURES ON PLAIN CONCRETE AND THOSE ON BITUMEN-COVERED CONCRETE

x - - - - x number of occurrences
 · ———· normal frequency distribution curve

range $+0.1$ degC to -0.2 degC and this includes half of the cases. As, however, the differences are so small and the number of very small differences is above average, it seems reasonable to assume that minimum temperatures at these two surfaces can be considered to be the same. The lower of these temperatures is called the 'road minimum temperature' for the rest of this paper.

Minimum temperatures over bare soil. Figure 2 shows that the thermometer on bare soil was between the 'concrete' thermometers and in line with them. Monthly mean values of road minimum temperature minus bare soil minimum temperature are given in Table III. From March to October the road minimum temperature was almost always higher than the bare soil minimum temperature; from November to February the road minimum temperature was lower on 28 per cent of occasions. The seasonal variation was statistically significant at the 1 per cent level.

Comparison of road minimum temperature and grass minimum temperature. The road minimum temperature was higher than or equal to the grass minimum temperature on 96 per cent of occasions. Monthly mean values of road minimum temperature minus grass minimum temperature are given in Table IV. The largest value was 6.0 degC in April.

Depression of road minimum temperature and grass minimum temperature below air minimum temperature. Monthly mean values of air minimum temperature minus road minimum temperature are given in Table V; daily values are shown on the upper part of Figure 5. The curve-fitting was confirmed by computer. A Fourier analysis showed that the curve was closely represented by a simple sine curve, the harmonics being negligible.

The equation is:

$$y = 0.48 + 1.22 \sin x$$

where y is the depression in degC and x is the day as an angle assuming 365 days = 360° .

The largest departures from the curve occurred in the summer months. For the purpose of forecasting ice on roads and runways the daily values between November and March were always within 2 degC of the curve and on most occasions within 1 degC of it.

Parrey³ took road minimum temperatures at Watnall during the winter months in 1967-68 and he concluded that 'for a given road, the depression of the road temperature at night below the air temperature at four feet depends largely on the length of time available for outgoing radiation'; he showed this diagrammatically by superimposing a curve of the duration from sunset to sunrise on the annual trend of depression of road minimum temperature below air minimum temperature. The length of night from sunset to sunrise at 52°N is drawn in the lower part of Figure 5. It fits the curve of air minimum temperature minus road minimum temperature with a very slight lag and strongly supports Parrey's conclusion. J. S. Hay⁴ considered road and air minimum temperatures on the M1 motorway near Newport Pagnell and on a slip road off the M4 motorway near Bray Wick. He found smaller mean values of air minimum temperature minus road minimum temperature, but larger extreme values.

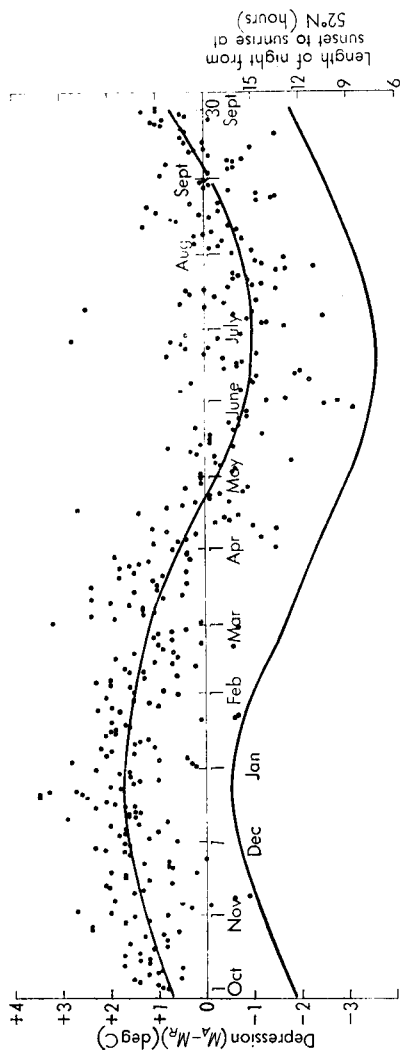


FIGURE 5—DEPRESSION OF ROAD MINIMUM BELOW AIR MINIMUM TEMPERATURE (UPPER CURVE) COMPARED WITH LENGTH OF NIGHT (LOWER CURVE)

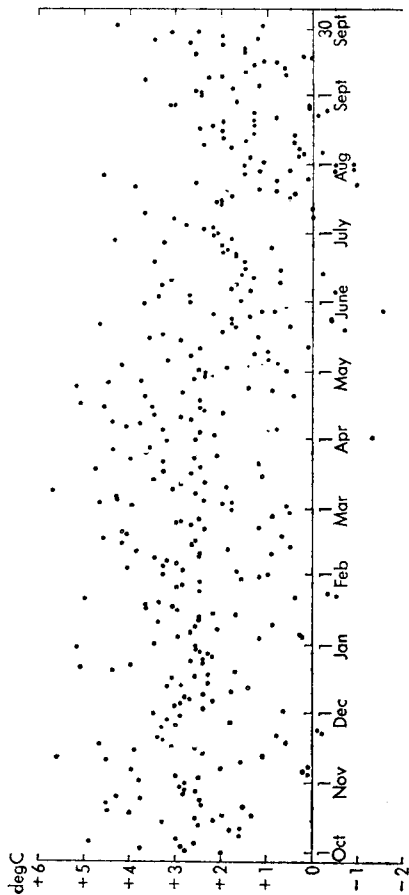


FIGURE 6—AIR MINIMUM TEMPERATURE MINUS GRASS MINIMUM TEMPERATURE AT WYTON—OCTOBER 1967 TO SEPTEMBER 1968

Daily values of air minimum temperature minus grass minimum temperature are shown in Figure 6. The scatter is about twice that of air minimum minus road minimum temperature and no attempt has been made to draw a line of best fit.

Temperature of thermometer embedded in concrete. In winter at 12 GMT this temperature is usually (but not always) about 2 degC below the air temperature. In summer it is usually about 3 degC above the air temperature but on sunny days it can be 10 degC above. The value of the 12 GMT temperature from within the concrete minus road minimum temperature read next morning shows large day-to-day variations — on one occasion it was 23 degC. No useful relationship between this difference and cloud and wind has yet become apparent. In the next stage of the experiment thermometers will be embedded at depths of 4 inches and 8 inches, and it is hoped that one of these will be at a depth to give a useful result.

Conclusions. As far as the results of one year's observations at one place can be considered to be of more general application, the following conclusions are suggested:

- (i) The depression of road minimum temperature below air minimum temperature is a function primarily of date, and can be obtained from a graph (Figure 5) to within 1 degC in most cases and to within 2 degC in all cases during the winter.
- (ii) Whether a road is made of concrete or concrete covered with bitumen seems to have very little effect on the minimum temperature at the surface. The two pieces of concrete on which this conclusion is based both had the same vertical thickness.
- (iii) Road minimum temperatures are less erratic spatially than grass minimum temperatures.
- (iv) Road minimum temperatures are almost always higher than grass minimum temperatures.
- (v) Road minimum temperature is normally slightly higher than the minimum temperature at the surface of bare soil.

Acknowledgements. The author thanks Group Captain D. S. V. Rake, O.B.E., A.F.C. for allowing the experiment to be carried out at Wyton and Mr S. E. Virgo, O.B.E. for helpful advice and criticism. He also thanks the Fire Section for cheerfully putting themselves to considerable inconvenience in avoiding the thermometers, and the staff of the Meteorological Office for willingly taking these non-standard observations.

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A DETERMINATION OF THE ALBEDO OF MORECAMBE BAY NORTH OF A LINE FROM ALDINGHAM TO BARE

By V. C. BENDELOW

Summary. Aerial photographs of Morecambe Bay were taken during low-tide situations in 1964 and 1967. Each photographic frame was divided into areas of ground-shade types based on photographic tone and the appearance of the surface texture. Ground measurements of albedo were made for each shade type and mean values obtained, from which an overall mean albedo of about 14 per cent was calculated for the area of Morecambe Bay under examination.

Introduction. In this study albedo, expressed as a percentage, is defined by the equation

$$A = \frac{I_r}{I_0} \times 100,$$

where I_r is the solar energy reflected by the surface and I_0 is the solar energy incident on the same surface for wavelengths in the region of 0.3 to 3.0 microns.

There were three main parts to the investigation:

- (i) The production of maps showing areal distributions of albedo in terms of ground shades on aerial photographs.
- (ii) The measurement (from the ground) of the albedo of each ground-shade type.
- (iii) The calculation of a mean value of the albedo for Morecambe Bay in a low-tide situation, using the values found in the previous two sections.

Method. The production of areal shade distribution maps was from aerial photographs of Morecambe Bay taken during low-tide situations. The limits of the area studied were taken as north of a line from Aldingham to Bare and the high-water mark on the coast, this being an area largely exposed at low tide (see Figure 1). High water extends the limit up the river Kent as far as Sampool Bridge and up the river Leven as far as Haverthwaite.

The possibility of using aerial photographs to estimate the albedo of the ground was first suggested and tested by Dr F. K. Hare and Dr S. Orvig in 1962.¹ They pointed out that those areas reflecting a high percentage of the incident radiation (high albedo) would appear light on aerial photographs. Similarly, areas of low albedo would appear dark. They also suggested that if the exact conditions of film, printing paper, exposure, development and printing were known, it should be possible to relate photographic shade to albedo. However, aerial photographs may appear to have the disadvantage, from the point of view of albedo studies, of being taken with a minus blue filter and of spanning only that part of the spectrum from 0.5 to 0.68 micron. Later investigation by Hare and Orvig showed that this comparatively narrow range of wavelengths is no great disadvantage.

Using this method, two ground-shade distribution maps for Morecambe Bay for the periods August 1964 and July to September 1967 were constructed from aerial photographs. In 1964 the photographs were taken at an altitude

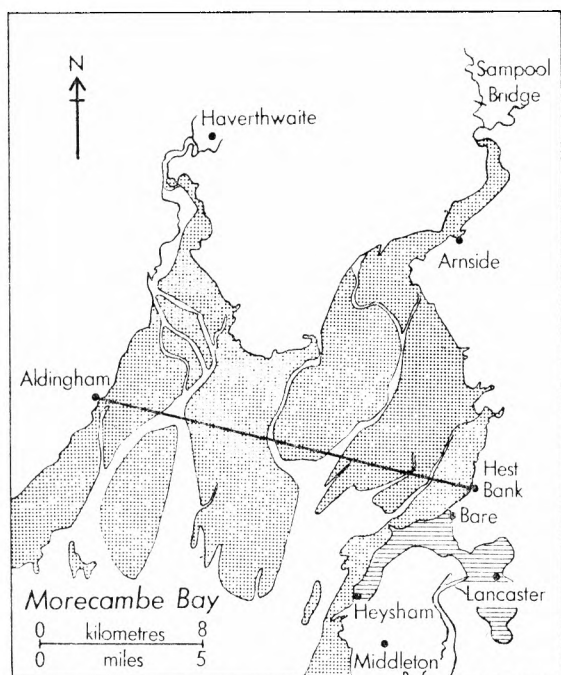


FIGURE 1 — THE MORECAMBE BAY AREA

The shaded part represents the extent of the sand which is exposed at low tide, and the hatching represents built-up areas.

of 10 000 ft on two consecutive days in August. In 1967 the altitude was 6000 ft and the photographic runs were made on six separate days. The method consisted of taking each photographic frame and dividing it up into ground-shade types, of which there are five.² The sub-division into types was based on photographic tone (using the Kodak grey scale) and appearance of the surface texture (using a stereoscope).

Since each aerial photograph overlaps the next in the run by 60 per cent, all areas of sand could be viewed on three consecutive frames. Also each run overlaps the adjacent run by 20 per cent, therefore areas within a 20 per cent border strip could be further checked with the adjacent photographic run.

Plate V shows an aerial photograph, taken at low tide, which has been divided into shade types to demonstrate the sub-divisions listed in Table I. The variation from the darkest to the lightest tones between the low and high water marks respectively is clearly seen, but the fact that the different shade types are clearly delineated suggests that the water content of the sand does not vary smoothly between high and low water mark.

Shade type (4) is clearly defined by the water's edge, while the line of demarcation between type (2) and type (3) may be related to the position of the water table. Shade type (1) was readily identified with salt marsh areas (using a stereoscope) while shade type (2 + 3) was associated with gulleys and streams.

TABLE I — SHADE TYPE SUB-DIVISIONS

Shade type	Surface texture	Grey scale number
(1)	Salt marsh	0.75-1.25
(2)	Dry sand	0.00-0.10
(3)	Wet sand	0.40-0.55
(4)	Water	0.75-1.00
(2+3)	Dry sand crossed by wet sand lattice*	0.00-0.55

*Dry sand crossed by a network of shallow streams giving the appearance of dark strips against a lighter base. These are not to be confused with ripples in uniform sand where the dark lines are shadows cast by the crests of the ripples.

Attempts to measure the albedo of each shade type from an aircraft flying at 200 ft (61 m) proved to be unsuccessful with the equipment and time available. The main calibration therefore had to be confined to measurements on the ground.

Ground measurements were taken using two solarimeters, one facing upwards and the other facing downwards, mounted on opposite ends of a horizontal bar a few feet above the ground and supported on a tripod. The readings were taken at Heysham, Middleton and Hest Bank at various positions along lines at right angles to the coast, all within a quarter of a mile of a central point for each shade type. Readings for shade (2 + 3) were limited to a transect down a gulley.

A mean albedo for the Bay was found by measuring the cumulative area of each shade type on both the 1964 and 1967 maps (using a planimeter) and assigning to each area the corresponding measured value of albedo. From these data an overall mean value of albedo was obtained for the Bay, north of a line from Aldingham to Bare, for low-tide situations.

Results. The results are summarized in Table II, showing the shade type distribution, and in Table III, showing the corresponding albedo values.

TABLE II—SHADE TYPE DISTRIBUTION

Shade type	1964		1967	
	Map area <i>cm</i> ²	Fraction of total area <i>per cent</i>	Map area <i>cm</i> ²	Fraction of total area <i>per cent</i>
(1)	404	8	600	4
(2)	434	9	606	4
(3)	1 468	30	8 932	52
(4)	584	12	1 755	10
(2+3)	1 972	41	5 071	30
Totals	4 862*	100	16 964*	100

*The difference in total map area is due to different map scales as the 1967 aerial photographs were taken at a lower altitude.

TABLE III—MEASURED VALUES OF ALBEDO

Shade type	Albedo (mean) <i>per cent</i>	Standard deviation <i>per cent</i>	Number of observations
(1) Salt marsh	15.7	2.4	20
(2) Dry sand	35.4 dry surface 17.0 damp surface	1.3 1.9	19 22
(3) Wet sand	15.9	1.8	21
(4) Water	10.8	0.4	16
(2+3) Lattice	12.7	0.8	10

Discussion of results.

Results for areas of different shade types. The two values of albedo given for shade type (2) require some explanation. In practice, sand areas of type (2) may embrace a wide range of surface moisture conditions. Under the driest conditions, when a greater proportion of the incident radiation is reflected, the albedo has a comparatively high value of about 35 per cent. But when sand of the same shade type and therefore of similar superficial appearance has a damp surface, less energy is reflected and the albedo has the much lower value of 17 per cent. This value may be compared with that obtained for shade type (3), i.e. wet sand, for which the albedo is about 16 per cent.

Presumably therefore, if the water content of sand of shade type (2) were progressively increased it would ultimately change its appearance from that of type (2) to that of type (3). This change in appearance is not however accompanied by much appreciable change in the albedo (17 per cent to 15.9 per cent, Table III).

Although a gradual transition in appearance from type (2) to type (3) areas may have been expected, the aerial photographs obtained show quite clearly that the change in appearance is quite abrupt. It is suggested that the well-defined boundary between sand of these two types is associated with the water table.

Since areas of shade type (2) with a damp surface have an albedo which does not differ appreciably from areas of shade type (3), it is convenient, under damp conditions, to group these two shade types together and attribute to them a mean value for the albedo of 16.5 ± 2 per cent. This then is the value that could be expected from both shade types during periods of prolonged rainfall or when low tide occurs in the early morning or late evening. It could even possibly apply during most of the winter months.

The lower value of 12.7 per cent for surface areas of type (2+3), i.e. 'dry' sand covered by wet sand lattice, can be explained satisfactorily by the fact that little, if any, of this type of surface is likely to be completely dry and that there will almost certainly be some surface water present which will absorb a greater proportion of the incident radiation.

A 'Student's' *t*-test carried out on these results showed that type (2) (damp surface) and type (3) probably belong to the same population whereas type (2+3) does not.

Finally, a comparison may be made between the mean albedo value of 10.8 per cent obtained for areas of shade type (4), i.e. water-covered areas at low tide, and the mean value for water alone, i.e. 8 per cent. The higher value of 10.8 per cent corresponds to turbid water near the shore. Thus for water under conditions of high turbidity in a shallow sandy estuarine area a higher value of albedo is obtained than for areas of deep water. It would be particularly interesting to know the precise value of albedo for the whole area at high tide, to compare its value with the known value for deep water, and also to investigate its variation (if any) with the depth of water in the Bay.

Results for the whole area. The value for the effective albedo for the whole area for low-tide situations in August 1964 and July–September 1967 may be summarized as follows:

- (i) Under dry conditions, with albedo value 35.4 per cent for shade type (2) :
Mean overall albedo 1964 : 15.5 per cent.
Mean overall albedo 1967 : 15.1 per cent.
- (ii) Under wet conditions, grouping shade types (2) damp and (3) together and allocating an albedo of 16.5 per cent :
Mean overall albedo 1964 : 14.0 per cent
Mean overall albedo 1967 : 14.3 per cent.

Thus in spite of differences between 1964 and 1967 in the tidal situations and in the areal extent of the different shade types, and in spite of a variation in albedo for shade type (2) from about 16 per cent to 35 per cent, the overall albedo appears to have remained more or less unchanged in both dry and damp conditions.

Further problems. It is satisfactory to note the general agreement between the results obtained for 1964 and for 1967. Nevertheless, the study poses several interesting problems that deserve further investigation; for example, the precise effect of moisture on areas of shade type (2), the reasons for the abrupt changes in appearance between different shade types (especially types (2) and (3)), the diurnal and seasonal variations of albedo, and the influence of atmospheric conditions.

Acknowledgements. The author wishes to thank the Meteorological Office for the loan of necessary equipment, Messrs C. S. Allcott and Son for permission to reproduce part of an aerial photograph and Hunting Survey for the supply of the photograph; also Professor Gordon Manley (University of Lancaster) and Mr A. S. Edmondson, M.Sc., (Royal Holloway College, University of London) for valuable discussion during the preparation of this paper.

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FORECASTING THE MOVEMENT OF ISALLOBARS INTO EASTERN ENGLAND

By J. M. NICHOLLS and G. A. CORFIELD

Summary. A method is given of forecasting pressure falls of 4 mb or more in 3 hours in eastern districts of England. The method utilizes Petterssen's kinematic rules to calculate the speed of a - 4-mb isallobar which has already appeared in some other area of the British Isles. A more usual method of calculating isallobaric speed is by following the movement of the isallobar on successive hourly charts. The advantage of the procedure described below over the 'chart-to-chart' method is that it enables a forecast to be issued earlier.

Introduction. Forecasts of pressure falls greater than 4 mb in 3 hours are required by some collieries in the U.K. owing to the association between these pressure falls and the expansion of large stagnant reservoirs of methane gas in waste areas of a mine, the gas at times overflowing into the ventilation system and working areas of the mine.¹

Forecasting of large pressure falls is thus an integral part of the work of the forecaster at some outstations, and a quick method of forecasting these falls from available synoptic charts was needed. Since 3 hours' notice of the start of a fall of 4 mb in 3 hours is required by the collieries, warnings should ideally be issued at least 6 hours before the arrival of the - 4-mb isallobar.

Special reference is made in this paper to north-east England since there is a requirement to forecast falls for collieries in that area. The method to be described can, however, be applied to all eastern and Midland areas of England. Forecasting for these areas is made comparatively easy since most systems associated with large pressure falls are eastward-moving depressions, troughs, or fronts, and the falls first appear in western areas.

The kinematic method of calculating isallobaric speed. The speed of movement of an isallobar in the direction of movement of an isallobaric low is given by Petterssen² as

$$C = - \frac{\frac{\partial}{\partial t} \left(\frac{\partial p}{\partial t} \right)}{\frac{\partial}{\partial x} \left(\frac{\partial p}{\partial t} \right)} \quad \dots (1)$$

Now $\frac{\partial}{\partial t} \left(\frac{\partial p}{\partial t} \right)$ represents the local change with time of the pressure tendency, and can therefore be evaluated as a finite difference from two consecutive hourly charts. Also $\frac{\partial}{\partial x} \left(\frac{\partial p}{\partial t} \right)$ can be evaluated as a finite difference, since it represents the change in pressure tendency with distance along a line parallel to the direction of movement of the isallobaric low and through the areas in question. An approximation to this direction is given by the line of movement of the system associated with the pressure falls or the direction of the warm-sector isobars as seen on the latest 3-hourly North Atlantic chart.

The time at which a pressure fall of 4 mb in 3 hours will start in area A is deduced from equation (1) as follows:

- (i) Watch for the hourly chart on which the - 4-mb isallobar first appears, and on this GG chart (GG representing the time of the chart to the nearest hour GMT) draw the - 3-mb and - 4-mb isallobars, in that order, as smooth lines (Figure 1(a)).
- (ii) Note the average change in tendency (i.e. tendency at GG minus tendency at (GG - 1)), at stations near this line, for stations which 'fitted' the - 4-mb isallobar on the GG chart. Let 'q' be the negative of this value (Figure 1(b)).



PLATE I—SKUA TEAM, GAN 1968

Front row: Cpl C. Atkinson, W/O C. G. Smith, Mr R. Almond, Dr R. Frith, W/O D. S. Monk, Cpl A. Houseman.

Back row: Mr D. E. Warner, Mr R. J. Shearman, Sgt F. Brumby, Sgt G. Hayward

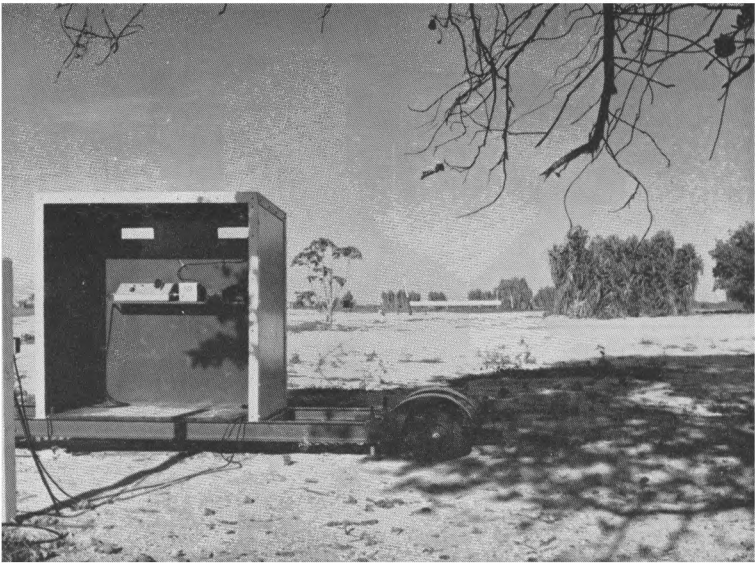


PLATE II—FIRING POINT WITH LAUNCHER PAD IN BACKGROUND

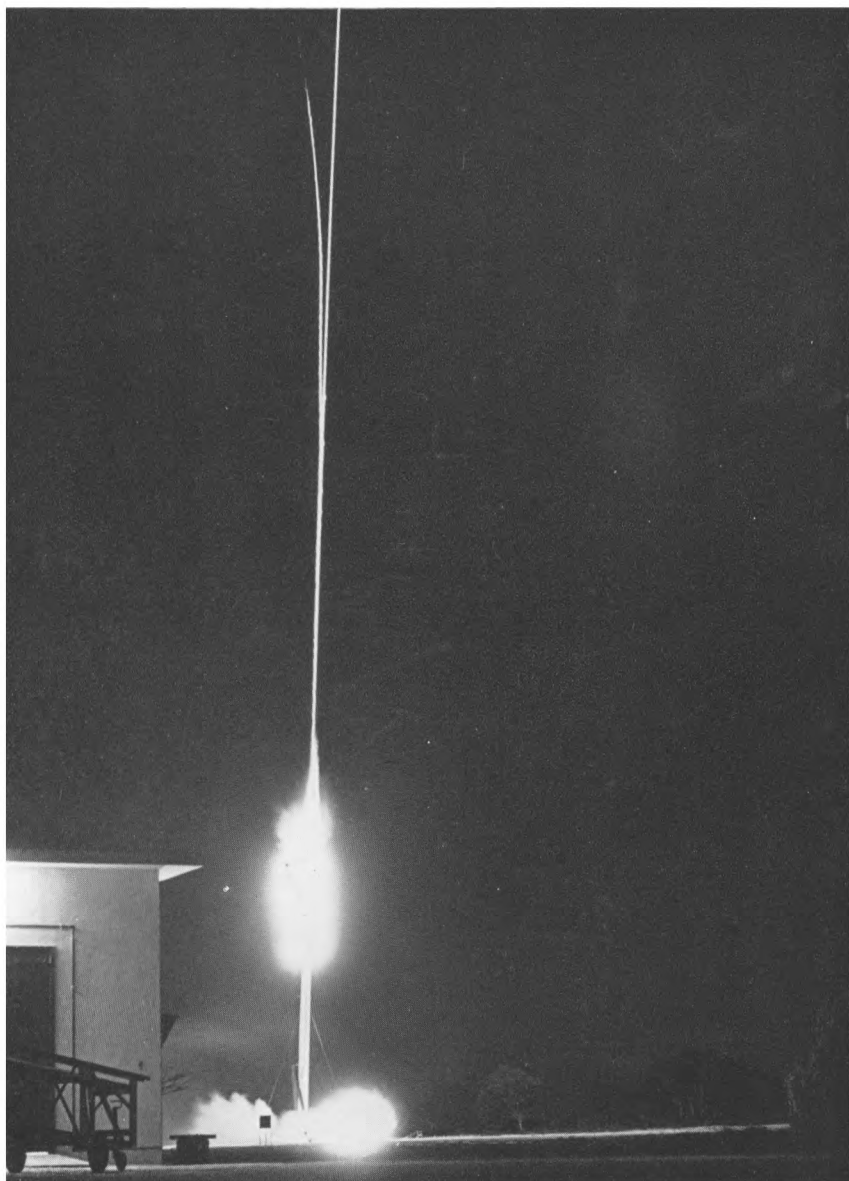
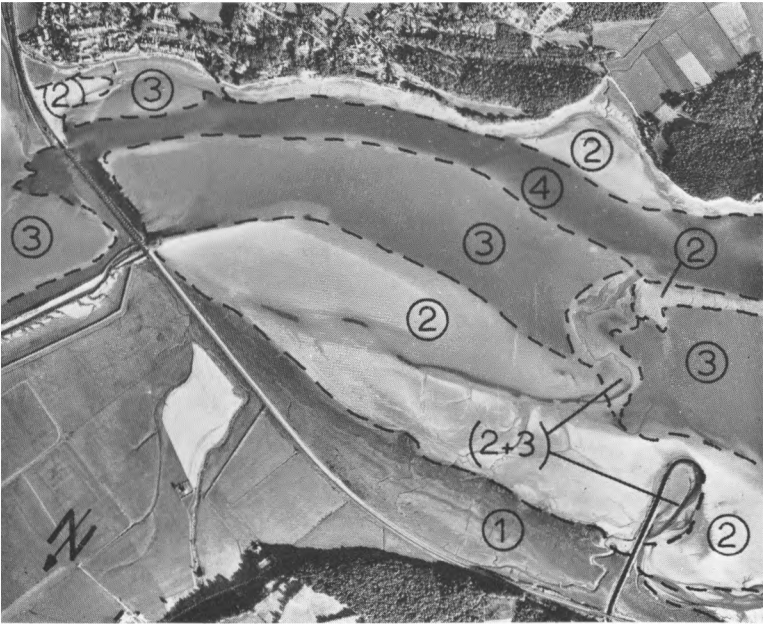


PLATE III—SKUA ROCKET LAUNCH, GAN

Time-lapse photograph shows the rocket path as a straight streak of light. The curved streak to the left is the detachable first stage or boost motor, which falls away and descends attached to a parachute.



PLATE IV—BOOST MOTOR DESCENDING ATTACHED TO A PARACHUTE AFTER
DAYLIGHT LAUNCH FROM GAN



Photograph by courtesy of Hunting Surveys

PLATE V—AN AERIAL PHOTOGRAPH TAKEN OVER THE RIVER KENT AT ARNSIDE
AT AN ALTITUDE OF 10 000 FT, AUGUST 1964.

The photograph has been divided up into shade types as an illustration of the method.
See page 306.

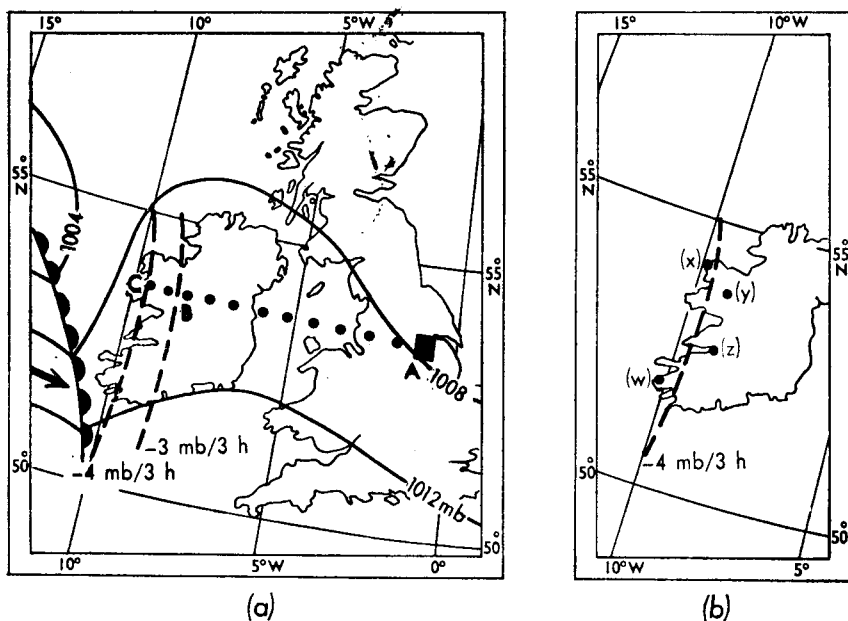


FIGURE 1 — CALCULATION OF SPEED OF ISALLOBARS

- (a) Chart GG from which r and x are obtained
 — — — isallobars
 ————— isobars

Heavy arrow shows direction of movement of system. Dotted line ABC is drawn through area A parallel to this arrow and intersects the -4-mb/3 h isallobar at C and the -3 mb/3 h isallobar at B. Then $BC = r$ and $AC = x$ n. miles.

- (b) Data from which q is obtained. The dashed line shows the position at time GG of the -4-mb/3 h isallobar. At stations near this line the figures in brackets (represented by x , y , etc.) give the change in the 3-hourly tendency between chart GG and chart GG-1. Then q is obtained as an average of these changes.

We have now calculated $-\frac{\partial}{\partial t} \left(\frac{\partial p}{\partial t} \right)$ in the form:

$$-\left\{ \left(\frac{\partial p}{\partial t} \right)_{GG} - \left(\frac{\partial p}{\partial t} \right)_{GG-1} \right\} = q \text{ (mb/3 h)/h.}$$

- (iii) On the GG chart draw a line through A parallel to the direction of motion of the system associated with the falls, as deduced from the GG chart or from the latest 3-hourly chart. If this line does not intersect the -4-mb isallobar, this fall is unlikely to occur in area A.
- (iv) Measure the distance ' r ' nautical miles (n. miles) between the intersections of this line with the -4-mb and -3-mb isallobars, on the GG chart, if these intersections exist.

We can now calculate $\frac{\partial}{\partial x} \left(\frac{\partial p}{\partial t} \right)$ in the form

$$\frac{-3 \text{ mb/3h} - (-4 \text{ mb/3 h})}{r} = \frac{1}{r} (\text{mb/3 h})/\text{n. mile.}$$

(v) The speed of translation ' c ' of the -4-mb isallobar is given by

$$c = \frac{q (\text{mb/3 h})/\text{h}}{1/r (\text{mb/3 h})/\text{n. mile}} = qr \text{ kt.}$$

- (vi) Measure the distance ' x ' n. miles from A along the line drawn in (iii) to the -4-mb isallobar. The time of arrival, assuming steady translation, will be at $(GG + x/qr)$ hours.
- (vii) Issue a warning that a pressure fall of 4 mb or more in 3 hours will begin, at A, 3 hours before the calculated time of arrival of the -4-mb isallobar.

The forecaster will have to use his judgement in application of instruction (iii). If the system associated with the falls were a mobile depression, the line would be drawn parallel to its forecast direction of motion over the next 12 hours or to the direction of its warm-sector isobars as seen on the latest 3-hourly North Atlantic chart. If the falls were associated with a frontal system moving in the circulation of a distant or slow-moving depression, the line should be drawn parallel to the warm-sector isobars.

Collieries also require a separate warning of falls of or greater than 8 mb in 3 hours; the above methods could of course be used to predict falls of this magnitude for eastern areas.

Two examples illustrating the use of the method:

Figure 2. On 15 March 1965 a depression moved north-eastwards from $53^\circ\text{N } 10^\circ\text{W}$ at 06 GMT to $57^\circ\text{N } 6^\circ\text{W}$ at 18 GMT. The first appearance of the -4-mb isallobar on an hourly chart was at 07 GMT (Figure 2(a)) and by applying instruction (ii) the value of ' q ' was found to be $0.8 (\text{mb/3 h})/\text{h}$ (Figure 2(b)). The system associated with the falls was a frontal trough, as deduced from the 06 GMT North Atlantic chart. By drawing the line in (iii) parallel to the 06 GMT warm-sector isobars and through area A on the 07 GMT hourly chart the distance (r) between the intersections of this line with the -3-mb and -4-mb isallobars was found to be 45 n. miles. Thus the speed of the isallobar was $0.8 \times 45 = 36 \text{ kt.}$ The distance away of the isallobar at 07 GMT was 300 n. miles giving an expected arrival time of 1515 GMT in area A. According to rule (vii) a warning could have been issued, based on the 07 GMT chart, that the pressure fall of 4 mb in 3 hours would start at 1215 GMT. The actual start of the fall of 4 mb in 3 hours was at 1300 GMT.

Figure 3. On 3 March 1965 there was a clear appearance of a -4-mb isallobar over western Scotland on the 00 GMT chart. The system associated with the falls was identified on the North Atlantic chart for 21 GMT on 2 March as a depression moving south towards Northern Ireland. A line drawn through area A on the 00 GMT chart parallel to the direction of motion of the depression would not cut the -4-mb isallobar and thus the evidence of the 00 GMT chart would not indicate a need for a warning of a fall of 4 mb in 3 hours in area A. Falls of 4 mb or more in 3 hours did not in fact occur in that area.

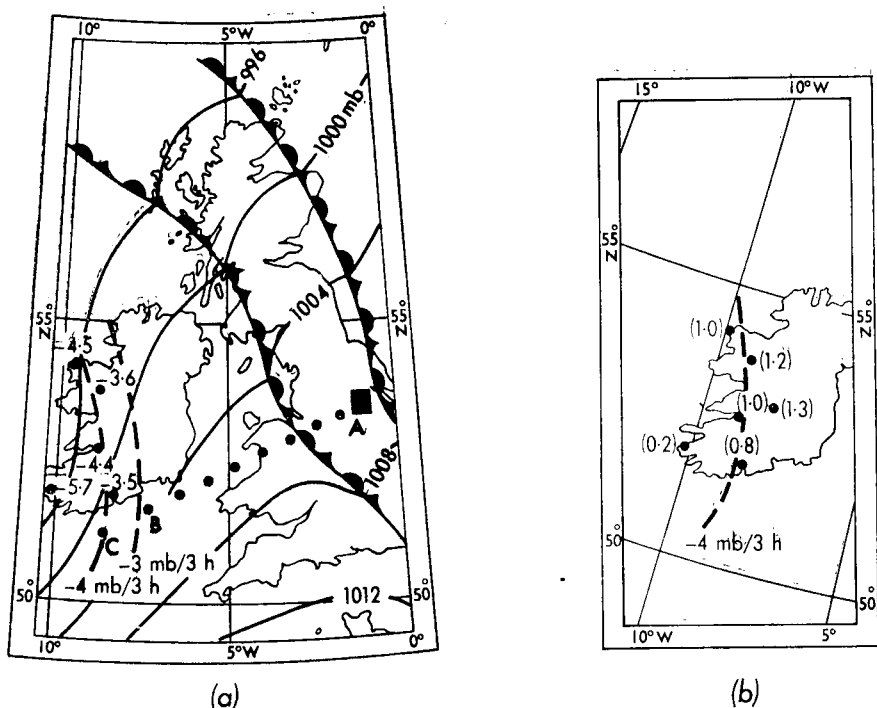


FIGURE 2 — CALCULATION OF TIME OF PRESSURE FALL OF 4 mb/3 h IN AREA 'A' ON 15 MARCH 1965

(a) Chart for 07 GMT 15 March 1965

— — — isallobars
— isobars

Dotted line ABC is drawn through area A parallel to direction of movement of system and intersects isallobars at B and C. BC=45 n. miles; AC=300 n. miles.

(b) Data from which q is obtained for 15 March 1965. The dashed line shows the position of the -4 mb/3 h isallobar at 07 GMT. The figures in brackets give the change in 3-hourly tendency between 0600 and 07 GMT and the average of these figures over southern Ireland is 0.8 mb.

In cases such as this, however, it is advisable to maintain an hourly watch on the movement of isallobars and if possible on the movement of the system associated with the pressure falls.

The causes of error in the method. In deriving the kinematic method it was assumed that no redistribution of pressure tendencies occurs within the isallobaric low as it moves from the initial area of occurrence of large pressure falls to area A (see Figure 1), but such a redistribution can cause errors in the calculated time of arrival of the -4 mb isallobar and may be associated with three types of change. These are (i) change in the rate of deepening (or filling) of the associated pressure system, (ii) change in the speed

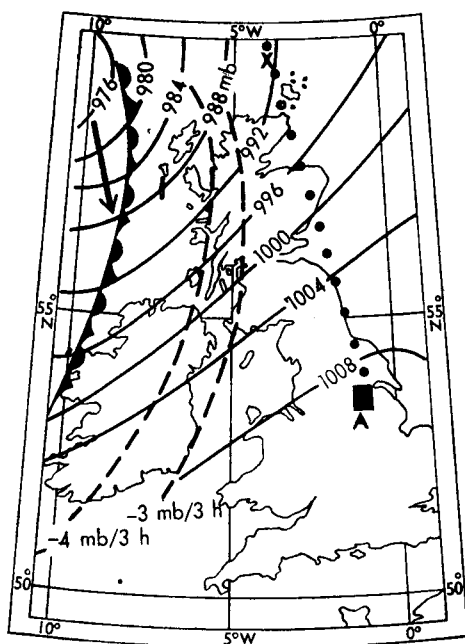


FIGURE 3 — EXAMPLE (00 GMT 3 MARCH 1965) WHERE FALLS OF 4 mb OR MORE IN 3 hours WERE NOT ADVECTED INTO AREA 'A'

— — — isallobars; ————— isobars.

Heavy arrow shows direction of movement of system. Dotted line AX is parallel to this direction and does not intersect the isallobars for -4 mb/3 h or -3 mb/3 h .

of the system, and (iii) change in the pressure gradients within the system during the calculated period of movement. It was also assumed that there would be steady linear translation of the isallobaric low to area A; thus errors in the calculated time of arrival may also arise because of a fourth type of change: namely, a change in the direction of movement of the associated pressure system.

The magnitude of these four changes which may contribute to errors would depend critically on the nature of the associated pressure system and the thermal flow in which it was embedded. For example one would expect all four changes to be small for a wave depression moving under a strong thermal gradient. However for a depression whose fronts are occluding the four changes would be greater in magnitude. It is worth while noting here, however, that a constant rate of deepening or filling is not associated with a change in the tendency distribution and therefore does not contribute to errors.

In association with the four types of change detailed in this section there will be an error in the calculated time of arrival of the -4-mb isallobar. In order to deduce a correction to be applied to the time calculated, as above, by using a method based on kinematic rules, it would be necessary to forecast quantitatively these changes over the period of advection and deduce individual corrections dependent on each type of change. This would, however, be a difficult and time-consuming task for the forecaster.

The intensity of the isallobaric low may be changed by diurnal oscillations of pressure; these occur with a period of 12 hours, the times of greatest fall being between 10 and 16 LMT and between 22 and 04 LMT. The fall may be about 1 mb/3 h but varies according to the season.³ It is difficult for the forecaster to take account of diurnal changes but they would obviously become of importance when falls originally near the warning limit were forecast to arrive in area A at times of maximum diurnal change.

Usefulness of the method. The only method previously in use of forecasting pressure falls of 4 mb or more in 3 hours was of following the movement of the -4-mb isallobar on successive hourly charts and thus deducing its speed. The accuracies of the forecast times of onset and the warning periods given by the 'chart-to-chart' method and the kinematic method were compared by using both methods, in retrospect, to forecast the start of pressure falls of 4 mb or more in 3 hours which had occurred over north-east England over a six-month period; the hourly U.K. charts and three-hourly North Atlantic charts were used strictly according to the prescribed methods, that is as they should have been used if forecasting in advance the onset of the falls.

Figures 4 (a) and (b) show the distribution of the number of hours warning given by each method for 49 cases of pressure falls of 4 mb or more in 3 hours, which occurred in the six-month period. ' $T_4 - T_a$ ' and ' $T_4 - T_b$ ' are the time differences between the actual time of onset ' T_4 ' of the pressure fall and the times of issue of the warning by the kinematic method (T_a) and 'chart-to-chart' method (T_b) respectively. The times of onset ' T_4 ' in the Newcastle and Doncaster areas were deduced from the Acklington and Finningley barograms. ' T_a ' and ' T_b ' are the times of the latest hourly chart used in each method plus $1\frac{1}{2}$ hours, which is added since the hourly chart is not available in the forecast office till $1\frac{1}{2}$ hours after the hourly observations and about $\frac{1}{4}$ hour is needed to use the methods. ' $T_4 - T_a$ ' has an average value of 3 hours 35 minutes and ' $T_4 - T_b$ ' an average value of 2 hours 50 minutes.

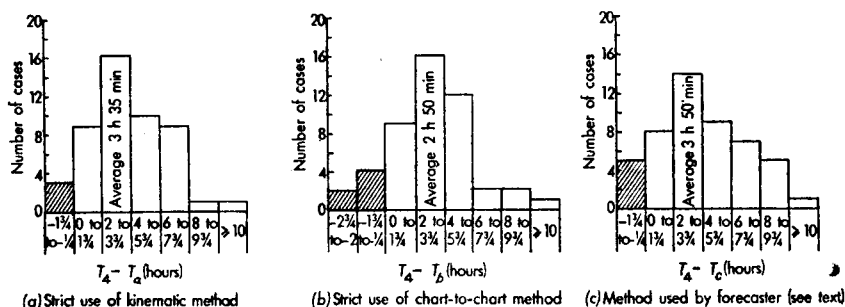


FIGURE 4 — WARNING PERIODS FOR 49 CASES OF FALLS OF 4 mb OR MORE IN 3 hours

T_4 = actual time of start of fall from barograph records;
 T_a = time of latest hourly chart used in kinematic method + $1\frac{1}{2}$ hours;
 T_b = time of latest hourly chart used in chart-to-chart method + $1\frac{1}{2}$ hours;
 T_c = time of issue of warning by forecaster. All times to the nearest $\frac{1}{4}$ hour.
 Hatching indicates that warnings were issued after start of fall.

Thus the kinematic method has the advantage of giving $\frac{3}{4}$ hour extra warning; this is because one more hourly chart normally has to be used to find the isallobaric speed by the 'chart-to-chart' method.

Figures 5 (a) and (b) show the distribution of the time differences between the actual time of onset (T_4) of the pressure fall and the forecast times of onset, ' T_1 ' and ' T_2 ', by the kinematic and chart-to-chart methods respectively. The histograms are not centred around zero since a late forecast was considered to be in more serious error than an early one. The average values of ' $T_4 - T_1$ ' and ' $T_4 - T_2$ ' are both 1 hour 15 minutes, showing that both methods have the same accuracy. Farr (private communication) has shown that the only difference between the calculated speeds of the isallobar by the two methods would be due to the use of finite differences instead of instantaneous derivatives in the kinematic method. The error introduced for this reason is however very small and it was thus expected that the accuracies of the methods would be similar.

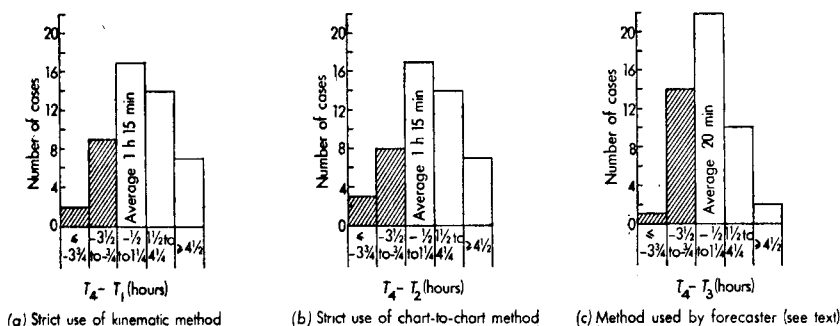


FIGURE 5 — ACCURACY OF FORECAST ONSET TIMES OF FALLS OF 4 mb OR MORE IN 3 HOURS FOR 49 CASES

T_4 = actual time of start of fall from barograph records;
 T_1 = forecast time of start of fall using kinematic methods;
 T_2 = forecast time of start of fall using chart-to-chart method;
 T_3 = forecast time of start of fall issued by forecaster.

Hatching indicates that fall commenced appreciably earlier than forecast.

Forecasts were also made on a routine basis, prior to the occurrence of the falls, during the six-month period. The forecasters were free to choose, during this period, which method to use and also free to modify the kinematic method if it became obvious that the modifications were resulting in better forecasts. Figure 4 (c) shows the distribution of the time difference ' $T_4 - T_c$ ' between the actual onset of the fall and the time ' T_c ' of issue of the warning by the forecaster. It was found from experience that if the kinematic method was applied to find the speed of the -3-mb isallobar when it first appeared on the hourly chart, and this speed was applied to the -4-mb isallobar if this appeared on the following chart then the warning could be issued a little earlier. Alternatively some forecasters achieved the same benefit by applying the kinematic method to 'adjusted' -4-mb and -3-mb isallobars, which were constructed on two successive hourly charts by multiplying by 3 the pressure falls over the hour previous to chart time. This method was used if falls of 3 mb or more in 3 hours were already occurring in the west, and the 'adjusted' -4-mb isallobar is in fact the locus of points where falls of $\frac{4}{3}$ mb have occurred

in the last hour. Warnings of pressure falls were given before the -4-mb isallobar appeared on the hourly chart; although this resulted in a few cases where warnings were given when falls of $4/3$ mb or more in one hour were not maintained and 3-hourly falls were slightly less than 4 mb, these cases were easily outweighed by those where this method produced a greater warning period. Forecasters, over the six-month period, found it beneficial to use the kinematic method, or its modifications as described above, in all cases of pressure falls except those preceding a post-frontal trough where the 'chart-to-chart' method gave better results. Figure 5 (c) shows the distribution of time difference ' $T_4 - T_3$ ' between the actual onset of the fall and the forecast time ' T_3 ' of onset, as issued by the forecaster prior to the event. The improved average time difference of 20 minutes is a result of the two modifications of the 'kinematic' method and of the ability to select between the two basic methods. It should be noted however that the improvement is made marginal owing to the increase in the number of cases where the forecast time of onset was after the actual time.

Longer-period forecasts. The forecasting methods discussed so far are dependent on pressure falls of 4 mb in 3 hours already occurring somewhere in the United Kingdom, and as a result of this the average warning which can be given of this fall occurring in eastern England is about $3\frac{1}{2}$ hours. The 24-hour surface forecast charts issued by Central Forecasting Office, Bracknell, were examined (using data over a period of a year) to see if they could be utilized to give earlier warning. The results showed that it would be inadvisable, at least at present, to forecast pressure falls of 4 mb or more in 3 hours by using 24-hour forecast charts of surface pressure. On such charts errors of timing are introduced and pressure gradients are not always forecast correctly although the 24-hour forecast chart may alert the forecaster to the possibility of large falls during a 24-hour period.

Conclusion. A method of forecasting large pressure falls has been described which is based on the deduction, from a kinematic equation, of the speed of an isallobar appearing on an actual chart. This method is as accurate as the 'chart-to-chart' method and allows the warning of the onset of the pressure fall to be issued earlier. Slight improvement of the kinematic method can be achieved by either of the small modifications suggested on page 316 to give earlier warning. When large pressure falls precede a post-frontal trough the 'chart-to-chart' method gives greater accuracy than the kinematic method of forecasting the time of onset of the large fall. The use of 24-hour forecast charts to forecast pressure falls of this magnitude is, at the moment, inadvisable. It has been found that a considerable improvement in forecasts of pressure falls of 4 mb or more in 3 hours has been achieved, on station, by the formulation and use of the rules described in this paper.

Acknowledgements. The authors are indebted to the staff at Bawtry for carrying out the tests described.

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METEOROLOGICAL ROCKET SOUNDINGS FROM GAN

By R. J. SHEARMAN

Summary. An account is given, together with an examination of the results, of the first SKUA meteorological rocket sounding campaign from the Island of Gan in the Indian Ocean.

On 25 September 1968 the first SKUA meteorological rocket was launched from the Island of Gan ($0^{\circ}41'S$ $73^{\circ}9'E$) in the Indian Ocean. Upper air observations are very sparse in equatorial regions, and until this time no soundings had been made above balloon levels within approximately 700 km of the equator. There had been regular launchings from Ascension Island ($8^{\circ}S$ $14^{\circ}W$) and Fort Sherman ($9^{\circ}N$ $80^{\circ}W$) and some soundings from Natal, Brazil ($6^{\circ}S$ $35^{\circ}W$), Thumba, India ($9^{\circ}N$ $77^{\circ}E$) and Kwajalein, Marshall Islands ($9^{\circ}N$ $168^{\circ}W$).

Soundings as close to the equator as Gan are particularly interesting because the continuous temperature gradient from the 'winter' to the 'summer' pole at these high levels suggests a cross-equatorial heat flow. The form of this flow will be influenced by the lack of Coriolis force at the equator. Rocket soundings will show how the atmosphere deals with the need for a general N-S flow in conditions of zero Coriolis force.

The quasi-biennial oscillation (the 26-month cycle) is at its strongest below 30 km in low latitudes. It is of interest to see how far it extends above this level, and also to investigate the annual and six-monthly cycles which have appeared in Ascension Island rocket results (Reed¹).

During the first campaign seven successful launchings were made between 25 September and 10 October 1968. The rockets and sondes used were those described by Almond.² Close contact was maintained, on each occasion, with an RAF Shackleton search aircraft until shortly before the instant of firing. The line of fire was on one of three bearings, as directed by this aircraft. This precaution was designed to protect the small native fishing boats which sometimes operate in the area. In fact the launcher bearing was only changed once, and then to avoid a much larger vessel. All but one of the soundings were made after the sun had set at 70 km, so that the sonde was in darkness for the whole of its descent, making radiation corrections unnecessary. Only the last firing took place at local midday, which is the standard launching time throughout the American Meteorological Rocket Network. The conventional radiosonde ground equipment was used to track the sondes and receive their signals.

Apogees of rockets ranged between 57 km and 64 km, somewhat lower (by approximately 5 km) than those attained during regular South Uist firings. This was due to higher densities aloft, and therefore greater drag experienced during the free-flight phase above 16 km. This was partially offset by the ability to fire always at maximum elevation, in consequence of fairly light surface winds.

In the SKUA system the sonde and parachute are ejected just after apogee, about 137 seconds after launch. The rocket body then falls away to splash down at about + 250 seconds. The sonde falls rapidly at first, and the parachute is not considered to be a good wind sensor until it is 4 or 5 km below apogee. Temperatures are recorded from about 3 km below apogee.

Winds. The zonal wind during the sounding period tended to be layered, with light westerlies at the surface, a pronounced band of easterlies from approximately 5 km to 26 km, and another weaker band of easterlies from 37 to 48 km. The heights of the upper and lower boundaries of these layers varied by only 2 or 3 km during the campaign.

The COSPAR* International Reference Atmosphere 1965 (CIRA 1965) includes tables giving mean zonal winds at various heights for each month of the year and for every 10 degrees of latitude and gives estimates of the variability of the wind.

Table I shows the mean zonal wind and extreme values at 2-km intervals, calculated from the Gan soundings, together with CIRA 1965 values for 1 October at 0° latitude. Westerly winds are shown positive.

From 38 km to 48 km there is fairly close agreement between the mean zonal wind and CIRA values. Elsewhere the observed values are within two standard deviations of the values given by CIRA 1965.

The meridional winds were generally light, although northerly components of 17 m/s and 22 m/s were observed at 44 km and, on separate occasions, southerly components of 12 m/s at 40 km and 17 m/s at 52 km.

Diurnal variation of meridional component. All the soundings were made at approximately 1900 local time, except the last which was at 1200. Table II shows the mean meridional component for the evening launches, the extreme values, and the components for the one daylight observation. (Southerly wind is positive).

Groves's³ value of diurnal variation for stations at around 30°N is about 10 m/s. Several soundings at South Uist (57°N) in June showed a variation of about 12 m/s at 50 km. The maximum change seems to be at approximately 50 km, both from Groves's and from South Uist results.

Below 50 km in Gan, the variability is too great for any estimate to be made of diurnal variation. Above 50 km components at 1200 can be explained in terms of some long-period 'synoptic-type' change, producing a 'trend' in the winds, the trend making the winds more northerly in this case. But between 1900 on 9 October and 1200 on 10 October the diurnal effect is opposed to this trend, making the meridional component more southerly towards midday. Therefore the trend is required to suppress a diurnal change of approximately 10 m/s and still produce a net 'northerly' increase of 5 to 10 m/s. (The trend was of this size above 50 km.) A change of 15 to 20 m/s is required in approximately 17 hours; this is far from impossible, but it is more than double the trend between previous evening soundings. It is possible that the diurnal variation is very much smaller at the equator. However a measurement of the diurnal variation can only be made by soundings which are made at least every six hours and in a series so that long-period type changes can be recognized.

The mean meridional wind was predominantly 'southerly' from 22 km to 40 km, northerly from 40 km to 50 km, southerly from 50 km to 54 km and northerly again above 54 km.

* Committee on Space Research of the International Council of Scientific Unions.

TABLE I — ZONAL WINDS FOR GAN, 27 SEPTEMBER TO 9 OCTOBER 1968, AND CIRA 1965 VALUES FOR 1 OCTOBER

Height	Gan zonal wind*		CIRA zonal wind*		CIRA standard deviation
	Mean	Extremes	<i>metres per second</i>		
<i>km</i>					
56	+32	+40	+25	+4	18
54	+34	+41	+31	+4	17
52	+31	+39	+26	+4	16
50	+19	+23	+14	+4	15
48	+5	+13	-6	+4	14
46	+1	+12	-10	+5	14
44	0	+6	-8	+4	13
42	-7	+1	-10	+2	12
40	-10	+6	-19	+1	12
38	-1	+6	-4	-1	11
36	+4	+5	+1	-4	11
34	+9	+12	+4	-7	10
32	+11	+18	+6	-11	9
30	+14	+21	+11	-15	9
28	+12	+15	+8	—	—
26	+1	+7	-8	—	—
24	-31	-24	-41	—	—
22	-27	-23	-33	—	—

* Note : Westerly winds are positive

TABLE II — MERIDIONAL WINDS FOR EVENING SOUNDINGS AND ONE DAYLIGHT SOUNDING AT GAN, 27 SEPTEMBER TO 10 OCTOBER 1968

Height <i>km</i>	Gan meridional wind*		Gan meridional wind*	
	Mean	Extremes	at approx. 1900 local time	at 1200 local time One sounding only
			<i>metres per second</i>	
56	-4	+4	-20	-26
54	+3	+10	-8	-14
52	+5	+15	-2	-7
50	0	+19	-12	-2
48	-3	+4	-9	0
46	-1	+9	-17	-6
44	-4	+7	-20	-10
42	-5	+7	-17	+6
40	-1	+13	-12	+17
38	+1	+5	-3	+5
36	+1	+4	-1	0
34	-3	+2	-9	-2
32	+1	+5	-6	-3
30	+1	+9	-2	-3
28	-2	+3	-7	+1
26	0	+5	-5	-4
24	+4	+6	-1	+9
22	+3	+5	-2	-2

* Note: Southerly winds are positive

Temperature. Figure 1 shows the range of observed temperatures for the sunset soundings, during the Gan campaign, at kilometre intervals, together with the corresponding CIRA 1965 profile and lower limit of variability. This variability was originally calculated by taking the difference between observed temperatures and the model, and because of lack of observations it can be expected to be exceeded on 50 per cent of occasions (Groves⁴). Accepting this, the agreement between the two profiles is remarkably good, particularly as CIRA 1965 was not adjusted for diurnal effects, and was constructed from American rocket temperatures, which were measured at local midday, whereas the first six Gan soundings were all made at 1900 local time in darkness.

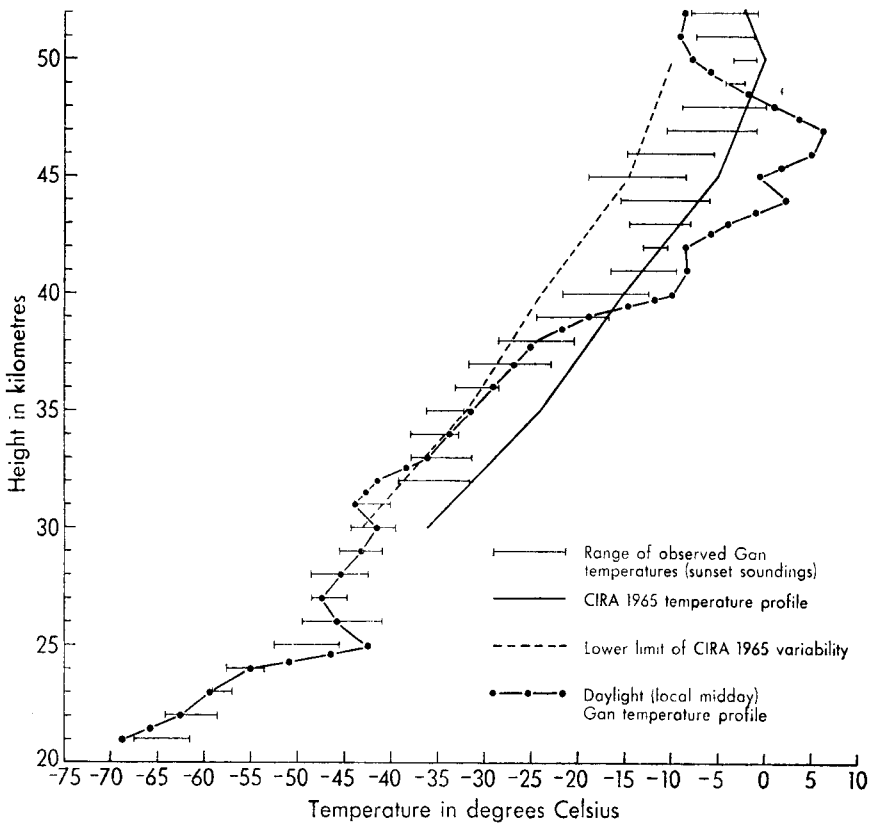


FIGURE 1 — COMPARISON OF OBSERVED TEMPERATURE AT GAN FOR LATE SEPTEMBER AND EARLY OCTOBER 1968 WITH COSPAR INTERNATIONAL REFERENCE ATMOSPHERE 1965

The one daylight temperature sounding from Gan indicated temperatures approximately 5 degC higher than those from the sunset firings, between 44 and 47 km (Figure 1). Table III shows the sequence of temperatures measured at the appropriate heights.

TABLE III — SEQUENCE OF TEMPERATURES AT GAN FROM 27 SEPTEMBER TO 10 OCTOBER 1968

Height	27	28	30	4	7	9	10*
km				degrees Celsius			
47	-8.7	-0.8	-3.7	-6.9	-3.0	-8.9	+3.9
46	-13.0	-6.8	-4.6	-4.8	-8.6	-9.8	+5.6
45	-17.3	-8.5	-7.4	-7.7	-8.2	-9.7	+1.9
44	-16.9	-14.3	-10.7	-8.5	-10.9	-6.0	+1.3
Mean							
44-47	-14.0	-7.6	-6.6	-7.0	-7.7	-8.6	+3.2

* Daylight sounding

There was a change of about 6 degC between 27 and 28 September, i.e. a 24-hour period. The change between the sunset sounding on the 9th and midday on the 10th is about 12 degC, over a 17-hour period. This seemed rather violent, and computational errors were suspected; subsequent checking, however, has shown nothing abnormal in either the original temperature traces or the calculations.

A possible source of error is radiation heating of the resistance-wire temperature sensor. The correction given by laboratory experiments for this height is approximately 4 degC, i.e. the temperature given by the sensor is 4 degC too high. In addition to this direct solar heating, there is reflected radiation, and long-wave radiation from the surrounding atmosphere. The reflected component was taken to be 10 per cent of the normally incident radiation, as the sonde was over the sea, and cloud was relatively sparse. The long-wave radiation was neglected both by day and by night, and is thought to be negligible compared with reflected solar radiation by day. At the equinox, in Gan, the sun is directly overhead at 1200 local time, so the temperature element swings regularly into and out of the shade of the parachute and its sonde. At the extremes of the swing it is completely exposed to the sun, the semi-angle of swing being greater than 45°. (Australian workers have used two cameras at right-angles in place of a sonde, and from the gyrations of the horizon and the frame speed have calculated the period and angle of swing.) The temperature record of this flight shows a regular temperature variation of 4 degC every 6 seconds, the normal period of swing for this parachute, which indicates that the laboratory correction is realistic.

Theoretically the temperatures at 1900 at these heights should be higher than, or at least comparable with, those at 1200,⁴ since the cosine law which holds for heating a surface area does not apply in heating a volume of the atmosphere. Heating will only decrease owing to passage through a thicker layer of atmosphere later in the day, and will therefore fall off more slowly than at the surface. There is also a lag between maximum heating rate and the attainment of maximum temperature.

If the radiation corrections are reasonably accurate, the theoretical diurnal effect holds, and computational errors are ruled out, then there seems to have been a strong synoptic-scale change between sunset on 9 October and midday on 10 October.

Variation in pressure surfaces. In the stratosphere in mid-latitudes there are large pressure changes attributable to travelling disturbances. Since there is a strong temperature gradient between 'summer' and 'winter' hemispheres in the stratosphere, a cross-equatorial heat transfer can be expected. This is likely to be most efficiently performed by such travelling synoptic-scale disturbances, in addition to the meridional circulation described by Murgatroyd and Singleton.⁵ The Gan soundings were therefore studied for evidence of these systems.

Figure 2 shows the heights of the 10-mb, 5-mb and 1-mb surfaces from 27 September to 9 October 1968. These observations seem to indicate the passage of a synoptic-scale disturbance, which was at its strongest at the 1-mb level, with a change in contour height of more than 350 m. Changes of 250 m and 200 m occurred at the 5-mb and 10-mb levels respectively. The magnitude

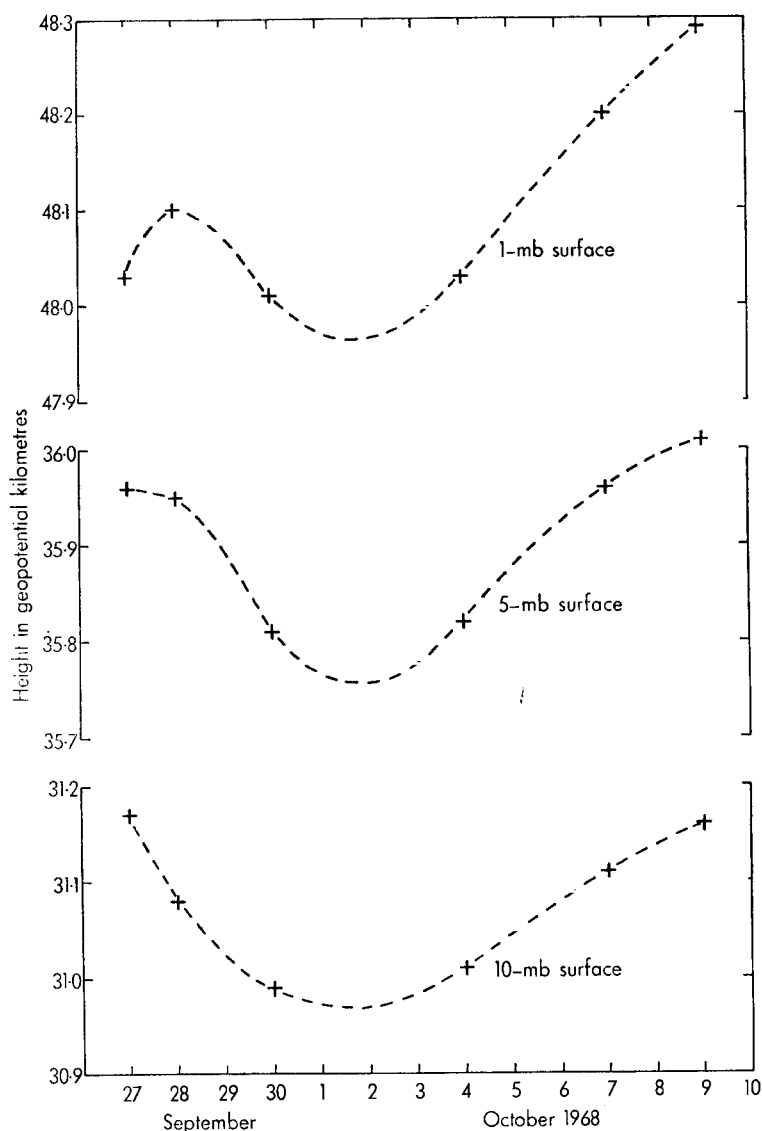


FIGURE 2 — HEIGHT OF 1-mb, 5-mb AND 10-mb SURFACES AT GAN, SEPTEMBER–OCTOBER 1968

of the disturbance fell off with decreasing height, being barely detectable at 100 mb (≈ 16 km). Figure 3 shows a similar disturbance of the zonal wind component at Ascension Island at 50 km (≈ 0.8 mb) and 40 km (≈ 3 mb) in both 1965 and 1966, on nearly the same time scale as the Gan system.

Future campaigns in Gan. It is intended to make a series of launchings each year from Gan. An agreement has been drawn up between the British and Indian governments, enabling the United Nations range at Thumba

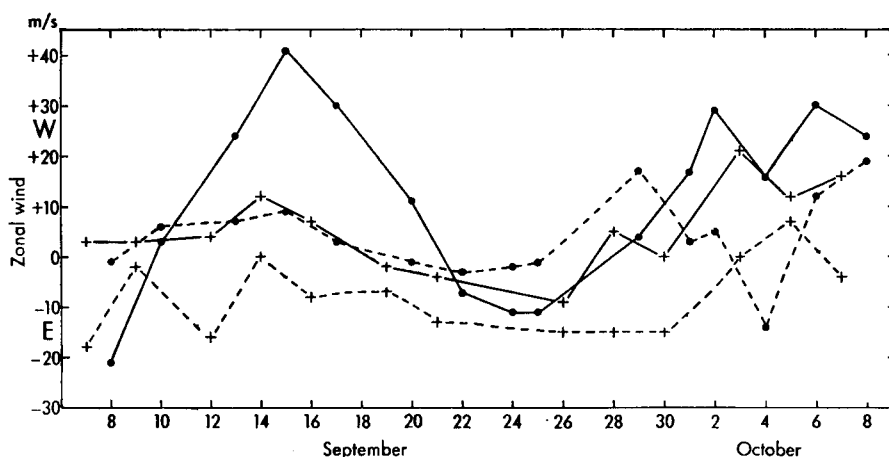


FIGURE 3 — ZONAL WIND AT ASCENSION ISLAND, SEPTEMBER–OCTOBER 1965 AND 1966

——— Zonal wind at 50 km 1965 + ——— + Zonal wind at 50 km 1966
 - - - - Zonal wind at 40 km 1965 + - - - + Zonal wind at 40 km 1966
 Westerly winds are positive

(8°32'N 76°57'E) to launch a number of SKUA rockets with standard Meteorological Office rocket-sonde payloads. It is hoped to carry out this programme in conjunction with a three-week campaign in Gan.

Acknowledgements. On behalf of the SKUA meteorological rocket team I would like to express appreciation for the co-operation and assistance of the personnel of Royal Air Force, Gan. Our thanks are also due to the radiosonde staff, who were extremely helpful at all times.

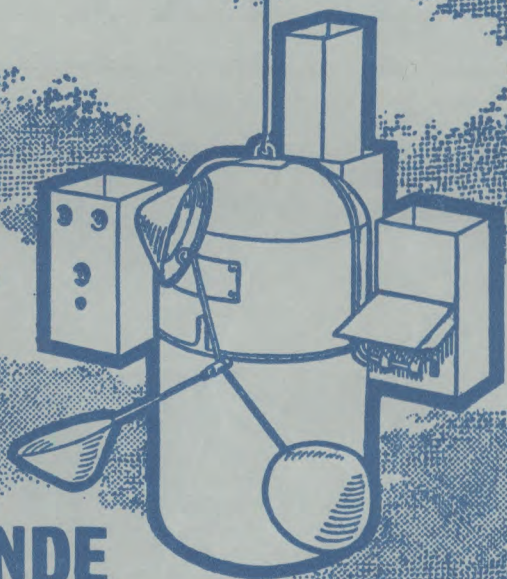
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OBITUARIES

It is with regret that we have to record the death of Mr H. J. Matthews, Senior Scientific Assistant, on 3 August 1969, and of Mr C. P. Brohan, Scientific Assistant, on 21 August 1969.

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FORECASTING LARGE 24-HOUR RAINFALL TOTALS IN THE DEE AND CLWYD RIVER AUTHORITY AREA FROM MARCH TO AUGUST

By C. A. S. LOWNDES

Summary. The synoptic type was noted for some 45 days when the 24-hour rainfall was more than 1.5 inches at any station in the Dee and Clwyd area of Wales during March–August 1911–68. Of the 26 days classed as cyclonic, 15 were associated with thunder; of the 14 days classed as westerly, only one was associated with thunder. A detailed study was made of a selection of stations and criteria were obtained for indicating large rainfall totals. For westerly types the criteria were similar to those previously obtained for the winter half of the year and the criteria were successfully tested on independent data. Criteria were also obtained for the cyclonic types and applied to independent data with limited success.

Introduction. An investigation is being undertaken by the Dee and Clwyd River Authority and the Water Resources Board into river regulation and there is therefore a special interest in forecasting rainfall in the drainage area of Lake Bala and the Chester Dee. Figure 1 shows the position of the Dee and Clwyd River Authority Area and includes stations mentioned in this report. In an earlier paper,¹ criteria were obtained for indicating 24-hour rainfall totals of 2 inches or more in the Dee and Clwyd area in the months September to February. For these six months the large rainfall totals were nearly all associated with westerly types as defined by Lamb,² in particular with the warm sector of deepening depressions or waves.

The present report is concerned with the forecasting of large 24-hour rainfall totals over the same area for the other six months of the year, March to August. For these months, the synoptic types associated with large rainfall totals were more varied and complex. For this reason, a relatively large number of occasions of heavy rainfall were needed for an adequate study of the synoptic types involved and it was found necessary to reduce the threshold value from 2 in to 1.5 in. As in the previous paper, rainfall amounts are given in inches and heights in feet, although the units now used are millimetres and metres. In the years 1911–68, for the months March–August, the dates of occasions when any station in the Dee and Clwyd area recorded at least 1.5 in of rain were extracted. Only readily available data were used, so that not all occasions were included. The synoptic type was noted for each of the days extracted. Of the 45 days, 26 were classed as cyclonic, 14 as westerly, 2 as easterly, 2 as south-easterly and 1 as north-westerly. Of the 26 days

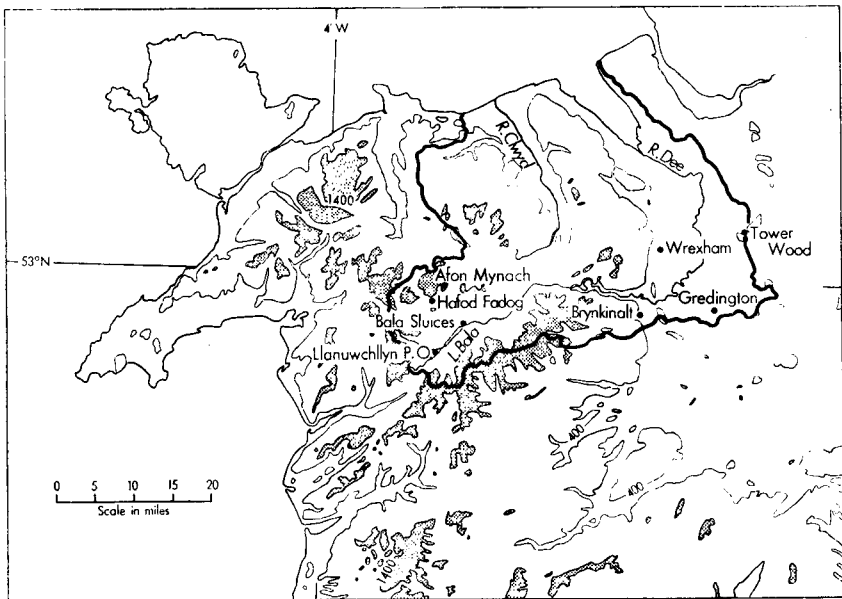


FIGURE 1—THE DEE AND CLWYD RIVER AUTHORITY AREA

The 400-ft contour is shown and areas above 1400 ft are shaded.
The boundary of the area is indicated by a thick line.

classified as cyclonic, 15 were associated with reports of thunder. Of the 14 days classified as westerly, only 1 was associated with reports of thunder or observations of atmospherics.

A detailed investigation was made of (i) seven of the westerly situations (numbered from 1 to 7 for convenience in this article), (ii) five of the cyclonic situations associated with thunder, numbered from 8 to 12 and (iii) five of the cyclonic situations not associated with thunder, numbered from 13 to 17. The dates and highest rainfall values were as follows:

(1) 6 June 1948, 1.53 in, (2) 3 April 1949, 1.85 in, (3) 2 April 1962, 3.50 in, (4) 23 August 1962, 1.73 in, (5) 26 August 1962, 1.74 in, (6) 7 July 1964, 2.10 in, (7) 19 March 1968, 3.15 in, (8) 31 May 1924, 5.31 in, (9) 18 July 1926, 2.47 in, (10) 11 August 1948, 1.83 in, (11) 3 July 1957, 1.50 in, (12) 18 July 1964, 1.61 in, (13) 18 August 1956, 2.31 in, (14) 9 March 1963, 1.50 in, (15) 8 May 1965, 2.13 in, (16) 21 June 1965, 1.65 in, (17) 1 April 1966, 2.08 in.

As in the months September to February, nearly all the highest rainfall totals for the westerly occasions were recorded at Afon Mynach (1200 ft), the highest of the stations, indicating the importance of the orographic effect in westerly situations throughout the year. For the cyclonic situations associated with thunder, all but one of the highest rainfall values were recorded at stations at heights between 300 ft and 500 ft, indicating the relative unimportance of the orographic effect. For the cyclonic situations not associated with thunder, all but one of the highest rainfall values were recorded at

stations at heights between 570 ft and 1200 ft, suggesting that on most occasions the orographic effect was of some importance. One example of the detailed descriptions of the westerly types, that for occasion (4), is given below.

Westerly types — the situation on 23 August 1962. The rainfall for the 24 hours ending 09 GMT on 24 August at some of the stations in the Area was (i) Afon Mynach, 1.73 in, (ii) Llanuwchllyn P.O., 1.35 in, (iii) Hafod Fadog, 1.31 in and (iv) Bala Sluices, 1.06 in.

Figure 2 shows the surface chart for 12 GMT on 22 August when a partly occluded depression (988 mb) was centred south of Greenland. By 06 GMT

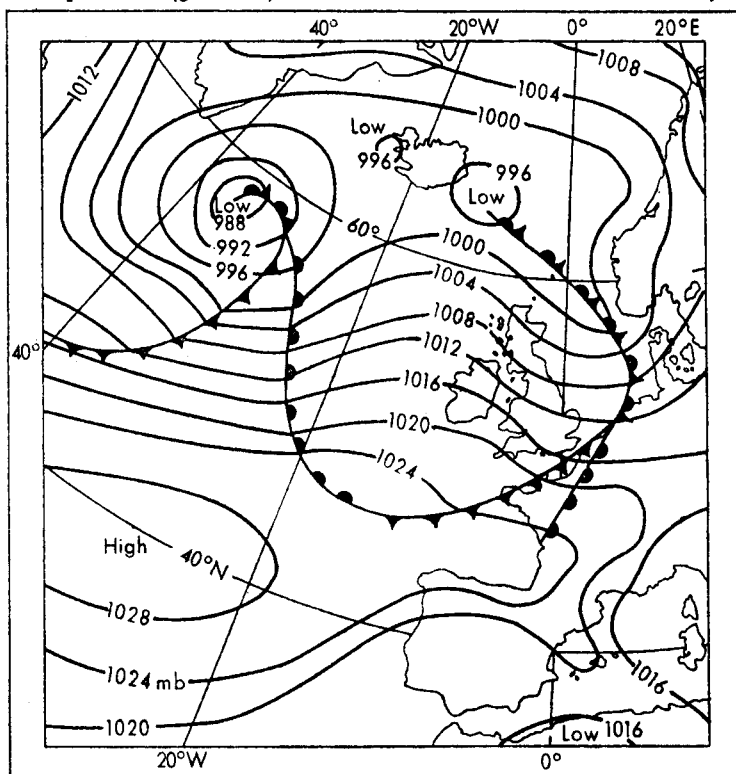


FIGURE 2—SURFACE CHART FOR 12 GMT, 22 AUGUST 1962

on the 23rd (Figure 3) the depression had moved eastwards to a position south of Ireland, having deepened to 984 mb. The associated warm front had reached western Ireland. Continuous slight rain was reported in Ireland by 03 GMT when 3-hour pressure falls of 3–4 mb had occurred over Ireland and falls of 1–2 mb over Wales, ahead of the warm front. Rain began at 09 GMT over north Wales. By 18 GMT (Figure 4) the depression was slow moving to the north-west of the British Isles and had deepened to 980 mb. The point of occlusion had moved eastwards just north of Scotland to the northern North Sea. The warm front now extended over the North Sea and south-east England and the cold front was lying across southern Scotland and southern Ireland, its easterly movement having been delayed by a small wave which moved eastwards across the Atlantic and dispersed to the south-west of Ireland by 16 GMT. Pressure falls of 3 mb were reported over Wales in the warm

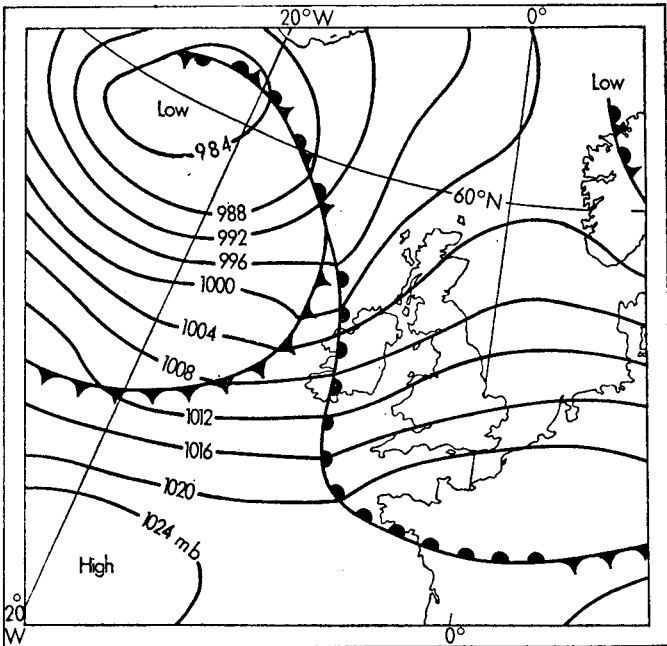


FIGURE 3—SURFACE CHART FOR 06 GMT, 23 AUGUST 1962

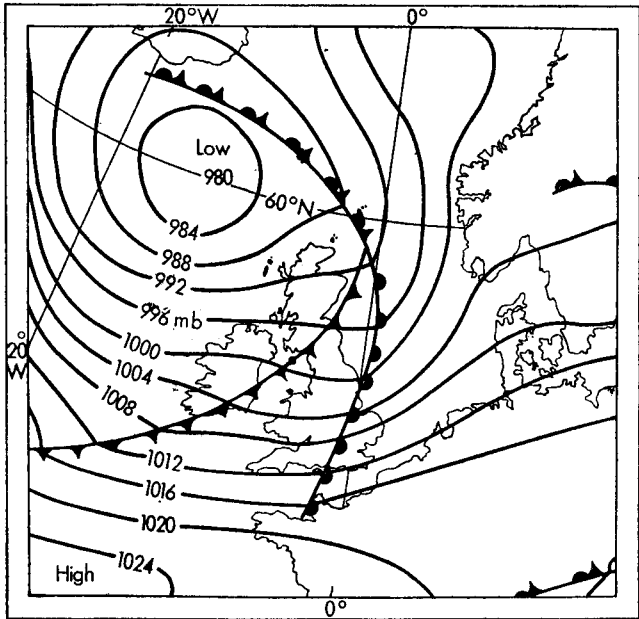


FIGURE 4—SURFACE CHART FOR 18 GMT, 23 AUGUST 1962

sector. The surface geostrophic wind in the warm sector in the vicinity of the Area was $260^\circ/50$ kt. The surface dew-point in the warm sector was 4°F (2°C) above the normal,³ i.e. above the average for the time of year. The cold front had moved east of the Area by 21 GMT. For the rest of the rainfall day there were showers and bright intervals over Wales. The depression moved slowly eastwards to a position north of the British Isles by 09 GMT on the 24th and filled slightly from 980 mb at 18 GMT on the 23rd to 982 mb at 09 GMT on the 24th. There were no reports of thunder or observations of atmospherics over the Area during the rainfall day.

The 500-mb chart for 12 GMT on the 23rd (Figure 5) suggested the presence of a west-south-westerly jet stream with its exit over Ireland. The Benwell criteria⁴ for heavy rainfall over the Area were not satisfied but it was considered to be a borderline occasion. The Area was situated to the right of the jet exit rather than to the left.

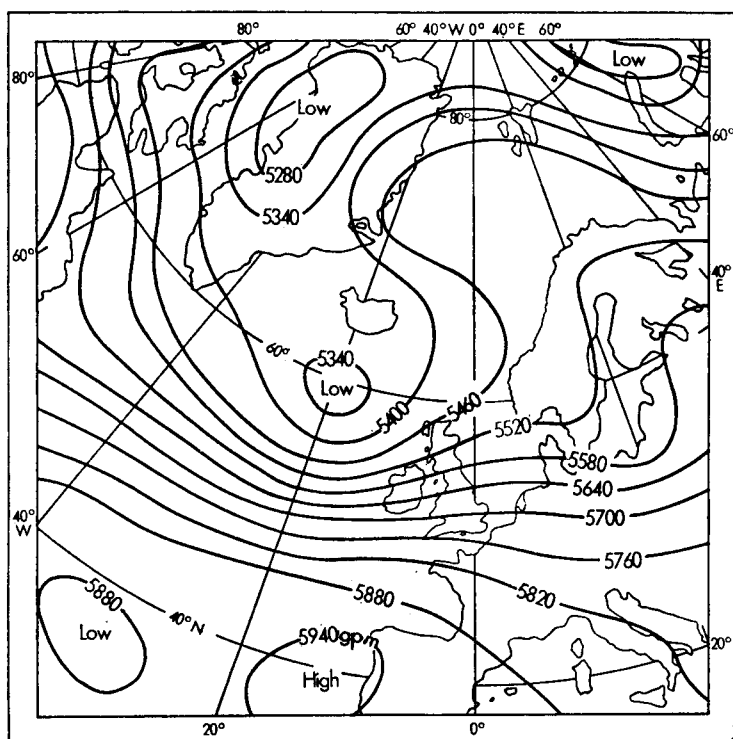


FIGURE 5—500-mb CHART FOR 12 GMT, 23 AUGUST 1962

Westerly types — the tracks of the depressions. Figure 6 shows the tracks of the depressions, wave-depressions and waves for occasions (1) to (7) listed in the introduction. The reference numbers of the occasions are used for numbering the tracks. The depressions or waves approached the British Isles from the north-west, west and south-west. In general, they moved north-eastwards across northern England or southern Scotland, or eastwards across northern Scotland or to the north of Scotland. On occasion (3) the

rain was partly associated with an occluding depression (3a) and partly with a wave on the cold front (3b). On occasion (7) the rain was partly associated with a wave (7a) and partly with a wave-depression (7b).

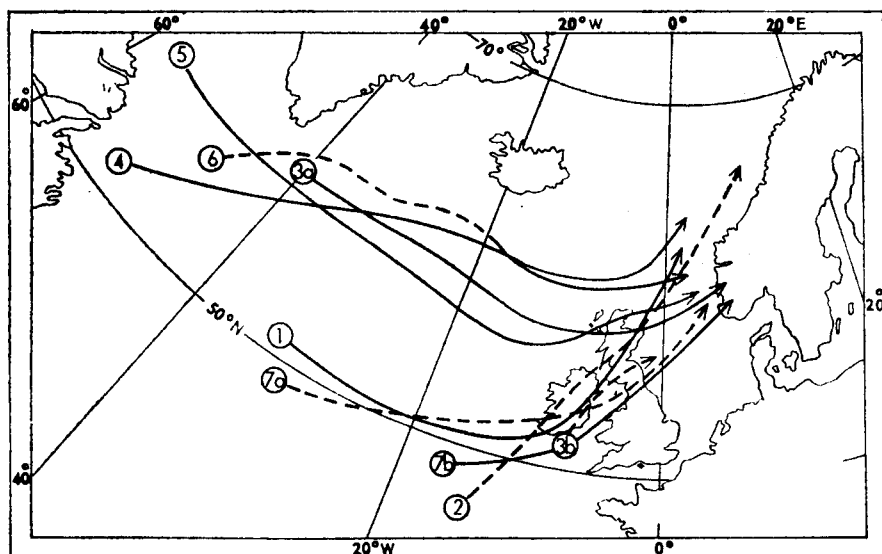


FIGURE 6—WESTERLY TYPES—TRACKS OF DEPRESSIONS AND WAVES
 ———— Track of depression. - - - Track of wave.

Westerly types — a summary of the seven occasions. The seven occasions showed some similarities as follows :

(i) The rainfall was associated on all occasions with a warm sector which moved eastwards across the Area. On occasion (2) the tip of a wave moved north-eastwards across Ireland and Scotland and on occasion (3b) one moved north-eastwards from southern Ireland across southern Scotland. On occasion (7a) the tip of a wave moved north-eastwards across Ireland and northern England. On occasion (1) the tip of a wave-depression moved north-eastwards across Ireland and Scotland and on occasion (7b) one moved north-eastwards from south of Ireland across the north coast of Wales and northern England; there was no occlusion. On occasions (4) and (6) the point of occlusion of a depression moved eastwards just north of Scotland and on occasions (3a) and (5) one moved eastwards across the north of Scotland and across central Scotland respectively.

(ii) With the exception of occasion (3a) the associated depression or wave deepened until 18 GMT on the actual day. On occasion (3a) the depression deepened until 00 GMT on the actual day, then showed no change during the next 24 hours.

(iii) On all occasions the lowest pressure at the centre of the associated depression or at the wave-tip during the rainfall day was between 964 mb and 984 mb.

(iv) With the exception of occasion (7a) there was a maximum 3-hour

pressure fall of between 3 mb and 6 mb ahead of the warm front. On occasion (7a) there was a fall of only 2 mb. On all occasions there was a maximum 3-hour pressure fall of between 3 mb and 5 mb in the warm sector.

(v) The surface dew-point in the warm air ranged from the normal to 9 degF (5 degC) above the normal.³

(vi) On all occasions the surface geostrophic wind speed in the warm sector was between 40 kt and 70 kt and the direction between 220° and 260°.

With the exception of occasions (4) and (7a) the Benwell criteria⁴ for heavy rainfall over the Area were satisfied. Occasions (4) and (7a) were considered to be borderline occasions.

Westerly types — criteria for indicating 24-hour rainfall totals of 1.5 in or more in the Dee and Clwyd Area in the months March to August.

(i) A deepening partly occluded depression, wave-depression or wave moves towards the longitude of the British Isles, keeping south of Iceland, from directions between north-west and south-west.

(ii) The point of occlusion or the wave-tip moves eastwards across or north of the British Isles, to the north of Wales and south of the Shetlands, i.e. a warm sector crosses the Area.

(iii) The depression or wave continues to deepen until 18 GMT on the 'rainfall day', i.e. 09 GMT (*d*) to 09 GMT (*d* + 1).

(iv) The central pressure or the pressure at the wave-tip falls to 984 mb or less during the rainfall day.

(v) There are 3-hour pressure falls of 3 mb or more ahead of the warm front and in the warm sector in the vicinity of the Area.

(vi) The surface dew-point in the warm sector is not below the normal³ in the vicinity of the Area.

(vii) The surface geostrophic wind speed in the warm sector is 40 kt or more and the direction is from 220° to 260° inclusive in the vicinity of the Area.

The above criteria were satisfied on all occasions except (3a) and (7a). The Benwell criteria⁴ for heavy rain over the Area were satisfied on all occasions except (4) and (7a).

Westerly types — a comparison of the criteria with those obtained for the months September to February. Criteria (ii) and (v) satisfy the corresponding criteria obtained for the months September to February.

Criterion (i) requires the depressions or waves to approach the British Isles from directions 'between north-west and south-west' compared with 'between north-west and west-south-west'.

Criterion (iii) requires the depression or wave to continue to deepen until 18 GMT compared with midnight on the 'rainfall day'.

Criterion (iv) requires the central pressure to fall to 984 mb or less compared with 988 mb or less.

Criterion (vi) requires the surface dew-point in the warm sector to be normal³ or above compared with 6 degF (3 degC) or more above the normal.³

Criterion (vii) requires the surface geostrophic wind direction in the warm sector to be from 220° to 260° compared with 230° to 280°. The wind speed is required to be 40 kt or more for both periods.

There is little difference between the two sets of criteria with the exception of criterion (vi) in which the large positive anomaly in the surface dew-point required in the winter half of the year is not required in the summer half.

The Benwell criteria⁴ for heavy rainfall over the Area were much more successful than in the winter half of the year. However, in both periods, the requirement that the Area should be below the left exit of the jet stream at 500 mb was the subject of rather critical decisions. The relative success of the criteria in the summer half of the year was due to the Area being situated, on average, below the centre of the exit, whereas in the winter half, the Area was situated, on average, below the right exit.

Westerly types — a test of the criteria on independent data. A test of the criteria was carried out for days classified as westerly in the months March to August for the five years 1964–68. These periods included two of the seven occasions on which the criteria were based, i.e. 7 July 1964 and 19 March 1968. Excluding these occasions, of the 222 days there were 4 on which the criteria were satisfied.

The dates and highest rainfall values recorded were as follows :

(i) 9 April 1965, 1.47 in, (ii) 22 March 1968, 1.95 in, (iii) 23 March 1968, 3.61 in and (iv) 1 April 1968, 1.62 in. All but one of the highest rainfall values were recorded at Afon Mynach (1200 ft) the exception being occasion (i) when 1.47 in was recorded at Llanuwchllyn P.O. (570 ft). All four days were associated with rainfall totals of 1.5 in or more. Of the 216 days when the criteria were not satisfied, there were 2 with rainfall totals of 1.5 in or more, i.e. 26 June 1966 (1.47 in) when a warm-front wave and a shallow wave-depression crossed Scotland, resulting in a very wide warm sector crossing the Area, and 19 August 1968 (2.08 in) when the warm front was associated with thunderstorms.

If the two occasions on which the criteria were partly based were included, the criteria would have indicated six of the eight occasions with totals of 1.5 in or more which actually occurred in westerly situations. No occasions with less than 1.5 in would have been indicated.

The Benwell rules⁴ indicated heavy rain over the Area on occasions (i), (iii) and (v) but the requirement that the left exit of the jet stream at 500 mb should be over the Area was the subject of rather critical decisions. On all these three occasions the Area was situated below the centre of the exit rather than below the left exit.

Westerly types — the result of reducing the number of criteria. It is obvious that the seven criteria are highly correlated and it might therefore be possible to reduce their number without seriously affecting their success as rainfall indicators. It was found that the number could be reduced to four by excluding (iv), (v) and (vi), resulting in the addition of only one day, 17 June 1965, when the rainfall total was 1.10 in, to the indications.

Westerly types — conclusions. About one-third of daily rainfall totals of 1.5 in or more in the Dee and Clwyd River Authority Area were associated in the summer half of the year with westerly types, in particular with the warm sector of deepening depressions or waves. Seven criteria for indicating totals of 1.5 in or more were obtained for the months March to August. In a test on independent data, four out of the six occasions with 1.5 in or more

which actually occurred in the westerly situations were indicated. No occasions with less than 1.5 in were indicated. The number of criteria could be reduced to four without seriously affecting their success as rainfall indicators.

Cyclonic types. One example of the detailed descriptions of the cyclonic types, that for occasion (12), is given below.

The situation on 18 July 1964. The rainfall at some of the stations in the Area for the 24 hours ending 09 GMT on 19 July was (i) Tower Wood, 1.61 in, (ii) Wrexham, 1.58 in, (iii) Brynkinalt, 1.54 in and (iv) Gredington, 1.50 in.

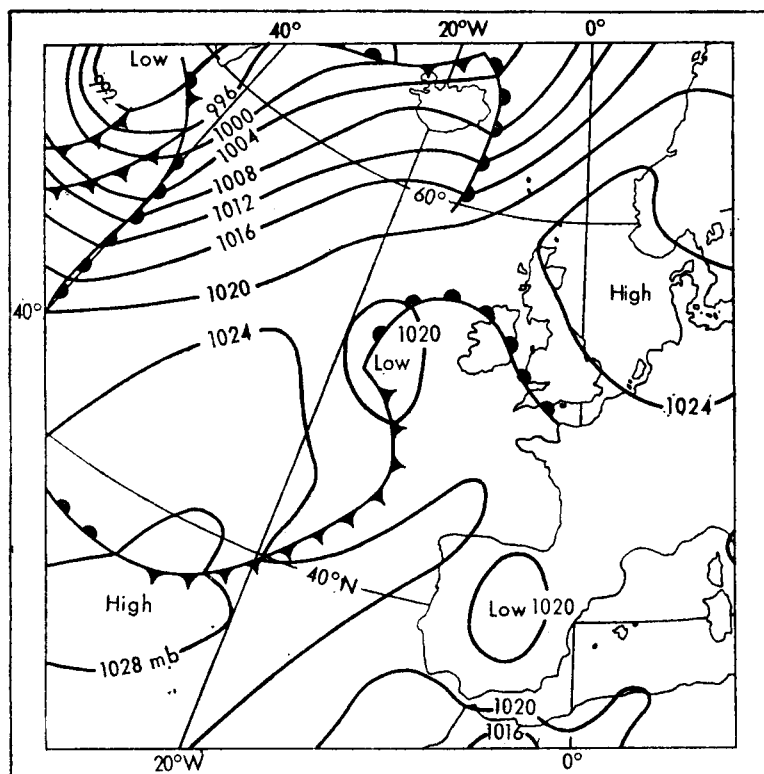


FIGURE 7—SURFACE CHART FOR 12 GMT, 17 JULY 1964

Figure 7 shows the surface chart for 12 GMT on 17 July when a depression (1020 mb) was centred to west of Ireland and an anticyclone (1024 mb) over the North Sea. By 00 GMT on the 18th (Figure 8) the depression had moved eastwards to the South-west Approaches with no change in pressure. The associated cold front was approaching Biscay and Spain. Three-hour pressure falls of 1 mb were reported in south-west England where thunderstorms had occurred. By 12 GMT (Figure 9) the depression was centred over south Wales, having deepened to 1016 mb with the cold front over north-west France and Biscay. Pressure falls of 1–2 mb had occurred over Wales and southern England. Widespread thunderstorms had occurred over Wales

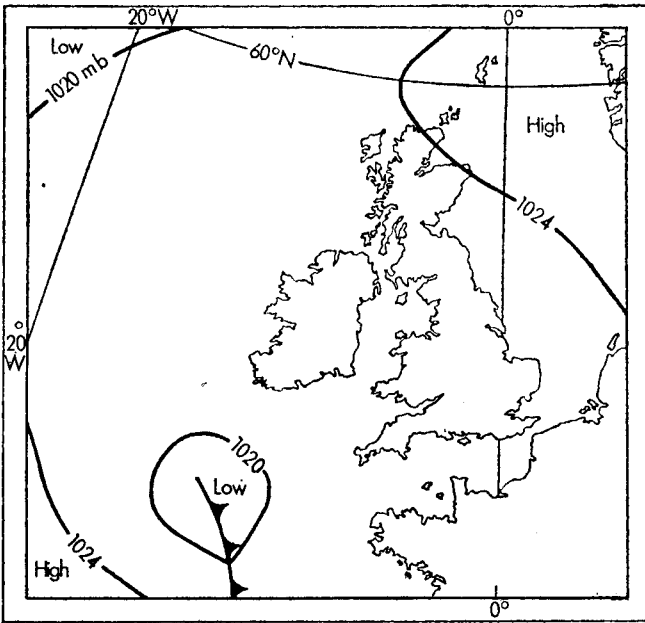


FIGURE 8—SURFACE CHART FOR 00 GMT, 18 JULY 1964

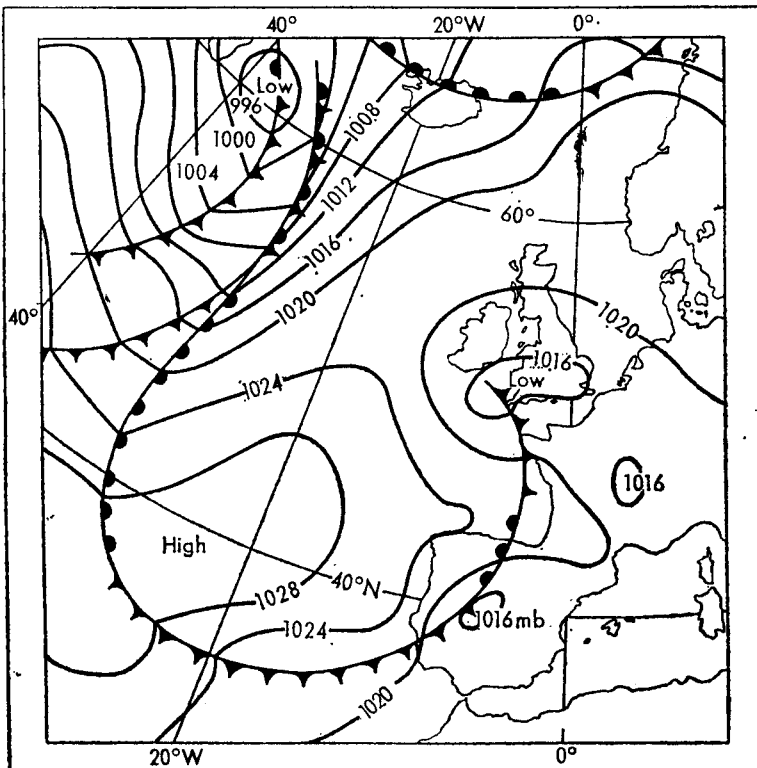


FIGURE 9—SURFACE CHART FOR 12 GMT, 18 JULY 1964

between 03 GMT and 09 GMT and over most of England by 09 GMT. By 00 GMT on the 19th (Figure 10) the depression had moved north-eastwards across Wales to northern England, having further deepened to 1012 mb. The cold front had moved eastwards across southern England to the North Sea. Pressure falls of 2 mb had occurred over Wales where further thunderstorms had been reported. The depression continued to move north-eastwards to the North Sea by 09 GMT, having further deepened to 1010 mb. The surface geostrophic wind over the Area during the rainfall day was light and variable.

The 500-mb chart for 00 GMT on the 19th (Figure 11) showed a large trough over the British Isles with a low over the Irish Sea. The trough moved eastwards across the British Isles whilst the low moved from south-west of Ireland, across Ireland and Wales to eastern Scotland from 12 GMT on the 17th to 12 GMT on the 19th. There were no winds of 70 kt or more in the region of the British Isles. The Benwell criteria⁴ for heavy rainfall over the Area were not satisfied.

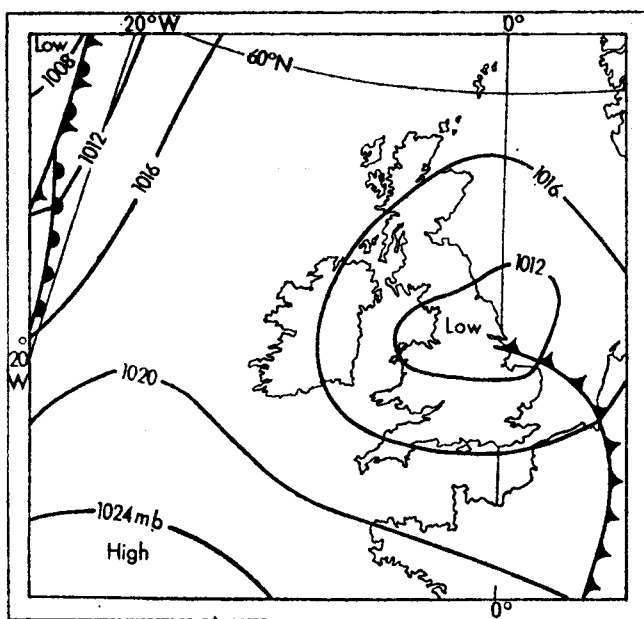


FIGURE 10—SURFACE CHART FOR 00 GMT, 19 JULY 1964

Cyclonic types associated with thunder — the tracks of the depressions. Figure 12 shows the tracks of the depressions for occasions (8) to (12) listed in the introduction. The reference numbers of the occasions are used for numbering the tracks. The depressions finally approached the British Isles from the south or south-west and moved northwards, north-eastwards or eastwards across Wales or England.

Cyclonic types associated with thunder — a summary of the five occasions.

(i) On occasion (8) a depression moved northwards from France across eastern England, with Wales coming within the cyclonic circulation. It is

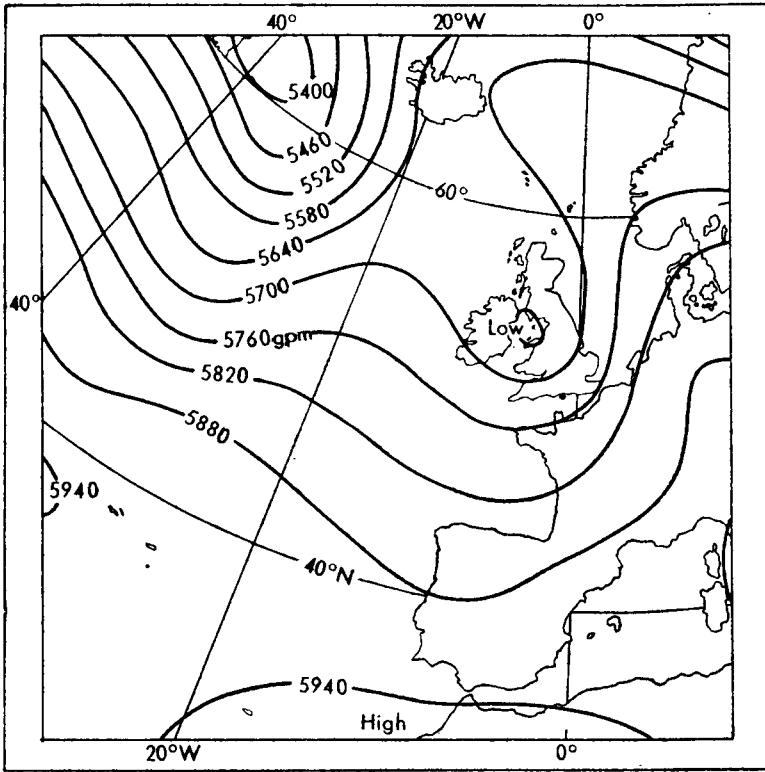


FIGURE 11—500-mb CHART FOR 00 GMT, 19 JULY 1964

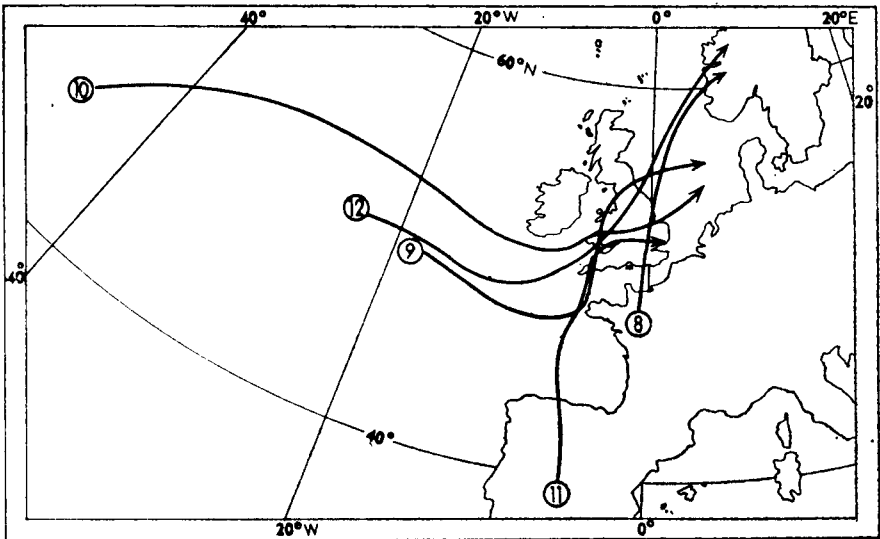


FIGURE 12—CYCLONIC TYPES ASSOCIATED WITH THUNDER—TRACKS OF THE DEPRESSIONS

not known whether any fronts were involved. On occasions (9), (10), (11) and (12) a depression from the south-west or south moved across Wales. On occasion (9) it is not known whether any fronts were involved. On occasions (10), (11) and (12) the depressions were associated with fronts, none of which crossed the Area. On occasion (10) a partly occluded depression crossed south Wales, the occlusion moving across south Wales and southern England and a secondary cold front moving southwards across Ireland and south Wales. On occasion (11) a wave-depression crossed south Wales and on occasion (12) a depression with an associated cold front crossed south Wales. Thus, on at least three of the five occasions, no fronts crossed the Area.

(ii) When approaching the British Isles, the depression deepened on all five occasions but on four of them the deepening was very slight. When crossing the British Isles, the depression deepened on three of the five occasions. On one occasion there was no change in pressure and on one occasion the depression filled.

(iii) The lowest pressure at the centre of the depression during the rainfall day ranged from 999 mb to 1010 mb.

(iv) The maximum 3-hour surface pressure fall over Wales during the rainfall day ranged from 1 mb to 3 mb.

(v) The surface geostrophic wind over the Area during the rainfall day was on all occasions either variable or light and variable.

The Benwell criteria⁴ did not indicate heavy rainfall over the Area on occasions (10), (11) and (12) when there were no jet streams at 500 mb in the region of the British Isles. There were no 500-mb data for occasions (8) and (9).

Cyclonic types not associated with thunder — the tracks of the depressions. Figure 13 shows the tracks of the depressions and waves for occasions (13) to (17) listed in the introduction. The reference numbers of the occasions are used for numbering the tracks. The depressions approached the British Isles from the south-west or west. On three occasions a depression moved eastwards or north-eastwards across Wales and on one occasion a wave moved eastwards across north Wales. On one occasion a depression moved north-eastwards across eastern Ireland to southern Scotland.

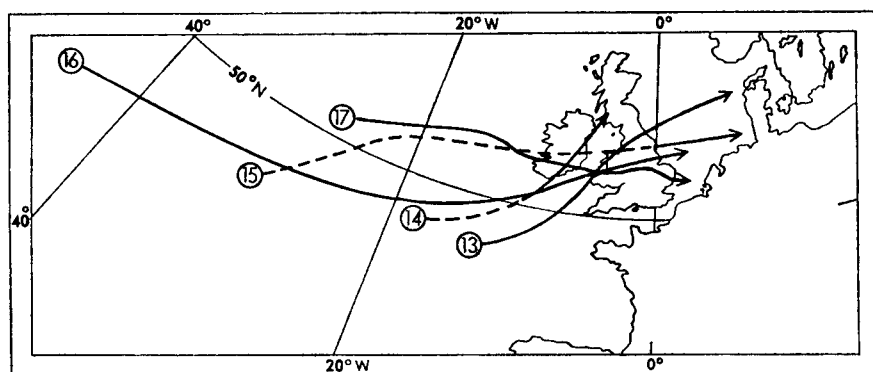


FIGURE 13—CYCLONIC TYPES, NOT ASSOCIATED WITH THUNDER—TRACKS OF DEPRESSIONS AND WAVES
 ————— Track of depression. - - - - - Track of wave.

Cyclonic types not associated with thunder — a summary of the five occasions.

(i) On occasion (14) a partly occluded depression moved north-eastwards from south of Ireland across eastern Ireland to Scotland, with Wales coming within the cyclonic circulation. The occlusion moved north-eastwards across Wales. On occasions (13), (15), (16) and (17) a depression or wave moved eastwards or north-eastwards across Wales. On occasion (13) a wave-depression moved north-eastwards across Wales, becoming partly occluded with the occlusion crossing the Area. On occasion (15) a wave moved eastwards across north Wales, the tip of the wave crossing the Area. On occasion (16) a partly occluded depression moved eastwards across Wales but the fronts did not cross the Area. On occasion (17) a partly occluded depression moved eastwards across south Wales. The associated occlusion did not cross the Area but a cold front associated with a polar low to the north of Scotland was quasi-stationary over the Area for most of the rainfall day. Thus, fronts crossed the Area on four of the five days.

(ii) When approaching the British Isles, the depression deepened on three of the five occasions and on one occasion filled very slightly. The wave showed no change in pressure.

When crossing the British Isles, the depression at first deepened then filled on one occasion, filled on two occasions and showed no change on one occasion. The wave deepened.

(iii) The lowest pressure at the centre of the depression or at the wave-tip during the rainfall day ranged from 968 mb to 1002 mb.

(iv) The maximum 3-hour surface pressure fall over Wales during the rainfall day ranged from 3 mb to 6 mb.

(v) The surface geostrophic wind over the Area during the rainfall day was variable or light and variable on four of the five occasions.

The Benwell criteria⁴ indicated heavy rainfall over the Area on occasion (15) but the criteria were not satisfied on the other four occasions, mainly because of the absence of jet streams at 500 mb in the region of the British Isles. Occasion (15) when the tip of a wave moved across the Area was on the borderline between the westerly (warm sector) type and the cyclonic type.

A comparison of the cyclonic types associated with thunder with those not associated with thunder.

(i) On the thundery occasions, the depression approached the British Isles from the south or south-west and on at least three of the five occasions no fronts crossed the Area. On the non-thundery occasions, the depression approached the British Isles from the south-west or west and on four of the five occasions a front crossed the Area.

(ii) On the thundery and on the other occasions, the depression either deepened or showed only slight changes in central pressure when approaching the British Isles, and deepened, showed little change or filled when crossing the British Isles.

(iii) The thundery depressions were generally less intense than the others, the lowest central pressure averaging 1001 mb for the thundery occasions and 991 mb for the others.

(iv) The thundery depressions were associated with relatively small 3-hour pressure falls over Wales, the maximum 3-hour fall averaging 2 mb for the thundery occasions and 4 mb for the others.

(v) The surface geostrophic wind over the Area was mainly variable or light and variable on thundery and on non-thundery occasions.

(vi) On the thundery and on the other occasions the Benwell criteria⁴ for heavy rain over the Area showed little success, mainly because of the absence of jet streams of 70 kt or more at 500 mb in the region of the British Isles. It is interesting to note that the westerly (warm-sector) types were nearly all associated with jet streams of 70 kt or more at 500 mb.

Cyclonic types — criteria for indicating 24-hour rainfall totals of 1.5 in or more in the Dee and Clwyd Area in the months April* to August.

(i) A depression finally approaches the British Isles from directions between west (tracking south of 54°N) and south.

(ii) As it approaches the British Isles, the depression deepens or shows only slight changes in central pressure, i.e. it is not obviously filling.

(iii) The depression moves eastwards, north-eastwards or northwards across Wales, or eastwards, north-eastwards or northwards across England, tracking south or east of Wales.

(iv) If the depression does not cross Wales, the cyclonic circulation of the depression extends over Wales.

(v) The central pressure falls to 1010 mb or less during the rainfall day.

Cyclonic types — a test of the criteria on independent data. A test of the criteria was carried out for days classified as cyclonic in the months March to August for the five years 1964–68. On many occasions, the rainfall associated with the movement of a depression across the British Isles was spread over two ‘rainfall days’. On these occasions, the highest rainfall total at any station over the two rainfall days was obtained, together with the duration of the rain estimated from hourly synoptic charts. On most occasions, the rain over the two days fell in less than 24 hours and was used as the 24-hour rainfall total. On a few occasions, the rainfall fell over a period of more than 24 hours and the two-day total was reduced in proportion to provide an estimated 24-hour total.

It soon became clear that there was no evidence that the criteria would be of use in March and the investigation was restricted to the months April to August.

The test periods included three of the occasions on which the criteria were based, i.e. 18 July 1964, 21 June 1965 and 1 April 1966. Excluding these occasions, of the 145 days there were 10 on which the criteria were satisfied. The dates and highest rainfall values recorded were as follows: (i) 17 May 1965, 1.16 in, (ii) 23 July 1965, 2.55 in, (iii) 31 July–1 August 1966, 1.05 in, (iv) 6 August 1966, 0.18 in, (v) 14–15 May 1967, 1.73 in, (vi) 27–28 May 1967, 1.06 in, (vii) 13 July 1967, 2.50 in, (viii) 1–2 July 1968, 2.59 in, (ix) 14 July 1968, 2.03 in, (x) 16 August 1968, 0.48 in.

* In a test of the rules on independent data it became clear that the criteria would be of no use in March.

Of the 10 occasions, 6 were associated with thunder, i.e. occasions (ii), (vi), (vii), (viii), (ix) and (x). Of the 10 days, 5 were associated with rainfall totals of 1.5 in or more, 3 with 1.0–1.4 in, and 2 were associated with totals of less than 1.0 in. Of the 135 days when the criteria were not satisfied, there were 4 with rainfall totals of 1.5 in or more, i.e. (i) 8 May 1965 (2.13 in) when a wave moved eastwards across north Wales, the wave-tip crossing the Area, (ii) 13 July 1965 (1.65 in) when a wave moved north-eastwards across Wales and later another moved north-eastwards across the Midlands, (iii) 12–13 August 1966 (1.50 in) when a depression moved northwards just west of Wales and (iv) 25 May 1968 (1.94 in) when a thundery trough with an associated occlusion moved north-eastwards across Wales.

If the 3 occasions on which the criteria were partly based were included, the criteria would have indicated 8 of the 12 occasions with totals of 1.5 in or more which actually occurred in cyclonic situations and also 3 occasions with 1.0–1.4 in and 2 occasions with less than 1.0 in.

Cyclonic types — conclusions. About one-half of daily rainfall totals of 1.5 in or more in the Dee and Clwyd River Authority Area were associated in the summer half of the year with cyclonic types, of which over one-half were associated with thunder. Five criteria for indicating totals of 1.5 in or more were obtained for the months April–August. In a test on independent data, five out of the nine occasions with 1.5 in or more which actually occurred in the cyclonic situations were indicated, together with three occasions with 1.0–1.4 in and two occasions with less than 1.0 in.

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AN EMPIRICAL APPROACH TO FORECASTING GRASS MINIMUM TEMPERATURES AND THE PROBABILITY OF GRASS MINIMA BELOW 0°C IN EASTERN ENGLAND

By L. P. STEELE, P. A. J. STROUD and S. E. VIRGO, O.B.E.

Summary. Depressions of the grass minimum temperature below the air minimum temperature at 10 stations in eastern England were examined for the period 1961–65. Depressions were obtained for various categories of night-time conditions defined according to weather, state of ground, cloud amount and geostrophic wind speed. Various statistical parameters were computed for the depression associated with each category. For 16 of the categories ogives were drawn showing the percentage of occasions when the depression was greater than a specified value. Each ogive was used to estimate the probability of occurrence of a specified depression under the conditions of the category. Finally a table was produced to give, for each specified forecast air minimum, an estimate of the probability of occurrence of a grass minimum below 0°C. The probabilities of various forecast errors in the specified forecast were combined, as necessary, with the probabilities of the depressions required to give a grass minimum below 0°C.

Purpose of the investigation. During the period October 1961–September 1965 Tinney and Menmuir collected and analysed detailed observations from 13 stations in eastern England and the Midlands in order

to provide data for use in forecasting air minimum temperatures and grass minimum temperatures. They completed the first part of the investigation¹ but circumstances prevented them from investigating grass minimum temperatures. The observations collected by Tinney and Menmuir have been used by the present authors to investigate the depression of the grass minimum temperature below the air minimum temperature at 10 of the stations. The 10 stations are :

Wyton	Waddington	Finningley	Marham	Mildenhall
Wittering	Cottesmore	Bassingbourn	Lindholme	Scampton.

Locations and heights above sea level are given in Figure 1 of the paper by Tinney and Menmuir.¹

There is considerable evidence that the night minimum temperature is generally lower at the tips of long grass than of short grass,² as all 10 sites are standard Meteorological Office enclosures in open exposures on airfields with broadly similar routines for cutting the grass, the data are probably as homogeneous as any which are likely to become available. As has been shown by Gloyne³ and others, minimum temperatures on bare soil and on concrete roads are usually not so low as grass minima.

The investigation had a twofold purpose : to examine the observed depression of the grass minimum temperature below the air minimum temperature at screen level and also to evolve a method of combining the results with the forecast air minimum temperature in order to obtain the probability of a grass minimum below 0°C for a given forecast air temperature.

Depression of grass minimum temperature below air minimum temperature. The simplest approach to forecasting the grass minimum temperature would be to average all the depressions of grass minimum temperature below air minimum temperature and to subtract this value from the forecast air minimum temperature, but this would be very rough and ready because of the large scatter of observed depressions about the mean. Better results would be obtained if the observations were separated into various categories distinguished from each other by weather, state of ground, cloud amount and wind speed, and if statistics were compiled for each category. This has been done in Table I and for easy reference each category has been designated by a letter in the right-hand column of the table.

Occasions when a front passed a station during the period between sunset and sunrise were excluded from the analysis for that station and occasions when fog occurred during the night were excluded from all categories except the last.

Wind speeds were expressed in terms of geostrophic wind rather than surface wind because Tinney and Menmuir used geostrophic wind speeds when they assembled the data and Craddock and Pritchard⁴ also used geostrophic winds.

The ranges of cloud amount were chosen as follows : 0-2/8 was chosen to include radiation nights, 6/8-8/8 was chosen to include nights which were predominantly overcast and 3/8-5/8 resulted from the choice of the other two; only low and medium cloud were taken into account.

Analysis of variance⁵ showed that at the 5 per cent level there was no significant year-to-year variation between the mean depressions at any station, and the average of four years could therefore be regarded as representative in all the categories in Table I.

Although the *t*-test⁶ showed that at the 5 per cent level the mean depression within a category at any one station was in most cases significantly different from the mean depression in the same category at another station, it will become evident later in the paper that this makes very little difference in practice and therefore, in order to obtain figures representative of eastern England as a whole, the data from all the stations within each category were treated as a single population.

Category P originally comprised three parts corresponding to three ranges of wind speed, but analysis of variance showed that there was no statistically significant difference between the parts at the 5 per cent level and so they were compounded into a single category.

Category Q consisted of the occasions when rain was falling for a substantial part of the night. This is a rather subjective definition but it gave rise to no difficulties in practice. Analysis of variance showed that all cases of rain falling could be combined, irrespective of wind speed. There were only 46 cases of snow falling during the night and this total is too small for statistical analysis, so it was assumed that, since all the cases of falling rain were from one population, all cases of falling snow would also come from a single population.

Cases of no precipitation but with the ground covered with snow were examined next, and again analysis of variance showed that at the 5 per cent level the variation with geostrophic wind speed is not significant. Nor is there any statistical difference between 0–2/8 and 3/8–5/8, but there is a statistically significant difference between 0–5/8 and 6/8–8/8; this explains the choice of categories S and T.

The final category U comprises only those fogs which formed early in the evening and persisted throughout the night; 21 GMT was taken as an arbitrary criterion for acceptance in this category. No attempt was made to separate these cases according to wind speed and, since the total number in the category was only 74, too few for statistical analysis of individual stations, this category was treated as though it consisted of a homogeneous population.

The results are summarized in Table I which is based on a total number of 6599 cases. As the distributions are not normal, there is no simple way of expressing, in terms of the standard deviation σ , the percentage of observations lying within various limits on each side of the mean. Percentages on each side of the median can however be easily calculated from the actual tabulations, and the 25 per cent limits and 45 per cent limits on each side of the median are shown in Table I. These correspond to ranges of 50 per cent and 90 per cent respectively.

Comments on Table I. Hogg⁷ investigated those depressions of the grass minimum temperature below air minimum which produced ground frosts*

* The definition of ground frost changed on 1 January 1961 from a grass minimum reading of '30.4°F or below' to '32°F or below' and on 1 January 1963 to 'below 32°F'.

TABLE 1—SUMMARY OF DEPRESSIONS OF GRASS MINIMUM TEMPERATURES BELOW AIR MINIMUM TEMPERATURES FOR 10 STATIONS IN EASTERN ENGLAND (OCTOBER 1961–SEPTEMBER 1965)

Weather and state of ground	Cloud amount <i>oktas</i>	Geostrophic wind speed <i>knots</i>	Number of cases	Mean depression	σ	Median <i>degrees Celsius</i>	25 per cent limits	45 per cent limits	Category			
No precipitation No fog No snow cover $T_{\min} \geq 0^{\circ}\text{C}$	dry	0-12 13-24 ≥ 25	366 584 182	3.35 3.08 2.70	1.33 1.31 1.06	2.8 2.8 2.3	2.0 2.0 1.9	4.0 3.7 3.1	A B C			
		moist or wet	0-12 13-24 ≥ 25	69 380 370	3.09 2.63 2.43	1.33 1.15 0.87	2.6 2.5 2.2	1.7 1.7 1.7	3.5 3.4 2.9	D E F		
			dry	0-12 13-24 ≥ 25	228 379 143	3.26 2.67 2.36	1.13 1.32 1.06	2.9 2.4 2.1	2.1 1.7 1.5	4.2 3.6 3.0	G H I	
	moist or wet	0-12 13-24 ≥ 25	118 290 287	2.89 2.50 2.32	1.07 1.59 0.96	3.0 2.1 2.0	1.7 1.5 1.5	3.7 3.4 3.1	J K L			
		dry	0-12 13-24 ≥ 25	366 544 214	1.67 1.52 1.37	1.25 1.12 0.87	1.4 1.2 1.1	0.7 0.6 0.7	2.4 2.1 1.8	M N O		
			moist or wet	All	893	1.63	1.08	4.3	0.8	2.1	P	
	Rain No snow cover $T_{\min} \geq 0^{\circ}\text{C}$ Falling snow	6-8	wind speeds									
			All	863	0.73	0.49	0.5	0.4	1.3	0.0	3.4	Q
		6-8	All	46	0.57	0.18	0.5	0.4	0.8	0.0	1.5	R
	No precipitation No fog	0-5	wind speeds									
			All	142	2.47	1.30	2.3	1.0	4.1	0.2	5.6	S
		6-8	wind speeds	61	1.47	1.29	1.2	0.4	3.0	0.1	4.7	T
Fog by 21 GMT $T_{\min} \geq 0^{\circ}\text{C}$	Sky obscured	All	74	0.42	0.24	0.2	0.0	0.6	0.0	1.6	U	

on radiation nights at 7 places in south-west England. The basis on which he selected his cases was different from that described in the present paper and therefore a subsidiary investigation was made using data which could be compared with Hogg's. This showed that the mean depression for the 7 places in south-west England on radiation nights with ground frosts was greater by about 1 degC than the corresponding figure for the 10 stations in eastern England. A note of warning must therefore be sounded; Table I applies specifically to eastern England and its use should not be extended to other parts of the country without good reason.

Type of soil, proximity of buildings and lie of the land have all been examined but no systematic explanation has been found for the different depressions at different stations. The correlation coefficient for daily values of the depressions in category A for Lindholme and Finningley, 5 miles apart on flat ground, was 0.7. That for Scampton and Waddington, 9 miles apart on the Lincolnshire Wolds but with the Witham gap between them, was 0.5. The coefficient for Bassingbourn and Wyton, 21 miles apart, was also 0.5, but the coefficient for Mildenhall and Honington, 13 miles apart, was only 0.2. There is therefore no simple way of transferring results obtained at one station to somewhere else in the neighbourhood and, unless actual observations are available from the place in question, the best that can be done is to use mean values for the area.

There is evidence that depressions on radiation nights are larger in spring and summer than in autumn and winter, but the seasonal means are within about 10 per cent of the annual means.

To summarize, tables corresponding to Table I could be constructed for each of the 10 stations but the extreme departure from any one of the means is about 1.5 degC at one station and all the others are within 1 degC. The seasonal variation is at most about 0.3 degC. These figures are within the tolerances acceptable to forecasters. Moreover when the table of probabilities discussed in the next part of this paper was worked out, it was found that these departures from the means made no more than a 5 per cent difference to the probabilities and therefore Table I constitutes a good working guide to the approximate depression of the grass minimum temperature below the air minimum temperature in eastern England.

The probabilities of grass minima below 0°C occurring with a given forecast night minimum air temperature. In a previous paper⁸ the authors showed that the errors in forecasting night minimum air temperatures by the method of Saunders^{9,10} in a year's test with data from 10 stations were normally distributed with a standard deviation of 1.89 degC and a mean of -0.3 degC. The percentage of errors lying within various ranges can therefore be obtained from tables and the results are shown in Table II. Ogives, showing the percentage of occasions in 1961-65 when the depression of the grass minimum temperature below the air minimum temperature was greater than a specified depression, were plotted for categories A-P and one of these ogives (the curve for category A) is shown in Figure 1. If the assumption is made that Table II can be applied to the data of 1961-65 it is possible to combine the information in Table II with the information in each of the ogives in turn to calculate the probability of a grass minimum

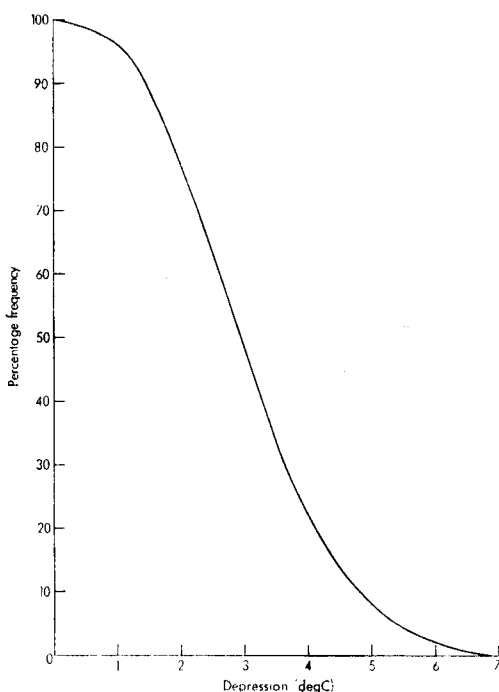


FIGURE 1—OGIVE, FOR CATEGORY A, SHOWING PERCENTAGE OF OCCASIONS WHEN THE DEPRESSION OF THE GRASS MINIMUM TEMPERATURE BELOW THE AIR MINIMUM TEMPERATURE WAS GREATER THAN CERTAIN SPECIFIED VALUES

below 0°C for each category corresponding to a specified forecast air minimum temperature. The method can best be explained by an example taken from category A, so that Figure 1 can be used in the calculations.

Suppose the forecast air minimum to be $+2^{\circ}\text{C}$ and that the forecast is based on the method of Saunders^{9,10} as tested by Steele, Stroud and Virgo.⁸

If the assumption is made that Table II (based on average values of mean error and standard deviation) can be applied to a selected sample of forecasts of 2°C , the percentage probability that a forecast of 2°C is correct within $\pm 0.5^{\circ}\text{C}$ can be read from Table II as 20.6 per cent. The actual air minimum will be $+2^{\circ}\text{C}$ and thus a depression greater than 2 degC is needed to give a grass minimum below 0°C . The assumption is then made that the average distribution of depressions in the 1961–65 sample can be used to represent the distribution in a selected sample, e.g. the correct forecasts of air minimum of 2°C in category A conditions. From Figure 1 depressions greater than 2 degC occur on 77 per cent of occasions in category A conditions, and thus grass minima below 0°C occur on 77 per cent of the 20.6 per cent of forecasts of 2°C which are correct, i.e. the percentage probability of a grass minimum below 0°C with a forecast air minimum of 2°C is 15.9 per cent if only the correct forecasts are considered.

Now suppose the forecast air minimum to be 1 degC too cold. This happens on 19.6 per cent of occasions (Table II). The actual minimum will be 3°C . A depression greater than 3 degC is needed for a grass minimum below 0°C and from Figure 1 this occurs on 48 per cent of occasions. The

TABLE II—PERCENTAGE PROBABILITY OF ERRORS IN FORECASTING NIGHT MINIMUM AIR TEMPERATURE

Error	Percentage probability*	Error	Percentage probability*
No error†	20.6		
1 degC too warm‡	16.5	1 degC too cold	19.6
2 degC too warm	10.0	2 degC too cold	14.1
3 degC too warm	4.6	3 degC too cold	7.7
4 degC too warm	1.7	4 degC too cold	2.9
5 degC too warm	0.5	5 degC too cold	1.7
6 degC too warm	0.1	6 degC too cold	0.1

* Based on a normal distribution with mean -0.3 degC and standard deviation 1.89 degC, as obtained in the 1967–68 sample.

† 'No error' is defined as a forecast minimum within ± 0.5 degC of an actual minimum.

‡ An error of '1 degC too warm' is defined as a forecast minimum of 0.5 to 1.5 degC warmer than the actual minimum.

percentage probability of a grass minimum below 0°C in this case is therefore $19.6 \times 0.48 = 9.4$ per cent. The process is repeated degree by degree until the probability of a grass minimum below 0°C is, for all practical purposes, zero. Now consider cases when the forecast air minimum of 2°C is too warm. The forecast will be 1 degC too warm on 16.5 per cent of occasions and on these occasions the actual air temperature will be $+1^{\circ}\text{C}$. A depression greater than 1 degC is needed to give a grass minimum below 0°C ; from Figure 1 this occurs on 96 per cent of occasions and the probability is $16.5 \times 0.96 = 15.8$ per cent. When the forecast is 2 degC too warm which occurs on 10.0 per cent of occasions the actual air temperature will be 0°C and all depressions will give a grass minimum below 0°C . The probability in this case is $10.0 \times 1.00 = 10$ per cent. Similarly when the forecast is 3 degC too warm, which occurs on 4.6 per cent of occasions, and the actual air temperature is -1°C all depressions give a grass minimum below 0°C and the probability is $4.6 \times 1.00 = 4.6$ per cent. The process is continued degree by degree until the forecast temperature is 5 degC too warm; thereafter probabilities are too small to be worth considering.

Finally all these separate probabilities are added together to obtain the total probability of a grass minimum below 0°C for a forecast air minimum temperature of 2°C . The same procedure is applied for forecast air minima below 0°C . Consider a forecast air minimum of -2°C and let the category be A. If the forecast error is in the range 2 degC too cold to 6 degC too warm all depressions give a grass minimum less than 0°C (the probability of an error greater than 6 degC is negligible). The probability for this range is, therefore, $(1.7 + 4.6 + 10.0 + 16.5 + 20.6 + 19.6 + 14.1) \times 1.00 = 87.1$ per cent.

If the forecast is 3 degC too cold, which happens on 7.7 per cent of occasions, the actual air minimum will be $+1^{\circ}\text{C}$ and depressions greater than 1 degC will give a grass minimum less than 0°C . From Figure 1 depressions greater than 1 degC occur on 96 per cent of occasions and the probability is, therefore,

$$7.7 \times 0.96 = 7.39 \text{ per cent.}$$

Similarly the probabilities for forecasts 4, 5 and 6 degC too cold are (2.9×0.77) , (1.7×0.48) and (0.1×0.22) per cent making a total probability in the range 3 degC too cold to 6 degC too cold of

$$(7.7 \times 0.96) + (2.9 \times 0.77) + (1.7 \times 0.48) + (0.1 \times 0.22) = 10.46 \text{ per cent.}$$

The total probability of a grass minimum below 0°C in category A when the forecast air minimum is -2°C is

$$87.1 + 10.46 = 97.56 \approx 98 \text{ per cent.}$$

The results for forecast air minimum temperatures between +8°C and -4°C for the various categories discussed above are given in Table III.

TABLE III—PERCENTAGE PROBABILITY OF A GRASS MINIMUM BELOW 0°C FOR CERTAIN FORECAST NIGHT MINIMUM AIR TEMPERATURES

Category*	Forecast air minimum (°C)												
	+8	+7	+6	+5	+4	+3	+2	+1	0	-1	-2	-3	-4
							<i>per cent</i>						
A	1	3	8	16	29	45	62	77	88	95	98	>99	
B	1	3	8	16	29	45	63	77	88	95	98	>99	
C	<1	2	5	11	21	37	55	72	86	94	98	>99	
D	1	3	7	14	26	40	57	73	87	94	97	>99	
E	1	2	6	13	24	39	56	73	85	93	97	>99	
F	<1	1	3	8	17	32	51	69	84	93	97	>99	
G	<1	3	8	15	28	44	61	76	87	94	98	99	>99
H	<1	2	5	11	21	35	53	70	84	92	97	99	>99
I	<1	1	4	8	17	31	48	66	81	91	97	99	>99
J	<1	2	5	12	23	39	57	73	86	94	98	99	>99
K	<1	1	4	9	19	33	50	67	82	91	97	99	>99
L	<1	1	3	7	15	29	47	65	81	91	96	99	>99
M	<1	1	3	6	13	24	38	56	72	85	93	98	>99
N		1	1	4	10	20	34	52	70	86	93	97	>99
O		1	1	3	8	17	32	50	69	84	93	97	>99
P		1	2	4	11	21	34	55	72	86	94	98	>99

* The categories are here assumed to be defined by forecasts of the various variables including air minimum.

Comparison with Lawrence's work. Lawrence¹¹ investigated the forecasting of grass minimum temperatures under clear skies and light winds. Following Faust¹² he used a quantity $H = T + E/2$, where T and E are the dry-bulb temperature and dew-point at 1500 GMT on the previous afternoon. As this takes no account of the state of the soil, he introduced as an additional variable the number of consecutive preceding days up to a maximum of 10 on which the reported rain was nil or a trace. He tested data for Dunstable and found a standard deviation of 1.70 degC. He also found that he could reduce his standard deviation to 1.65 degC if some allowances were made for soil temperature at 4 inches. Very few stations possess soil thermometers; none exist at any of the 10 stations from which the data used in the present investigation were obtained, and therefore the appropriate figure for a comparison of the two methods is 1.70 degC.

This standard deviation relates to the method alone; errors in forecasting whether the night in question will be a radiation night are not included. Steele, Stroud and Virgo⁸ obtained a value of $\sigma_n = 1.35$ degC for the error inherent in the method for obtaining air minimum temperatures. The standard deviation of the depression of the grass minimum below the air minimum for radiation nights in Table I (categories A and D) is 1.33 degC. These two standard deviations can be compounded; they give 1.89 degC as the standard deviation of the error inherent in the method described in the present paper applied to forecasting of grass minima on radiation nights. This figure is about the same size as that obtained by Lawrence, though not quite as good. On the other hand, radiation nights constitute only a small fraction of the total number of nights included in Table I.

Discussion. It is hoped that Table I will serve as a general forecasting guide to the depression of the grass minimum temperature below the air minimum temperature in various circumstances in eastern England. For certain purposes forecasters are asked to state the probability of the occurrence of a grass minimum below 0°C so that the user can weigh the cost of taking precautions against the possible loss which he might suffer if he failed to do so. It is hoped that Table III will be a useful tool for forecasters issuing this kind of forecast in eastern England. The table has been worked out to the nearest 1 per cent. It is unlikely to be used in this form, but any forecaster who wishes to do so can round off the figures to the nearest 10 per cent or any other value which suits his purpose. When this is done, the statistically significant differences between stations mentioned earlier should be of no consequence and the table should be representative of eastern England as a whole.

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AN INVESTIGATION INTO THE DEPRESSION OF THE GRASS MINIMUM TEMPERATURE BELOW THE AIR MINIMUM TEMPERATURE AT COTTESMORE

By A. G. SILLS

Summary. A simple diagram was constructed from data for April 1967 to mid-July 1968 for Cottesmore to assist in forecasting the depression of the grass minimum below air minimum when the cloud amount and geostrophic wind speed over the night are given. The diagram gave successful results with independent data and results compared favourably with those obtained by the method of Steele, Stroud and Virgo.

Introduction. In a paper by Steele, Stroud and Virgo¹ depressions of the grass minimum temperature below the air minimum temperature in 1961–65

for 10 stations in eastern England were analysed, the mean depressions being calculated for various categories according to weather, state of ground, cloud cover and geostrophic wind speed. Means for each of the 10 stations were calculated and those for Cottesmore are shown in column (a) of Table I. The capital letters in column (g) identify the categories used by Steele, Stroud and Virgo. These mean depressions together with forecasts of air minima based on the method of Saunders² were used to forecast grass minimum temperatures at Cottesmore during the period of the observations (1961-65). This method produced some poor forecasts in various categories. The purpose of the investigation described in this paper was therefore to find an improved method of forecasting for Cottesmore the grass-minimum depression below air minimum temperature.

Method. It was apparent from a superficial analysis of grass minima that cloud and wind were of major importance. A scatter diagram was therefore plotted, with the 1800-0900 GMT mean low-cloud amount and mean geostrophic wind as variables, using data for the period April 1967 to mid-July 1968. Only low cloud, base 8000 ft or less, was considered and sky obscured was counted as 8/8. Best-fit isopleths of grass-minimum depression below air minimum were drawn and Figure 1 was produced.

The main features of the diagram are :

- (i) the insignificance of geostrophic wind with 8/8 cloud;
- (ii) the increase in the depression when cloud is broken, i.e. 7/8 or less;
- (iii) the importance of geostrophic wind with little or no cloud.

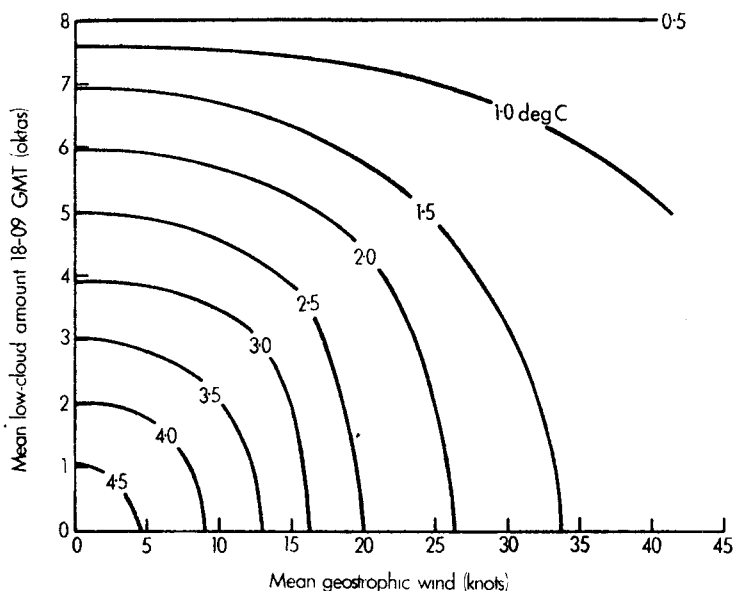


FIGURE 1—ISOPLETHS OF GRASS MINIMUM DEPRESSION BELOW AIR MINIMUM TEMPERATURE AT COTTESMORE

Tests of the method. To assess the errors inherent in the diagram method, actual observations were used to derive depressions from the diagram for each of the categories for which there were observations, and these depressions were

checked against actual depressions. There were 262 grass minima available in the period covered by the diagram (April 1967 to mid-July 1968) but only 184 fitted into the categories A to Q defined by Steele, Stroud and Virgo. Mean errors and root-mean-square errors are listed in Table I.

For comparison the 'Cottesmore mean' depressions calculated for each category in 1961-65 are also listed in Table I along with the corresponding mean errors and root-mean-square errors obtained when checking the 'Cottesmore mean' against actual depressions in the 1967-68 period. In Table I the 'Cottesmore mean' method is checked against independent data whilst the diagram method is checked on dependent data. The diagram method shows smaller mean errors in 8 out of 12 categories and also smaller root-mean-square errors in 8 categories and in the sample taken as a whole.

TABLE I—COMPARISON OF ERRORS BETWEEN ACTUAL GRASS MINIMUM DEPRESSIONS AND THOSE DERIVED FROM THE 'COTTESMORE MEAN' AND THE COTTESMORE DIAGRAM

'Cottesmore mean' depression (a) degC	Number of cases (b)	Using 'Cottesmore mean' Mean error (c)	Using Cottesmore diagram Root-mean-square error (d) degrees Celsius	Mean error (e)	Root-mean-square error (f)	Category (g)
3.01	11	-0.15	0.78	+0.34	0.80	A
2.98	7	+1.04	1.18	+0.70	0.97	B
		No observations within category				C
		No observations within category				D
2.13	11	+0.15	0.48	+0.50	0.58	E
2.19	10	+0.60	0.57	-0.08	0.29	F
3.00	10	-0.53	0.67	-0.40	0.57	G
2.02	4	-0.35	0.75	-0.73	0.91	H
		No observations within category				I
		No observations within category				J
2.18	13	-0.36	0.98	-0.52	0.93	K
1.96	13	-0.25	0.42	+0.19	0.52	L
1.81	8	+0.16	0.86	-0.07	0.64	M
1.23	6	-0.18	0.79	-0.10	0.78	N
		No observations within category				O
1.47	50	+0.21	0.79	-0.18	0.65	P
0.47	41	-0.17	0.68	+0.07	0.52	Q
		Weighted means				
	184	-0.01	0.72	-0.05	0.53	All

For a further test the diagram was applied to all 262 observations and estimates were obtained for the depression on all occasions including those which did not fit into the categories used in the Steele, Stroud and Virgo method. These included nights with snow cover, precipitation, air-mass change, etc., and results are shown in Table II(a). Note that 87 per cent of the errors were within ± 1 degC. The median value of the depression during 1967-68 was 1.6 degC (extremes 0.0 and 4.8 degC). The relatively small

TABLE II—MEAN ERROR AND DISTRIBUTION OF ERRORS USING THE COTTESMORE DIAGRAM FOR ALL CASES DURING TWO PERIODS IN 1967-68

	Number of cases	Mean error degC	Root-mean-square error degC	Distribution of errors within certain limits (degC)		
				± 0.5	± 1.0	± 1.5
(a) April 1967-mid-July 1968	262	+0.06	0.70	60	87	97
(b) Mid-July-December 1968	100	+0.06	0.73	65	90	96
					per cent	98

range of depressions is probably associated with physical characteristics of Cottesmore, such as topography or type of soil. The 'Cottesmore mean' depression for all categories 1961-65 was also 1.6 degC, and when this mean depression was used over the 1967-68 observations, 78 per cent of all errors were within ± 1 degC.

A check of the diagram method using independent data for mid-July-August 1968 is shown in Table II(b). Results are similar to those in Table II(a) but the period of the independent test is rather short for firm conclusions to be drawn. The check suggests that the diagram method is capable of giving good results at a particular station, provided that the air minimum can be forecast accurately.

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THE VARIATION OF VERY LOW CLOUD BASE WITH TIME AND DISTANCE AND WITH HEIGHT

By N. E. DAVIS

Summary. The record of the cloud-base recorder at Wyton is used to determine the correlation coefficient between the lowest cloud base at one time and the lowest cloud base at periods of from 1-15 minutes later. The correlation coefficients vary considerably from one set of observations to another but on average fall to about 0.50 after 15 minutes. The standard deviation of the difference between the lowest cloud base at one time and the lowest cloud base at periods of from 1-15 minutes later is also determined. The standard deviation increases to about 100 feet after 10 minutes.

An estimate is made of the correlation coefficient between the lowest cloud base at one point and the lowest cloud base at another point up to 3 miles distant. The corresponding standard deviation of the difference is about 100 feet at a distance of about 2 miles.

A comparison with some earlier work by Harrower indicates that the standard deviation of the difference between the lowest cloud base at one time and the lowest cloud base t minutes later is of the form

$$\sigma = 4h^{1/2}t^{1/2}$$

where σ is measured in feet and h is the mean height of the cloud base in feet.

Introduction. Dunaeva¹ described an experiment in which simultaneous observations of low-cloud height, visibility, temperature, dew-point and wind were made every 15 minutes following the appearance of cloud with a base at or below 300 metres. Dunaeva found that the correlation coefficient, between the cloud base at one time and the base 15, 30, 45, 60, 75 and 90 minutes later, varied quite considerably from one set of consecutive observations to another.

The present paper uses records from the cloud-base recorder which records the height of the base of the cloud immediately overhead at approximately 1-minute intervals.

Choice of data. The record of the cloud-base recorder at Wyton (52°21'N 00°07'W) was examined and four occasions were chosen for further study. As the height of the cloud base was to be extracted at exact minute intervals

(by interpolation from the cloud-base recorder values at approximately 1-minute intervals) the quality of the record had to be exceptionally good (smoothing between readings to cover a doubtful record would defeat the object of the study). Only cases with 8/8 cloud cover could be considered. As the cloud-base recorder gave only the height of the cloud immediately overhead, the recorder did not record anything if a hole (however small) was immediately overhead. Further, the 8/8 cloud cover had to have a continuous base. If, for example, the cloud cover consisted of a uniform sheet of 8/8 cloud at 800 feet with 3/8 or 4/8 thin cloud at 200 feet, i.e. with a distinct gap between the 2 layers, then the recorder would sometimes record 200 feet and sometimes 800 feet. If a minute interval fell midway between a 200-foot reading and the following 800-foot reading, an interpolated value of 500 feet would be incorrect as there was no cloud at this level at all and yet no other value could be ascribed. Finally, for the first part of the investigation, only cases in which the cloud base descended at some time or other during the period to below 300 feet were considered. This last restriction was deliberately chosen so that the investigation would be confined to cases in which the cloud base was varying at about the minimum permitted height for aircraft landing.

The last two restrictions in the event were nearly mutually exclusive as turbulence generated by the ground frequently breaks the lowest cloud into patches.

The four cases chosen were:

0301-0500 GMT on 8 July 1967
 0201-0300 GMT on 13 July 1967
 0001-0200 GMT on 28 July 1967
 1001-1100 GMT on 23 August 1967

Variation of cloud height with time. Values of the height of the lowest cloud were read every minute throughout the periods given and the correlation coefficient r_t between the height of the lowest cloud and the height of the lowest cloud t minutes later was calculated for each of the four occasions for all values of t from 1 to 15. These values are given in Table I. If we consider these four occasions as a representative sample of the variation of very low cloud base with time, then the four occasions can be combined together to give an estimate of the average correlation coefficient. This estimate is given by the last line in Table I and diagrammatically in Figure 1.

TABLE I — CORRELATION COEFFICIENT BETWEEN HEIGHT OF LOWEST CLOUD AND HEIGHT OF LOWEST CLOUD t MINUTES LATER

Date	t minutes														
1967	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
8 July	0.67	0.58	0.55	0.57	0.54	0.48	0.45	0.53	0.53	0.41	0.40	0.36	0.29	0.28	0.23
13 July	0.87	0.86	0.78	0.73	0.68	0.66	0.67	0.60	0.61	0.56	0.55	0.55	0.51	0.58	0.49
28 July	0.52	0.34	0.28	0.29	0.28	0.25	0.20	0.20	0.19	0.12	0.03	0.09	0.05	0.24	0.19
23 Aug.	0.94	0.87	0.84	0.82	0.82	0.84	0.83	0.83	0.80	0.78	0.77	0.75	0.73	0.74	0.69
Four series combined	0.83	0.75	0.72	0.72	0.70	0.68	0.63	0.67	0.66	0.61	0.58	0.56	0.52	0.55	0.51

The mean height of the lowest cloud base over the periods given were 316 feet on 8 July, 221 feet on 13 July, 377 feet on 28 July and 428 feet on 23 August with standard deviations of 100, 35, 79 and 152 feet respectively.

The main feature of Table I is the large range of correlation coefficients from 0.52 to 0.94 after 1 minute and 0.77 to 0.03 after 11 minutes. On 23 August the general cloud base rose throughout the hour of record and the high correlation is due to this relatively long-period change. On 28 July the general

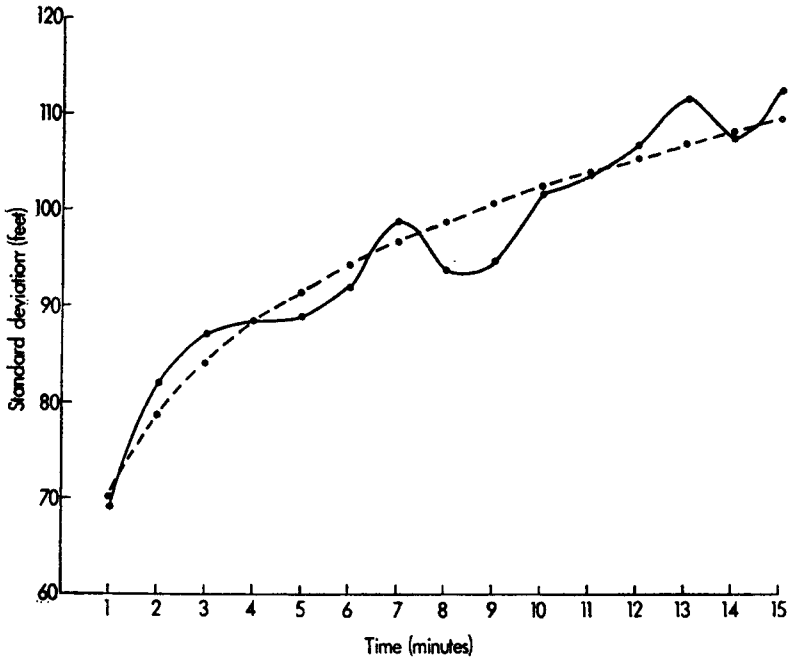


FIGURE 1 — STANDARD DEVIATION OF THE DIFFERENCE BETWEEN HEIGHT OF LOWEST CLOUD AND HEIGHT OF LOWEST CLOUD t MINUTES LATER
 . ——— . Combined examples. - - - - $\sigma = 70t^{1/2}$

cloud base remained constant throughout the two hours of record but the minute-by-minute values oscillated in an almost random manner about the general average. The period of sampling — 1 hour for 13 July and 23 August and 2 hours for 8 and 28 July — is only 4 to 8 times greater than the largest period of correlation (15 minutes), so that long-period changes are in general cut out and the correlation coefficient is thus reduced.

The nearness of the ground probably damps down all medium eddies and enhances those with periods of a few minutes or less. A closer examination of the data of Table I shows that oscillations in the correlation coefficient occur with approximate periods as shown in Table II.

TABLE II — PERIODS OF OSCILLATIONS IN CORRELATION COEFFICIENT COMPARED WITH CORRESPONDING CLOUD HEIGHT

Date 1967	Mean cloud height <i>feet</i>	Period of oscillations in correlation <i>minutes</i>
13 July	221	3½
8 July	316	4-4½
28 July	377	4½
23 Aug.	428	5

This table appears to indicate that the nearness of the ground does have an effect on eddies at cloud base level.

The aviator, however, is not concerned with the correlation coefficient but with the variation in cloud base from the time a decision is made to land to the actual moment of landing. To this end, in Table III is given the standard deviation,

$$\sigma = [\Sigma(d_i - M_t)^2/n]^{\frac{1}{2}}$$

of the difference, d_i , between the cloud height at one time and the cloud height t minutes later, where M_t is the mean difference over the period considered.

TABLE III — STANDARD DEVIATION OF THE DIFFERENCE BETWEEN HEIGHT OF LOWEST CLOUD AND HEIGHT OF LOWEST CLOUD t MINUTES LATER

Date	t minutes														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1967								feet							
8 July	81	92	95	94	97	103	107	99	97	108	109	112	118	117	123
13 July	17	18	23	25	27	27	27	30	29	31	32	32	33	31	34
28 July	78	92	96	96	97	99	102	103	104	108	114	111	114	103	106
23 Aug.	51	74	83	87	87	83	84	87	91	95	97	99	101	101	109
Four series combined	69	82	87	87	89	92	99	94	95	102	105	107	112	108	113

Figure 1 shows the curve for the combined set of observations, and also the curve

$$\sigma = A t^{\frac{1}{2}} \quad \dots (1)$$

(where $A = 70$ when σ is measured in feet and t in minutes). The best-fit curve $\sigma = A t^{\frac{1}{2}}$ is obtained by straight line regression of $\log \sigma$ on $\log t$ over the 15 combined values of σ in Table III. The correlation coefficient between $\log \sigma$ and $\log t$ over these 15 values is 0.80.

Apart from 13 July, after about 10 minutes the standard deviation of the difference increases to some 100 feet. This means that if a decision were made on the basis of a report 10 minutes old, the cloud base would already have changed by more than 100 feet on some 30 per cent of occasions. If a landing were made 15 minutes after the report, the change on some 30 per cent of occasions would be 110 feet. To some extent this variation is enlarged by the method of measurement. The cloud-base recorder gives only the base of the cloud immediately overhead. If for example there were 8/8 of cloud at 300 feet and 4/8 cloud at 200 feet, the cloud-base recorder would show oscillations between 200 and 300 feet according to whether there was a cloud cell at 200 feet immediately overhead or not. On the other hand a trained meteorological observer would report a steady state of 8/8 at 300 feet and 4/8 at 200 feet. Nevertheless, for a landing aircraft, if the cells and holes at 200 feet were sufficiently large, the cloud base would effectively fluctuate between 200 and 300 feet.

Variation of cloud height with distance. As low-cloud base height is known to be variable, the decision to proceed with landing an aircraft is frequently made on final approach some 2 or 3 miles from the airfield on the basis of the cloud actually experienced at that point. The question therefore arises regarding the variation of cloud base with distance. The mean surface wind speed for each of the occasions in Table I was extracted from the Wyton observations, 50 per cent was added and the result was assumed to be the mean speed at the cloud level. By using this mean speed, and by assuming that the variations in cloud base are effectively carried along in the airstream

without change, the correlation coefficients with respect to time in Table I were converted into correlation coefficients with respect to distance for each of the occasions. These values are given in Table IV. In Table V are given the standard deviations of the difference between the cloud base at one place and the cloud base at another at distance d .

TABLE IV — CORRELATION COEFFICIENT BETWEEN CLOUD BASE HEIGHT AT ONE POINT AND CLOUD BASE HEIGHT AT ANOTHER POINT AT DISTANCE d

Date	Distance d								
	1000 ft	1000 yd	1 mile	2000 yd	1½ miles	3000 yd	2 miles	4000 yd	3 miles
1967									
8 July	0.66	0.56	0.49	0.46	0.54	0.43	0.38	0.29	0.22
13 July	0.87	0.80	0.68	0.66	0.64	0.60	0.56	0.55	0.50
28 July	0.48	0.29	0.23	0.20	0.16	0.04	0.06	0.24	0.00
23 Aug.	0.96	0.85	0.82	0.82	0.83	0.83	0.81	0.78	0.73

TABLE V — STANDARD DEVIATION OF THE DIFFERENCE BETWEEN HEIGHT OF LOWEST CLOUD AT ONE POINT AND HEIGHT OF LOWEST CLOUD AT DISTANCE d

Date	Distance d								
	1000 ft	1000 yd	1 mile	2000 yd	1½ miles feet	3000 yd	2 miles	4000 yd	3 miles
1967									
8 July	82	95	101	104	97	107	110	118	120
13 July	17	22	27	27	28	30	31	32	34
28 July	82	96	100	102	105	113	113	103	120
23 Aug.	46	79	88	87	83	85	90	94	101

The correlation coefficients with respect to distance show a wider variation than those with respect to time but in view of the approximate method used this is not surprising.

In 1955, an experiment was carried out at London/Heathrow Airport in which simultaneous observations of cloud height by means of two cloud searchlights were made at two points on the airfield some 1.8 miles apart, whenever there was more than 4/8 cloud below 1500 feet. A total of 251 observations when the cloud base was below 1000 feet were analysed by Harrower (unpublished). The mean difference in cloud height between the two sites was 16 feet and the standard deviation about the mean was 143 feet. This value is somewhat greater than those above and it suggests that, as Harrower used cloud bases up to 1000 feet, the standard deviation of the difference between the cloud base at two nearby points or at the same point some minutes later depends to some extent on the general level of the base of the cloud. The constant A in equation (1) would appear to depend on h , the mean height of the cloud.

A re-examination of the records at Wyton was made and a further six cases in 1967 were extracted in which cloud was 8/8 with base between 500 and 2500 feet. Table VI gives the correlation coefficient between height of lowest cloud and height of lowest cloud t minutes later and Table VII gives the standard deviation in feet of the difference between the height of the lowest cloud and height of lowest cloud t minutes later for these six cases.

In Table VI the range of correlation coefficient is even larger than in Table I. On 21 October the general cloud base rose from 670 to 1400 feet during the hour of sampling. On 2 August, on the other hand, the cloud base during the hour of sampling varied rapidly and erratically about the mean level of 1838 feet.

TABLE VI — CORRELATION COEFFICIENT BETWEEN HEIGHT OF LOWEST CLOUD AND HEIGHT OF LOWEST CLOUD t MINUTES LATER

Date 1967	t minutes														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2 Aug.	0.03	-0.03	-0.00	0.42	-0.04	-0.21	0.05	0.13	-0.13	-0.27	-0.09	0.01	-0.10	-0.32	0.26
21 Oct.	0.97	0.92	0.88	0.85	0.83	0.84	0.84	0.84	0.78	0.79	0.75	0.70	0.70	0.73	0.74
1 Nov.	0.61	0.43	0.36	0.23	0.19	0.18	0.21	0.35	0.38	0.39	0.49	0.35	0.25	0.13	-0.01
30 Nov.	0.49	0.36	0.51	0.19	0.32	0.45	0.23	0.14	0.22	-0.05	-0.13	0.19	-0.02	0.03	0.08
3 Dec.	0.59	0.53	0.41	0.30	0.28	0.08	0.05	-0.06	-0.05	-0.05	-0.08	-0.05	0.01	0.07	0.10
14 Dec.	0.32	0.23	0.14	0.25	0.16	-0.18	-0.01	-0.01	0.05	-0.04	0.00	0.06	0.16	0.05	0.13

TABLE VII — STANDARD DEVIATION OF THE DIFFERENCE BETWEEN HEIGHT OF LOWEST CLOUD AND HEIGHT OF LOWEST CLOUD t MINUTES LATER

Date 1967	Mean height	t minutes														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2 Aug.	1838	155	162	162	123	164	180	149	144	166	177	153	144	154	166	126
21 Oct.	1124	46	71	85	96	100	95	94	94	106	104	113	122	122	116	114
1 Nov.	675	75	89	95	104	106	107	105	94	91	87	80	91	98	106	115
30 Nov.	1186	39	42	38	47	41	40	45	48	46	50	52	44	48	46	46
3 Dec.	1462	66	72	80	87	88	101	103	109	106	106	108	106	105	97	97
14 Dec.	2118	194	207	220	207	220	263	245	244	239	250	245	241	227	243	234

Table VII does show a tendency for the standard deviation to increase with the height of the mean cloud base and equation (1) can be written approximately as

$$\sigma = 4 h^{\frac{1}{2}} t^{\frac{1}{2}}$$

when σ and h are measured in feet and t in minutes.

It may be concluded that standard deviation of the difference between the height of low cloud at one point and the height of low cloud at the same point t minutes later, rises to 100 feet after about 10 minutes when the mean cloud base is 500 feet or below and to about 200 feet after about 10 minutes when the mean cloud base is about 2000 feet. Furthermore the standard deviation of the difference between the height of low cloud at one point and the height of low cloud at another point d miles away rises to 100 feet when d is about $1\frac{1}{2}$ miles and the mean cloud base is 500 feet or below and to about 150 feet when d is about $1\frac{1}{2}$ miles and the mean cloud base is about 1000 feet.

Minimum landing conditions for aircraft should not only specify the height of the cloud base but should also take note of the variability. A situation with an average height of 300 feet and a standard deviation of 200 feet is potentially more dangerous than one also with an average height of 300 feet but with a standard deviation of only 20 feet. An automatic cloud-base recorder with its minute-by-minute readings, though it does not give the actual cloud base the aircraft will find on landing, does give, in general, the average height of the cloud base and an estimate of the variability can be obtained by the observer from the range of the recorded heights over the last 15 or 20 minutes, using the formula² connecting range and standard deviation.

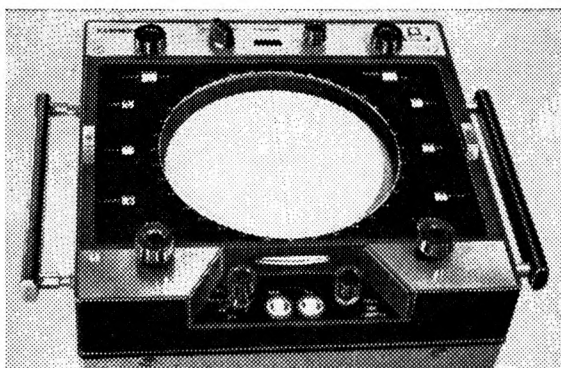
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CORRECTION

Meteorological Magazine, September 1969, p. 296. The name of the reviewer should read R. MURRAY.

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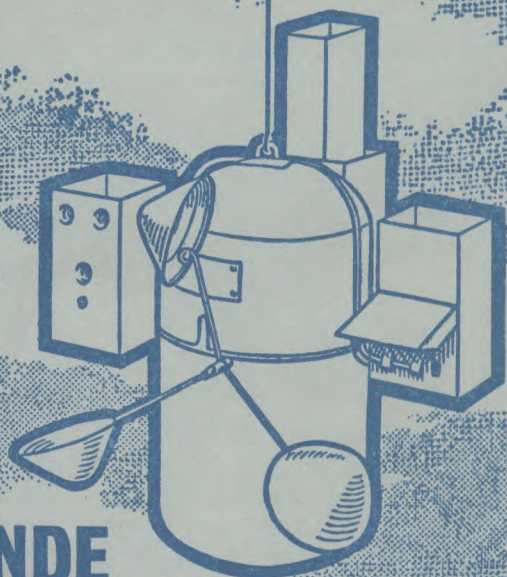
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AN ANALYSIS OF MONTHLY MEAN PRESSURE PATTERNS NEAR THE BRITISH ISLES, WITH POSSIBLE APPLICATIONS TO SEASONAL FORECASTING

By R. F. M. HAY

Summary. A catalogue has been made of monthly mean pressure patterns in the vicinity of the British Isles during each month of the period December 1873 to November 1963. Analysis of the results suggests that a well-known rule due to Baur, related to forecasting for late winter in Germany, can also be applied to central England; and a few other seasonal relationships likely to be useful for long-range forecasting have also been disclosed.

Introduction. Monthly pressure patterns near the British Isles have been used in long-range forecasting in a variety of ways besides being a valuable research tool. Recently a catalogue of these patterns has been compiled for each month in the period December 1873 to November 1963 and this catalogue now serves as a homogeneous classification for the period as a whole, and simplifies objective comparisons between particular months and seasons.

The method of classification adopted is broadly similar to the one used by Lamb¹ in the preparation of his catalogue of classified daily synoptic patterns for a similar period of years in the vicinity of the British Isles. A full description of the rules observed by the writer in preparing this catalogue of monthly pressure patterns is available, together with the complete catalogue, in the Meteorological Office, Bracknell.*

The most useful data in this catalogue are the descriptions of the pressure patterns of each month in terms of their curvature and directions of airflow near the British Isles. Thus the patterns in two typical cases would be described as 'cyclonic westerly' (CW) and 'anticyclonic north-westerly' (ANW). Curvature is related to the three categories — cyclonic (C), straight flow (F) and anticyclonic (A), while direction is given referred to the eight main directions, i.e. N, NE, etc., or to 'no direction' (O).

* After a little practice a nearly uniform classification of these monthly pressure patterns can be achieved by anyone with sufficient synoptic experience. This was shown by the results of an independent assessment by another scientist of a sample of 98 months selected at random from the whole period covered by the catalogue. Only 2 months were found when the classification he obtained was appreciably different from that given in the catalogue, and another 4 months when the independent description differed slightly from that in the catalogue.

Analysis of the catalogue. Only a preliminary analysis of the material has so far been attempted, and this paper presents the results of a study mainly devoted to the winter months.

TABLE I—FREQUENCIES* OF DIRECTION OF MONTHLY MEAN FLOW NEAR THE BRITISH ISLES IN DECEMBER, JANUARY AND FEBRUARY, SUBDIVIDED ACCORDING TO TEMPERATURE QUINTILES

DECEMBER temperature (quintiles †)	SW	W	Direction of flow							No direction	Totals
			NW	N	NE	E	SE	S			
5	7	7	0	0	0	0	1	2	0		17
4	7	10	0	0	0	0	0	0	0		17
3	10	10	1	0	0	0	0	0	0		21
2	4	9	2	0	0	0	0	2	0		17
1	4	4	4	1	1	1	2	0	1		18
Totals	32	40	7	1	1	1	3	4	1		90
JANUARY temperature (quintiles †)											
5	7	11	0	0	0	0	0	0	0		18
4	9	7	0	0	0	0	0	1	0		17
3	9	7	1	0	0	0	0	1	0		18
2	9	6	0	0	0	0	0	3	0		18
1	3	3	2	2	0	3	5	1	0		19
Totals	37	34	3	2	0	3	5	6	0		90
FEBRUARY temperature (quintiles †)											
5	10	8	0	0	0	0	0	1	0		19
4	6	9	0	0	0	0	0	1	0		16
3	8	8	1	0	0	0	0	1	0		18
2	4	5	6	0	1	0	2	1	0		19
1	0	0	0	2	2	4	4	4	2		18
Totals	28	30	7	2	3	4	6	8	2		90
3-month totals	97	104	17	5	4	8	14	18	3		270

* Each frequency includes cyclonic, straight-flow and anticyclonic patterns.

† Temperature quintiles related to the month of the same name during winters 1874-1963.

Frequency distributions of monthly pressure patterns by directions and according to quintiles of temperature in central England are given in Table I. (Quintile 1 (very cold) is sometimes denoted in this article by T_1 , and notation such as T_{45} is used to denote a month with temperature in quintile 4 or 5, i.e. mild or very mild.) Table I shows the following interesting features :

- (i) 31 out of 34 mild Decembers (T_{45}) occur with SW and W types of pattern.
- (ii) 7 Decembers (out of 90) showed NW types of pattern; 4 of these were T_1 Decembers and 2 were T_2 Decembers.
- (iii) NW types of pattern are rare in January.
- (iv) 33 out of 35 mild Februaries (T_{45}) occur with SW and W patterns.
- (v) 6 out of 7 Februaries having a NW pattern were cold (T_2).

Analysis of winter monthly pressure patterns as a whole. Tables II and III afford further insight into the characteristics of winters in the British Isles, and show up the high proportion of mild winter months (T_{45}) which are associated with SW and W pressure patterns. Table III also shows that a high proportion of very cold and cold winters (T_{12}) occur with cyclonic

TABLE II—FREQUENCIES OF DIRECTION OF MONTHLY MEAN FLOW NEAR THE BRITISH ISLES IN DECEMBER, JANUARY AND FEBRUARY, SUBDIVIDED ACCORDING TO CURVATURE OF PRESSURE PATTERNS

Type of curvature	Months	Direction of flow								No direction	Totals
		SW	W	NW	N	NE	E	SE	S		
Cyclonic (C)	December	18	20	4	1	1	0	1	2	1	48
	January	19	13	2	1	0	0	1	4	0	40
	February	12	14	2	0	1	0	1	5	1	36
	Winter months	49	47	8	2	2	0	3	11	2	124
		(40*)	(37)	(6)	(2)	(2)	(0)	(2)	(9)	(2)	(100)
Straight flow (F)	December	10	10	0	0	0	0	1	0	0	21
	January	7	9	0	1	0	2	1	2	0	22
	February	6	9	1	0	0	0	1	1	0	18
	Winter months	23	28	1	1	0	2	3	3	0	61
		(37)	(46)	(2)	(2)	(0)	(3)	(5)	(5)	(0)	(100)
Anticyclonic (A)	December	4	10	3	0	0	1	1	2	0	21
	January	11	12	1	0	0	1	3	0	0	28
	February	10	7	4	2	2	4	4	2	1	36
	Winter months	25	29	8	2	2	6	8	4	1	85
		(29)	(34)	(10)	(2)	(2)	(7)	(10)	(5)	(1)	(100)

* Figures in brackets are percentage frequencies.

TABLE III—FREQUENCIES OF DIRECTION OF MONTHLY MEAN FLOW IN WINTER NEAR THE BRITISH ISLES, SUBDIVIDED ACCORDING TO OVERALL WINTER TEMPERATURE QUINTILES AND TO CURVATURE OF PRESSURE PATTERNS

Type of curvature	Quintiles	Direction of flow								No direction	Totals
		SW	W	NW	N	NE	E	SE	S		
All types	5	28	23	1	0	0	0	1	4	0	57*
	4	24	25	1	1	1	0	0	2	0	54
	3	24	19	5	0	0	1	3	4	1	57
	2	10	25	6	1	3	1	1	3	1	51
	1	11	12	4	3	0	6	9	5	1	51
	All	97	104	17	5	4	8	14	18	3	270
Cyclonic (C)	5	15	9	0	0	0	0	1	2	0	27
	4	12	11	0	0	0	0	0	2	0	25
	3	14	11	0	0	0	0	1	3	1	30
	2	4	12	5	0	2	0	0	1	1	25
	1	4	4	3	2	0	0	1	3	0	17
	All	49	47	8	2	2	0	3	11	2	124
Straight flow (F)	5	4	9	0	0	0	0	0	1	0	14
	4	7	7	0	0	0	0	0	0	0	14
	3	5	4	1	0	0	0	1	0	0	11
	2	5	4	0	1	0	0	1	1	0	12
	1	2	4	0	0	0	2	1	1	0	10
	All	23	28	1	1	0	2	3	3	0	61
Anticyclonic (A)	5	9	5	1	0	0	0	0	1	0	16
	4	5	7	1	1	1	0	0	0	0	15
	3	5	4	4	0	0	1	1	1	0	16
	2	1	9	1	0	1	1	0	1	0	14
	1	5	4	1	1	0	4	7	1	1	24
	All	25	29	8	2	2	6	8	4	1	85

* The number of years included in each winter temperature quintile differs from the numbers of years included in the monthly temperature quintiles in Table I. The numbers for the winter quintiles are shown below :

Quintile :	T_5	T_4	T_3	T_2	T_1
No. of winters :	19	18	19	17	17

NW and anticyclonic W patterns. A rearrangement of this data in Table IV contrasts the distribution of cyclonic pattern directions during T_{12} winters with the distribution during the remaining winters (T_{345}).

TABLE IV—FREQUENCY OF DIRECTION OF MONTHLY MEAN FLOW IN WINTER (CYCLONIC PATTERNS ONLY), SUBDIVIDED ACCORDING TO TWO GROUPS OF QUINTILES OF WINTER TEMPERATURE

Winter temperature (quintiles)	Direction of flow					Totals
	SW	W	NW	SE, S	N, NE, E, No direction	
T_{12}	8	16	8	5	5	42
T_{345}	41	31	0	9	1	82
All	49	47	8	14	6	124

A value of chi-square of 29.23 was found for this 5×2 contingency table, which indicates that the difference between the distribution of monthly pressure pattern directions in T_{12} winters and in T_{345} winters is significant at better than the 0.1 per cent level. The largest contribution to the value of chi-square is made by winter months having cyclonic NW pressure patterns. Synoptic implications of this result have been discussed elsewhere.² Similar tables (not reproduced here) were derived to show distributions of cyclonic pattern directions for T_1 contrasted with T_{2345} winters, also for T_2 contrasted with T_{1345} winters, and these suggest that the association of cyclonic NW pressure patterns with T_2 winters is stronger than it is with T_1 winters.

December pressure patterns and subsequent late winter temperatures (mean of January and February). Table V yields results of some use for forecasting late winter temperatures (January and February together) in central England.

TABLE V—DISTRIBUTION OF TEMPERATURE IN JANUARY–FEBRUARY FOLLOWING VARIOUS DECEMBER PRESSURE PATTERNS

Curvature	December pressure pattern	Direction of flow	Number of cases in each temperature quintile (January and February)					Totals	Chi-square*
			T_1	T_2	T_3	T_4	T_5		
Straight flow	}	W	9	2	3	3	3	20	8.0
Anticyclonic									
Cyclonic,	}	W	14	4	6	8	8	40	7.0
Straight flow,									
Anticyclonic	}	SW	1	9	9	7	6	32	6.7
Cyclonic,									
Straight flow,	}	SW	0	4	6	4	4	18	5.3
Anticyclonic									
Cyclonic	}	All directions excluding SW and W	2	3	3	1	1	10	2.0
Cyclonic									

* The value of chi-square for the 10 per cent significance level is 7.8.

It is evident that westerly patterns (straight flow and anticyclonic) in December are favourable for cold late winters, while south-westerly patterns are not. These results suggest that Baur's rule³ relating the westerliness of the first half of December over Germany with late winter temperatures in that country, also applies broadly to central England. The last result in the table suggests that any December when the pressure pattern has been cyclonic (with the direction not SW or W) is seldom followed by a T_{45} winter, although this conclusion is based upon too few cases for it to be significant.

Applications of monthly pressure patterns to forecasting winter temperatures (central England). From the catalogue of monthly pressure patterns a table (not included here) was derived, giving frequencies of monthly pressure patterns in each month of the autumns which respectively preceded winters in central England in quintiles 1, 2, 3, 4 and 5. In order to simplify subsequent analysis the 27 individual monthly pressure patterns already described were grouped together. Descriptions of these groups (e.g. cyclonic blocked) were chosen to relate to large-scale synoptic patterns, while the pressure patterns included in each of the seven groups were intended to be representative of synoptic patterns typical of autumn (Table VI).

TABLE VI—GROUPING OF PRESSURE PATTERNS

Group	Description of group of pressure patterns	Pressure patterns included in group
1	Cyclonic blocked	CO, CNE, CE, CSE
2	Anticyclonic blocked	AO, ANE, AE, ASE, FNE, FE, FSE
3	Cyclonic progressive	CSW, CW, CNW
4	Mixed progressive	FSW, FW, FO (col)
5	Anticyclonic progressive	AW
6	Northerly meridional	CN, FNW, FN, ANW, AN
7	Southerly meridional	ASW, CS, FS, AS

A comparison made between the expected and actual frequencies of these seven groups of synoptic patterns in autumn months in a contingency table related to subsequent winter temperatures in central England proved of little value for the forecasting of extreme winters (T_1 and T_5). Next the case of winters following autumns when the grouped pressure pattern was cyclonic progressive and/or mixed progressive (groups 3 and/or 4) in all three months was considered. The 24 autumns when these conditions were satisfied were followed by 3, 10, 6, 3 and 2 winters in the quintiles 1 to 5 respectively. For this distribution the value of chi-square is 8.9, which is significant at just below 5 per cent. In this instance a forecast of a winter in T_{123} would have been correct in 19 cases out of 24, (79 per cent).

The contingency table (not included here) showing associations between monthly pressure patterns in autumn months and subsequent winter temperature quintiles was next used to derive frequencies of cyclonic, straight-flow and anticyclonic patterns in September and October in the same year. In this instance no account was taken of the directions of the patterns. The results, statistically significant in the majority of cases, are shown in Table VII.

TABLE VII—DISTRIBUTION OF WINTER TEMPERATURES FOLLOWING VARIOUS
PRESSURE PATTERNS IN EARLY AUTUMN

Case	Curvature patterns in :		Winter temperatures (quintiles)					Totals	Chi-square	Significance level <i>per cent</i>	
	Sept.	Oct.	1	2	3	4	5				
1	C	C	}	4	14	9	3	7	37	10·9	4
	F	C									
	C	F									
2	C	C	}	4	11	6	3	2	26	9·8	5
	F	C									
	C	F									
3	F	C		4	6	2	0	0	12	11·3	4
4	A	A	}	5	0	3	7	6	21	7·3	11
	F	A									
	A	F									

Cases 1, 2 and 3 in Table VII are useful for the forecasting of cold winters (T_3), while case 4 has some potential value for forecasting mild winters (T_{45}).

Broad-scale considerations.

(i) *For forecasting winter temperatures.* Table VIII shows the relative frequencies of 'progressive' (P) and 'blocked' (B) months in autumns before winters in the various temperature quintiles. Progressive months have been defined as all months with patterns of groups 3, 4 and 5, and blocked months as all those with patterns of groups 1, 2, 6 and 7 as defined in Table VI.

TABLE VIII—RATIO (P/B) OF FREQUENCIES OF PROGRESSIVE (P) AND BLOCKED (B) MONTHS IN AUTUMNS PRECEDING WINTERS IN SPECIFIED TEMPERATURE

Winter temperature quintile	Ratio of progressive/blocked months*						
	Autumn	Sept.	Oct.	Nov.	{ Sept. Oct.	{ Oct. Nov.	{ Sept. Nov.
5	1.5	2.8	1.1	1.1†	1.9	1.1†	1.9
4	2.0	0.8†	2.0	8.0	1.3†	3.5	2.0
3	2.4	3.7	2.2	1.7	2.8	1.9	2.5
2	4.7	4.7	7.5	3.3	5.8	4.7	3.9
1	1.4†	1.8	0.9†	1.8	1.3	1.3	1.8†
All winters	2.1	2.2	1.8	2.2	2.0	2.0	2.2

* Progressive months are groups 3, 4 and 5 of Table VI.

Blocked months are groups 1, 2, 6 and 7 of Table VI.

† Minimum ratios in each month or season. Maxima are shown in bold figures.

This table shows that autumns before T_2 winters have a much larger ratio (P/B) of progressive to blocked months than autumns before any other type of winter. It is noteworthy also that both autumn and October pressure patterns show little difference in their P/B ratios between very mild (T_5) and very cold (T_1) winters. A possible explanation for these small P/B ratios, found in autumn before both T_5 and T_1 winters, may be that many of these winters also have small P/B ratios; that is they are rather blocked. Some support for this view can be found in Table III which shows that monthly mean pressure patterns with a south-westerly direction occur more frequently during T_5 winters than during winters of any other type; while patterns with a south-easterly direction occur more frequently during T_1 winters than during any other types of winter. However, a full explanation must await further research.

The high value of P/B (8.0) found in November before T_4 winters (Table VIII) is worth attention for its possible forecasting value, although the small value found for P/B before T_5 winters (1.1) suggests that the former value may arise from a statistical accident.

The results considered in this paper suggest that attempts to forecast cold winters (T_2) in central England are more likely to be successful than any such attempts for winters in other quintiles, and that further progress is required to find differences in autumn circulation which will distinguish successfully between subsequent very mild and very cold winters.

(ii) *For forecasting spring and autumn temperatures.* Two more associations have so far been found (a) between winter and the following spring, and (b) between summer and the following autumn, which may be useful in forecasting. Results are shown in Tables IX and X.

TABLE IX—DISTRIBUTION OF SPRING TEMPERATURES FOLLOWING SPECIFIED OCCURRENCES IN WINTER MONTHS

	Spring temperatures (quintiles)					Totals	Chi-square	Significance level
	1	2	3	4	5			
Winter months of mixed progressive* pattern	8	9	6	19	9	51	10.2	Better than 5 per cent
Winters with 1, 2 or 3 months of mixed progressive pattern	7	9	4	16	8	44	8.5	8 per cent

* Group 4 of Table VI.

TABLE X—DISTRIBUTION OF AUTUMN TEMPERATURES FOLLOWING SPECIFIED OCCURRENCES IN SUMMER

	Autumn temperatures (quintiles)					Totals	Chi-square	Significance level
	1	2	3	4	5			
Summer months of blocked or meridional pattern*	13	13	4	5	5	40	10.5	Better than 5 per cent
Summers with 1, 2 or 3 months of blocked or meridional pattern*	10	10	4	5	5	34	5.1	Not significant
Summers with 1, 2 or 3 months of meridional pattern excluding 1-month occurrences in July	10	9	2	4	4	29	8.4	Approximately 8 per cent

* Groups 1, 2, 6 and 7 of Table VI.

It is concluded that winters with months showing mixed progressive pressure patterns are significantly associated with mild springs (T_4) to follow.

It is concluded that summers with blocked and meridional pressure patterns (notably in June and August) are significantly associated with cold and very cold autumns (T_{12}) to follow.

Conclusions.

- (i) Cold and very cold winters (T_{12}) are associated with monthly pressure patterns in which cyclonic NW patterns predominate.
- (ii) In December westerly patterns (straight and anticyclonic isobars) show some association with cold late winters. South-westerly patterns do not seem to be associated with very cold late winters. This result is broadly in line with the rule due to Baur which applies for a similar period over Germany.
- (iii) For autumns when pressure patterns were cyclonic progressive and/or mixed progressive (groups 3 and 4 as defined in Table VI), the 24 winters following had 3, 10, 6, 3 and 2 winters in the quintiles 1-5 respectively.
- (iv) The frequency of progressive months (groups 3, 4 and 5) in autumn shows a gradual increase through colder winters (i.e. T_6 to T_2), accompanied in the same circumstances by a large decrease in the frequency of blocked months (groups 1, 2, 6 and 7). October figures agree well with autumn figures while November shows marked disagreement. The relative frequencies of these pressure groups in autumn months before cold winters are markedly different from

those before very cold winters; the autumn values for very cold winters in fact revert to values which are nearly identical with those found before very mild winters.

- (v) Winters with months showing mixed progressive pressure patterns are associated with a mild spring (T_4).
- (vi) Summers with months showing blocked and meridional pressure patterns are associated with cold and very cold autumns (T_{12}).

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THE RECORD-BREAKING RAINFALL IN SOUTH-WEST ENGLAND ON 28-29 JULY 1969

By G. C. BRIDGE

The dry and mainly sunny conditions enjoyed by the south-west during July were brought to an abrupt end on the 28th of the month when rain began early in the morning, turning moderate around midday and heavy during the afternoon, thereafter generally persisting at this intensity through the evening and night until around 0300 GMT and finally ceasing at approximately 0800 GMT on the morning of the 29th. The unusual persistence of this intense rainfall led to widespread dislocation of traffic in many parts of Cornwall and Devon, because many roads suddenly acquired a treacherous surface. Roads were obstructed by localized flooding, or by mud, rubble and trees from rapidly swollen streams and rivers. If it had not been for the very dry state of the ground prior to the rain (soil moisture deficits of about 75-100 mm were common), widespread flooding would undoubtedly have occurred, which in conjunction with the relatively high tides at the time would have led to much more drastic consequences.

Synoptic situation. The synoptic situation may be seen by reference to Figures 1 and 2. A fairly shallow wave depression with central pressure of approximately 1014 mb had travelled across the Atlantic from west to east close to the 45°N parallel, and had then deepened appreciably to 1006 mb as it turned more east-north-east over the Western Approaches. The depression continued on this track travelling along the English Channel, with the warm front making only slow progress over southern England, but with the cold front accelerating eastwards over France. It would appear that the warm front may well have crossed north-westwards over much of the region during the evening to return eastwards as a pseudo-cold front early in the morning.

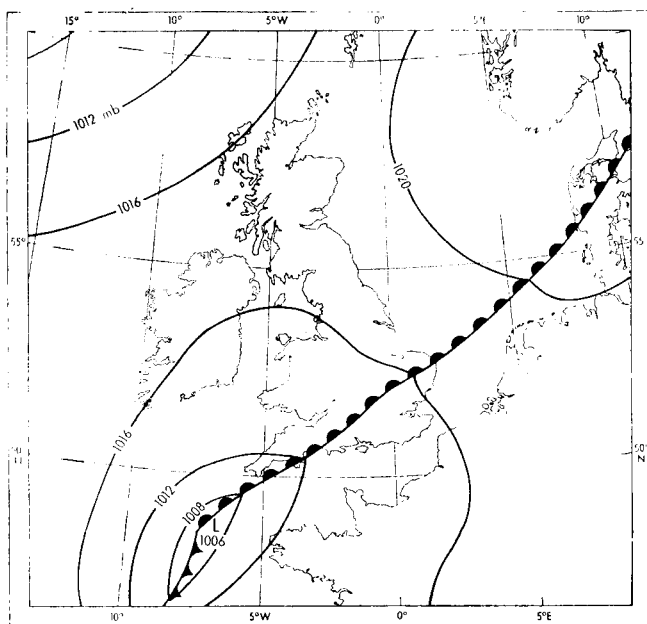


FIGURE 1—SYNOPTIC SITUATION AT 12 GMT, 28 JULY 1969

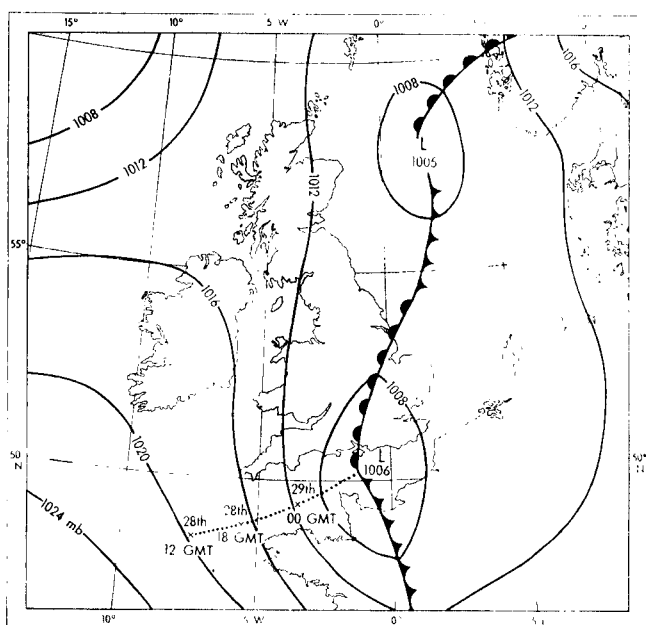


FIGURE 2—SYNOPTIC SITUATION AT 06 GMT, 29 JULY 1969, ALSO SHOWING TRACK OF DEPRESSION DURING PRECEDING 18 HOURS

Inspection of the 1000-500-mb thickness and 500-mb contour chart for 00 GMT, 29 July 1969, as shown in Figure 3, revealed quite marked troughing in the flow aloft associated with the depression. The upper south-south-west winds ahead of the centre maintained the flow of warm moist air which was becoming increasingly unstable as shown by the presence of thunderstorms over France. Continued advection of colder air from the west led to a packing of the thickness lines, or in other words an increased thermal contrast across the front, so enhancing and maintaining its activity. This would give one possible explanation for the persistence and the intensity of the rainfall.

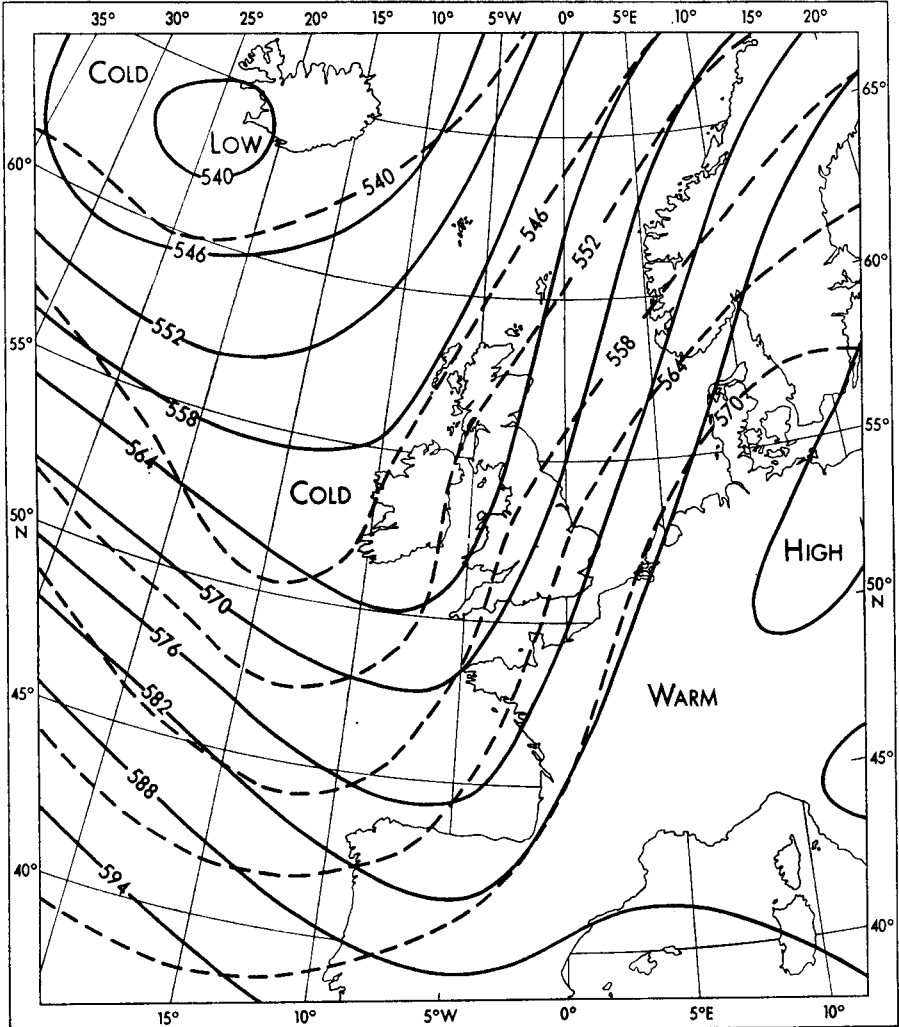


FIGURE 3—ISOPLETHS OF THE 1000-500-mb THICKNESS AND THE 500-mb CONTOURS AT 00 GMT, 29 JULY 1969

----- 1000-500-mb thickness ————— 500-mb contours
Thicknesses and contours are expressed in geopotential decametres.

Benwell¹ has written of the possibility of using the jet stream at 500 mb as a predictor of heavy rain. On the occasion now under discussion the speeds

of the jet at 500 mb and 300 mb were marginally of sufficient strength to satisfy his suggested criteria. At 12 GMT, 28 July the direction of the jet was 220° , the most southerly direction of Benwell's criteria, but by 00 GMT, 29 July the jet had backed to 200° .

The pattern of the flow at 500 mb and 300 mb was not dissimilar to that during the period of heavy rain² which affected an area from east Devon to the Wash, on 10–11 July 1968.

In the early hours the frontal cloud became more unstable, which in conjunction with probable orographic uplift development, led to the formation of scattered thunderstorms over and to the south of Dartmoor.

Rainfall and distribution. The 24-hour rainfall at Mount Batten, Plymouth, totalled 113.2 mm and broke all previous records. Out of a series of observations extending over nearly 50 years at the station, the previous highest daily fall was 77 mm, which occurred on 15 August 1952 at the time of the Lynmouth flood disaster. The July monthly total was 132.7 mm, compared with the 35-year mean monthly rainfall of 65.5 mm taken over the period 1916–50.

Rainfall records were also broken at the Exeter Airport, Chivenor and St Mawgan Meteorological Office stations, together with those for several of the climatological stations in the area.

The persistent intensity of the rainfall may be seen from the autographic record for Mount Batten, as shown in Figure 4. The highest rainfall rate registered during the late evening was 29.3 mm in 80 minutes, which can be classified as a noteworthy fall. However, under Bilham's 'Classification of heavy falls of rain in short periods', published in *British Rainfall* 1935, the fall of 113.2 mm over a period of about 18 hours can be classed as a 'remarkable' fall. Inspection of the open-scale autographic record revealed a further short-term high fall rate of 2 mm in 2 minutes, which occurred just before midnight. Higher rainfall rates than these have been recorded at the station in the past but the persistence on this occasion was most unusual.

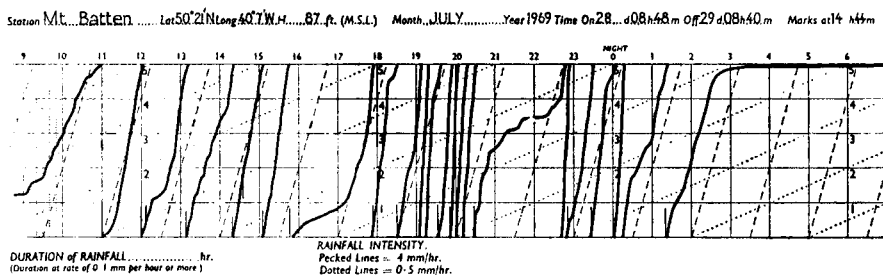


FIGURE 4—DIAGRAMMATIC REPRESENTATION OF RAINFALL RECORD FOR MOUNT BATTEN METEOROLOGICAL OFFICE, 28–29 JULY 1969

This order of fall may well have been fairly general over much of Devon at different times of the night since the Meteorological Office at Exeter Airport recorded a maximum fall rate of 29.7 mm in the hour between 0200 and 0300 GMT.

The rainfall distribution pattern for the south-west may be seen in Figure 5. Isohyets were compiled using data from the meteorological and climatological stations in the area, together with data acquired from the Cornwall, Devon and Somerset River Authorities. These data were collected immediately after the event and do not necessarily include all which may be available; consequently a more detailed examination of the data could give rise to some changes in the isohyets. However, further data obtained from the Devon River Authority since this occasion revealed a much more comprehensive network of gauges and hence isohyets are constructed on the basis of fuller information over Devon than elsewhere. A representative list of gauges may be found in Table I, with their corresponding numbered locations shown in Figure 6 but readings from all gauges were used in constructing the isohyets. The wealth of data for Devon was such that gauges listed are those which represent a fairly even coverage over the area, together with those showing extreme values.

TABLE I—RAINFALL FOR 24 HOURS ENDING 0900 GMT 29 JULY 1969 RECORDED BY VARIOUS RAIN-GAUGES IN THE SOUTH-WEST OF ENGLAND

Location number*	Location	Rainfall mm	Location number	Location	Rainfall mm
1	Penzance	88.1	33	Kings Nympton	100.4
2	St Ives	83.8	34	Brayford	82.4
3	Culdrose	86.4	35	Cheldon Barton	103.9
4	Gwennap	101.8	36	Hillerton	113.0
5	St Mawgan	71.1	37	Avonwick	111.6
6	Constantine Bay	67.8	38	Blackpits Gate	115.1
7	St Austell	93.7	39	Winstitchen	85.9
8	Bugle	74.9	40	Yellam	108.4
9	Delabole	88.9	41	Dartington Hall	105.7
10	Camelford	95.3	42	Porlock	94.5
11	Bude	72.9	43	Newhouse Park	110.0
12	St Cleer	100.3	44	Stoodleigh	106.6
13	Liskeard	99.1	45	Torquay	80.4
14	Hartland Point	58.9	46	Leigh Farm	98.3
15	Bastreet	114.3	47	Tiverton	101.8
16	Launceston	113.3	48	Withycombe	123.2
17	Milton Damerel	95.8	49	Exeter Airport	101.6
18	Virginstow	138.4	50	Clyst St Lawrence	105.9
19	Ellbridge	145.0	51	West Quantoxhead	97.8
20	Eastcott	98.9	52	Crowcombe	106.9
21	Tavistock	125.7	53	Hemyock	113.5
22	Plymouth Hoe	120.1	54	Wellington	106.7
23	Chivenor	70.6	55	Taunton	99.3
24	Mount Batten	113.2	56	Coran	101.6
25	Bury	106.6	57	Yarcombe	100.3
26	Southcott	142.7	58	Wembdon	105.4
27	Barnstaple	58.4	59	Bridgwater	94.0
28	North Hessary Tor	144.4	60	Chard	88.1
29	Princetown Prison	129.5	61	Morecombelake	45.0
30	Okehampton	113.3	62	Priddy	95.8
31	Burrator	114.8	63	Yeovilton	62.7
32	Post Bridge	113.3	64	Salcombe	72.4

* See Figure 6 for position of location numbers.

The most noticeable feature of the chart is the large area of Devon and east Cornwall with a fall of 100 mm or more, and a peak fall of over 140 mm to the west and south-west of Dartmoor. It is of interest to include at this point the fall of 168.8 mm recorded near Fernworthy Reservoir, on Dartmoor. This gauge however is an interrogable tilting-bucket type and the doubtful accuracy of its recorded rainfall is such that it has not been included in the preparation of the distribution diagram. The BBC transmitting station on North Hessary Tor collected 144.4 mm, whilst Princetown Prison recorded

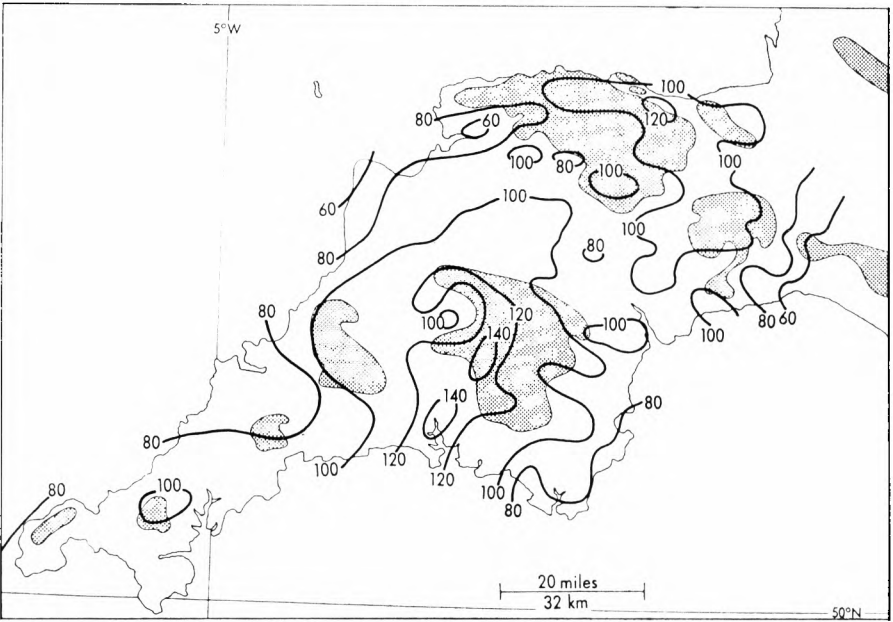


FIGURE 5—RAINFALL FOR THE 24 HOURS ENDING 0900 GMT, 29 JULY 1969
Isohyets are in millimetres. Ground above 800 feet is shaded.

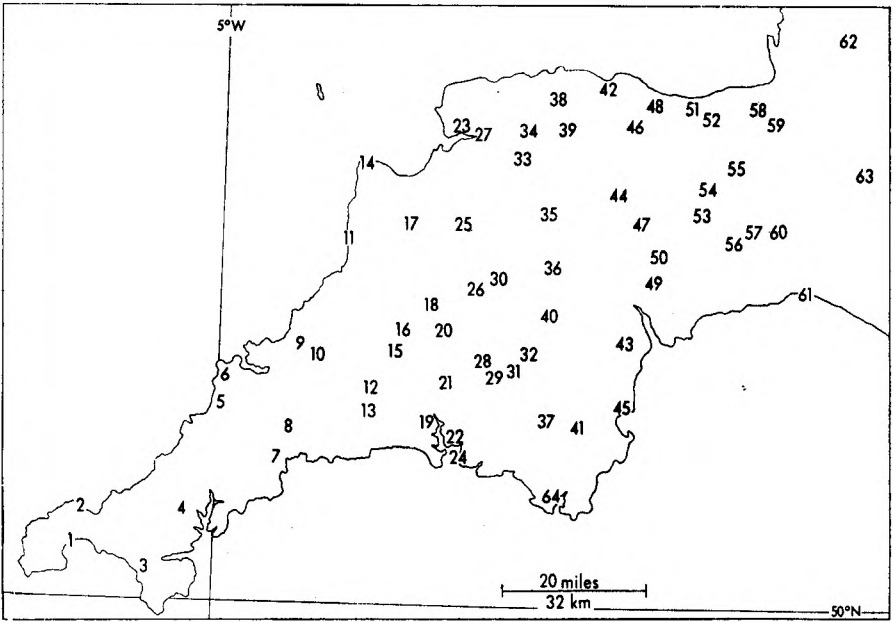


FIGURE 6—DISTRIBUTION OF RAIN-GAUGES LISTED IN TABLE I

129.5 mm on this occasion. Out of nearly 40 years of rainfall observations from the Prison, this value has been exceeded only twice in the past with falls of 136.9 mm in November 1931 and 173.5 mm in November 1946. It is conceivable, however, that this latter fall may well have been equalled or even exceeded on the occasion now under discussion, over a locality on the Moor with maximum exposure.

It is surprising to find the absence of any marked peaks over Exmoor or the high ground on the Devon-Somerset border, but this may well be attributed to the sheltering effect of Dartmoor during the southerly low-level flow prior to the passage of the frontal belt to the east.

In passing, however, it is of interest to recall that between 200 and 250 mm of rain³ probably fell in 24 hours over parts of Exmoor at the time of the Lynmouth flood disaster in August 1952, but this was localized, and rainfall over the remainder of the region was substantially less than on the occasion here described.

Acknowledgements. The author is indebted to the Cornwall, Devon and Somerset River Authorities for making relevant rainfall records available.

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THE SHELTON REGULATOR CLOCK AT EDINBURGH METEOROLOGICAL OFFICE

By W. K. YOUNG

Summary. The probable history of a regulator clock, made in 1756 by John Shelton, is put on record, including its adventures during the last 213 years, its association with the first voyage of Cook around the world, the Mason-Dixon Line, Ben Nevis Observatory, and the first voyage to Botany Bay.

Introduction. Any attempt to write the history of a scientific instrument, over a hundred years old, is bound to be dogged by conflicting information or the complete lack of it. However, an effort has been made to compile the adventures of one clock which has been in existence for over 200 years.

This article is based on the facts published in scientific journals during the life of the clock. Three excellent articles by Lt Cdr H. D. Howse (listed on p. 373) which are published in *Antiquarian Horology*, contain most of the references for those who wish to delve further into the individual events.

John Shelton. In the eighteenth century, when the modern scientific enlightenment of man commenced, Britain fared well in her share of inventors, explorers and scientists. Some of the greatest names of that period are still spoken of with reverence today.

Sadly, one man who deserves recognition for his craftsmanship is known only to the few interested bodies. Even in his own time he suffered hardships

he had not deserved. This man was John Shelton. Born in 1702 in Clerkenwell, London, he had become apprentice to a clockmaker by the age of 10. Eight years later he became a member of the Clockmakers' Company. While in his forties he worked for George Graham, the inventor of the dead-beat escapement and the mercury pendulum. These years were to bring him to the fore-front as a clockmaker of great repute. So highly thought of was he, that James Short, of the Royal Society, recommended his work to the crown of Russia in 1767.

By 1745 Shelton had his own shop in Shoe Lane, London. An early example of his work, showing little of the design of his later, and more famous, clocks is now kept by the Herschel family. In 1749 while still working for Graham, he made a clock for the Royal Observatory at Greenwich, in Graham's name, and this clock appears to have been used as the basic design on which his later work was modelled.

Alas, his eyesight eventually failed and in 1777 a letter was written on his behalf asking the Royal Society to assist him, as he was destitute. He faded into obscurity leaving only his clocks to sustain his memory.

Description of the Shelton regulator clock at the Meteorological Office, Palmerston Place, Edinburgh. The clock in this story is 5 ft 3 in tall and 1 ft 4 in wide at its widest point. The case is made from mahogany and parts of the back are strengthened by a second layer of the same wood. The movement is made of brass and steel and is almost completely in its original form. The face is 12 in square and has separate dials for minutes and seconds. The hours are seen through a small aperture in the central zone of the face. It is extremely accurate and is temperature compensated to perform equally well in all climates. There is one point of design that is unique when compared with the other Shelton regulators. The point of suspension of the pendulum has always been on the case although on other Shelton clocks the suspension was on the movement at first, being altered at some later date. It was assembled in 1756, and John Shelton signed and dated it, a thing he did not do on later clocks. (See Plates I and V.)

History of the clock. Several clocks were purchased from John Shelton for the eighteenth century Transits of Venus. It seems almost certain that five Shelton regulators which survive today are the 'Transit' clocks which were bought by the Royal Society and the Board of Longitude. The account which follows gives the most probable history of the Edinburgh clock. There is some difficulty in identifying which of the five clocks was used in various experiments before 1841, though the Edinburgh clock was used, for example, in the Foster experiments of 1828 to 1831, described later in the text. The Rev. Nevil Maskelyne took a Shelton clock, probably the Edinburgh clock, to St Helena to assist in the measurement of the transit of Venus across the sun in June 1761. On this same expedition it was taken to the Cape of Good Hope to make a comparison of gravitational attraction measured at Greenwich, St Helena and the Cape. In 1762 it was returned to London, where it was checked before being sent to Barbados to test the accuracy of the first really usable marine chronometer, 'Harrison's No. 4'. On arrival in Barbados the clock was used as a standard for one year to check the running of 'Harrison's No. 4', which had been entered in a competition, worth £20 000, for the first simple and reliable method of measuring longitude to within half a degree.

In 1765 the same clock probably went on a voyage to America and had its first accident. The ship ran aground on the coast of Pennsylvania. The spring suspension point was broken, and was repaired by Charles Mason and Jeremiah Dixon. The clock was then used to 'measure' the latitude of the boundary between Maryland and Pennsylvania — the 'Mason-Dixon Line'. This having been done, the clock was sent back to London.

After further checks and overhaul the clock was given to Lieutenant James Cook for use in measuring another transit of Venus, due in June 1769. Cook sailed to Tahiti via Cape Horn and after his observations returned to England by way of New Zealand, Australia, Java and the Cape of Good Hope, thus completing one circumnavigation of the earth. It is thought that the next experiment in which the clock was involved was in 1774. The Rev. Nevil Maskelyne, having used the same clock previously, used it in his investigation of the mass of Schiehallion, a mountain in Perthshire. The clock then had a rest and little is known of its whereabouts.

In January of 1787 a large fleet sailed to Botany Bay, in Australia. A Shelton regulator was taken and this was fitted up at Sydney Bay. The clocks used on the second and third voyages of Cook were fitted to tripods, but the clock used in Sydney was mounted on a post in the manner used by Mason and Dixon in 1766. It seems likely therefore, that the clock used was the same clock and could be the Edinburgh clock, this not having been adapted for use with the tripod. The clock returned to England in 1792. The clock was next stored and probably remained in St Katharine's Street, London, until 1820. Confusion as to which clocks were used in the experiments during the period 1820-28 arises from the fact that there were many Sheltons in existence and available. An attempt was made to list the instruments of the Royal Society in 1827, which did a little to alleviate the disorder. However, it is certain that the clock being described in this article did sail, in February 1828, to the South Atlantic. There Captain Foster made many gravity measurements and there, also, the clock had its second accident. A storm blew up while it was on Deception Island and the observatory tent was moved. The clock continued to function but, at times, stopped for several seconds. A clockmaker's mark shows that it was repaired at the Cape of Good Hope in July 1829. The experiment was then continued, but after the sudden and accidental death of Captain Foster the clock was returned to London in April 1831.

Again confusion arises as to which clocks were where in the ensuing years. In 1841, a clock was made available as a standard timepiece for Kew Observatory. It was later called 'K.O.' by the Kew Committee; this was also scratched on the clock, thus identifying it for the future. The clock in Edinburgh bears this mark.

The clock now in Edinburgh was loaned to Airy in 1854 for pendulum experiments to be carried out at Harton Colliery, near South Shields. The case of the clock bears marks which show how it was adapted by Airy to suit his experiments. It is interesting to note that Airy believed the clock was previously used by him at Dolcoath Mine, Cornwall, in 1826. This is not necessarily true but, if so, then his attempt to repeat the Dolcoath experiment in 1828 was done with another Shelton of similar design. On return to Kew the clock joined three others which were kept there in between experiments.

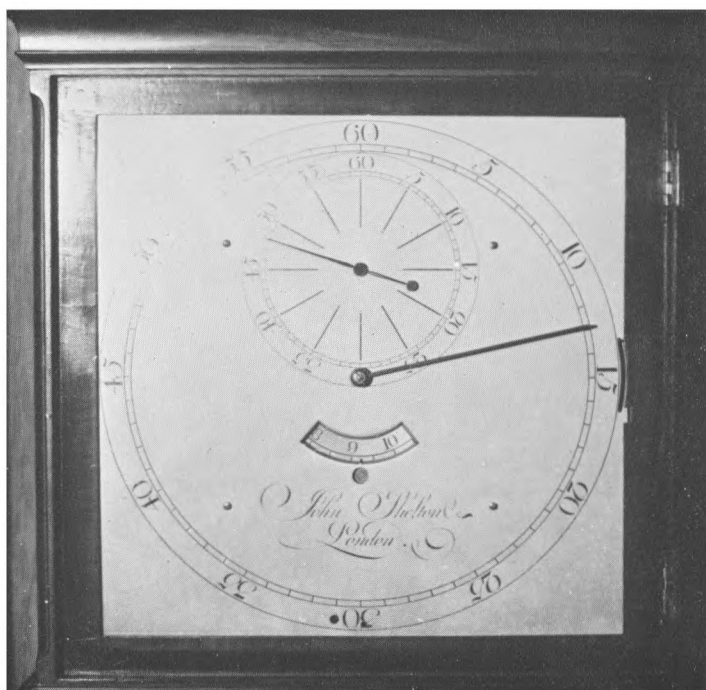
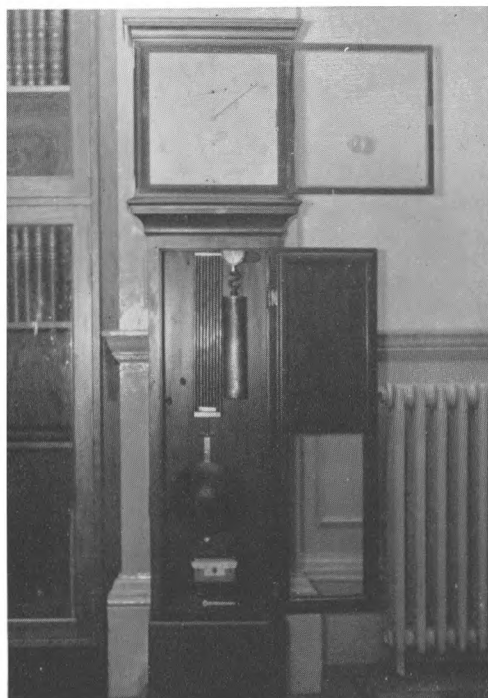
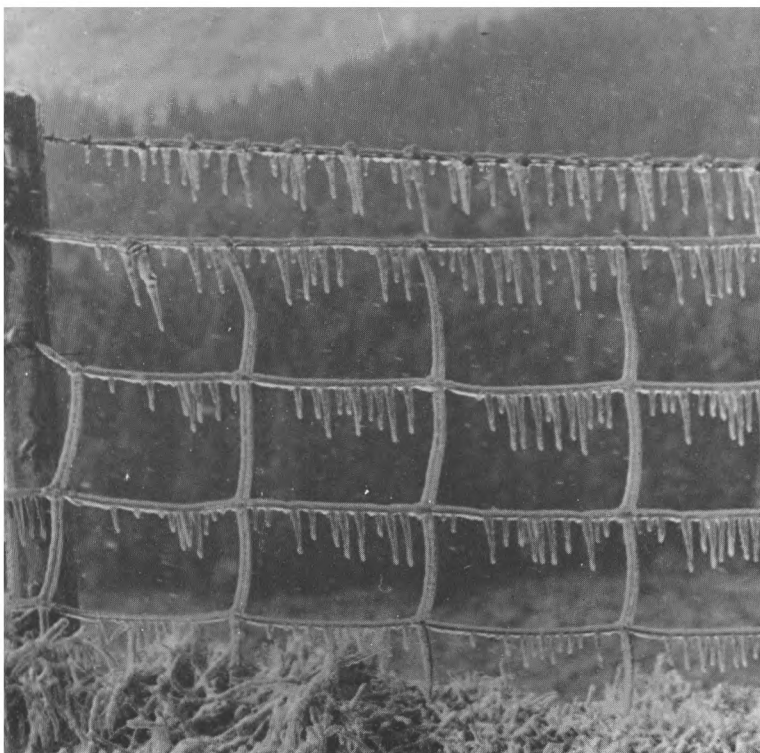


PLATE I—THE REGULATOR CLOCK MADE BY JOHN SHELTON IN 1756



Photographs by John Dudley-Davies

PLATE II—RAIN ICE IN THE LLANIDLOES AREA, CHRISTMAS EVE 1968

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Photograph by John Dudley-Davies

PLATE III—RAIN ICE IN THE LLANIDLOES AREA, CHRISTMAS EVE 1968
The accumulation of ice caused damage to young spruce and larch trees.



Photograph by N. Elkins

PLATE IV—SNOW ROLLERS AT KIRKWALL
See p. 387

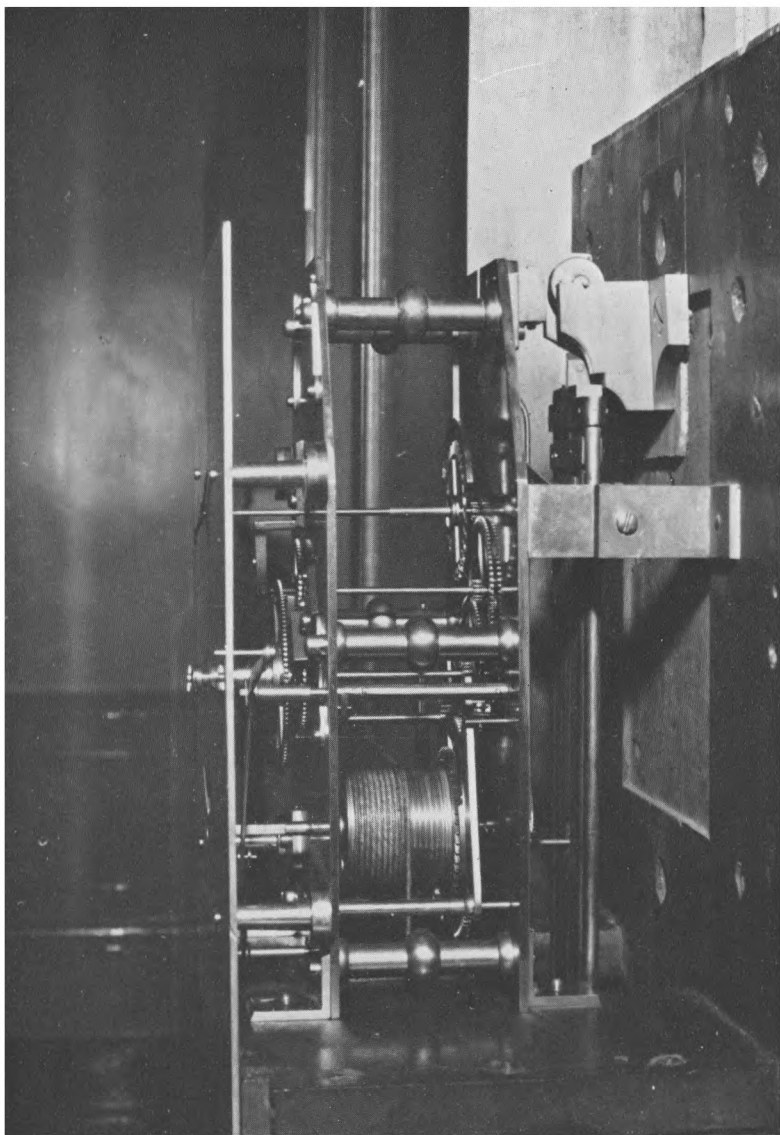


PLATE V—THE MECHANISM OF THE REGULATOR CLOCK MADE BY JOHN SHELTON
IN 1756

Note that the pendulum is suspended from the back of the case.

'K.O.' was transferred to the Scottish Meteorological Society in 1888 and fitted in the new Ben Nevis Observatory as the standard mean-time clock. In 1904, owing to lack of funds, Ben Nevis Observatory was closed and 'K.O.' was sent back to Kew for repairs and cleaning.

Eskdalemuir Magnetic Observatory was opened in 1908 and the clock was modified so that it supplied pulses for the recording instruments. It remained there until 1960 when it was superseded by modern electronic devices and transferred to Edinburgh.

The Meteorological Office in Palmerston Place, Edinburgh, now has custody of this famous clock along with many of the instruments of the Ben Nevis Observatory. It stands against the south wall of the library and is firmly screwed to the wall to prevent vibrations in the floor from affecting its performance.

The many 'scars' of its adventures can be seen around the case and movement. These are, in themselves, proof of its adventures, since they can be related to the descriptions, diagrams and incidents recorded in the chronicles of the great men who used it.

There is no doubt that this clock has done well in the 213 years of its life and has been a perfect example of the great skill of the unfortunate John Shelton.

Acknowledgements. I am indebted to Lt Cdr H. D. Howse, M.B.E., D.S.C., R.N., of the National Maritime Museum, and the Superintendent of the Meteorological Office, Edinburgh, for their help and encouragement. To the many other people who have aided my researches in the last 2 years I also extend my thanks, especially the patient members of the library staff of the Royal Society of Edinburgh, and the staff of the Royal Scottish Museum.

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551-509:323-7

A METHOD OF DERIVING REPRESENTATIVE TEMPERATURE PROFILES, INCLUDING THE TROPOPAUSE, FROM THE THREE-LEVEL FORECAST MODEL

By W. R. BRADY

Summary. An objective method is described for estimating heights and temperatures at various pressure surfaces and at the tropopause, if the heights of the standard surfaces 1000, 500, 200 and 100 mb are known or forecast. The stratosphere is first assumed isothermal and in a normal situation the significant tropopause temperature is taken to be equal to the mean temperature of the 200-100-mb layer. Special estimates are made when preliminary tests show that the tropopause is low. A temperature at 500 mb is chosen according to certain assumptions and a mean tropospheric lapse rate is then used to obtain the height of the significant tropopause temperature. Special methods are described for obtaining temperature at 200 mb. To obtain heights and temperatures at other pressure levels, layer thicknesses

can be added to or subtracted from the nearest pressure level whose height is known, working upwards within the troposphere and downwards within the stratosphere to avoid using the layer containing the significant tropopause. The thickness of this layer can be found as a remainder when the other layers have been calculated, and then a revised tropopause temperature can be obtained. A series of computing models known as tropopause models have been developed to control the computations.

A test made on actual data over the northern hemisphere for each of the 12 months showed results which compared well with actual values and which gave more detail than could be obtained by regression methods. Some possible advantages and applications are discussed.

Introduction. Predictions of contour heights at 1000, 500 and 200 mb are obtained by means of the 2-layer baroclinic forecasting model but the heights at the remaining standard levels and all the temperature fields from 850 to 100 mb were, until recently, obtained by a simple 3-level regression technique. This technique is based on the application of seasonally dependent coefficients to *D*-values (departures from the International Civil Aviation Organization (ICAO) standard atmosphere heights and temperatures) for 1000, 500 and 200 mb.

Woodroffe¹ showed that 4-level regression using 100-mb data would give significantly better results, particularly at 300 mb, and with the introduction of a 100-mb barotropic forecast in June 1968, 4-level regressions were introduced for the standard levels above 400 mb. All the equations now used have variable coefficients according to the season and certain coefficients are functions of the 1000–500-mb thickness. These changes have reduced the large errors, especially those in 200-mb temperatures, which occurred with the 3-level regressions but considerable smoothing of spatial gradients is inevitable with any form of regression. Another disadvantage is the arbitrary date which must be applied for the change of seasonal coefficients for use over all parts of the forecast area, irrespective of latitude or the synoptic situation.

The objectives of this paper are firstly, to describe a method for deriving the vertical temperature profile, including the tropopause discontinuity, over the whole forecast area at any time of the year, from the four forecast heights of the pressure surfaces at 1000, 500, 200 and 100 mb, and secondly, to show that by applying the technique to actual data and so eliminating forecast errors the results achieved by this method give improved representation of temperature gradients both vertically and horizontally, and that temperature profiles so derived will be hydrostatically consistent with the heights at each standard level.

Calculation of the significant tropopause height. The four heights of the pressure surfaces at 1000, 500, 200 and 100 mb and the interconnecting thicknesses cannot possibly specify the detailed structure which is observed on some profiles since the thicknesses are for very deep layers and, used in an unrelated fashion, will give no more than a reasonable estimate of the temperature near the middle of each layer. Marked discontinuities of lapse rate can and do occur within the troposphere at surface and subsidence inversions and in frontal zones, but these rarely match the importance of the discontinuity at the tropopause, where the lapse change is not only very marked but also maintained through deep layers of the atmosphere. It is necessary therefore first to determine the tropopause height before any calculations of the remaining heights and the full temperature profile between

standard levels are possible but, because of the limited amount of information available, a single discontinuity (from now on referred to as the significant tropopause height or H_i) must be assumed.

Before the procedure for calculating H_i is discussed in detail it will simplify the problem if all the facts available from the basic data are determined first. From the four heights of the pressure surfaces at 1000, 500, 200 and 100 mb the three thicknesses 1000–500 mb, 500–200 mb and 200–100 mb may readily be obtained and from these the mean temperatures of the three layers 1000–500 mb, 500–200 mb and 200–100 mb are found by using the thickness equation,

$$z = \frac{RT_m}{g} \log_e \frac{P_o}{P}, \quad \dots (1)$$

in the form

$$T_m = \frac{z}{\frac{R}{g} \log_e \frac{P_o}{P}}, \quad \dots (2)$$

where P_o = pressure at the lower level,
 P = pressure at the upper level,
 R = specific gas constant,
 g = acceleration due to gravity,
 z = thickness of the layer P_o to P , and
 T_m = mean temperature of the layer P_o to P .

It will be convenient to refer to these mean temperatures as $T_{m(10-5)}$, $T_{m(5-2)}$ and $T_{m(2-1)}$ respectively. The difference between $T_{m(10-5)}$ and $T_{m(5-2)}$ is important as it will give an indication of the mean tropospheric lapse rate between the mid points of the 1000–500-mb and 500–200-mb layers provided that both layers are predominantly tropospheric. This mean tropospheric lapse rate Γ , may be expressed in degrees Kelvin per metre by the formula :

$$\frac{T_{m(10-5)} - T_{m(5-2)}}{\left[\frac{R}{g} \log_e \frac{690}{320} \right] [T_{m(10-5)} + T_{m(5-2)}] / 2}, \quad \dots (3)$$

where 690 mb and 320 mb are taken to be the points of intersection of the saturated adiabatics, corresponding to the layer thicknesses, with the mean isothermal temperatures of the layers 1000–500 mb and 500–200 mb respectively, and the expression $[T_{m(10-5)} + T_{m(5-2)}] / 2$ is the mean temperature of the layer from 690 mb to 320 mb.

With no information above the 100-mb surface available, an initial assumption is made that the lower stratosphere is isothermal and that its temperature is approximately equal to $T_{m(2-1)}$. At a later stage of the computations however, it will be shown how this assumption is modified when the final 200-mb temperature is derived.

A starting height and temperature is now required for the H_i calculation. Nothing is known about the temperature at the 1000-mb and 200-mb levels and it seems that the 500-mb level may be the best reference level since a very good estimate of the temperature can be made.

Consider the deep layers 1000–500 mb and 500–200 mb in Figure 1. CX and WQ are the isothermals and DY and ZP are the equivalent saturated adiabatics corresponding to the respective thicknesses. KL represents the mean tropospheric lapse rate between 690 and 320 mb. The temperatures at Y and Z at 500 mb are determined by the saturated adiabatics DY and ZP and will be referred to as T_Y and T_Z respectively. It follows that if ZP and WQ are taken to be the extreme possible values of the *actual* mean lapse rate within the layer 500–200 mb and similarly, if DY and CX represent the extreme values of the *actual* mean lapse rate within the layer 1000–500 mb,

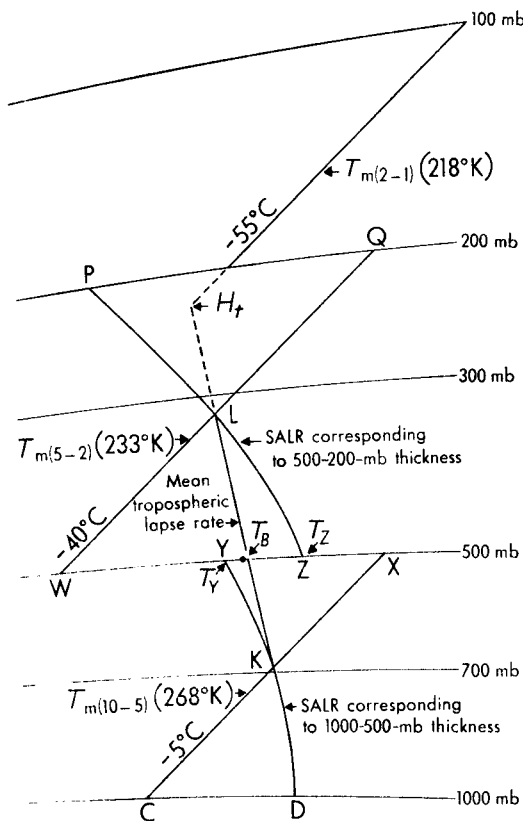


FIGURE 1—SIMPLIFIED TEPHIGRAM SHOWING THE INITIAL COMPUTATIONS WHICH MAY BE MADE FROM THE HEIGHTS OF THE PRESSURE SURFACES AT 1000, 500, 200 AND 100 mb

then the 500-mb temperature should be between the values of Y and Z. It has been found that the actual 500-mb temperature is approximately equal to the mean of W, Y, Z and X and this value should lie very close to the point of intersection of KL with the 500-mb level. This value of the 500-mb temperature will henceforth be referred to as the *B*-value (T_B) and will be used extensively in all the computations where the layers 500–200 mb and 1000–500 mb are predominantly tropospheric. The H_t calculation is now straightforward and proceeds as follows :

$$H_i = \frac{T_B - T_{m(3-1)}}{\Gamma_i} + H_{500} \quad \dots (4)$$

When the stratosphere exists down to or below the 300-mb level, Γ_i and hence the B -value of the 500-mb temperature will be unrealistic and so it is necessary to detect such a situation before the calculations already described are allowed to proceed.

In Figure 2 the effect of a lower tropopause on the relative differences between the mean temperatures of the three layers 1000–500 mb, 500–200 mb and 200–100 mb and also the values of W , Y , X , Z and T_B at the 500-mb level can be seen. An example of an actual profile is shown as a dashed line in Figure 2 and, to simplify comparison with Figure 1, the 500–200-mb thickness is the same in each case and therefore gives the same mean temperature, $T_{m(5-2)} = -40^\circ\text{C}$ (233°K). It will be seen from a study of Figure 2 that the real mean tropospheric lapse rate shown by the actual profile is greater than KL and in fact lies between KL and KY where KY is the saturated adiabatic lapse rate (SALR) corresponding to the 1000–500-mb thickness. The actual 500-mb temperature T_{500} is lower than the B -value

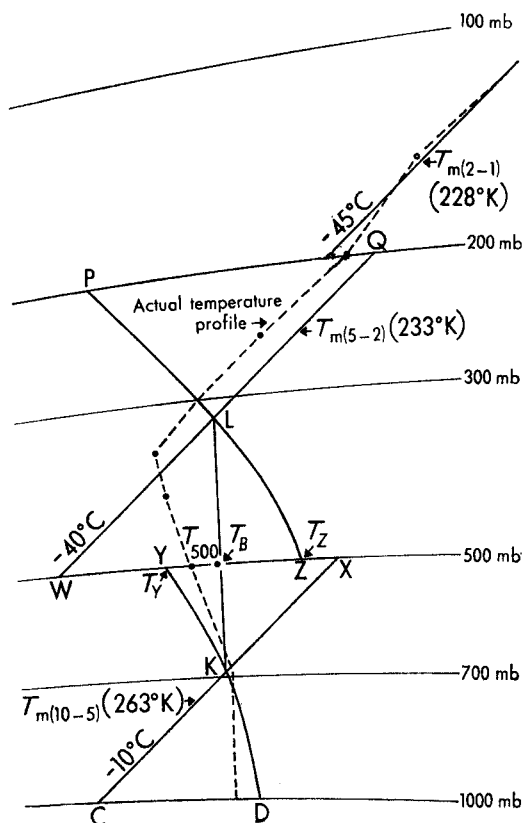


FIGURE 2—AN EXAMPLE OF AN ACTUAL TEMPERATURE PROFILE WITH A TROPOPAUSE BELOW 300 mb SHOWING THE RELATIONSHIP BETWEEN THE B -VALUE (T_B) AND THE ACTUAL 500-mb TEMPERATURE (T_{500})

and lies between the values of T_B and T_Y . With very low tropopause situations, the value of T_Y will be found to approach the temperature at W, i.e. $T_{m(5-2)}$ for two reasons. Firstly, the 1000–500-mb thickness with cold air masses is relatively low (i.e. the mean temperature $T_{m(10-5)}$ will be low) and therefore the upper part of the saturated adiabatic corresponding to the 1000–500-mb thickness will be steeper as the SALR approaches the dry adiabatic lapse rate (DALR) at lower temperatures and secondly, since the stratosphere extends well down into the 500–200-mb layer, the value of $T_{m(5-2)}$ will not decrease by anything like the same amount. In fact in Figures 1 and 2 the values of $T_{m(5-2)}$ are the same, i.e. W has a similar value but Y is $6\frac{1}{2}$ degC lower in Figure 2. Finally, with low tropopause situations, the difference between $T_{m(5-2)}$ and $T_{m(2-1)}$ is normally small and as the stratosphere extends further into the 500–200-mb layer the values of $T_{m(5-2)}$ and $T_{m(2-1)}$ will more nearly approach one another. These facts may be used to make tests on the basic data to determine the type of low tropopause, and the following modifications to equation (4) for obtaining H_i are made at this stage. Firstly, the B -value of T_{500} is revised to T'_{500} by giving an increased weighting to the T_Y value so the the resulting 500-mb temperature to be used in the H_i calculation is actually lower than the B -value and secondly, Γ_i is modified by determining the lapse rate from K to the revised T_{500} value and extrapolating upwards to an isothermal value equivalent to a mean value of $T_{m(5-2)}$ and $T_{m(2-1)}$.

The equation for calculating H_i would now become :

$$H_i = \frac{T'_{500} - \frac{T_{m(5-2)} + T_{m(2-1)}}{2}}{((T_{m(10-5)} + 1) - T'_{500}) / (H_{500} - H_{700})} + H_{500}, \quad \dots (5)$$

where T'_{500} is in degrees absolute and the value of H_{700} is precalculated as follows :

$$H_{700} = H_{500} - \left[\left(\frac{R}{g} \log_e \frac{700}{500} \right) \left(\frac{T'_{500} + (T_{m(10-5)} + 1)}{2} \right) \right]. \quad \dots (6)$$

The expression in square brackets in equation (6) is the thickness of the 700–500-mb layer using the mean temperature obtained by taking the mean of the two temperatures at 500 and 700 mb. Initially the 700-mb temperature is assumed to be equal to the value of $T_{m(10-5)}$ but with the addition of 1 degC to compensate for the fact that the point K is not exactly coincident with the 700-mb level.

The tropopause models. Having achieved the prime object of allocating a height to the significant tropopause discontinuity between the 500-mb and 100-mb levels and also having obtained a starting temperature at 500 mb, the next aim is to break down the deep 500–200-mb layer by calculating the 300-mb height. To do this, the thickness of either the 500–300-mb or the 300–200-mb layer is required and clearly the position of the tropopause is very important. If H_i is well above the 300-mb level a good approximation to the actual 300-mb temperature is obtained by extrapolation of KL in Figure 1 from 320 mb to 300 mb. The 300-mb height can then be calculated by :

$$H_{300} = H_{500} + \left(\frac{RT_m}{g} \log_e \frac{500}{300} \right), \quad \dots (7)$$

where $T_m = \frac{1}{2}(T_{500} + T_{300})$. Conversely, if H_t is calculated to be well below the 300-mb level, then the equation required for obtaining the 300-mb height will be :

$$H_{300} = H_{200} - \left(\frac{RT_m}{g} \log_e \frac{300}{200} \right), \quad \dots (8)$$

where $T_m = \frac{1}{2} \left(T_{300} + \frac{T_{m(2-1)} + T_{m(5-2)}}{2} \right)$.

If the computed value of H_t falls close to the 300-mb level then both equations (7) and (8) must be solved and the mean of the two results taken. It should be pointed out, however, that although the 300-mb level is close to the middle of the deep layer 500–200 mb of which the total thickness is known, the actual value of T_{300} will vary with the change of H_t within the 500–200-mb layer. This variation was found to be surprisingly small and in over 5000 examples tested more than 90 per cent fell within the range of $T_{m(5-2)}$ and $T_{m(5-2)} - 6$.

The value $(T_{m(2-1)} + T_{m(5-2)})/2$ used as a starting temperature at the 200-mb level in equation (8) was found to be accurate enough to obtain a good 300-mb height with the low tropopause types.

It is now possible to use equation (2) to calculate the mean temperatures of the 500–300-mb and 300–200-mb layers and, after making adjustments for height difference, to assign these values to the 400-mb and 250-mb temperatures provided that the tropopause does not intervene.

A series of temperature profiles, each one showing greater detail than its predecessor, are then generated by repeated application of equations (1) and (2) in such a way as to preserve hydrostatic consistency between the four given heights and the derived heights and temperatures. Layer thicknesses are added to or subtracted from the nearest pressure level whose height is given, or just calculated, to produce the heights for the missing standard levels. The calculations are made working upwards within the troposphere and downwards within the stratosphere, to avoid using the layer containing the significant tropopause height. The detailed application of the technique therefore varies with the tropopause height and a series of computing models, known as tropopause models, have been developed to control the computations depending on the value assigned to the significant tropopause height.

The 200-mb temperature. The expression $(T_{m(2-1)} + T_{m(5-2)})/2$ used as the preliminary starting temperature at 200 mb in equation (8), although accurate enough to obtain good results for the 300-mb height with low tropopause situations, cannot be accepted as the final 200-mb temperature. This temperature is the most difficult value of all to deduce from the limited basic data available and the problem is made more complex by the fact that the average tropopause lies close to this level and that the 100-mb height is obtained by an independent barotropic forecast. The initial assumption that the lower stratosphere is isothermal would mean that the 200-mb temperature would equal the value $T_{m(2-1)}$ in all cases where the significant tropopause height was calculated to be below the level of the 200-mb surface. Such an assumption would clearly lead to gross errors in the 200-mb temperature in an unacceptably large number of cases. However, if the original

assumption that the whole 200–100-mb layer is isothermal is restricted to the 150–100-mb layer, then a preliminary 150-mb height may be obtained by the equation :

$$H_{150} = H_{100} - \left[\left(\frac{R}{g} \log_e \frac{150}{100} \right) (T_{m(2-1)}) \right], \quad \dots (9)$$

where the expression in square brackets is the thickness of the 150–100-mb layer.

At this stage of the computations there are several possible 200-mb temperature values which must be considered. They are :

- (a) The $T_{m(2-1)}$ value.
- (b) The temperature at the 200-mb level derived by using the lapse rate from T_{250} at H_{250} to T_{150} at H_{150} provided that H_t does not lie between the 250-mb and 150-mb levels.
- (c) The temperature at the 200-mb level derived by extrapolation of the lapse rate from T_{300} at H_{300} to T_{250} at H_{250} provided that H_t does not lie between the 300-mb and 200-mb levels.
- (d) The temperature at the 200-mb level derived by using the lapse rate from :
 - (i) the temperature T_t at the significant tropopause height to T_{150} at H_{150} when H_t is below the 200-mb level, or
 - (ii) T_t to T_{250} at H_{250} when H_t is above the 200-mb level.

These values may be calculated by means of the following equations :

$$a = T_{m(2-1)}, \quad \dots (10)$$

$$b = T_{250} - \left[\frac{(H_{200} - H_{250})(T_{250} - T_{150})}{(H_{150} - H_{250})} \right], \quad \dots (11)$$

$$c = T_{250} - \left[\frac{(H_{200} - H_{250})(T_{300} - T_{250})}{(H_{250} - H_{300})} \right], \quad \dots (12)$$

$$d(i) = T_t - \left[\frac{(H_{200} - H_t)(T_t - T_{150})}{(H_{150} - H_t)} \right], \quad \dots (13)$$

where T_t is precalculated as follows :

$$T_t = T_{250} - \left[\frac{(H_t - H_{250})(T_{300} - T_{250})}{(H_{250} - H_{300})} \right], \quad \dots (14)$$

$$d(ii) = T_{250} - \left[\frac{(H_{200} - H_{250})(T_{250} - T_t)}{(H_t - H_{250})} \right], \quad \dots (15)$$

where $T_t = T_{m(2-1)}$.

The actual value used in the final computations within each tropopause model will, of course, depend on the significant tropopause height calculation, but it has been found necessary to use combinations of these values in models where H_t lies between the 150-mb and 250-mb levels.

The tropopause temperature. As stated earlier, the calculations within each tropopause model are designed to operate upwards through the tropo-

sphere and downwards through the stratosphere in order to avoid the layer between two standard levels containing the tropopause itself. It follows therefore that the thickness of this layer becomes available after all the other work has been completed. Equation (2) is now used again to find the mean temperature of this layer in which the tropopause lies and the tropopause temperature may now be fitted to the profile such that the temperature assigned to H_t is as consistent as possible with the thickness of the layer.

If the mean temperature of the layer containing the tropopause is represented by x° and P_t is the significant tropopause pressure converted from H_t , then the tropopause temperature may be calculated by the equations :

$$T_t = x - \frac{(\frac{1}{2}(P_o + P) - P_t)(x - T_1)}{\frac{1}{2}(P_o - P)}, \quad \dots (16)$$

when $P_t \leq \frac{1}{2}(P_o + P)$, or

$$T_t = x + \frac{(P_t - \frac{1}{2}(P_o + P))(T_2 - x)}{\frac{1}{2}(P_o - P)}, \quad \dots (17)$$

when $P_t > \frac{1}{2}(P_o + P)$; temperatures T_1 and T_2 refer to the upper and lower pressure levels P and P_o of the layer.

The alternative would be to compute the lapse rates immediately above and below the layer and by extending them to H_t to obtain the tropopause temperature by taking a mean of the two results. The objection to this is that it would take no account of the thickness of the layer containing the tropopause and might lead to some inconsistencies in the final profile.

Results. This type of repetitive calculation is ideally suited to the electronic computer and so an ALGOL programme was written and developed to perform the required computations on actual data so that results could be compared with actual values. The data used for this work were the 00 GMT upper air observations received at the Central Forecasting Office (CFO) for the 15th of each month from January 1968 to December 1968 except that data for January 1968 were replaced by those for January 1967 for technical reasons. All observations which passed a simple quality control were used and the total number of ascents exceeded 4500 taken from all parts of the northern hemisphere.

The four heights of the surfaces at 1000, 500, 200 and 100 mb were extracted from each observation in turn and the computations made to deduce the heights at the remaining standard levels and the full temperature profile. The results obtained were then compared with the actual values at each level and a statistical summary of the errors for both height and temperature was made. The results are reproduced in Table I.

It should be remembered that the technique described in this paper deliberately sets out to achieve detail, where detail exists, and so attempts to avoid the 'middle-course' approach typical of many forms of regression. In some situations however, the tropopause modelling technique will give incorrect results which are reflected in the overall statistics in Table I. For example, when a double-tropopause situation exists in the actual temperature profile, then the significant tropopause must be a compromise and will result

TABLE I—STATISTICAL SUMMARY OF HEIGHT AND TEMPERATURE ERRORS OBTAINED BY APPLYING THE TROPOPAUSE MODELLING TECHNIQUE TO ACTUAL DATA USING THE HEIGHTS AT 1000 mb, 500 mb, 200 mb AND 100 mb

1967 January 1968 February March April May June July August September October November December Overall results	No. of obs.	(a) Mean height errors and standard deviations										(b) Mean temperature errors and standard deviations									
		Standard levels (mb)										Standard levels (mb)									
		850	700	400	300	250	150	geopotential metres				850	700	500	400	300	200	150	100	degrees Celsius	
	Mean	+7	0	-1	0	-2	+1					+0.1	-0.9	+0.1	0	0	-0.3	-0.1	-0.2		
	σ	18	17	16	24	17	13					2.7	1.7	2.3	2.2	1.6	2.6	1.2	2.5		
	Mean	+9	+3	-3	-3	-6	-5					+0.5	-0.9	-0.2	-0.4	0	-0.6	-0.3	+0.9		
	σ	16	17	13	22	16	14					2.8	1.6	2.0	1.9	1.6	2.5	1.1	2.4		
	Mean	+4	0	-2	-3	-5	-4					+0.6	-0.6	-0.2	-0.4	+0.1	-0.6	-0.3	+0.6		
	σ	16	18	15	25	19	15					2.7	1.8	2.3	2.2	1.6	3.2	1.1	2.3		
	Mean	-2	-6	0	-1	-4	0					0	-0.2	+0.6	-0.3	-0.1	+0.1	-0.1	-0.4		
	σ	13	13	11	18	14	12					2.3	1.5	1.7	1.7	1.4	2.3	1.1	2.1		
	Mean	+1	-5	-1	0	-3	+2					+0.1	-0.5	+0.5	-0.2	+0.1	+0.1	+0.1	-0.9		
	σ	14	15	13	22	17	14					2.2	1.4	1.9	1.9	1.6	2.8	1.2	2.5		
	Mean	-1	-5	-4	-3	-5	+1					+0.4	-0.2	+0.2	-0.6	+0.4	-0.3	+0.3	-0.9		
	σ	12	12	11	19	16	16					2.0	1.4	1.6	1.6	1.4	2.8	1.2	2.8		
	Mean	-2	-5	-5	-5	-6	-2					+0.6	-0.2	+0.1	-0.7	+0.4	-0.8	+0.4	-0.5		
	σ	12	12	12	22	17	14					2.0	1.4	1.6	1.8	1.5	2.8	1.3	2.8		
	Mean	-1	-4	-5	-5	-6	-3					+0.7	-0.3	+0.1	-0.8	+0.3	-0.5	+0.2	-0.7		
	σ	11	12	11	19	17	14					2.2	1.4	1.7	1.5	1.4	2.9	1.2	2.6		
	Mean	-1	-4	-3	-2	-5	-1					+0.9	-0.1	+0.2	-0.4	+0.3	-0.6	+0.2	-0.7		
	σ	11	12	11	19	16	16					2.1	1.3	1.5	1.6	1.4	3.0	1.1	2.6		
	Mean	-1	-6	0	0	-1	-2					+0.3	-0.3	+0.6	-0.3	+0.2	-0.9	+0.3	-0.6		
	σ	12	13	11	20	15	14					2.0	1.3	1.8	1.6	1.3	2.6	1.3	2.5		
	Mean	+7	+1	-4	-5	-4	0					+0.7	-0.9	0	-0.6	+0.2	-0.3	0	-0.2		
	σ	14	15	14	24	19	14					2.5	1.5	2.1	1.9	1.2	2.4	1.1	2.4		
	Mean	+11	+6	-4	-4	-5	0					+1.0	-1.1	-0.3	-0.4	-0.1	0	-0.2	+0.2		
	σ	16	17	14	24	16	14					2.6	1.7	2.1	2.0	1.6	2.5	1.2	2.7		
	Mean	+3	-2	-3	-3	-4	-1					+0.5	-0.5	+0.2	-0.4	+0.1	-0.4	0	-0.3		
	σ	14	14	13	21	17	14					2.3	1.5	1.9	1.8	1.5	2.7	1.2	2.5		

σ = Standard deviation.

in errors of both height and temperature in the layers near the tropopause, but experience has shown that the results achieved by 4-level regression techniques show similar errors in these situations.

It may be argued that since the results shown in Table I are based on actual data then, if the tropopause modelling technique is used on forecast heights, any forecast errors should be combined with these results. This is of course correct but it should be borne in mind that no allowance has been made in the statistics shown in Table I for either random or standard radiosonde errors in the data used and that all the included observations from all parts of the northern hemisphere were therefore accepted as perfect.

The reader may be interested to see the charts reproduced in Figures 3, 4 and 5. Figure 3 shows the 24-hour forecast of 500-mb temperature for 00 GMT on 11 December 1968 produced by the tropopause modelling technique, and Figure 4 is the chart produced by regression methods using the same forecast data. Figure 5 is the actual 500-mb temperature pattern

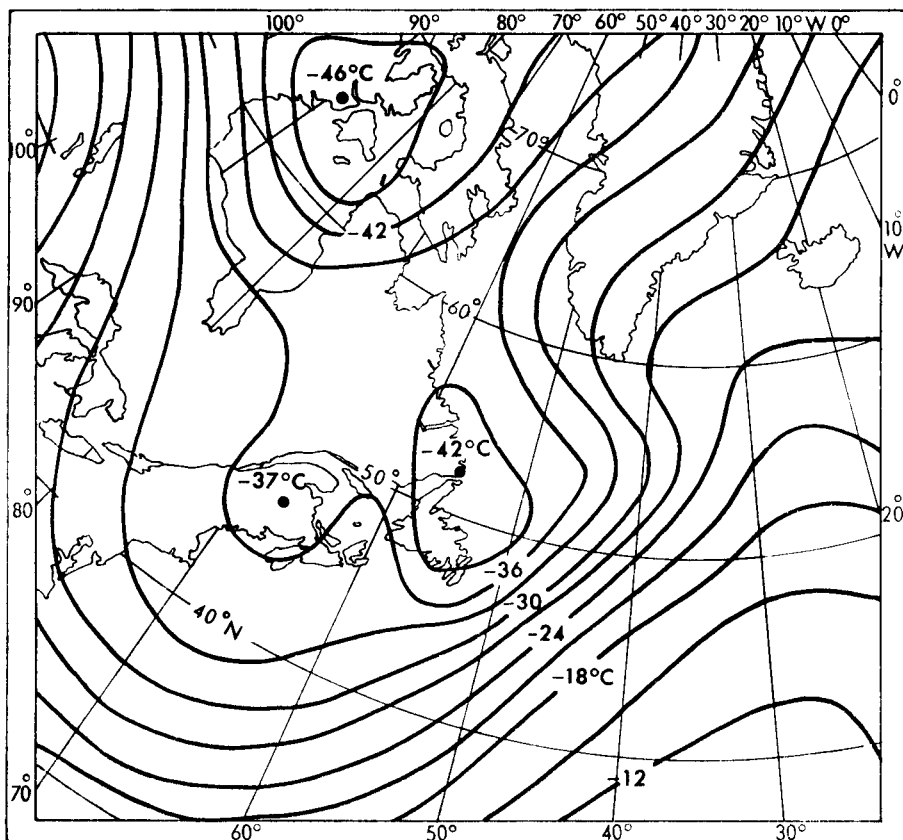


FIGURE 3—24-HOUR FORECAST OF 500-mb TEMPERATURE FOR 00 GMT, 11 DECEMBER 1968, DERIVED BY THE TROPOPAUSE MODELLING TECHNIQUE USING THE FOUR FORECAST HEIGHTS OF THE SURFACES AT 1000, 500, 200 AND 100 mb
Isoleths are at intervals of 3 degC.

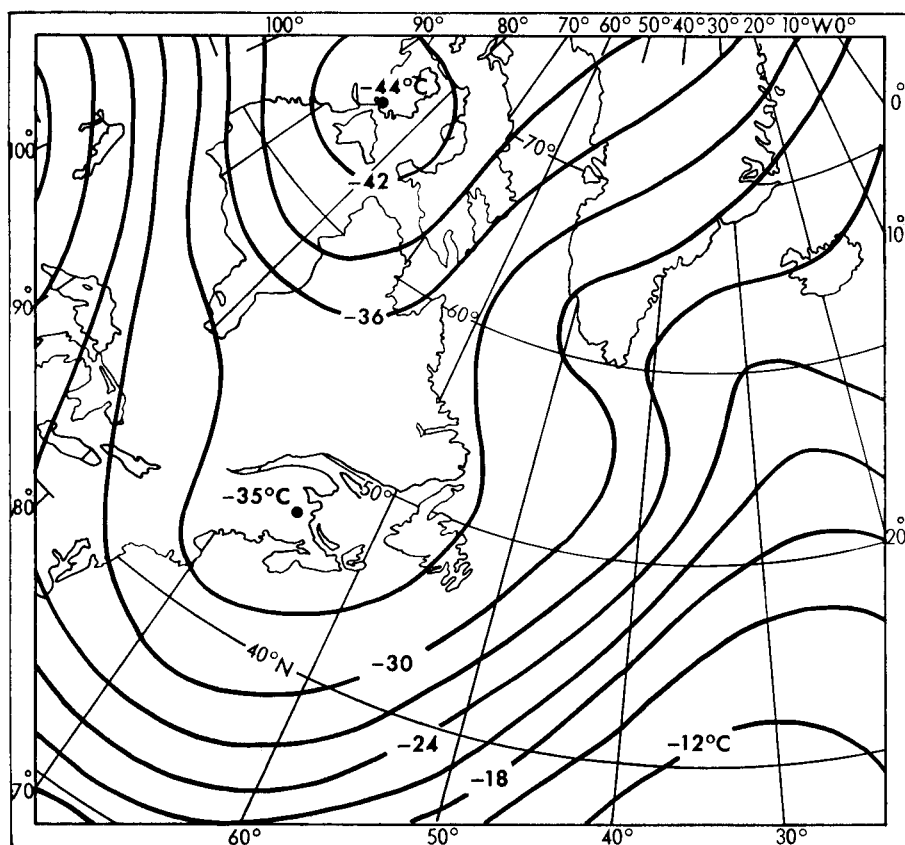


FIGURE 4—24-HOUR FORECAST OF 500-mb TEMPERATURE FOR 00 GMT, 11 DECEMBER 1968, CALCULATED BY REGRESSION EQUATIONS USING THE SAME FORECAST HEIGHTS AS THOSE USED IN FIGURE 3

at the time of verification drawn in CFO. This is a good example of the detail which can be extracted from the four forecast heights by using this method and it is interesting to notice the way in which the detail is lost in Figure 4 particularly over the north-west Atlantic.

Discussion. The tropopause modelling technique offers an alternative to regression methods for obtaining heights and temperature profiles not provided by the main forecast model. On the information at present available it has many advantages and applications and some of the more important ones may be briefly summarized as follows :

- (i) It will function without the necessity of using variable seasonal coefficients and is virtually independent of latitude.
- (ii) The computational procedures within the models work on forecast data, limited though these may be, without any reference to the ICAO Standard Atmosphere and therefore *D*-values are unnecessary.
- (iii) The method uses the basic material provided by the main forecast programme to calculate the significant tropopause height and

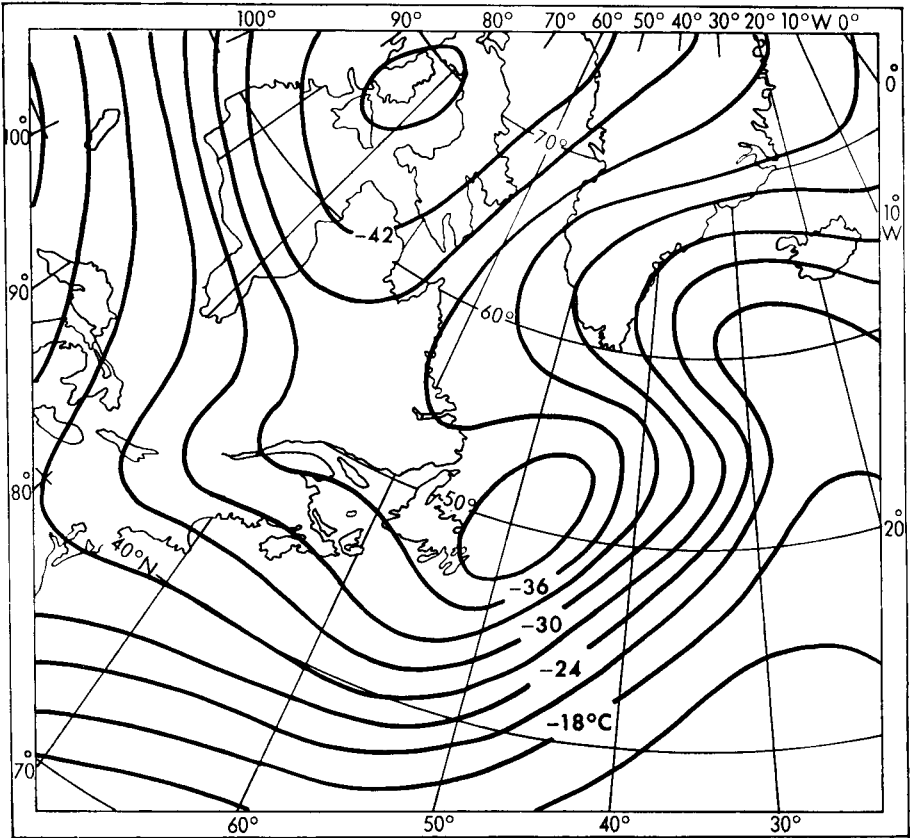


FIGURE 5—THE ACTUAL 500-mb TEMPERATURE CHART FOR 00 GMT, 11 DECEMBER 1968, DRAWN FROM THE CENTRAL FORECASTING OFFICE CHART

temperature as well as the heights and temperatures of the remaining standard levels. Forecast tephigrams could therefore be extracted for any grid point in the forecast area.

- (iv) Because the technique is based on the thickness equation, hydrostatic consistency between levels is assured, and the introduction of a significant tropopause discontinuity increases the prospect of identifying and maintaining more precise vertical and horizontal wind shears.
- (v) Charts of the significant tropopause height and the freezing-level height could be added to the operational output.
- (vi) By assuming H_i to be approximately the height of the maximum wind, it should be possible to use the temperature profiles and vertical wind shears above and below the level of H_i to produce a maximum wind chart. This possibility is being investigated.
- (vii) The technique described in this paper, although intended for use with the forecast heights at 1000, 500, 200 and 100 mb provided by the main forecast model, could be applied equally well to the analysis programmes. Contour charts derived in this way would obviate the necessity for a multi-level computed analysis which would

take up considerably more computer time with no assurance of better results over the sparse data areas such as the North Atlantic.

There are, of course, some disadvantages also and they may be briefly summarized as follows :

- (i) By definition the significant tropopause height implies a single major discontinuity. Should there be in fact two such discontinuities, then a compromise result will be obtained but, at least, the results under these circumstances will be very little different from those produced by regression.
- (ii) Since the method is aimed at an improved representation of spatial gradients of both height and temperature it must therefore increase the chance of generating larger errors at a point in space when the forecast heights from the basic forecasting model are seriously in error.

Acknowledgements. The author wishes to thank Mr R. Dixon and Mr E. A. Spackman for their advice and help with ALGOL programming. Acknowledgement is also made to Mrs M. Odell and Mrs M. Holmes of Met. O. 2b for the considerable amount of work involved in translating the ALGOL programme for use with the COMET operational programmes.

REFERENCE

1. WOODROFFE, A.; A regression technique for objective forecasts at 300 mb. *Met. Mag.* London, 95, 1966, p. 129.

LETTER TO THE EDITOR

551·577·61:551·578·72(761/769)

Storm damage in Texas

Having just returned from one of my quick dashes across to the west coast, I write to tell you of an unusual weather experience while it is fresh in my mind.

On Tuesday, June 17, we drove into Amarillo, Texas Panhandle, at about 9.30 p.m. (fortunately picking the north side) under a wild sky — having completed 800 miles that day. We freshened up, had a drink and were in the local restaurant by 9.50 p.m. At 9.59 it started to rain very heavily for about 15 minutes and we fortunately were on the fringe of a storm. Returning to our motel, we found all the television programmes were cut so that the local station with some five outside reporters could give a blow-by-blow report of the damage which occurred in the south-west area (where we had been an hour before the storm broke).

The centre of the storm which hit the town apparently was about 1 mile in diameter and moving south-east. The hail was reported by eye-witnesses on the television as being the size of baseballs and in 10 minutes built up to 10 inches deep on the ground. Over 50 per cent of shop windows in the area and practically all house windows were broken, roofs were caved in and owners tied their cars to trees to prevent them being washed away by the flash floods which quickly followed (the temperature before the storm was 92°F). It was estimated in the town, by comparison with a less severe storm in 1963, that the damage caused in 10 minutes was \$5 000 000.

Even the following morning, the normal dry washes which, as you know, run across the open country, were quite full of water.

Amazing. Any aircraft in this, even on the ground, would, I am sure, be a little bent.

R. J. FENNER

(Representative in the U.S.A. of the Air
Registration Board)

NOTES AND NEWS

551.578.466:77

Snow rollers at Kirkwall, Orkney

At 1500 GMT on 13 February 1969, large cylinders of snow were noticed lying on a snowbed some 50 yards from the Meteorological Office at Kirkwall Airport, Orkney (see Plate IV). The snowbed was on a shallow slope facing north where the snow had drifted, and was about 18 cm deep. Most of this was old snow but over this was about 1 to 2 cm of fresh snow. The cylinders, 3 large ones and numerous tiny ones, had formed and rolled uphill downwind. Their tracks were visible and measured about 10 metres in length. The largest cylinder was 35 cm long and 31 cm in diameter. The ends were hollowed out and the movement and growth could be seen from the shape of the track. It was deduced that they had formed during a squall at about 1435 GMT when the wind increased from 360°/12 kt to 360°/28 kt in a few seconds, as they had not been noticed prior to this. While measuring the cylinders it was noticed that small balls of dislodged snow were rolling uphill in the same manner. Although the sudden increase of wind was assumed to be the cause, the possibility that they had been caused by the slipstream of a light aircraft at about the same time could not be ruled out. The weather conditions during the period are given below :

Time GMT	Wind degrees/kt	Weather	Dry-bulb temperature degrees C	Relative humidity per cent
1250	300/12	snow shower	+0.8	80
1305	310/14	moderate snow shower		
1320	330/12	moderate snow shower		
1350	270/07	moderate snow shower	-0.3	96
1418	350/12	snow grains	+0.4	
1435	360/28	squall		
1450	340/31 gusting to 43	snow shower	+0.5	93

W. Kuhn¹ records a similar phenomenon and states that in Switzerland snow rollers are said to be exceptional. A. N. Tucker² records their formation at Kinloss, Morayshire.

N. ELKINS and D. LINKLATER

REFERENCES

1. KUHN, W.; Snow cylinders at Geltwil, Switzerland. *Met. Mag., London*, 97, 1968, p. 350.
2. TUCKER, A. N.; Snow rollers at Kinloss airfield, 2 April 1968. *Met. Mag., London*, 97, 1968, p. 192.

REVIEW

Catalog of meteorological instruments in the Museum of History and Technology, By W. E. Knowles Middleton. 285 mm × 215 mm, pp. v + 128, illus., Smithsonian Institution Press, Washington, D.C., 1969. Price: \$3.25.

This catalogue is much more than a listing and description of items in the Smithsonian collection. It contains a brief history of meteorological instruments illustrated by photographs of examples in that collection. As the author points out, museums acquire scientific instruments largely by chance and to some extent the resulting collections are unbalanced. Further, many instruments when received are not in a fit state for exhibition, as, more often than not, they require expert restoration. This is particularly so with certain types of meteorological equipment which, throughout their working lives, have been exposed to the weather. The Smithsonian collection is no exception to this general experience. Examples of thermometers, barometers and barographs are numerous whereas anemometers and wind vanes are held in relatively small numbers.

Following an introduction, the catalogue is divided into 10 chapters, each dealing with a particular instrument or group of instruments. With the author's remarks in mind, it is no surprise to find that Chapter 2 — barometers and barographs — extends to some 25 pages whereas Chapter 9 — upper air instruments, not telemetering — extends to 5 pages.

The book can be read as a story and, despite a degree of imbalance, is a valuable introduction to the history of meteorological instruments. The pictures and the general presentation are pleasing. The author must be congratulated for producing a catalogue in this form.

N. E. RIDER

OFFICIAL PUBLICATION

The following publication has recently been issued :

Observer's handbook, Third Edition.

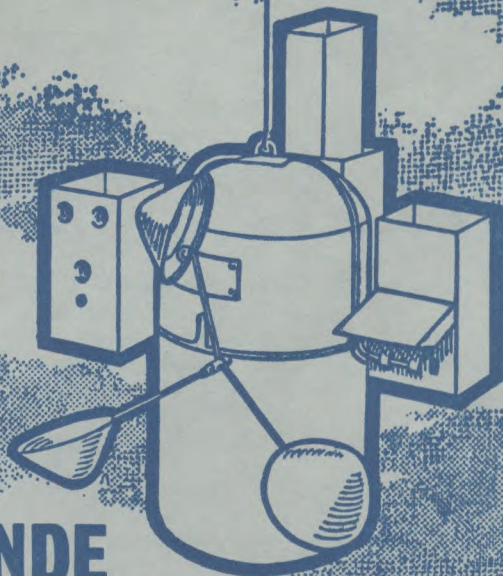
This new edition of the *Observer's handbook* incorporates many changes in observational procedures accepted within the past few years within the World Meteorological Organization including new definitions of clouds and 'meteors' and new instructions and nomograms for the determination of visibility at night. Many plates and diagrams are new, including a completely new set of cloud photographs.

This book will help both the amateur and professional meteorologist to make good observations of the weather. Details of international coding procedures which are subject to revision from time to time have been omitted but the sources of these procedures are indicated where necessary. Fairly detailed instructions, however, are given for recording observations at climatological stations and health resort stations. Metric units have been used wherever practicable and new tables are consequently included.

CORRECTION

Meteorological Magazine, May 1969, p. 142, Table I, Type 6, row of figures should read : 77 1·7 33 1·5 39 1·3

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NOTICES

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